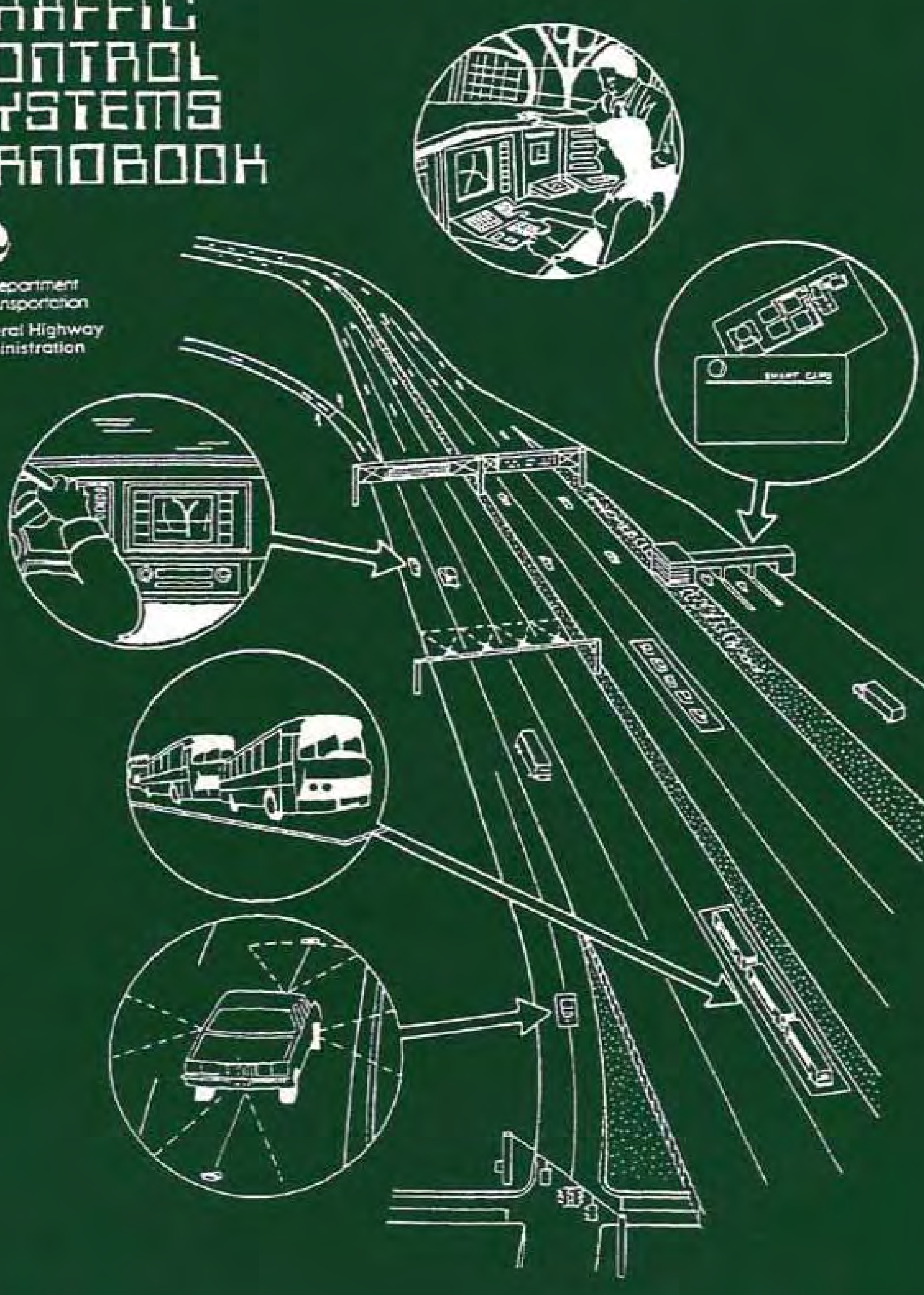
TRAFFIC CONTROL SYSTEMS HANDBOOK

U.S. Department of Transportation
Federal Highway Administration



FOREWORD

This handbook provides an easy-to-use reference on traffic control systems. It recommends decision-making processes in selection, implementation, and operations of a traffic control system.

The handbook should prove useful to agencies considering the implementation, upgrading, or expansion of a traffic control system, as well as by system designers responsible for making decisions on the various features of the system. The handbook also targets administrators, traffic engineers, transportation planners, and students. The cost data provided generally represent the state-of-the-practice at the time of handbook preparation; however, handbook users should develop their own cost data for analysis of specific projects.

NOTICE

Publication Number: FHWA-SA-95-032
HTA-30/5-96(3M)EW
February 1996

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yards	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3

NOTE: Volumes greater than 1000 l shall be shown in m^3.

Symbol	When You Know	Multiply By	To Find	Symbol
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5(F-32)/9 or (F-32)/1.8	Celcius temperature	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.71	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	Celcius temperature	1.8C + 32	Fahrenheit temperature	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

Technical Report Documentation Page

1. Report No. FHWA-SA-95-032	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Traffic Control Systems Handbook		5. Report Date February, 1996 6. Performing Organization Code
7. Author(s) Robert L. Gordon, Robert A. Reiss, Herman Haenel, E. Ryerson Case, Robert L. French, Abbas Mohaddes, and Ronald Wolcott		8. Performing Organization Report No.
9. Performing Organization Name and Address Dunn Engineering Associates 66 Main Street Westhampton Beach, NY 11978		10. Work Unit No. (TRAIS) 11. Contract or Grant No. DTFH61-92-C-00103
12. Sponsoring Agency Name and Address Department of Transportation Federal Highway Administration Office of Technology Applications 400 Seventh Street, SW Washington, DC 20590		13. Type of Report and Period Covered Final Report July 1992 - January 1996 14. Sponsoring Agency Code

15. Supplementary Notes

FHWA Contracting Officer Technical Representative (COTR): John McCracken (HTA-32)

16. Abstract

This *Traffic Control Systems Handbook* updates the 1985 edition (FHWA IP-85-11) and broadens the scope to include ITS technology and concepts. The Handbook recommends decision-making processes in selection, implementation and operations of a traffic control system and describes ITS plans and programs.

The *Traffic Control Systems Handbook*:

- Serves as a basic reference in planning, designing and implementing effective traffic control systems,
- Provides an updated compendium of existing traffic control technology for the advanced designer and user,
- Describes existing and evolving traffic control system technology, and
- Aids understanding and facilitates training in the traffic control system field.

The Handbook targets:

- Administrators,
- Traffic engineers,
- Transportation planners, and
- Students.

In addition to summarizing the state-of-the-practice, chapters include *A Look to the Future* section where appropriate. In this way, the material separates *proven* technology from systems and elements currently under development.

17. Key Words traffic control systems, freeway traffic management systems, integrated traffic management systems, detectors, controllers, communications, intelligent transportation systems, traveler information systems, measures of effectiveness	18. Distribution Statement No Restrictions. This Document is available to the public through the National Technical Information Service, Springfield, Virginia 22161

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of pages	22. Price
Unclassified	Unclassified	684	

Form DOTF 1700.7 (8-72) Reproduction of completed page authorized

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Executive summary

This *Traffic Control Systems Handbook* updates the 1985 edition (FHWA IP-85-11) and broadens the scope to include ITS technology and concepts. The Handbook also recommends decision-making processes in selection, implementation and operations of a traffic control system.

The *Traffic Control Systems Handbook*:

- Serves as a basic reference in planning, designing and implementing effective traffic control systems,
- Provides an updated compendium of existing traffic control technology for the advanced designer and user,
- Describes existing and evolving traffic control system technology, and
- Aids understanding and facilitates training in the traffic control system field.

The Handbook targets:

- Administrators,
- Traffic engineers,
- Transportation planners, and
- Students.

The Handbook organization follows a basic *systems engineering* approach, i.e., the material covers:

- Control concepts,
- Hardware elements,
- System selection and implementation,
- Ongoing system management, and
- Intelligent Transportation Systems (ITS).

The Handbook covers *control concepts* in the following chapters:

- Available and Emerging Traffic Control Systems Technology assists users in the overall system selection process.
- Control Concepts – Urban and Suburban Streets discusses control concepts, practices and operational experience,
- Control and Management Concepts – Freeways discusses freeway control concepts, implementation, installation and operation, and
- Control and Management Concepts – Integrated Systems discusses high-level traffic control and management strategies.

The Handbook covers *hardware elements* in the following chapters:

- *Detectors* discusses methods of traffic detection,
- *Local Controllers* discusses types of controllers and applications,
- *System Controllers* discusses concepts and traffic systems hardware,
- *Communications* provides an overview of data communications, and
- *Traveler Information Systems* provides information on modes of communication to the driver.

The Handbook covers *System Selection and Implementation* in the following chapters:

- *Selection of a System* provides direction and guidance for system selection, and
- *Design and Implementation* provides insight for design, procurement and installation of a system.

The Handbook discusses *ongoing traffic systems management* in the chapter, *Systems Management*.

Finally, the Handbook overviews ITS activities in the chapter, *ITS Plans and Programs*.

In addition to summarizing the state-of-the-practice, chapters include *A Look to the Future* section where appropriate. In this way, the material separates *proven* technology from systems and elements currently under development.

CHAPTER 1
INTRODUCTION

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CHAPTER 1
INTRODUCTION

Photo courtesy of Texas Department of Transportation

Figure 1-1. Contemporary traffic operations display.

1.1 SCOPE AND OBJECTIVES

In 1985, the Federal Highway Administration published the second edition of the *Traffic Control Systems Handbook* to present basic technology used in planning, designing, and implementing traffic monitoring and control systems for urban street and freeway applications. That publication presented a compendium of applicable technology, concepts, and practice in the traffic control field. It proved useful in:

- Fostering understanding and acceptance of such systems, and
- Implementing proven advances in traffic monitoring and control.

This updated version of the *Traffic Control Systems Handbook* aims to:

- Retain valuable material and basic scope from the second edition, and
- Update discussions of concepts and equipment to reflect the current state of the art.

Specifically, the revised Handbook deals with:

- Advances in control technology,
- Real-world applications experience, and
- Other emerging technologies which include Intelligent Vehicle Highway Systems (IVHS).

This updated version of the *Traffic Control Systems Handbook* maintains the following major objectives:

- Provide a compendium of existing traffic control system technology,
- Aid understanding of the basic elements of traffic control systems,
- Broaden the viewpoint of the traffic management field,
- Serve as a basic reference for the practicing traffic engineer in planning, designing, and implementing new and effective traffic control systems, and
- Serve as a training aid in the field of traffic control systems.

The Handbook targets a wide range of potential users - administrators, roadway designers, and traffic operations engineers, both experienced and newly assigned.

Handbook readers may also find useful other handbooks published by FHWA. These include:

- Freeway Incident Management Handbook (1),
- Communications Handbook for Traffic Control Systems (2), and
- Traffic Detector Handbook (3).

1.2 ORGANIZATION OF HANDBOOK

This *Traffic Control Systems Handbook* retains the basic systems engineering organization used in the second edition. The material covered deals progressively with:

- Control concepts,
- Individual hardware elements,
- Guidance on how to select and implement a system, and
- A discussion on ongoing system management.

Table 1-1 summarizes overall handbook organization.

1.3 ROLE AND IMPACT OF TRAFFIC CONTROL SYSTEMS

The traffic signal impacts virtually everyone every day. Even on uncongested routes, stops at traffic signals punctuate an urban or suburban area trip. School children obediently wait for a traffic signal to interrupt traffic so they can cross a busy thoroughfare. Drivers confidently place their own and their passengers' physical safety in a signal's allocation of right-of-way.

People accept and in some cases demand traffic signals to assure safety and mobility. Drivers usually assume that the responsible agency can efficiently operate signals, so motorists usually report only the most obvious failures. Inefficient operation annoys some motorists but produces no strong public reaction. However, inefficiencies silently steal dollars from the public in increased fuel cost and longer trip times. Users normally perceive signals as working if they turn red and green; if they operate suboptimally, this becomes a concern, not a crisis.

Research and application demonstrate the effectiveness of signal system improvements in reducing the incidence of:

- Delays,
- Stops,
- Fuel consumption,
- Emission of pollutants, and
- Accidents.

The systematic *optimization of signal timing plans* in most signal systems represents an essential continuing element of traffic control system management. Achieving this optimization is labor intensive and costly for most existing traffic control systems. As a result, the number of timing plans and the frequency with which they are updated is often limited by the resources available to perform these functions.

Certain traffic systems have been termed *adaptive*, i.e., they have the capability to automatically change the signal timing in response to both short term and longer term variations in traffic. These systems not only provide more effective control of traffic, but also require fewer human and financial resources to update the system's database. However, they often require more extensive deployment of traffic detectors.

1.4 TRAVEL DEMAND MANAGEMENT (TDM)

A highly developed system of streets, highways, freeways, and some form of public transportation serves most North American cities. Growth in travel demand, however, seems to outpace the ability to provide new or expanded facilities and service. This pressure places great emphasis on reducing travel demand to *reduce the loading of facilities*, particularly at peak hours.

The wide spectrum of TDM actions includes:

- Promotion of non-auto and high-occupancy vehicle (HOV),
- Preferential treatment of high-occupancy vehicles,
- Reduced peak period travel,
- Preferential parking for HOV,
- Telecommuting,
- Non-standard work week such as four 10 hour days, and
- Transit and paratransit service improvements.

Table 1-1. Organization of handbook chapters.

Chapter Number	Chapter Title	Purpose	Topics
2 Control Overview	• Available and Emerging Traffic Control Systems Technology	• Assist users in the overall system selection process	• Control and management system functions • Range of agency needs • Range of options available • Available technology • A look to the future
3 Control Concepts	• Urban Concepts — Urban and Suburban Streets	• Discuss control concepts, practices, and operational experiences	• Control variables • Sampling • Filtering and smoothing • Traffic signal timing parameters • Traffic signal phasing • Isolated intersection • Arterial street control • Network control • Incremental benefits of control • Special control • A look to the future
4 and 5 Control and Management Concepts	• Control and Management Concepts — Freeways	• Discuss freeway control concepts, implementation, installation, and operation	• Ramp metering • Exit ramp control • Mainline control • Incident management • Integration • High occupancy vehicle priority control • A look to the future
	• Control and Management Concepts — Integrated Systems	• Discuss high-level traffic control and management strategies	• Traffic corridors • Strategies for control of traffic corridors • A look to the future
6 - 10 Hardware Elements	• Detectors	• Discuss methods of traffic detection	• Types of detectors • Detector operations summary • Vehicle detector locations and configuration • Emerging detector technology • A look to the future
	• Local Controllers	• Discuss types of controllers and applications	• Types of operation • Range of applications • Controller evolution • Types of local controllers • Pretimed controller • Full-actuated controllers • Model 170 and NEMA controllers • Local controller coordination • Factors in controller selection • New controllers • A look to the future

Table 1-1. Organization of handbook chapters (continued).

Chapter Number	Chapter Title	Purpose	Topics
6 - 10 (continued) Hardware Elements	• System Control	• Describe concepts and hardware of traffic systems	• Arterial, small network and closed-loop systems • UTCS and derivative systems • Other network based systems • Time-base coordination (TBC) • Optional control and other software features • Freeway operations center • Traffic operations center concepts • Software availability • A look to the future
	• Communications	• Provide an overview of data communications	• Basic concepts • Alternative communication media and technologies for traffic systems • Communication system planning
	• Traveler Information Systems	• Provide information on modes of communication to the driver	• Static signs • Changeable message signs • Transportable signs • Highway advisory radio • Motorist aid systems • Citizens Band (CB Radio) • Commercial radio • Cellular mobile phone systems • Lane control signals • In-vehicle information, navigation, and route guidance systems • A look to the future
11 and 12 Selection and Implementation	• Selection of a System	• Provide necessary direction and guidance for system selection	• Federal-Aid requirements • System selection process
	• Design and Implementation	• Provide necessary insight for design, procurement and installation of a system	• System implementation • Procurement approach • Design plans and specifications • Deliverable services • Project management • Implementation pitfalls
13 Ongoing System Management	• Systems Management	• Discuss traffic systems management	• A system management team concept • Operation of traffic control systems • Staff requirements and organization • Maintenance of traffic control system
14 ITS	• ITS Plans and Programs	• Provide overview of ITS activities	• Current U.S. ITS programs • Worldwide ITS programs • ITS planning in the U.S. • ITS standards

Many TDM measures impact or depend on the efficient and effective use of:

- Traffic signal systems,
- Freeway monitoring and control systems, and
- Traveler information systems.

For example:

- Efforts to promote transit usage become less effective if buses meet unnecessary delay from inefficiently operated signals, and
- Vanpool and transit usage become more attractive, if these vehicles can travel on uncongested high occupancy vehicle freeway lanes.

Thus, urban and freeway control systems and traveler information systems can prove critical to the operational effectiveness of multimodal transportation facilities.

1.5 SYSTEM EVOLUTION

Urban Streets

The development of traffic control systems for urban streets has paralleled the development and use of the automobile. After World War I, rapid growth in automobile traffic led to requirements for special personnel, signals and systems to address the problem.

Today, in typical urban areas, approximately two-thirds of all vehicle-miles of travel, and even a higher percent of vehicle-hours of travel take place on facilities controlled by traffic signals (4). To a major extent, therefore, the quality of traffic signal operation determines urban vehicular traffic flow quality.

Traffic signals originated with signaling system technology developed for railroads. In 1914 (5), Cleveland, Ohio installed the first electric traffic signal in the United States. Salt Lake City in 1917, introduced an interconnected signal system where six intersections were manually controlled as a single system (6). In 1922, in Houston, Texas, 12 intersections were controlled as a simultaneous system from a central traffic tower. This system proved unique by using an automatic electric timer.

The year 1928 saw the introduction of a flexible-progressive pretimed system. Municipalities quickly accepted these pretimed systems and widespread installation followed in virtually every U.S. city. Their success resulted from:

- Simplicity (almost any electrician could understand them),
- Reliability (rugged components resulted in minimum maintenance), and
- Relatively low cost.

However, early pretimed systems had limited flexibility. They could respond only to predicted traffic changes via preset changes on a time-clock. But predicting traffic conditions proved difficult because of the needed data collection efforts. Agencies usually avoided timing changes because of the staffing and time resources required to make changes at each local intersection controller.

Traffic-actuated local controllers using pressure detectors became available during the period 1928-1930. The controllers proved a first step toward traffic-actuated control but applied only to isolated intersections.

In 1952, Denver, Colorado advanced the state of the art of traffic control systems by developing and installing an analog computer control system. This system applied some actuated isolated intersection control concepts to signalized networks. Sampling detectors input traffic flow data, and the system adjusted its timing on a demand rather than time-of-day (TOD) basis. Over 100 of this type system were installed in the United States in the period 1952-1962.

In 1960, Toronto conducted a pilot study using a digital computer to perform centralized control functions (7). The amount of traffic data available from this form of control proved a fortunate by-product. While the computer used for the test was archaic by today's standards - an IBM 650 with about 2,000 words of drum memory - the success of this control system approach encouraged Toronto to proceed with full-scale implementation. The city placed 20 intersections under computer control in 1963, and later expanded the system to 885 intersections by 1973.

International Business Machines (IBM) began a cooperative development in 1964 with the City of San Jose, California, to further develop a computer traffic control system (8). The project used an IBM 1710 computer. Control concepts developed and implemented proved successful in significantly reducing stops, delays, and accidents.

Beginning in 1965, the City of Wichita Falls, Texas, contracted for the delivery of an IBM 1800 process-control computer for traffic control. This system was placed in daily operation in 1966, controlling 56 intersections in the central business district. It was later expanded to include 78 intersections. San Jose, California, shortly thereafter made a transition to an IBM 1800 computer, and similar systems were installed in Austin and Garland, Texas; Portland, Oregon; Fort Wayne, Indiana; New York City; and

Baltimore, Maryland. In these systems, traffic signals were controlled by using stored timing plans developed off-line.

In 1967, the Bureau of Public Roads (currently the Federal Highway Administration (FHWA)), began to develop the Urban Traffic Control Systems (UTCS) Project. The system was installed in Washington, D.C., to develop, test, and evaluate advanced traffic control strategies (9). The system, completed in 1972, contained 512 vehicle detectors whose outputs determined signal timing at 113 intersections. Extensive data processing, communications, and display capabilities were made available to support traffic control strategy research. Later efforts produced the Extended and Enhanced versions of the software package that implemented these concepts.

During the 1970s, over 300 computer-controlled signal systems were installed throughout the world. As computer hardware became smaller, faster, and less costly, traffic-responsive control for street networks and arterials became more prevalent. Examples of European traffic-responsive control systems include: Glasgow, Scotland; Toulouse, France; and Madrid, Spain. In the United States, traffic-responsive control systems were installed in several cities such as Los Angeles, California; Boulder, Colorado; Albany, New York; and Overland Park, Kansas.

The 1970's also saw continuing research and development of software packages and models for digital computer and microprocessor-based traffic control systems. The Transport and Road Research Laboratory (TRRL) in Great Britain developed the advanced centrally controlled traffic system, Split, Cycle and Offset Optimization Technique (SCOOT), in the 1970's with implementation taking place in Glasgow and other cities in the 1980's. SCOOT has recently been installed in several North American cities including Toronto, ON. Another advanced system, Sydney Coordinated Adaptive Traffic System (SCATS), developed in Australia, has recently been implemented in Oakland County, MI, and many other cities throughout the world. SCOOT and SCATS initiated the deployment of *adaptive* control systems. Other *adaptive* control techniques, represented by Optimized Policies for Adaptive Control (OPAC) and Microprocessor Optimized Vehicle Actuation (MOVA), have also begun to be implemented.

RT-TRACS (Real Time Traffic Adaptive Control System), currently under development by FHWA, represents the first major attempt to develop a traffic responsive control system in the U.S. since the UTCS projects of the 1970's.

The experience gained during this evolution shows that substantial reductions in travel delays, stops, fuel consumption, and vehicle emissions can accrue from control system efficiency and aggressive traffic signal management. However, in conventional (non-adaptive) systems, full realization of benefits depends on the frequent updating of timing plans to optimize traffic flow.

Freeways

Ever increasing traffic demands and congestion has forced attention on improving freeway flow through advanced traffic management and control. Although freeways were originally conceived and designed as free-flowing, limited-access facilities, the need for control systems has become apparent. In California, Illinois, Michigan, and Texas, several pioneering studies (10-15) investigated ways to improve freeway operation. This work, initiated in the early 1950's, led to increased deployment of freeway surveillance and control systems.

The earliest freeway surveillance system began operation in 1962 on Detroit's Lodge freeway. The system included lane control, variable speed limit signs and some CCTV. In the early 1960's, the then Port of New York Authority (now Port Authority of New York and New Jersey) installed photocell detectors in the Lincoln Tunnel and experimented with metering vehicles into the tunnel to preserve capacity. Chicago began its now extensive system in 1963 on the Congress Street (now Eisenhower) Expressway with loop detection every 1/2 mile (to locate equipment near utilities) and data communication to a control center via leased phone lines. The system also pioneered ramp metering. Houston developed a surveillance system on the Gulf Freeway which included loop detection, ramp metering and CCTV. Los Angeles initiated its current basin-wide ramp metering program in 1967. Seattle and Atlanta also installed systems in the 1960's.

Later systems proved direct descendants of these earlier efforts. Detection technology (loops), spacing, metering layouts and system architectures followed the experiences gained in these pioneering systems.

Research, development and deployment of freeway surveillance and control systems has progressed rapidly. Studies and experiments produced new concepts of control and introduced new applications of advanced control equipment including:

- Traffic operations centers (TOCs),
- Changeable Message Signs (CMS), also termed Variable Message Signs (VMS),
- Highway Advisory Radio (HAR), and
- Media tie-ins.

Freeway traffic management now encompasses a greater range of activities including:

- Freeway traffic control,
- Incident management,
- Aid to stranded motorists,
- Coordination with other facilities, and
- Traveler information systems.

Coordination with other facilities has expanded to the concept of Integrated Traffic Management Systems (ITMS) which coalesces all aspects of transportation management within a community.

Traveler Information Systems

Driver information systems have expanded as well, to the general category of Advanced Traveler Information Systems (ATIS). ATIS exploits a whole spectrum of media including:

- On-freeway and on-street dynamic signing and highway advisory radio,
- Commercial media,
- Displays at major traffic generators, and
- In-vehicle information and displays.

Dynamic in-vehicle information will become increasingly available to motorists. FHWA projects such as TRAVTEK, ADVANCE and FAST-TRAC demonstrate different techniques available to provide traffic and guidance information within the vehicle.

1.6 Present Status – Traffic Surveillance and Control

The 1980's and early 1990's has witnessed widespread acceptance and implementation of advanced traffic control and management systems - for both freeways and urban streets. Use of the computer has become the accepted way to control streets and highways and has been accelerated by the revolutionary advances, and associated cost reductions, in computer, communications and electronic technology. Local microprocessor controllers have virtually eliminated operational constraints previously imposed by hardware capability. Today, constraints on effective system operation are generally not technical but institutional, jurisdictional or financial.

Present activity in traffic monitoring and control systems has advanced beyond experimentation to their deployment as effective operational tools. Basic control concepts have been refined through the experience of multiple users. An effective network of system designers, manufacturers, and suppliers exists to offer choices in system selection. The cooperative participation of governmental agencies (Federal, state, local) and commercial and professional organizations (manufacturers, consultants) continues in the development efforts of hardware and software. A prime example has been the development of the Model 170 controller unit.

1.7 Intelligent Transportation Systems (ITS)

Intelligent Transportation Systems (ITS) use advanced technology to provide a range of user services to:

- Improve mobility, safety and transportation productivity,
- Make optimum use of existing facilities and energy resources, and
- Address environmental issues.

Table 1-2 lists these services.

ITS has traditionally been divided into six different functional categories as shown in Table 1-3.

Although each type has distinctive features, they share many of the same technologies, and functional requirements (APTS and CVO, for example). ATMS plays a special role, however, because it contains the central traffic database upon which most of the other systems depend.

Far more than just the application of advanced technology, ITS:

Table 1-2. ITS user services.

ITS User Services	
Travel and Transportation Management • En Route Driver Information • Route Guidance • Traveler Services Information • Traffic Control • Incident Management • Emissions Testing and Mitigation * **Travel Demand Management** • Pre-Trip Travel Information • Ride Matching and Reservation • Demand Management and Operations** **Public Transportation Operations** • Public Transportation Management • En Route Transit Information • Personalized Public Transit • Public Travel Security **Electronic Payment** • Electronic Payment Services	**Commercial Vehicle Operations** • Commercial Vehicle Electronic Clearance • Automated Roadside Safety Inspection • On-Board Safety Monitoring • Commercial Vehicle Administrative Processes • Hazardous Materials Incident Response • Commercial Fleet Management **Emergency Management** • Emergency Notification and Personal Security • Emergency Vehicle Management **Advanced Vehicle Control and Safety Systems** • Longitudinal Collision Avoidance • Lateral Collison Avoidance • Intersection Collision Avoidance • Vision Enhancement for Crash Avoidance • Safety Readiness • Pre-Crash Restraint Deployment • Automated Highway Systems

** Added July 1992*

*** Renamed from Travel Demand Management*

Table 1-3. ITS functional categories.

Abbreviation	Category	Examples
ATMS	Advanced Traffic Management Systems	• Adaptive traffic signal control • Electronic road pricing and toll collection
ATIS	Advanced Traveler Information Systems	• Vehicle navigation and route guidance • Intermodal travel information
APTS	Advanced Public Transportation Systems	• Vehicle location and schedule monitoring • Real-time transit, ride share and HOV information
CVO	Commercial Vehicle Operations	• Automation of administrative and regulatory aspects • Fleet dispatch and management • Automatic vehicle identification, weigh-in motion
ARTS	Advanced Rural Transportation Systems	• Road/weather information systems • Automated *Mayday* systems
AVCS	Advanced Vehicle Control Systems	• Intelligent cruise control • Lane following and collision avoidance

Provides seamless operation across jurisdictional boundaries,

- Provides a wide variety of cost-effective user services,
- Uses an integrated transportation systems approach,
- Is multi-modal in scope,
- Becomes a major factor in transportation planning,
- Provides evolutionary, incremental, not revolutionary change,
- Is funded and implemented through public/private partnerships,
- Involves consensus building among all stakeholders,
- Addresses institutional, legal and other non-technical issues,
- Provides opportunities for industry and business,
- Encourages entrepreneurial initiatives, and
- Encourages university and other research.

With the systems-level approach taken by ITS, the driver, vehicle and roadway are viewed as interacting components of the transportation system rather than as separate systems.

The ITS vision is that a comprehensive National ITS Program comparable in scope to the Interstate Highway Program will be implemented during the next 20 years with major participation from the public and private sectors. The primary goal is *to produce an efficient, balanced transportation system* which:

- Is seamless across the nation,
- Fosters a new level of cooperation between the public and private sectors,
- Develops a vigorous U.S. ITS industry, and
- Provides an attractive, effective public transportation system that complements and interacts smoothly with an improved roadway system (16).

References- Chapter I

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CHAPTER 2
AVAILABLE AND EMERGING TRAFFIC CONTROL SYSTEMS TECHNOLOGY

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CHAPTER 2
AVAILABLE AND EMERGING TRAFFIC CONTROL SYSTEMS TECHNOLOGY

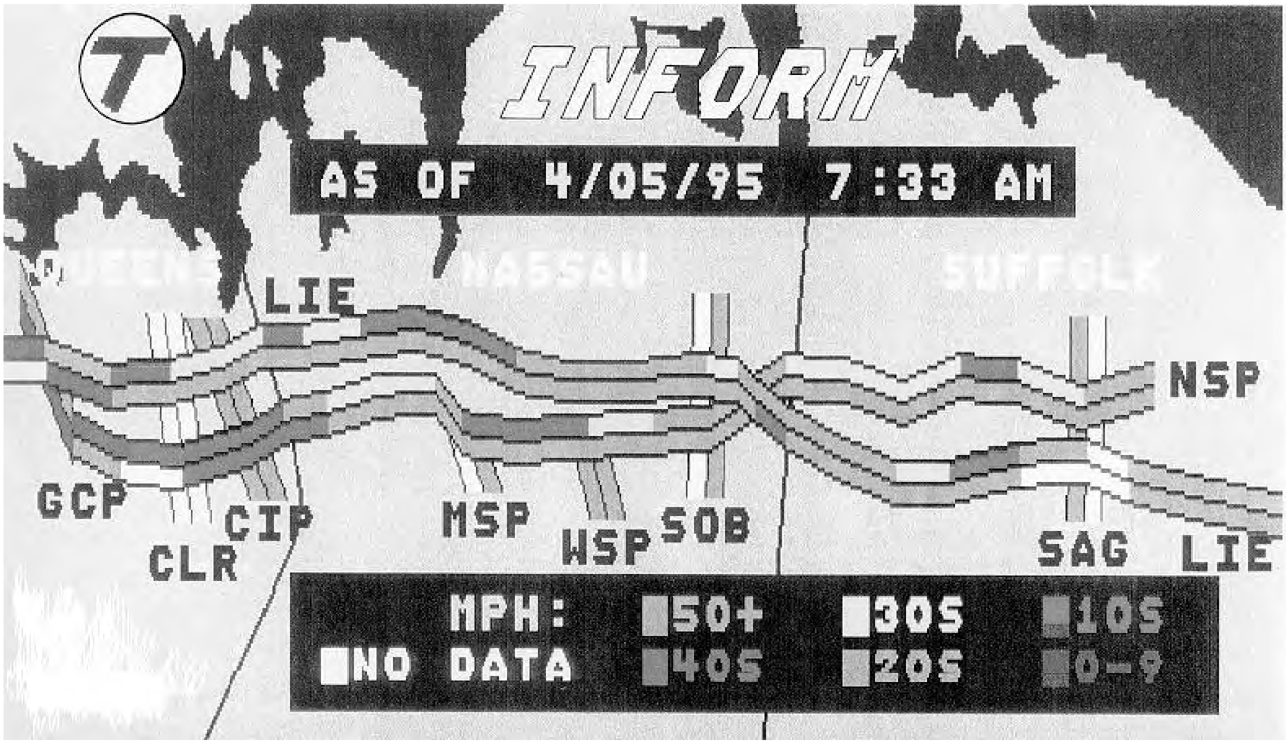

Figure 2-1. New York State Department of Transportation visual traffic information project (VTIP).

2.1 Introduction

This Handbook assists users in *defining, evaluating, and selecting systems* that match their needs. This chapter presents a broad overview of system functions and available options for both hardware and software. It focuses on system selection factors that lead to successful operations. Table 2-1 shows the organization of this chapter.

Since the 1985 edition of the Traffic Control Systems Handbook, traffic control systems technology has seen significant advances in the following areas (1):

- Traffic operations centers,
- Computer architectures,
- Operator displays,
- Systems communications,
- Field controllers,
- Changeable message signs, and
- Detectors.

Furthermore, surface street signals and freeways use newly developed control strategies. Emerging technologies and concepts now emphasize:

- Real-time communication with motorists,
- Control of corridors,
- Integration of traffic signals with freeway monitoring systems, and
- Integration of traffic control with public transportation.

2.2 Control and Management System Functions

Traffic management systems control a *real-time* process, within constraints, to produce an optimum (or consistent) result. For example, control and management may:

Table 2-1. Chapter 2 organization.

Section Title	Purpose	Topics
Control and Management System Functions	Describes basic functions of traffic control systems	• Traffic control system functions • Traffic control structure
Integrated Traffic Management Systems	Describes the purpose and methodology for integration of transportation control, management, and information systems	• Information sharing and integration • Integration of control/monitoring systems
Range of Agency Needs	Describes conditions and reasons for upgrading or installing new traffic systems	• Existing hardware • Conditions • System requirements
Range of Available Options	Describes system alternatives and selection criteria	• Transportation systems management (TSM) relationships • Control system options • Criteria for selection
Available Technology	Describes available hardware and software options, characteristics and applications	• Hardware • Software
A Look to the Future	Describes future applications of traffic control systems	• Corridor control • Advanced traffic management systems (ATMS) • Advanced traveler information systems (ATIS) • Traffic adaptive control systems • Multi-jurisdictional traffic management

- Optimally allocate right-of-way among competing demands within a group of signalized intersections (corridor or network control), and
- Respond to some exception-type condition (incident management) (2).

Traffic Control System Functions

Modern traffic control systems exercise their control in the structure shown in figure 2-2, closing the loop of control functions within a time interval. Table 2-2 summarizes these control system functions.

Traffic Control Structure

Effective traffic control operates as a closed-loop process. Figure 2-3 illustrates an interactive dynamic traffic control/management system with a structure that combines traffic management and traveler (driver) information systems.

The upper loop represents conventional traffic control where detectors in the infrastructure monitor traffic and an operations center executes control by means of:

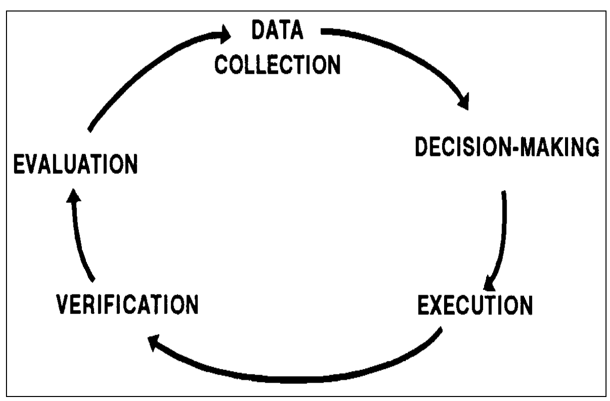

Figure 2-2. Basic functions of a traffic control system.

Table 2-2. Control system functions.

Function	Purpose	Element	Technique
Data Collection (Monitoring)	Provides basis for traffic control and management Comprehensive system may include all or most elements listed	Point detectors	Gathers traffic flow data: • volume • lane occupancy • speed Provides intersection-specific data Provides system-sampling data
		CCTV monitoring	Detects and verifies incidents Serves as information/data gathering tool. Monitors the end of queues.
		Automatic vehicle identification (AVI)	Collects information on: • vehicle classification • vehicle identification • vehicle probes • transit vehicle locations
		Environmental sensors	Gathers weather, air quality, and related data at remote sites
		Traffic operations center	Gathers data from other traffic operations centers, cellular telephones, CB radio, helicopters, spotters and other manual sources

Table 2-2. Control system functions (continued).

Function	Purpose	Element	Technique
Decision-Making	Select appropriate response to prevailing or expected conditions Apply computing technology to expand decision-making capability	Data fusion	Processes or fuses information from a variety of sources
		Signal control	Uses time-of-day plans or real-time control based on detection data
		Freeway control	Provides ramp meter and traveler information message strategies for recurring and non-recurring congestion
		Corridor management and control	Integrates control of freeways and adjacent surface arterials
		Incident management	Coordinates spectrum of activities related to detection and response to traffic incidents
		Alternate routing	Advises travelers on best routes to destination
		Road pricing (future)	Sets tolls to encourage off-peak travel
		Traveler information	Provides travelers with real-time information at home, workplace, shopping or in the vehicle
		Speed advisories	Advises drivers on best speeds for prevailing conditions

Table 2-2. Control system functions (continued).

Function	Purpose	Element	Technique
Execution	Implements control decisions and traveler information through traffic operations centers (TOCs) and field equipment	Flow control	Coordinates traffic signals on arterials, networks, or corridors
		Integrated freeway and arterial management	Coordinates freeway controls, ramp metering, and changeable message signs with arterial signals in a corridor. Reassigns traffic to alternate routes.
		Motorist information through changeable message signs (CMS)	Traffic and weather condition information and limited route guidance
		Motorist information through highway advisory radio (HAR)	Traffic and weather condition information and route guidance
		In-vehicle information systems (future)	Same as CMS but only to equipped vehicles

Table 2-2. Control system functions (continued).

Function	Purpose	Element	Technique
Verification	Assures that control decisions result as intended	Hardware monitoring	Verifies that signal actually displays intended signal interval at appropriate time Verifies that CMS displays desired message Performs reasonableness checks on traffic data collected Performs self-checks on central computer and peripherals Uses error checking codes to verify integrity of communications
		CCTV visual observation	Verifies detection of incident by automated algorithms Enables operator to classify incidents Verifies that incident management personnel properly perform duties
Evaluation	Measures performance to refine control decisions Uses feedback to continue through control and management loop	Analyzes measures of effectiveness (MOEs)	Uses MOE such as stops, delay, travel time, fuel consumed, pollutants emitted and others Defines level of improvement or degradation in system performance

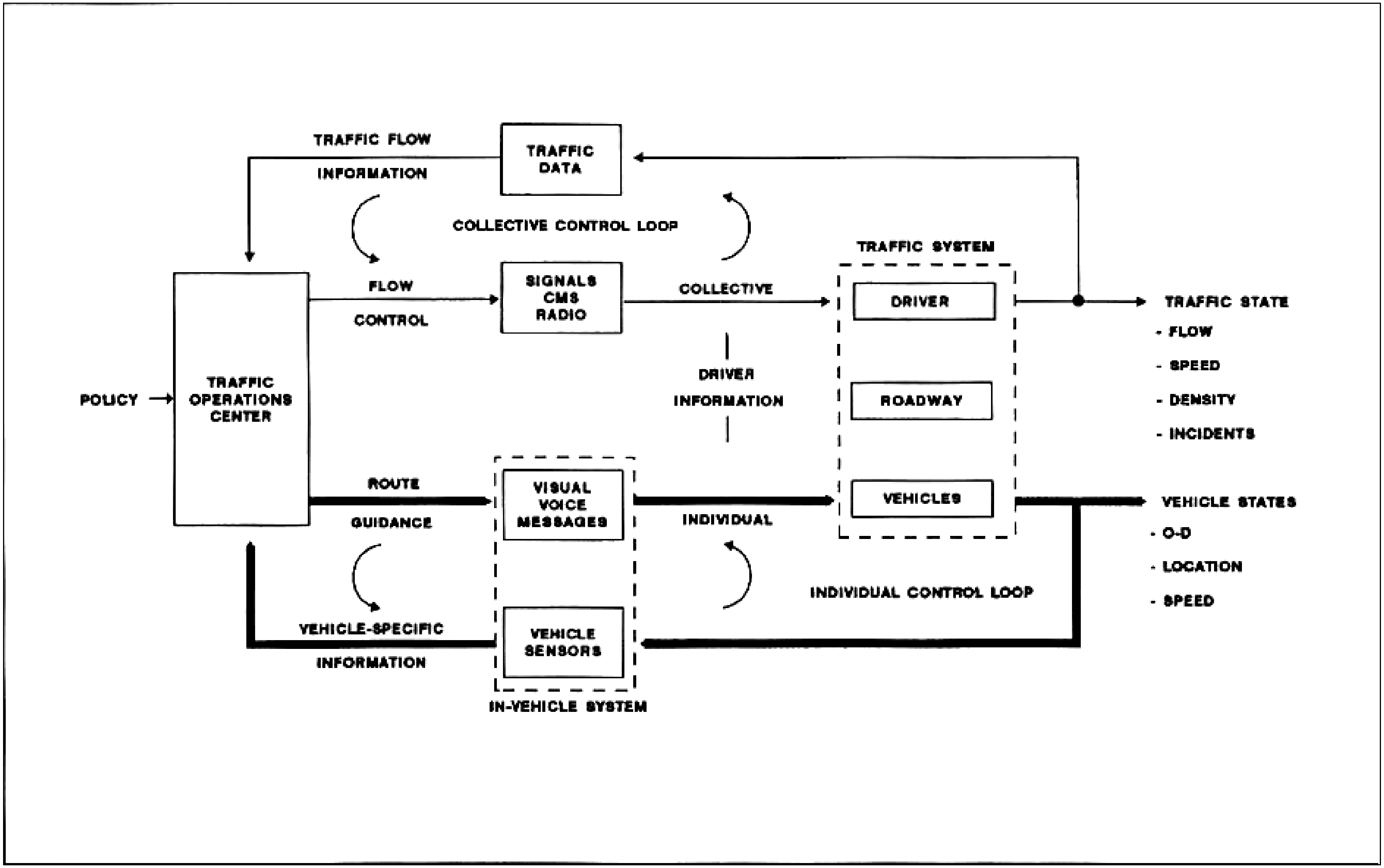

Figure 2-3. Interactive dynamic traffic management.

Table 2-3. Typical early pretimed system.

Function	Method
Data Collection	Manual means external to control system
Decision-Making	Flexible time-of-day (TOD), day-of-week (DOW) basis
Execution	One-way commands over multiwire cable
Verification	Infrequent observation and motorists' complaints
Evaluation	Labor-intensive field data collection (frequently not performed due to expense)

- Signals,
- Changeable message signs, and
- Radio messages to the driver.

This represents collective control since the system does not differentiate between individual vehicles and drivers. The same message goes to all who can receive it.

In early pretimed traffic signal systems, the loop took a long time to close because it entailed an extended series of discrete operations as shown in table 2-3. The process summarized in table 2-3 often proved workable, yet inefficient.

Today, however, control systems have advanced to where the control loop closes in real-time. In addition to controlling traffic flow through different control strategies, today's systems influence traffic demand by:

- Using special signal timing concepts, and
- Communicating with travelers.

Future systems will provide route guidance through in-vehicle systems.

Communication among field elements has advanced to where the system can receive and assimilate information from various sources, including other traffic control systems, for effective real-time system/corridor management.

The bottom loop of figure 2-3 represents a route guidance system that monitors each vehicle's status and sends it to the traffic operations center. The traffic operations center sends information to each driver by means of in-vehicle displays and messages. This represents individual control since the system can selectively address individuals with traffic and other information rather than a group of drivers as in the upper loop. While individual control is not currently employed at a significant level, it will become an increasingly important traffic management process in the future.

The implications of integrating these 2 types of control become far reaching, from both the monitoring and control points of view. Using the FM sideband, for example, the traffic operations center or a private service can selectively communicate traffic and other information to the vehicle's car radio. In this case, the individual control loop remains open since few vehicles can transmit their status back to the operations center. However, conventional traffic detectors sense any flow changes resulting from these messages (e.g., route diversion); thus the loop closes by coupling between the 2 systems. Furthermore, as vehicles become equipped with 2-way communications, they can act as probes in the network. This will significantly enhance existing traffic databases and allow much improved control.

The type of message sent to the vehicles will evolve as shown in figure 2-4.

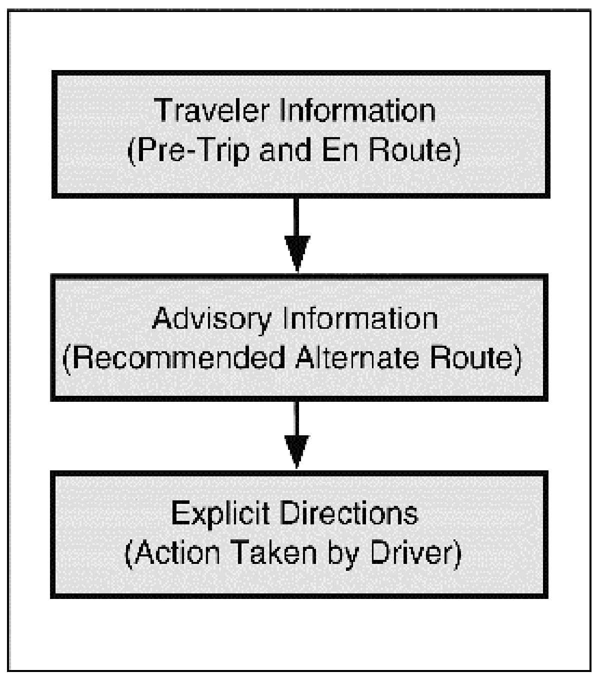

Figure 2-4. Evolution of messages sent to vehicles.

The last message type in the figure represents the coordination stage in which traffic controls will coordinate with vehicle routing to assure overall optimal control of the network. This stage corresponds to the configuration shown in figure 2 -3, where the 2 coupled, closed-loop systems provide fully interactive dynamic traffic management. With the transition to integrated traffic management systems, in-vehicle systems will certainly become an increasingly important source of information for the driver.

2.3 Integrated Traffic Management Systems (ITMS)

ITMS coalesce all aspects of transportation management within a community (3). They integrate and coordinate:

- Hardware with software elements,
- Traffic signal systems,
- Freeway management systems,
- Traveler information systems,
- Transit/HOV systems, and
- Parking information.

Thus, traffic control and monitoring systems become but one element of ITMS.

System integration makes maximum use of resources. These can range from personal communication among operating agencies to a sophisticated central computer that supervises individual arterial and freeway traffic control systems throughout an area. Integration allows operating agencies to better manage the transportation system and more efficiently employ personnel. It allows agencies to allocate vehicles and people to the transportation system as efficiently as possible by accounting for the conditions or attributes of all elements within the system. Information sharing can occur among:

- Computer systems,
- Operators,
- Designers,
- Operating agencies,
- The public, and
- Public broadcasting and other information services.

Integrated management systems can perform many functions not traditionally included in operations center performance capabilities. Examples include:

- Demand management through congestion pricing,
- Bicycle traffic control, and
- Environmental sensing.

The design and operation of an urban system needs cooperation and communication among agencies. Integrated traffic management requires at a minimum:

- Information sharing and integration, and
- Integration of control, information and monitoring systems.

Information Sharing and Integration

Information sharing proves one key element of system integration. Information exchange may involve sharing data from historical databases with operators or managers of other systems so they can plan or develop control strategies. Managers of one system can identify trends in other systems that may affect the operation of their own system. They must process or fuse the information provided from different sources as discussed previously.

Integration of Control/ Monitoring Systems

The most familiar element of traffic management system integration involves control, information and monitoring. Integration of multi -agency control and monitoring systems allows agencies to make system control decisions and advise the traveler based on conditions in other systems.

Traffic engineers and operators make changes in system operation based on historical and real -time data obtained from their own system(s) and data received from other systems. System operators use real-time data to reduce congestion at a particular moment. In both instances, personnel from other agencies whose system(s) will be affected by the change must concur.

The computers of 2 or more agencies must also share information to enable rapid changes in signal timing plans and freeway controls to prevent and alleviate congestion. The computers remain subject to manual override by the operator(s).

An example of manual operation involves construction projects that require coordination of control systems for the term of the project. The coordination activities may involve:

- Simple retiming of traffic signal systems based on projected diversions, or
- Real-time manual selection of timing plans based on observations of field conditions.

During the unusual circumstances of traffic disruption and diversion caused by construction activities, manually coordinated control systems can prove beneficial.

The integration of 2 or more systems can permit smooth flow of traffic throughout the urban area. It also allows adjacent systems to accommodate traffic arriving from other systems. As an example, a freeway control system should readily handle large volumes of traffic or changes in traffic patterns resulting from:

- An adjacent traffic signal system during daily peak periods,
- Incidents,
- Special events,
- Nearby parallel roadway construction, and
- Weather.

Interchange of information permits this and, in so doing, provides the benefit of optimum system operation.

Control and monitoring system integration can take place among control systems:

- With different functions (e.g., freeway and arterial control systems), or
- Among geographically separated control systems.

In either case, the systems may fall under the same or different jurisdictions. Table 2-4 shows some of the control system types amenable to integration. Any of those listed may join with systems of the same type in different geographical areas or under different jurisdictions. Figure 2-5 illustrates the Los Angeles Smart Corridor System that integrates various functions and communicates with California Department of Transportation (CALTRANS) and other systems (4).

Also note that the Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA) includes *integrated traffic control systems* in the definition of operational improvements.

2.4 Range of Agency Needs

Although each agency with responsibility for traffic control systems represents a unique entity, with no two exactly alike, many similarities exist. Table 2-5 shows typical traffic control system *responsibilities* while table 2-6 lists typical system needs of agencies.

Existing hardware--In most jurisdictions, traffic control hardware represents an accumulation of different age equipment from multiple manufacturers, purchased over an extended time, using low-bid procurement techniques. Maintenance level of effort and quality greatly affect the hardware's current condition. For example, though the hardware's characteristics permit integration into a system, its physical condition and reliability may preclude continued use. In other cases, existing field hardware might not prove compatible with the desired control system, again precluding continued use. Recent years have seen significant effort in standardizing traffic controller hardware. This will facilitate future replacement.

The conditions which create a need to *upgrade* or *install* new traffic systems include:

- Growth and/or changes in traffic demand create a need to examine the adequacy of existing traffic control systems. When traffic flows well below available capacity and no recurrent congestion (or motorist perception of congestion) occurs, little public sentiment develops for control system improvement. However, as flows approach capacity and congestion becomes evident, demand for, and need of, improved control system operation increases. Although agencies should not postpone control system improvements until congestion appears, significant funding for major improvements generally follows public perception of need. Changes in traffic demand may also highlight the functional inadequacy of the existing control system in achieving full use of available capacity.

- Frequent failure of older equipment that results in degraded and inefficient on-street operation.
- The need to obtain improved traffic control through the use of modern hardware and software technologies not supported by existing equipment.

Another condition that may require upgrading an existing system or installing a new one occurs when the agency desires to incorporate motorist information capability. The agency can achieve this improvement by:

Table 2-4. Systems amenable to integration.

System Type	Elements	Reasons for Integration	Benefits of Integration
Freeway Management	Ramp metering Incident detection Closed circuit television (CCTV) Electronic monitoring High occupancy vehicle (HOV) lanes Toll facilities Transitways Connector metering	Conditions on freeways and arterials often impact each other Severe congestion on one facility causes diversion to another	Can best handle redistributed traffic
Arterial Management	Coordinated signal control • time-based (manual integration) • distributed • central system control	Same as freeway management systems	Same as freeway management systems
Traveler Information Systems (TIS)	Current accurate real-time information allows drivers to make intelligent decisions on: • routes traveled • time of travel • mode of travel	Accurate information available from freeway or arterial management systems	Can prove effective in transportation network management
Incident Management	Detection • electronic monitoring • closed circuit television • field observation • cellular telephone reports • other Verification Response Removal Scene management Incident management teams Other	Information made available on alternate routes from freeway and arterial management systems, which in turn use incident information to modify control strategies. TIS can use incident information to inform public and direct traffic to alternate routes.	Can reduce delay and secondary accidents through improved response and scene management Can enhance performance of incident management teams
Construction Traffic Management	Combinations of previous systems	Modify freeway management strategies Improve coordination or update control plans on arterials Increase emphasis on incident management Improve traveler information	Mitigate disruption due to construction Mitigate environmental impacts of construction
Weather Information	Remote stations sense: • ice • snow • fog • other environmental conditions	Weather data used for setting advisory speeds and dispatching crews	Can reduce accident potential Can reduce overtime costs by dispatching crews only when necessary

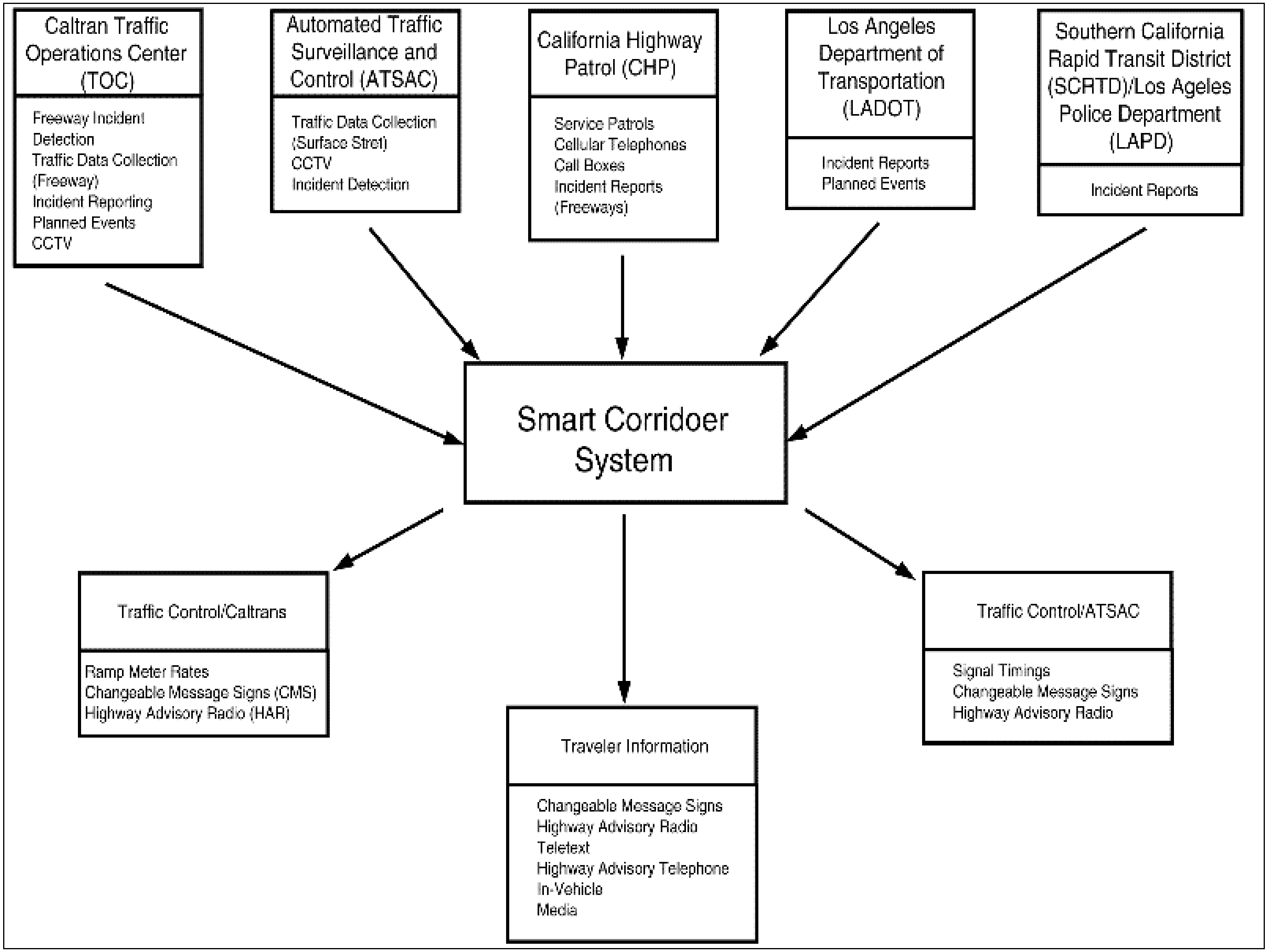

Figure 2-5. Smart corridor base functions

Table 2-5. Typical responsible agencies.

System Type	Responsible Agency	Responsibility
Freeway Control	State Departments of Transportation	Install, operate, maintain
Urban and Suburban Street	Local jurisdiction (City/County)	Operate, maintain (often installed by State DOT)
Region- or Area-wide Control	Committee of representatives from all affected agencies	Manages system. Traffic Operations Center (TOC) resides in one jurisdiction which may operate it.

Table 2-6. Typical system needs.

System Type	Potential Subsystems	Special Features
Freeway	• Ramp metering • Incident detection • Video monitoring	• Special events
Urban and Suburban Street	• Network of closely spaced intersections in a central business district (CBD) • Open- and closed-network arterial systems • Isolated intersections	• Railroad preemption • Lane control • HOV lane control • Peak-hour turn restrictions • Fire (or emergency vehicle or transit) preemption • Special events
Integrated	• Combinations of freeway control and urban street systems	• Communication compatibility with freeway control, urban street and traveler information systems

- Integrating incident management and route guidance elements into the existing system, or
- Installing a newer, cost beneficial control technology.

The definition of traffic control system needs for a specific agency does not lend itself to a cookbook approach. As a design process, it requires the application of experience and detailed examination of:

- Conditions,
- Capabilities,
- Desires, and
- Commitments.

This definition of system requirements proves an important element of a feasibility or predesign study. Chapter 11 includes further details of such studies. Experience has shown that the agency should establish specific traffic control system objectives in the following areas:

- *Traffic Operations*--The ability to respond to existing and anticipated future traffic operations requirements. Specific objectives might include:

  - Obtain maximum efficiency in terms of minimum delay, minimum stops, and maximum capacity utilization consistent with the safety of operation,
  - Detect, verify and manage traffic incidents on a real-time basis, or

- Provide motorists with real-time traffic or routing information.

- *Reliability*

  - Minimum control system downtime,
  - Minimum cost of maintenance, and
  - Maximum ability for automated detection and reporting of equipment failures.

- *Adaptability*--The ability to satisfy traffic operation requirements over a long period of time under changing conditions.
- *Implementation*-- Ease of installation or changeover from an old system to a new one with minimum technical problems and disruption of traffic flow.
- *Ease of Operation*--The ability to easily develop and maintain system databases including generation and maintenance of timing plans.

2.5 Range of Available Options

Transportation Systems Management (TSM) Relationship

Since first introduced in the mid-1970s, transportation systems management (TSM) has evolved from a list of about 150 low-cost actions to the productive use of existing transportation resources through their coordinated operations and improved management. TSM implies "a philosophy about planning, programming, implementation, and operations that calls for improving the efficiency and effectiveness of the transportation system by improving the operations and/or services provided" (5). TSM, then, provides an umbrella philosophy that aims to:

- Analyze the total system, and
- Improve operation and safety before capital-intensive projects add significant capacity.

Roark classifies TSM actions within 9 different urban operating environments, including (6):

- Freeway corridor,
- Arterial corridor,
- Central business district (CBD),
- Regional operating environment,
- Neighborhood,
- Major employment site (non-CBD),
- Outlying commercial center,
- Major activity center, and
- Modal transfer point.

In contrast, Wagner uses two primary strategies -- *supply* and *demand* (7). *Supply* strategies focus on changing the quality of vehicular flow, whereas *demand*-oriented strategies target decreasing the *quantity* of vehicular travel. Supply actions include:

- Arterial signal coordination,
- Signal removal or flashing operation,
- Freeway monitoring and control,
- Incident management,
- Parking prohibition,
- Turn controls, and
- Bottleneck-removal programs.

Demand actions include:

- Carpools,
- Vanpools,
- High occupancy vehicle (HOV) priority treatments, and
- Variable work hours.

In both classification schemes, traffic control systems and their effective operation prominently affect TSM and prove vital to the full realization of several other TSM actions. For example, it does little good to entice drivers to ride the bus or join a vanpool if inefficiently operating traffic signals stop or delay *all* vehicles (including buses and vans).

Control System Options

Operational objectives of traffic control systems include making the best use of existing roadway and freeway network capacity and reducing trip times, without creating adverse environmental impacts (8). This section describes various control system options available to achieve these objectives. These include options for:

- Surface street signal systems,
- Freeway and corridor systems, and
- Other control and management techniques.

Surface Street Signal System Options. Controlling the movement of vehicles through signalized intersections provides the major effect on traffic flow in urban areas. The control strategies shown in table 2-7 can achieve signalized intersection control.

Freeway and Corridor System Options. Freeway management represents an expanded concept that includes traffic control supplemented by operations such as:

- Incident management,
- Aid to stranded motorists, and
- Driver information messages.

By controlling traffic under varying conditions, these activities also improve operations and safety during:

- Off-peak,
- Incidents, and
- Maintenance activities.

Freeway and corridor control options fall into the categories shown in table 2 -8.

Other Control and Management Options. The integration of traffic management traveler information and vehicle management systems provides a more coordinated and effective control system. Table 2-9 shows additional options for enhancing integrated operations.

Criteria for Selection

Previous tables show the range of alternative systems available to meet a jurisdiction's traffic control needs. Making the most appropriate selection requires critical self-examination and consideration of life-cycle issues concerning:

- System acquisition,
- Operation, and
- Maintenance.

Matching a control system's capabilities to a set of *identified* agency requirements proves the most crucial element in system selection. Viable candidates should satisfy these requirements in a cost effective way.

The agency should also match the system's sophistication to the staff's anticipated ability to operate and maintain it. Similarly, to assure system success, the agency must demonstrate its commitment to ongoing staffing and maintenance costs. As described in new Federal regulations (see chapter 11 and Appendix A), the availability of funds to procure traffic control systems must also include a similar commitment to provide adequate resources for operation and maintenance.

Chapter 11 provides a more detailed discussion of a suggested system selection process that uses an effectiveness-analysis approach. The chapter also describes a utility/cost analysis approach.

2.6 Available Technology

Available control system technology has progressed to the point where current hardware and software capabilities provide the designer with a wide range of control concepts. The transportation engineer or control system designer now has a large array of hardware and software options from which to choose in defining alternative control systems. The challenge is to use them effectively in achieving improved on-street traffic performance.

Hardware

Subsequent chapters in this Handbook describe in depth the various hardware elements of a control system. Components and subsystems include: detectors, local controllers, changeable message signs, operator displays, central computers and field masters. Table 2-10 summarizes descriptions of available system hardware.

Software

Chapters 3, 4, and 8 describe software used in traffic control systems. This includes real-time control software, optimization software and simulation software.

Real-Time Control software developed for local controllers allows the controller to function as a signal switching unit by:

- Receiving detector inputs,
- Processing status data,
- Computing timing, and
- Driving signal lamp load switches.

Manufacturers of standard NEMA controller units provide such software (or firmware) as a part of the device. By contrast, both manufacturers and users have developed Model 170 software.

System vendors have developed closed-loop system software packages to generate:

Table 2-7. Surface street signal options.

Option	Main Characteristic	Control Technique	Method	Application
Isolated Intersection Control	Does not consider adjacent signalized intersections	Fixed Time (pretimed)	Assigns right-of-way according to a pre-determined schedule Can manually derive green splits in proportion to expected demand Can use computer program to optimize timing in accordance with performance measure	Intersections with predictable traffic patterns Frequently saturated intersections
		Traffic Actuated (semi or full)	Adjusts green time according to real-time demand measured by detectors on one or more approaches Modernized Optimized Vehicle Actuation (MOVA) (see section 3.13) trades off stopping approaching vehicles against holding already stopped vehicles OPAC (see section 3.13) establishes optimal phase switching time	
Arterial Street Control	Operates arterial signals as a system	Pretimed Coordination	Uses off-line computer programs to generate optimal timing plans (see sections 3.8 and 3.9)	Can be used where communications interconnect is not available Can be used where traffic patterns are relatively repeatable
		On-Street Masters	Time-of-day; master schedules timing plans or implements manual plans Traffic-responsive; master interrogates sampling detector stations and chooses cycle, split and offset based on volume and/or occupancy Embeds control strategies in software. Can store detector data for later printout. Uses two-way communications for local controller feedback.	Can control small to medium length arterials

Table 2-8. Freeway and corridor system options.

Option	Main Characteristic	Control Technique	Method
Detector Monitoring	Monitors real-time traffic data	Senses volume, occupancy and speed at instrumented locations	Commonly uses inductive loops Beginning to deploy video processing and other types of detectors
Ramp Metering	Controls demand at ramps Smooths merge maneuvers	Limits and regulates the rate at which vehicles enter the freeway. Avoids overloading facility.	Uses traffic signals. Commonly releases single vehicle per green interval. Can use time-of-day rate plans. Can operate traffic-responsively based on real-time detector data. Operator can modify rates.
CCTV Monitoring	Verifies presence of an incident and determines nature and severity. Assesses congestion conditions.	Can use pan, tilt and zoom to obtain desired scene	Uses cameras, transmission systems, monitors and peripheral devices
On-Highway Motorist Information Devices	Updates motorists on current traffic conditions	Assists motorists in deciding on appropriate route choice. Warns drivers of: recurrent congestion; incidents; pre-planned activities such as: special events, construction, and maintenance.	Commonly uses changeable message signs (CMS) and highway advisory radio (HAR)
Incident Management Support	Detects and verifies incidents	Provides information to public	Uses TOC, CMS and HAR. Can use direct electronic feed to media.
Corridor Control	Treats urban freeways and adjacent arterials as integrated system	Optimizes corridor capacity by directing traffic from overloaded links to links with excess capacity	Uses software algorithms to compute control settings which optimize roadway network
Areawide Coordination	Treats isolated intersections, arterials, networks and corridors as integrated system	Can use information and data from one subsystem to assist decision making in another subsystem	Requires full cooperation among involved jurisdictions

Table 2-9. Other control and management options.

Option	Main Characteristic	Control Technique	Method
Media and Private Information System	Provides travel information using recent advances in communications and computer technology	Manages travel demand by modifying trip in accordance with real-time information	Uses electronic route maps, tourist guides, service directories at a fixed site or in the vehicle. Uses personal computer with compact disk read only memory (CD-ROM), television or hand-held devices.
Regionwide Information System (9)	Transforms individual mobility into an integrated, cooperating system	Coordinates transportation operations in metropolitan areas, provides travel choices and aids to a traveler for selecting the best trip	Provides information and control assistance to the traveler. Uses in-vehicle and hand-held devices.
In-Vehicle Information System	Provides information to the motorist in the vehicle	Provides information on current location relative to destination Advises best route	Vehicle can communicate with a traffic operations center via a long-range communication link or via a short-range link to a roadside infrastructure
Kiosks	Provides information centers at major trip generators	Manages travel demand by modifying trip in accordance with information presented at kiosk	Uses a wide variety of databases; detailed maps; business directories; transit schedules; tourist information; real-tme traveler information updates; locations of various services.
Parking Information	Provides parking information to motorists	Allows selection of appropriate route to parking facilities, thereby reducing travel time	Information transmitted to motorists via on-board equipment or roadway devices such as CMS or HAR
Weather Information	Provides weather condition information to motorists	Advises appropriate speeds for prevailing conditions	Remote weather stations sense snow, ice, fog and other conditions affecting driving conditions

Table 2-10. Hardware overview.

Category	Current Practice		Trend		Discussed in Chapter
	Type	Characteristics	Type	Characteristics	
Detectors	Loops	Proven reliable; failures due more to pavement installation than electronic malfunctions. Provides vehicle presence which can be converted to MOEs such as: volume, lane occupancy, speed, stops and delays.	Devices such as: radar, microwave, sonic, video imaging processing, infrared Environmental sensors such as: ice, snow, fog	Non-pavement invasive	6
Local Controllers	NEMA Models 170 and 179	Microprocessor based *smart* devices that offer extensive and flexible control capability. Features provided to enhance integration into systems. Provides interchangeability and maintainability.	Advanced controllers such as Model 2070 (10)	Offer greater flexibility and capability	7
System Controllers	Time-based on-street masters, PC-based closed-loop systems, central computer master See table 2-3	Types listed in order of increasing complexity/ capability Central computer master typified by Urban Traffic Control System (UTCS) derivative systems High speed PC-based systems typically use closed-loop system designs with a distributed level of hierarchical control	Systems such as SCATS, SCOOT, RT-TRACS	Adaptive signal control	3

Table 2-10. Hardware overview (continued).

Category	Current Practice		Trend		Discussed in Chapter
	Type	Characteristics	Type	Characteristics	
Communications	Time division multiplexed (TDM) using twisted wire pair or fiber optic cables	Frequently used for user-owned wire line systems Fiber optics commonly used for video signals	Radio systems based on area radio networks, point-to-point microwave and spread spectrum technologies	Reduces high installation costs associated with user-owned wire lines	9
	Leased voice grade channels	Frequently used for data communications in lieu of user-owned system	Leased high speed data channels such as T1 Coder-decoder (codec) technology	Can communicate video signals on T1 channel Reduces data rate requirements on leased high speed digital channels when used for video transmission	
Display and Control	Workstation	Comprised of PCs or comparably sized terminals System controlled via computer keyboard and mouse Display screens feature graphical user interfaces (GUI) Color graphics, including maps shown on terminals or large projection displays Flexibility and multiple display capability generally has replaced wall map display common to earlier systems			8

Table 2-10. Hardware overview (continued).

Category	Current Practice		Trend		Discussed in Chapter
	Type	Characteristics	Type	Characteristics	
Display and Control (continued)	Workstation	Graphic map displays can focus on smaller areas with increasing level of detail User can easily modify displays to show new locations Can transmit graphic displays to other locations such as: - dispatch centers - transportation administrative areas - public display areas	Video walls	Additional flexibility in combining CCTV images with computer-generated graphics	8
Changeable Message Signs (CMS)	Fiber optic Light emitting diode (LED) Flipped disk Hybrid	Used in freeway and arterial management systems to inform drivers of congestion and incidents	LED	Improved LED performance likely in both visibility and reduced degradation	10

- Intersection data reports,
- Graphic displays, and
- System status reports.

Software programs for on-street masters in distributed systems supervise:

- Communication,
- Data processing, and
- Monitoring of the local intersections together with the central computer.

Many centrally controlled traffic systems currently being installed feature the UTCS First Generation (1-GC) signature matching algorithm for real -time - traffic-responsive control. Unlike earlier UTCS systems, these contemporary systems usually store signal timing plans at the intersection. Many also feature the ability to update timing plans with a minimum of manual operation (1.5 GC). We term these systems *UTCS derivative systems*.

Advanced centrally controlled traffic systems developed abroad, SCOOT from the United Kingdom and SCATS from Australia, have seen implementation in the United States. Chapters 3 and 8 describe these systems, and others that provide a greater level of traffic responsiveness than UTCS First Generation algorithms.

Chapter 3 describes *Optimization and Timing Plan Development*, which includes available programs such as PASSER II-90, PASSER III-90, PASSER IV, and TRANSYT-7F.

Originally developed in England, TRANSYT -7F has become an *Americanized* version and seen wide use in developing optimized network timing plans. It represents the most comprehensive tool for traffic signal timing and analysis. For coding TRANSYT - 7F data, several commercially developed programs exist that can reduce database preparation time significantly. These include:

- EZ-TRANSYT,
- Quick-7F, and
- PRETRANSYT.

Chapters 3 and 4 describe *simulation* models for use in urban street and freeway applications. Models include:

- TRAF-NETSIM,
- NETFLO,
- FREQ,
- INTRAS,
- INTEGRATION, and
- CORFLO.

2.7 A Look to the Future

Activities undertaken over the past few years will lead to extensive changes in the traffic control system field in the near future.

Advanced Traffic Management Systems (*ATMS*) and *Advanced Traveler Information Systems* (*ATIS*) represent two of the major ITS categories (see chapter 14) and will receive increasing emphasis.

Tables 2-11 and 2-12 show the future environment for ATMS and ATIS respectively.

The RT-TRACS (Real Time Traffic Adaptive Control System) project represents the first major attempt to develop a traffic responsive system control algorithm in the United States since the UTCS projects of the 1970s. This FHWA sponsored study aims to develop and field evaluate a real-time, *traffic-adaptive* signal control system suitable for use in an ITS environment by 1997. In addition to real-time control, RT-TRACS will incorporate all applicable features of existing systems, and also new architectures and technologies. Furthermore, it promises significantly greater cost-effectiveness than systems currently available. This control strategy will also significantly improve on currently used traffic signal control concepts to provide:

- The best possible signal timing in all types of traffic situations, and
- Updated signal timings with limited effort.

In this context, RT-TRACS will include as its goals and objectives the ability to:

- Control the entire spectrum of traffic conditions, including undersaturated and oversaturated flow, and congestion management in real -time.
- Recognize the possible requirements for different types of traffic control strategies, and implement the strategy most appropriate for existing demand characteristics and local area/system-wide objectives.
- Accept different measures of effectiveness based on the requirements of the local traffic engineer and the traffic flow/network situation.
- Influence traffic demand through the use of various signal timing concepts, including metering, variable phasing, reversible lanes, and phase skipping.

Table 2-11. The future environment for ATMS.

Trends	Implications for ATMS
• Increasing Congestion	• Greater responsivity to real-time traffic conditions • More emphasis on corridor management and diversion • More rapid incident detection • More intensive management of incidents • New strategies and controls for areas with saturated flow • Areawide management of traffic operations
• Emphasis on HOV Usage	• Controls associated with HOV facilities • Priority controls
• Environmental Concerns	• Emphasis on emission reduction control strategies • Emphasis on compliance with Clean Air Act
• Scarcity of Funds	• Increase in number of toll facilities and in automatic vehicle identification techniques for toll collection and enforcement

Table 2-12. The future environment for ATIS.

Trends	Implications for ATMS
• Increasing Congestion	• Greater emphasis on areawide provisions for TIS including: - traffic condition databases - increased emphasis on delivery of traffic information by on-highway and in-vehicle techniques • Increased emphasis on traffic management using TIS to perform assignment functions
• Emphasis on HOV and Transit Usage	• Inclusion of transit and paratransit information on TIS information networks and TIS devices
• Improvement of Driver Perception of Traffic Controls and Motorist Information	• In-vehicle presentations of traffic signals and regulatory, warning and information signs

- Disseminate information collected and/or calculated by the system to other control systems (e.g., ITS), the media, and other government agencies.
- Interface with other transportation control systems for effective system/corridor management, such as freeway metering systems, and for effective people movement, such as transit vehicle control systems (including buses and Light Rail Vehicles).
- Monitor itself to permit the implementation of truly intelligent and effective adaptive traffic control, that adjusts its operation based on the success or failure of past performance.
- Adapt to the needs of all types of jurisdictions, from small isolated cities to large urban areas.
- Control costs through flexible deployment strategies, so that initial start -up costs and annual maintenance costs do not preclude installation and continued operation of the system.

Davies indicates that adaptive traffic control based on real-time optimization could make a major contribution in relieving urban congestion through more efficient use of the existing highway system in urban areas (11). Real-time systems have undergone thorough testing and evaluation in other countries, and have proven to give very significant benefits in comparison to their implementation costs. Adaptive traffic control systems provide additional benefits over pretimed systems by responding to:

Flow variations within a signal plan period, and
Daily and seasonal fluctuations.

Adaptive systems also adjust automatically to long-term changes in traffic conditions, avoiding the aging disbenefits that occur when agencies do not regularly update pretimed signal plans.

The analyses indicate that United States systems will achieve the significant benefits seen in other countries with adaptive control. Specific benefits of adaptive traffic control will prove greatest with:

- Short links,
- High flows,
- Significant flow variations in a signal plan period, and
- Networks that interface with freeways.

Of these factors, traffic flow volume dominates in determining overall benefit levels. As flow levels increase, the benefits of adaptive techniques will become even more significant.

Major efforts in large metropolitan areas such as Los Angeles, which includes over 80 different jurisdictions, will establish agreements among agencies for multi-jurisdictional traffic management. Elements currently being studied and evaluated include (11):

- Control,
- Monitoring,
- Institutional issues,
- Maintenance and operation,
- Data sharing,
- Traffic operations centers,
- Traveler information systems, and
- Interties with freeway operation centers.

Currently, several corridor control projects such as the Santa Monica Freeway Smart Corridor are being developed, tested and evaluated. Additionally, FHWA has conducted research to support coordinated corridor control (12).

A vision for future systems includes the following characteristics:

- More responsive to traffic patterns (adaptive traffic control),
- Provision of more interaction/communication with the traveler,
- Use of advanced technologies in both hardware and software,
- More operator-free monitoring and reliance on artificial intelligence/expert systems,
- Extensive application of image processing for both detection (surveillance) and monitoring,
- Open architecture, providing ease of equipment compatibility and expandability,
- Significant data sharing and interties with other jurisdictions, and
- Significant interties between arterials and freeways.

Advancements in providing congestion and real-time routing information to the motorist will complement these advances in traffic control. Chapter 10 describes the considerable research currently conducted in this area.

References - Chapter 2

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CHAPTER 3
CONTROL CONCEPTS - URBAN AND SUBURBAN STREETS

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CHAPTER 3
CONTROL CONCEPTS - URBAN AND SUBURBAN STREETS

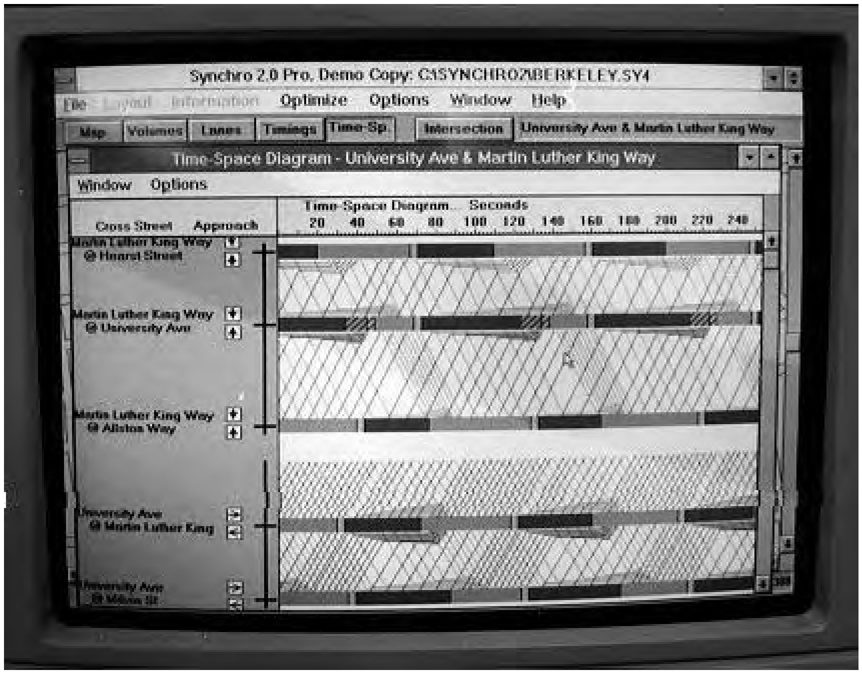


Figure 3-1. Time-space diagram display.

3.1 Introduction

This chapter discusses traffic control concepts for urban and suburban streets including:

- Definitions,
- Standard practice, and
- Operational experience.

In planning and designing a traffic signal control system, one must first understand the applicable operational concepts. These concepts fall into two categories: *signalized intersection control* and *signal-related special control.*

Signalized intersection control concepts include:

- Isolated intersection control — Controls traffic without considering adjacent signalized intersections,
- Arterial intersection control (open network) — Provides progressive traffic flow along the arterial. In this case, the signals must operate as a system,
- Closed network control — Coordinates a group of adjacent signalized intersections, such as found in the central business district (CBD) of a city, and
- Areawide system control — Treats all or a major portion of signals in a city (or metropolitan area) as a total system. Isolated, open-or closed-network concepts may control individual signals within this area.

Signal-related special control concepts include:

- High Occupancy Vehicle (HOV) Priority Systems,
- Preemption/Priority systems — Traffic control strategies which assign priority for the movement of certain types of vehicles such as buses, high-occupancy vehicles (HOV), and emergency vehicles,
- Directional controls — Special controls designed to permit unbalanced lane flow on surface streets,
- Television monitoring, and
- Overheight Vehicle Control Systems.

The chapter gives special consideration to the development of signal timing plans using both manual and computer-aided techniques. To the extent practical, the chapter provides example applications of the various procedures. Table 3-1 shows the organization of this chapter.

3.2 Control Variables

Control variables are measurements, or estimates, of certain variables which describe traffic conditions. They are used to select and evaluate traffic-responsive control strategies. Control variables commonly used for street control include:

- Vehicle presence,
- Flow rate (volume),
- Occupancy and density,
- Speed,
- Headway, and
- Queue length.

Generally, presence detectors (refer to Chapter 6) sense these traffic variables. Table 3-2 describes the fundamental methods used for measuring and estimating these control variables from detector data.

In addition, certain environmental factors become control variables to account for influences of environmental conditions on traffic performance. Environmental conditions include:

- Pavement surface conditions (wet or icy),
- Weather conditions (rain, snow, or fog), and
- Vehicle emissions.

Environmental sensors can detect these conditions (refer to Chapter 6).

3.3 Sampling

A microprocessor at the field site usually *samples* presence detectors to establish the detector state, thus replicating the detector pulse. The finite time between samples generates an error in the pulse duration which leads to errors in speed (most noticeable) and occupancy.

Equation 3.10 represents the maximum percentage error for any vehicle:

$$\%\mathrm{E} = \frac{100S}{T - S} \qquad (3.10)$$

Where:

% E = Percent error in occupancy

S = Inverse of the sampling rate, seconds per sample

T = Presence time for a vehicle with an average length at a given speed

Based on its statistical distribution, the percentage error becomes:

$$\%\mathrm{E}_{SD} = 100 \ \frac{S}{\sqrt{6}\,T} \qquad (3.11)$$

Averaging data over a period of time reduces this error.

3.4 Filtering and Smoothing

Traffic data consists of two distinct components, *non-random* and *random,* as described in Table 3-3 (4).

Figure 3-4(a) shows a typical 30-minute sample of detector volume data obtained during a period when the deterministic component remained essentially constant. Figure 3-4(b) shows the occupancy data for that period during which the signal system operated with a one minute cycle and without smoothing (to be discussed later). Thus, the volumes represent actual counts sensed by the detector.

Figure 3-5 (4) shows a typical example of a deterministic component representing an A.M. peak period condition. In many traffic control systems, the traffic responsive control law should respond quickly and accurately to the deterministic data components. Since both the deterministic and random components appear together in the detector data, this objective can only be accomplished imperfectly. A *first order* data filter often provides data smoothing to suppress the random component. The smoothing equation which performs this function is:

$$\bar{x}(m) = \bar{x}(m-1) + K(x(m) - \bar{x}(m-1)) \qquad (3.12)$$

Where:

$\bar{x}(m)$ = Filter output after the mth computation

$x(m)$ = Filter input data value (average value of variable between m-1 and m instants)

K = Filter coefficient in the range 01; (K=1 represents no filtering)

Table 3-1. Chapter 3 organization.

Section Title	Purpose	Topics
Control Variables	Describes variables that affect traffic performance	• Control variable definitions • Environmental conditions
Sampling	Describes process of establishing detector state	• Sampling equations
Filtering and Smoothing	Describes components of traffic data	• Smoothing equations
Traffic Signal Timing Parameters	Defines signal timing variables	• Cycle length • Phase • Interval • Split • Offset
Traffic Signal Phasing	Describes vehicle and pedestrian movements	• Phasing options - left-turn phasing - phase sequencing
Isolated Intersections	Describes operation and performance of isolated intersections	• Basic considerations • Traffic flow • Types of control • Intersection timing requirements
Arterial Street Control	Describes operation of signals as a system (open network)	• Basic considerations • Time-space diagram • Timing plan elements • Traffic flow variations • Timing plan development
Network Control	Describes operation of signals where arterials cross (closed network)	• Basic considerations • Off-line timing plan techniques • On-line network traffic control techniques • Saturated flow conditions • Network simulation
Special Controls	Describes special traffic control applications	• Directional controls and lane control signals • HOV priority systems • Preemption/Priority systems • Television monitoring • Overheight vehicle control systems
Benefits	Describes the benefits, applications, and impacts of different levels of control	• Estimating fuel consumption • Estimating vehicle emissions • Estimating highway user costs • Impacts of traffic signal system improvement • Cost-effectiveness comparisons
Measures of Effectiveness (MOEs)	Describes MOEs and criteria for selecting MOEs	• MOEs • Description • Calculation
A Look to the Future	Describes issues in applying new techniques to traffic systems	• Improved estimation of traffic variables • Improved traffic control strategies • Incident detection for urban intersections

Table 3-2. Control variable definitions.

Variable	Definition	Equation	Detection Method
Vehicle Presence	Presence (or absence) of a vehicle at a point on the roadway	N/A	Detector closes electrical circuit when vehicle enters field of detection. Circuit held closed as long as vehicle remains within field, up to some maximum (say 5 minutes).
Flow Rate (Volume)	Number of vehicles passing a point on the roadway during a specified time period	$Q = N/T$ (3.1) Q = Vehicles/hour passing over detector N = Number of vehicles counted by detector during time period, T T = Specified time period, in hours	Output scanned periodically by circuitry or field microprocessor near detector site. Detector usually scanned at intervals ranging from 1/30 second to 1/240 second. Vehicle count accumulated over time interval (e.g., every 4 to 5 seconds) by computer. Best to set time interval equal to a fraction of signal cycle lengths; otherwise sampling (aliasing) errors will occur (1).
Occupancy	Percent of time that a point on the roadway is occupied by a vehicle	$\theta = \frac{100}{TL} \sum_{i=1}^{N} (t_i - D)$ (3.2) Where: θ = Raw occupancy, in percent T = Specified time period, in seconds t_i = Measured detector pulse presence, in seconds L = Ratio of the effective length of the vehicle plus the loop to the vehicle length N = Number of vehicles detected in the time period, T D = Difference between detector dropout and pickup times	For most contemporary detectors, D is usually less than 20 milliseconds and does not produce significant occupancy errors. The value L is best obtained experimentally. Many systems use occupancy only in a relative sense, i.e., to compare thresholds or table values for changing controls or implementing displays and alarms. When used in this way, the value of L may be taken as unity. Thus, traffic systems often implement the following equation: $\theta_A = \frac{100}{T} \sum_{i=1}^{N} t_i$ (3.3) Where θ_A approximates occupancy

Table 3-2. Control variable definitions (continued).

Variable	Definition	Equation	Detection Method
Speed	Distance traveled by a vehicle per unit time	Either 1 or 2 detectors can measure speed (see figure 3-2). $V = \frac{3.6 \times 10^6 d}{5,280 (t_1 - t_0)}$ (3.4) Where: 1 Detector (passage time) V = Speed, in mi/hr d = Mean vehicle length plus effective loop length, in ft t_0 = Time when detector turns on, in millisec (ms) t_1 = Time when detector turns off, in ms 2 Detector (speed trap) d = Distance between detectors, in ft t_0 = Time upstream detectors turns on, in ms t_1 = Time downstream detector turns on, in ms Traffic control systems commonly use this equation, which assumes a vehicle moves at constant velocity through the 2 detector *speed trap*. When only 1 detector is used, a mean vehicle length must be assumed. Because the actual vehicle length varies considerably (e.g., because of variations in numbers of trucks and buses), using 2 detectors yields more accurate speed measurements. However, speed traps at representative locations can be used periodically to update the average effective vehicle length used to determine vehicle speeds by the passage-time method at single-detector locations.	To date, most surveillance systems have used inductive loop detectors. These detectors only discern conditions at the loop locations. Surveillance systems often use these point detector stations as surrogates for conditions on a section of roadway. The relationship between the average spot speed and the speed over a section of roadway (space-mean speed) is given by Ashton (2). $\overline{U_s} = \frac{N}{\sum_{i=1}^{N} (^1/V_i)}$ (3.5) Where: $\overline{U}s$ = Space-mean speed over a roadway section, in mi/hr (km/hr) V_i = Speed of vehicle i crossing a detector station anywhere within the roadway section N = Number of vehicles detected

Table 3-2. Control variable definitions (continued).

Variable	Definition	Equation	Detection Method
Speed (continued)		The vehicle length, L_V, in ft is determined from a speed-trap measurement as follows: $L_V = \left(\frac{1}{2}\right)\left[(t_{11} - t_{01}) + (t_{12} - t_{02})\right]\left(\frac{5{,}280\,V}{3.6x10^6}\right)$ (3.6) Where: V = Speed determined from the speed-trap calculation, in mi/hr t_{0i} = Time when ith detector of speed-trap turns on, in milliseconds t_{1i} = Time when ith detector of speed-trap turns off, in milliseconds An alternative method shown in equation 3.7 can compute the average speed over a cycle T from volume and occupancy (3) $V = C\ \frac{Q}{\theta}$ (3.7) Where C is a calibration coefficient best obtained experimentally	

Table 3-2. Control variable definitions (continued).

Variable	Definition	Equation	Detection Method
Density	Number of vehicles per lane mi (km)	$Q = K\bar{U}s$ (3.8) Where: Q = Volume of traffic flow, in v/hr K = Density of traffic flow, in v/mi $\bar{U}_s$ = Space-mean speed, in mi/hr (km/hr) While density is an important quantity in traffic flow theory, most traffic control systems do not use this parameter directly for implementing flow control. Density (K) may be directly computed from count and speed measurements by equation 3.9, which was obtained by substituting equations 3.1 and 3.5 into equation 3.8. $K = \left(\frac{1}{T}\right)\sum_{i=1}^{N}\left(\frac{1}{V_i}\right)$ (3.9) Where: N = The number of vehicles detected during time, T V_i = Speed of vehicle i crossing a detector in a lane K = Density of detectorized lane	See flow rate and speed
Headway	Time spacing between front of successive vehicles, usually in one lane of a roadway	N/A	Time difference between beginning of successive vehicle detections (see figure 3-3)

Table 3-2. Control variable definitions (continued).

Variable	Definition	Equation	Detection Method
Queue Length	Number of vehicles stopped in a lane behind the stopline at a traffic signal	N/A	Cannot be measured directly by a single presence detector For example, if a detector were located upstream some distance from the stop line at a traffic signal, the determination of whether or not each vehicle would have to stop is made as it approached the traffic signal detector. This prediction would be based on the measured speed of the vehicle, signal timing, distance of the detector from the stopline, and the current queue length. If it were predicted that the vehicle would have to stop, one would be added to the current queue length. If the signal were green, the queue length would be reduced in accordance with a predetermined flow rate. The SCOOT traffic control system, described in section 3.9, uses such an approach. The use of video processor detectors (section 6.2) facilitates the determination of queue length by providing multiple detection points in the queue.

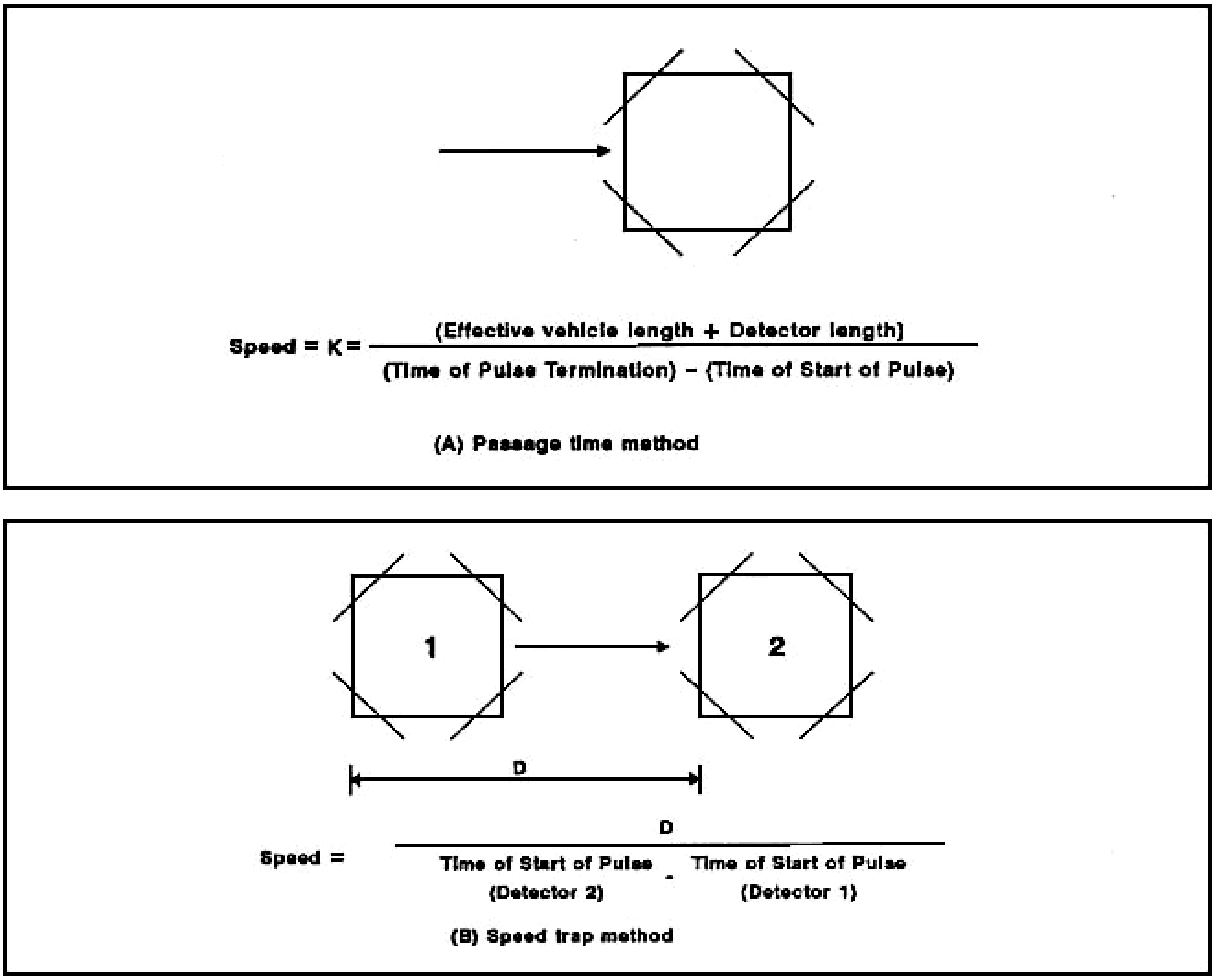


Figure 3-2. Speed measurements using presence detectors.

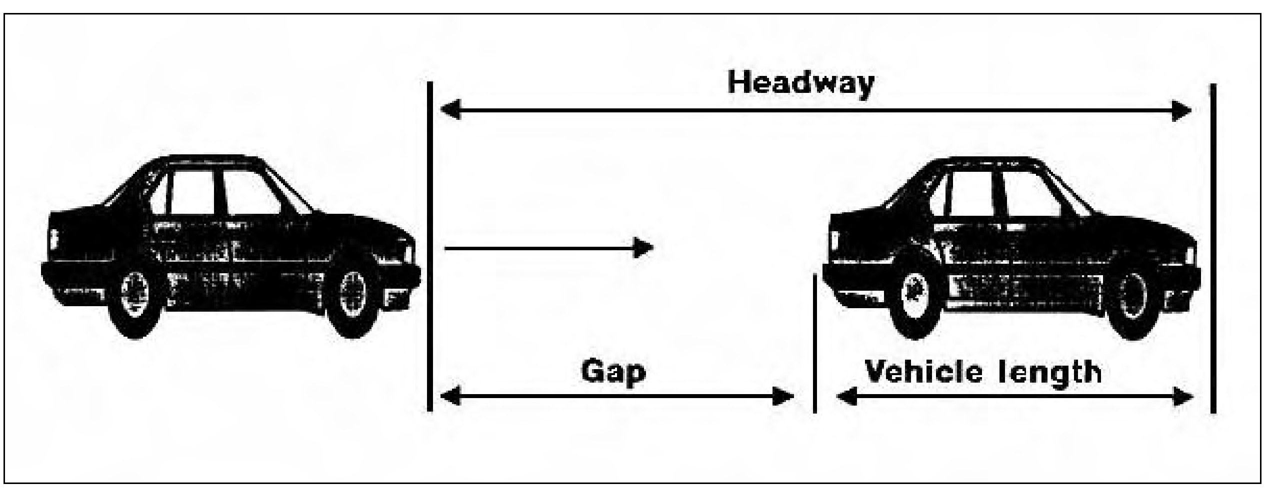
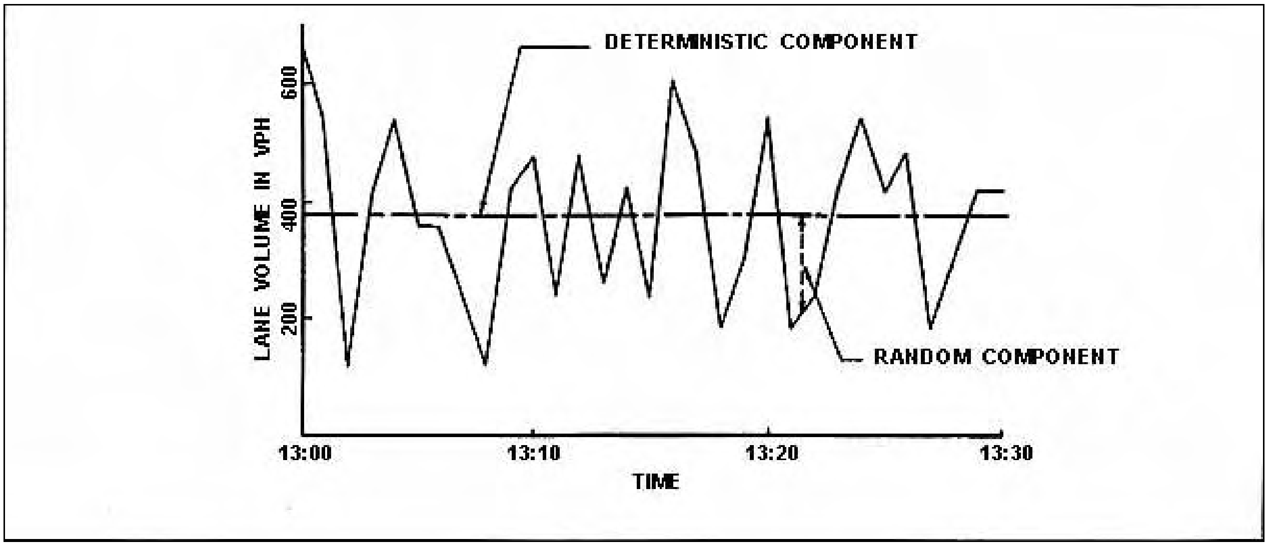


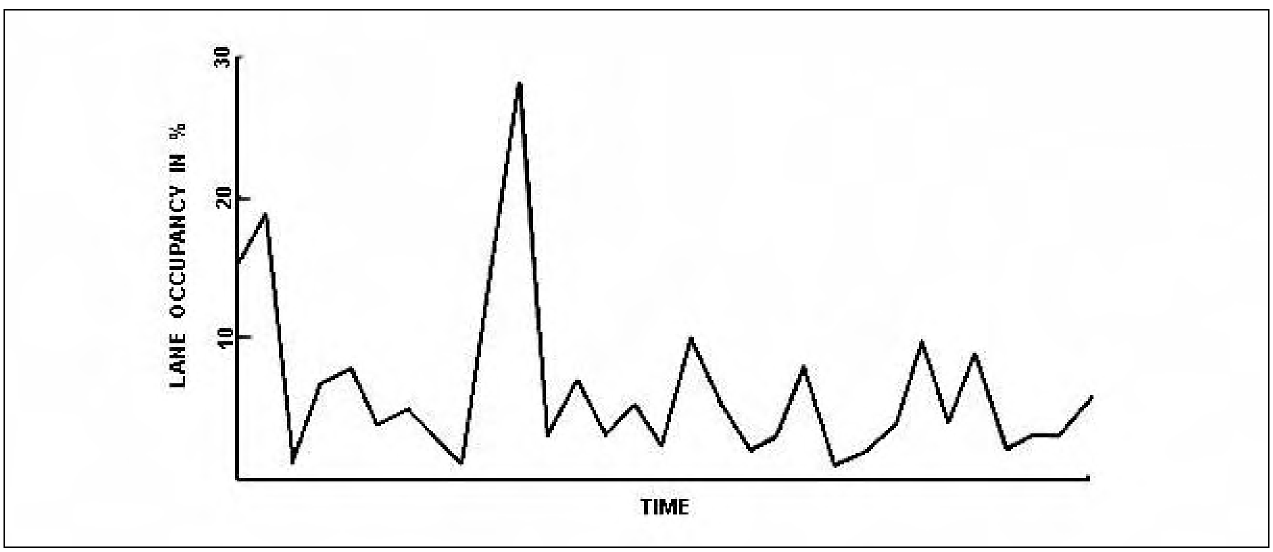
Figure 3-3. Headway determination.

Table 3-3. Traffic data components.

Component	Characteristic	Source
Nonrandom	Deterministic	• Changes in basic service demand • Ability of intersection to service demand
Random	Variational about deterministic component Characterized by a Poisson or other probability distribution	• Nondeterministic changes in value from cycle to cycle



(a). Volume



(b). Occupancy.

Figure 3-4. Deterministic and random components when demand is constant.

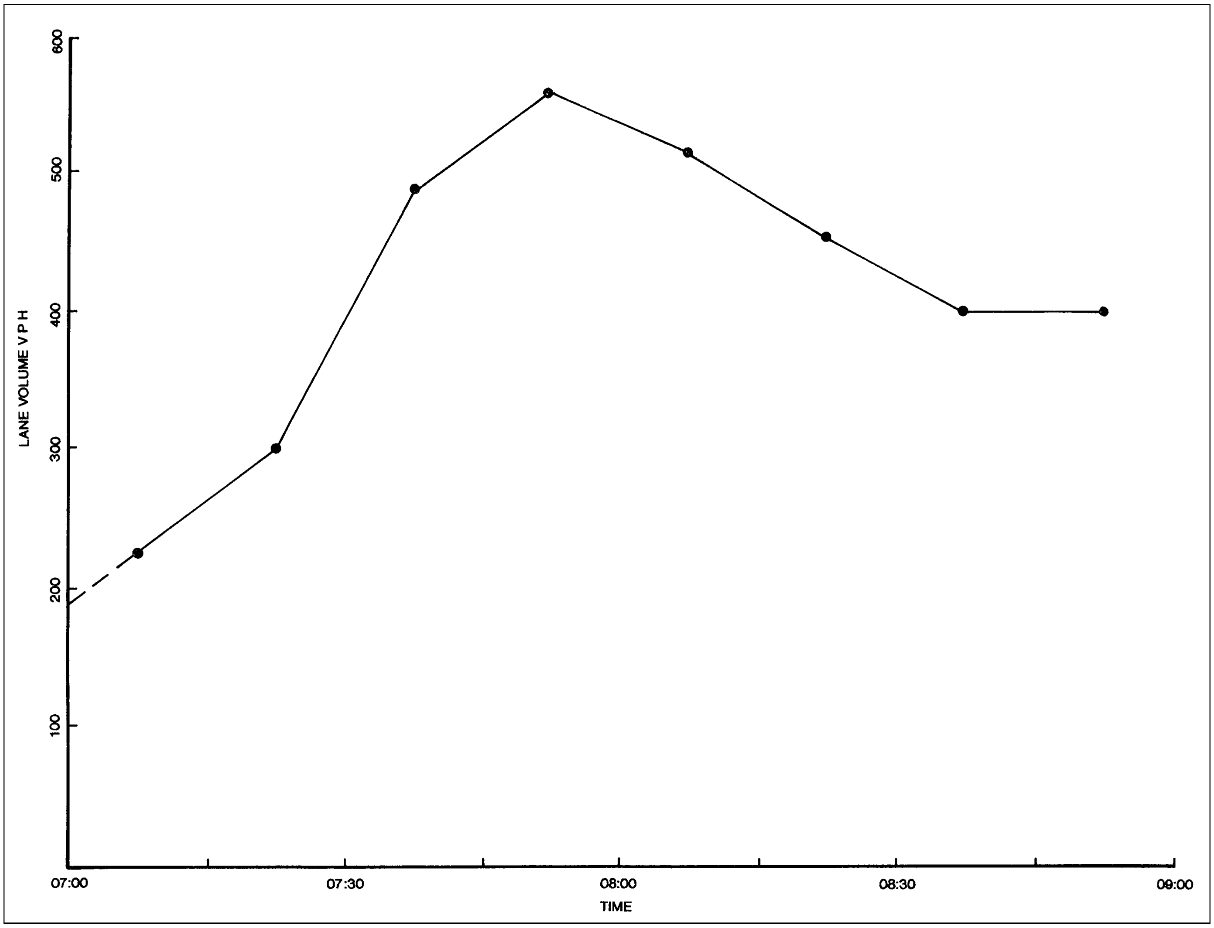


Figure 3-5. Deterministic component of volume during a.m. peak period.

Figure 3-6 (4) shows the smoothing effect of the filter on the traffic data of Figure 3-4(a) when processed by Equation 3.12 with various values for K.

Although the filter reduces the effect of the random component, it develops an error in the faithful reproduction of the deterministic component when that component is changing.
Figure 3-7(a) shows the lag in the filter output. Figure 3-7(b) shows the magnitude of this error for the input data of Figure 3-5.

Gordon (4) describes a technique for identifying the appropriate coefficient by determining the coefficient which equates the errors developed by both components.

3.5 Traffic Signal Timing Parameters

Table 3-4 provides definitions of the fundamental signal timing variables.

3.6 Traffic Signal Phasing

Phasing reduces conflicts between traffic movements at signalized intersections. A phase may involve:

- One or more vehicular movements,
- One or more pedestrian crossing movements, or
- A combination of vehicular and pedestrian movements.

The National Electrical Manufacturers Association (NEMA) has adopted and published precise nomenclature for defining the various signal phases to eliminate misunderstanding between manufacturers and purchasers. Figure 3-8 illustrates the assignment of right-of-way to phases by NEMA phase numbering standards and the common graphical techniques for representing phase movements. In this figure, the signal cycle consists of two primary phase combinations (Phases 2 + 6 and Phases 4 + 8) which provide partial conflict elimination. This arrangement separates major crossing movements, but allows left-turn movements to conflict. Thi s may

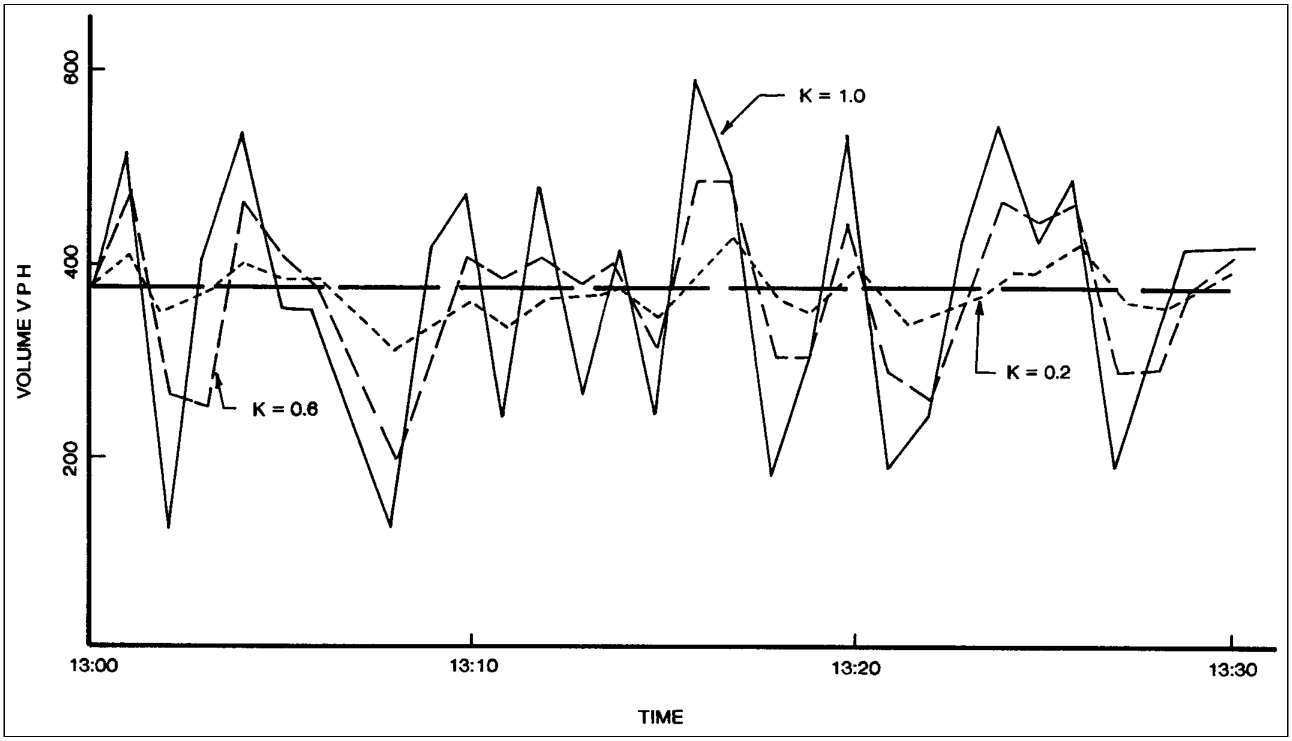


Figure 3-6. Effect of variation in smoothing coefficient on random component.

prove acceptable if left-turn movements remain light, but if heavy, these movements may also require separation. Figure 3-9 illustrates a 4-phase sequence separating all vehicular conflicts. Section 7.7 more fully discusses the NEMA phase designations.

Phasing Options

Left-Turn Phasing

As suggested by the previous discussion, phasing becomes primarily a left-turn issue. As left-turns and opposing through volumes increase, the engineer should consider left-turn phasing. Figure 3-10 defines left-turn phasing options as illustrated in Figure 3-11.

The most common practice allows opposing left -turns to move simultaneously as *concurrently* timed phases.

Holding the number of phases to a minimum generally improves operations. As the number of phases increases, cycle lengths and delays generally increase to provide sufficient green time to each phase. The goals of improving safety (by adding left-turn phases), and operations at a signalized intersection may conflict, particularly with pretimed control.

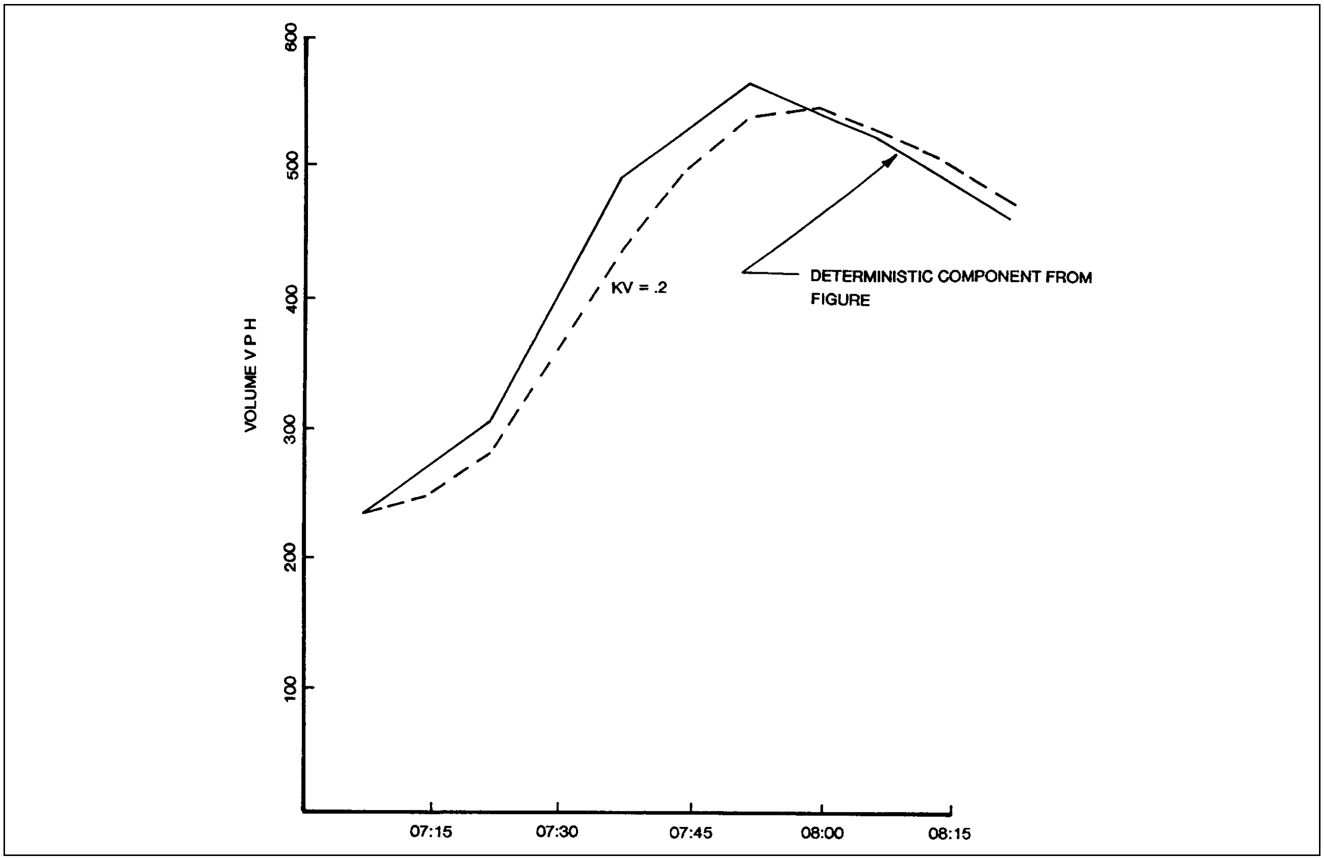
Table 3-5 shows advantages and disadvantages of other options for left-turn phasing.
Although the Manual on Uniform Traffic Control Devices (MUTCD) (5) does not provide warrants for left-turn phasing, several states and local agencies have developed their own guidelines. The Manual of Traffic Signal Design (6) and the Traffic Control Devices Handbook (7) summarize representative examples of these guidelines.

Reference 8 provides a recent set of guidelines for left-turn protection. The report provides guidance on:

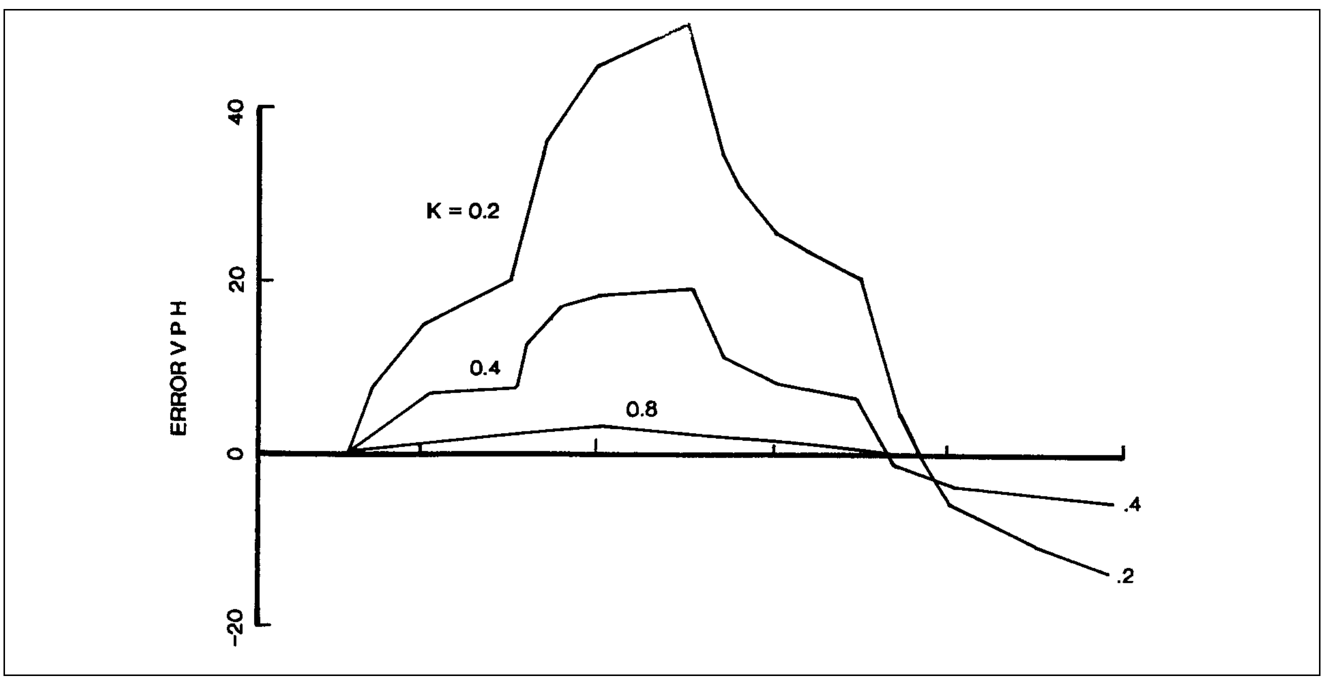
- Justification of protected left-turn phasing,
- Type of left-turn protection, and
- Sequencing of left-turns.

Phase Sequencing

Operational efficiency at a signalized intersection, whether isolated or coordinated, depends largely on the controller's signal phasing versatility. *Variable-sequence* phasing or *skip-phase* capability proves particularly important to multi-phase intersections where the number of change intervals and start-up delay associated with each phase can reduce efficiency considerably.



(a). Filter response to deterministic component.



(b). Deterministic error at filter output.

Fig 3-7. Filter response and output to deterministic component and error.

Table 3-4. Signal timing variable definitions.

Variable	Definition
Cycle Length	The time required for 1 complete sequence of signal intervals (phases).
Phase	The portion of a signal cycle allocated to any single combination of 1 or more traffic movements simultaneously receiving the right-of-way during 1 or more intervals.
Interval	A discrete portion of the signal cycle during which the signal indications (pedestrian or vehicle) remain unchanged.
Split	The percentage of a cycle length allocated to each of the various phases in a signal cycle.
Offset	The time difference (in seconds or in percent of the cycle length) between the start of the green indication at 1 intersection as related to the system time reference point.

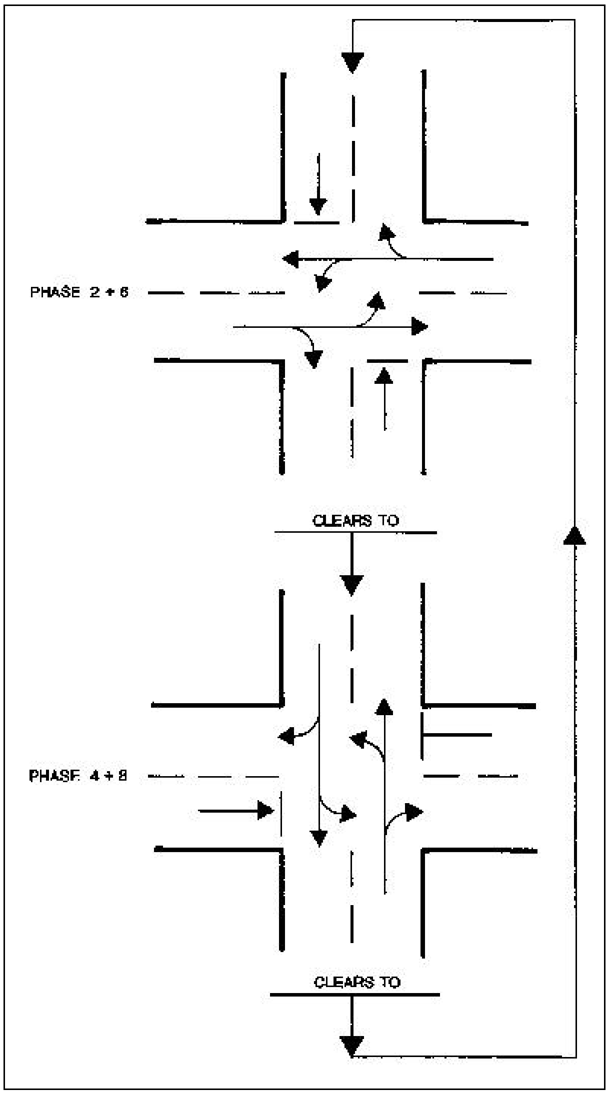


Figure 3-8. Two-phase signal sequence.

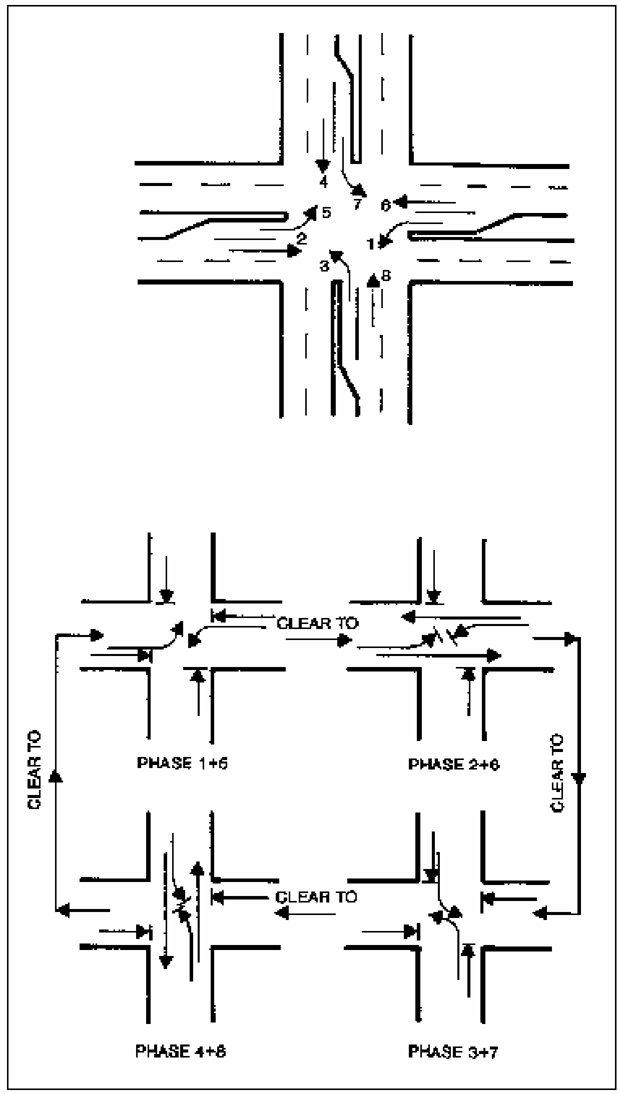


Figure 3-9. Four-phase signal sequence.

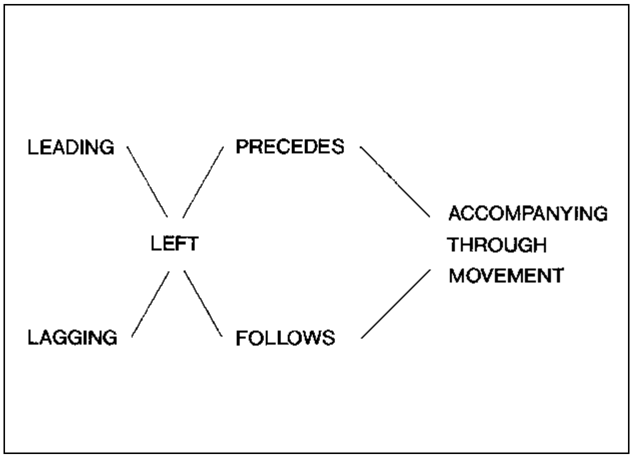


Figure 3-10. Left-turn phasing definitions.

Modern controller units can provide skip-phase capability. Each set of stored timing plans has a distinct phase sequence changeable by:

- Time clock,
- Time-base coordinator, or
- Externally, by a remote system master.

Full-actuated traffic control illustrates variable-sequence phasing. In the upper part of Figure 3-12, all approach lanes have detectors. Using these detectors and traffic-responsive equipment, phases can be skipped with no traffic present, and certain movements terminated when their traffic moves into the intersection. This capability produces a *variation* in the phasing sequence. The lower part of Figure 3-12 illustrates primary phasing options for a full-actuated intersection. The phasing options selected may be changed with the signal timing plan.

3.7 Isolated Intersections

Basic Considerations

The major considerations in the operation of an isolated intersection are:

- Safe and orderly traffic movement,
- Vehicle delay, and
- Intersection capacity.

Vehicle delay results from:

- *Stopped time* delay (time waiting during red), and
- *Total* delay (stopped time delay plus stop and startup delay).

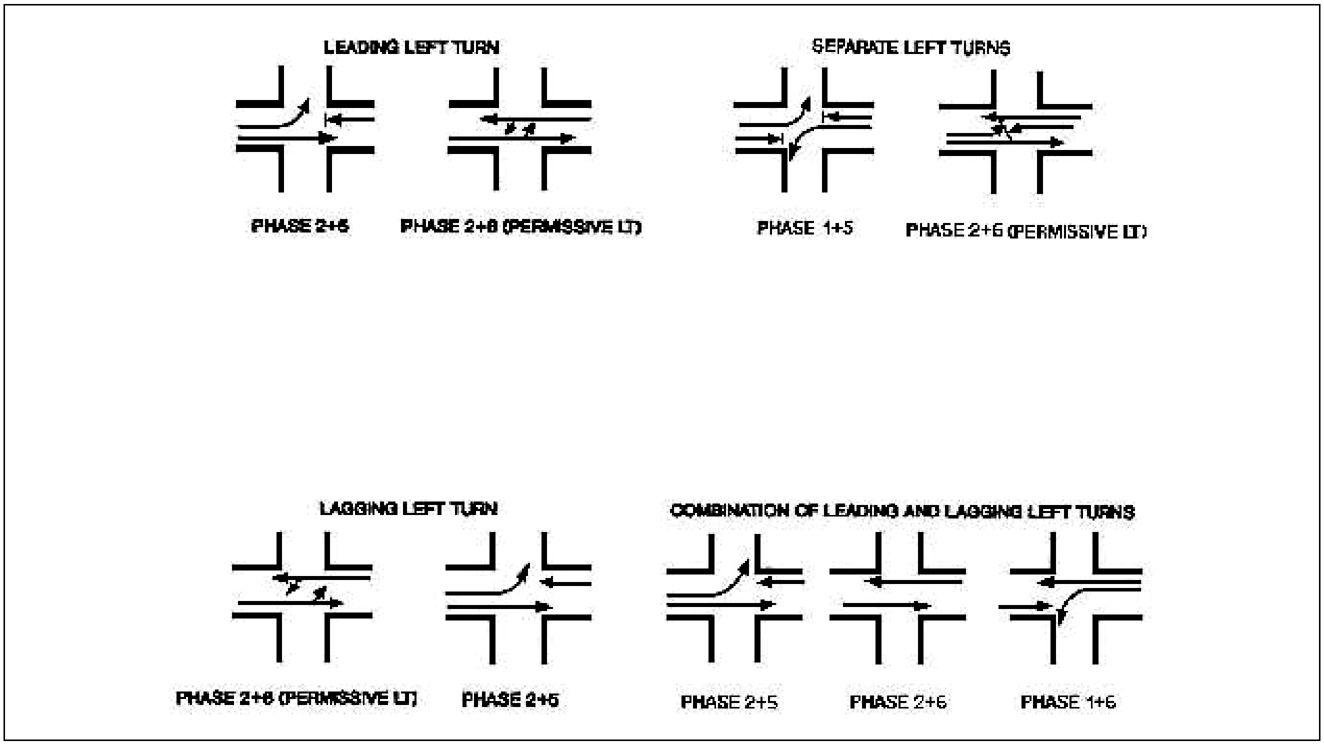


Figure 3-11. Dual-ring left-turn phasing options.

Table 3-5. Additional left-turn phasing options.

Option	Advantage	Disadvantage
Use traffic actuated instead of pretimed left-turn phase	Gives unused left-turn phase time to related through traffic movement	Requires additional detectors
Provide protected/permissive left-turn movement	Reduces delay and queuing	High speeds, blind or multilane approaches or other circumstances may preclude this technique
Change left-turn phase sequences with timing plan changes	Improves progression	Motorists may not expect changed phase sequences

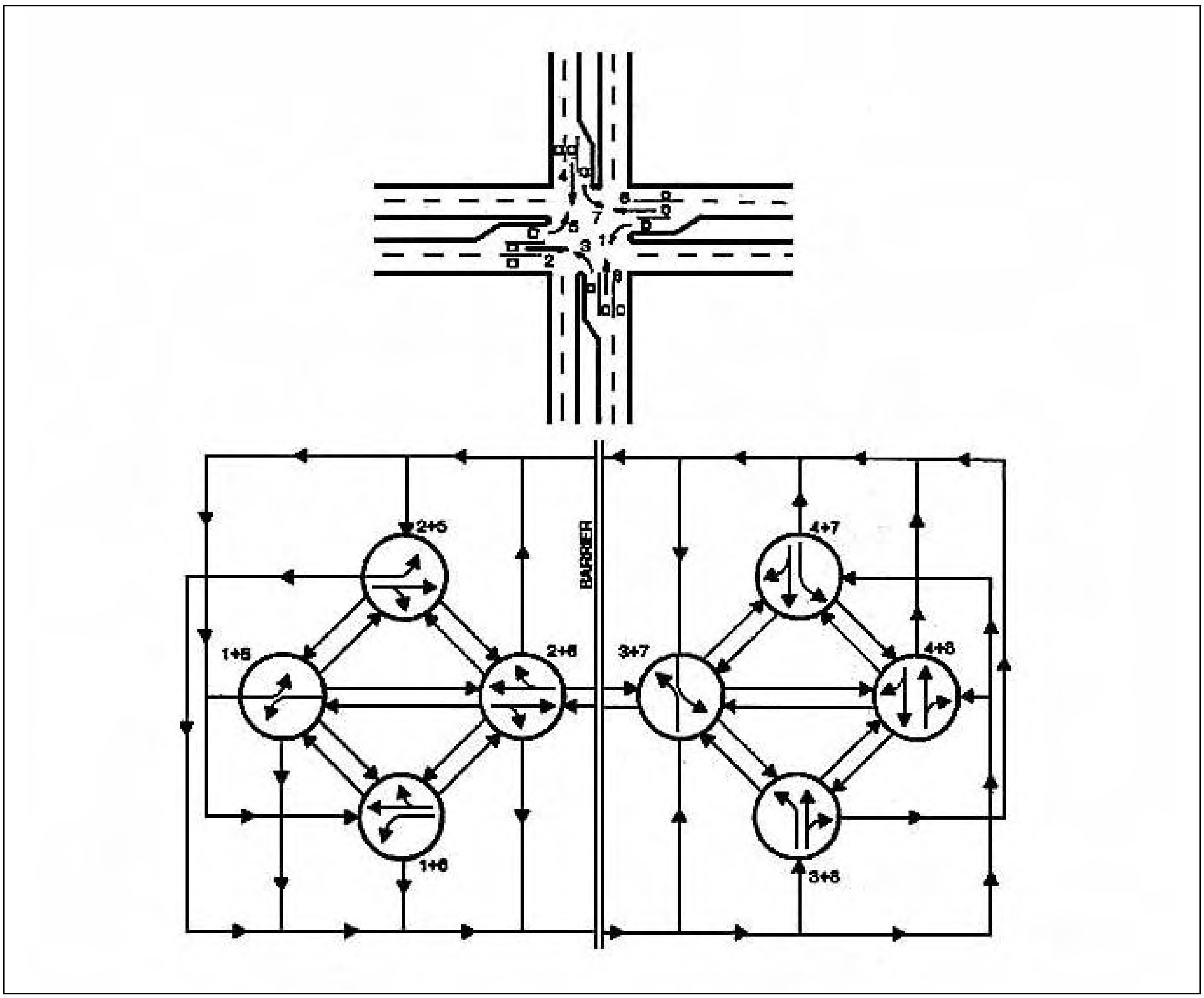


Figure 3-12. Primary phasing options for 8-phase dual-ring control (left-turn first).

Ideally, minimizing total delay will:

- Maximize intersection capacity, and
- Reduce the potential for accident-producing conflicts.

However, these two objectives may not prove compatible. For example, using as few phases as possible and the shortest practical cycle length minimizes delay. However, reducing accidents may require multiple phases and longer cycles, as well as placement of approach detectors to eliminate effects of a possible dilemma zone (see Section 6.3). This placement may not prove optimum for delay minimization. Therefore, it is necessary to exercise engineering judgement to achieve the best possible compromise among these objectives.

Traffic Flow

In analyzing intersection delay or capacity, the flow characteristics of traffic prove fundamental. Vehicles occupy space, and for safety require space between them. With vehicles moving along continuously in a single lane, the number of vehicles passing a given point over time will depend on the average headway. For example, for an average headway of two seconds, a volume of 1,800 vph (3,600 sec/hr x 1 veh/2 sec) results.

Two factors influence capacity at a signalized intersection:

Conflicts occur when two vehicles attempt to occupy the same space at the same time. This requires allocation of right-of-way to one line of vehicles while the other line waits.

The *interruption* of flow for the assignment of right-of-way introduces additional delay. Vehicles slow down to stop, and also experience delay when again permitted to proceed.

These factors (*interruption* of flow, *stopping*, and *starting* delay) reduce capacity and increase delay at a signalized intersection as compared to free-flow operations. Vehicles which arrive during a red interval must stop and wait for a green indication, and then start and proceed through the intersection as illustrated in Figure 3-13. The delay which occurs as vehicles start moving is followed by a period of relatively constant flow. In terminating traffic flow, some time is also lost at the end of a green indication.

Table 3-6 presents data on typical vehicle headways (time spacing) at a signalized intersection as reported by Greenshields (9). These data illustrate basic concepts of intersection delay and capacity.

Types of Control

Traffic signal control for isolated intersections falls into two basic categories:

- Pre-timed, and
- Semi and fully traffic actuated.

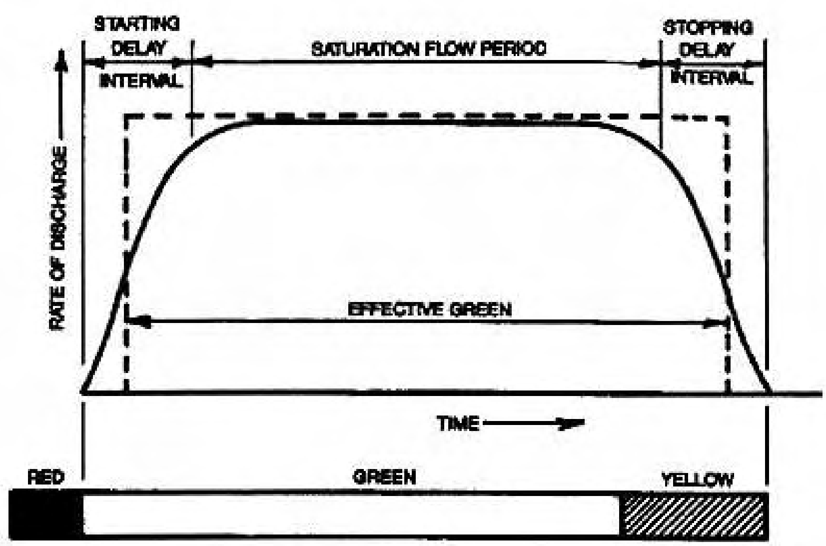


Figure 3-13. Queue discharge across the stopline.

Table 3-6. Vehicle headway data.

Position in Line	Observed Time Spacing (Sec)	Time Spacing at Constant Flow (Sec)	Added Startup Time (Sec)
1	3.8	2.1	1.7
2	3.1	2.1	1.0
3	2.7	2.1	0.6
4	2.4	2.1	0.3
5	2.2	2.1	0.1
6 and over	2.1	2.1	0.0

Source: Reference 9

Each type offers varying performance and cost characteristics depending on the installation and prevailing traffic conditions. Because of the relative complexity of the problem and rapid changes in the state-of-the-art, no universal method exists for determining the optimal control type at an intersection.

Traffic-actuated control will generally prove effective under one or more of the conditions in Table 3 -7 (5).

NCHRP Report 233 (10), the Manual of Traffic Signal Design (6), and the Traffic Engineering Handbook (11) contain additional guidelines and information to aid the engineer in selecting the appropriate type of signal control.

Table 3-7. Conditions for traffic-actuated Control.

- Light, generally fluctuating and/or unbalanced traffic volumes
- Heavy side-street traffic movements and delay only during peak hours
- Pedestrian or accident experience warrants set forth in the *Manual on Uniform Traffic Control Devices* are the only warrants met
- Signal controls 1-way movement of 2-way traffic at the intersections
- Signal installed at a nonintersection location

Table 3-8 summarizes the characteristics of pre -timed and traffic-actuated control.

Intersection Timing Requirements

Pre-Timed Controller

For isolated intersection control with pretimed equipment, the engineer must determine:

- Cycle length,
- Phase lengths (or cycle split), and
- Number and sequence of phases.

This timing must:

- Relate to the characteristics of traffic flow at the intersection, and
- Establish each phase length (green interval plus yellow change interval) and total cycle length.

Traffic-Actuated Controller

Traffic-actuated control equipment automatically determines cycle length and phase lengths based on detection of traffic on the various approaches. The major requirement is to set the proper timing values for each of the functions provided by the controller unit (see Table 3-9).

Webster Optimum Settings

Webster (12) used computer simulation and extensive field observations to study isolated intersection

Table 3-8. Characteristics of pretimed and traffic-actuated control.

	Pretimed	Traffic-Actuated
Definition	Assigns right-of-way according to a predetermined schedule	Assigns right-of-way according to real-time measures of traffic demand obtained from vehicle detectors placed on 1 or more approaches. Adjusts green times and possibly phase sequence (i.e., skip-phase). Full range of capability depends on equipment type and requirements.
Characteristics	Fixed sequence of right-of-way assignments (phases) and time interval for each signal indication based on historic traffic patterns. Left-turn phases may be actuated in some cases. No recognition given to instantaneous traffic demand except when detectors used for left-turns or other minor movements. Major elements of pretimed control include: • Fixed cycle length • Fixed phase lengths unless left-turns are actuated • Number and sequence of phases	See table 3-7 Basic timing parameters consist of: • Minimum green • Passage time interval (vehicle interval) • Maximum interval Traffic-actuated control can operate in the following principal operational modes: • Semi-actuated • Full-actuated • Volume-density • Queue-length • Lane-occupancy
Application	Well-suited to intersections with predictable traffic patterns or frequently saturated conditions	Initially determine the minimum phase interval timing by calculating the pretimed cycle length for each peak period using one of the methods discussed later in this section. Then, increase the timing for each phase by 10 to 15 percent. Since NEMA and 170 controllers can provide Max 1 and Max 2 settings, assign: • One set of phase intervals (a.m. peak) to Max 1 • The second set of phase intervals (p.m. peak) to Max 2 Choose either Max 1 or Max 2 for off-peak conditions. Fine tune through field observations. Fine tuning of all settings important to ensure appropriateness and verify operations.
Hardware	Controller can be: • Solid-state • Microprocessor-based • Electromechanical (using motors, gears, and relays) NEMA TS2 and 170 controllers may be used for pretimed control. These have capability to provide traffic actuated left-turn and other minor movements in a pretimed cycle. See chapter 7 for further detail on these controllers	Typical intersection approach with vehicle detection illustrated in figure 3-14. Can install more than one point detector on high-speed approach. Distance from detector to stopline influences the time setting of the 3 basic timing parameters.

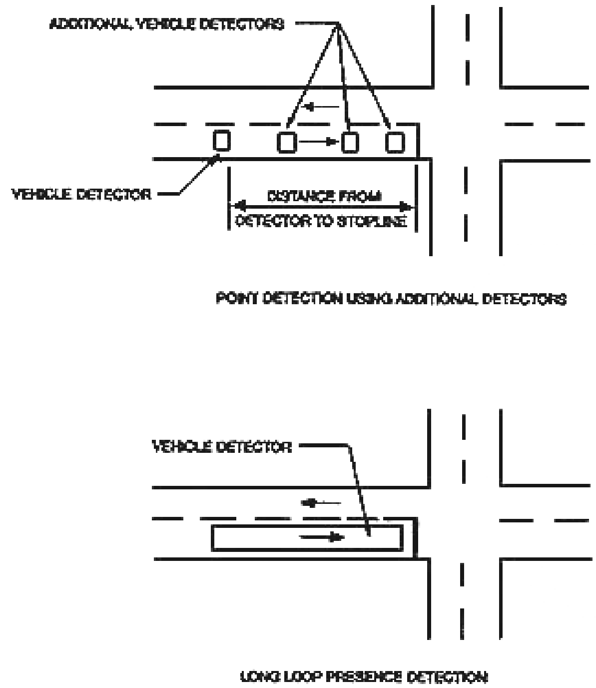


Figure 3-14. Traffic detection on intersection approach.

operation. This work applies to either regular unchannelized or high-type fully channelized intersections. However, Webster fundamentally assumes random vehicle arrivals and no saturation. Webster developed the classic equation for delay shown in Table 3-10.

Webster shows that a *critical lane* has the highest ratio of flow to saturation flow. Y denotes this ratio, where Y = Max (q/S) for a given phase.

Webster developed an optimum cycle-length formula for pretimed application. This formula yields the cycle length that will produce minimum total vehicle delay. Reference 13 develops a similar formula for actuated applications. Table 3-11 shows both formulas.

The formulas of Table 3-11 calculate cycle length at a given isolated intersection. The equations usually yield cycle lengths (C_o) shorter than those defined by other methods. In practice, longer cycle lengths are commonly found. Webster also concluded that delay does not significantly increase for cycle length variation in the range of $0.75C_o$ to $1.5C_o$. Webster's methods prove sensitive to errors in estimates of vehicle flow rate and saturation flow. See Allsop (14) for a discussion of this subject.

Webster further recommended distributing green time to each phase in proportion to the critical lane volumes on each phase. Table 3-12 shows the calculation of green time for a two-phase pretimed intersection.

Table 3-13 illustrates the use of Webster's methods for the intersection shown in Figure 3-16.

Critical Movement Analysis

An alternate approach to intersection capacity analysis and the development of timing plans is based on traffic flow on critical lanes. This approach, described in Drew (15) and *Transportation Research Circular 212* (16) was not the approach selected for the *1994 Highway Capacity Manual* (17).

Traffic-Actuated Control

Using traffic-actuated control at isolated intersections enables the timing plan to continuously adjust in response to traffic demand. However, the potential to minimize delay and maximize capacity will only be realized with careful attention to:

- Type of equipment installed,
- Mode of operation,
- Location of detectors, and
- Timing settings.

Table 3-9. Interval settings.

Interval	Requirement	Calculation/Operation
Minimum Green	**Basic** (no Volume-Density Feature): • Service number of cars potentially stored between detector and stopline or the number normally stopped if a single detector is located a significant distance from the stopline • Remains constant	**Point detection:** Compute minimum green interval times for various detector setback distances assuming: • Start-up delay of 4 seconds • Average headway between discharging vehicles of 2 seconds • Minimum green time at least (4 +2 n), where n is number of vehicles between detector and stopline Compute n assuming an average vehicle length of 20 to 26 ft (6.1 to 7.9 m) For detectors located approximately 120 ft (36.6 m) or more from stopline, minimum green time may equal 18 seconds or longer. The length of minimum green time reduces ability to respond to traffic demand changes. Therefore, consider 120 ft (36.6 m) as upper limit for single detector placement and at speeds of 35 mi/hr (56.3 km/hr) or less. **Long loop presence detection** (or a series of short loops): Set initial interval close to zero when the detector loop ends at the stopline. If the loop ends at some distance from the stopline, use this distance to determine initial interval with point detection. See Chapter 6 for further discussion of vehicle detector placement and relationship to approach speed.
	Traffic-Actuated (Volume-Density Feature): Initial interval based on number of vehicle actuations stored while other phases serviced	When there are serviceable calls on opposing phases, and no additional vehicles cross the detector, terminate phase at the end of this minimum green time. Where pedestrians cross and no separate pedestrian crossing indications exist, (e.g., WALK-DONT WALK), minimum green time should ensure adequate pedestrian crossing time.

Table 3-9. Interval settings.

Interval	Requirement	Calculation/Operation
Passage Time (Vehicle interval, extension interval, or unit extension)	Time required by a vehicle to travel from detector to intersection. With a call waiting on an opposing phase, represents the maximum time gap between vehicle actuations that can occur without losing the green indication. As long as the time between vehicle actuations remains shorter than the vehicle interval (or a preset minimum gap), green will be retained on that phase subject to maximum interval. To ensure *rapid operation*, set vehicle interval as short as practical.	Once the passage time interval timing is initiated and an additional vehicle is detected, present vehicle interval timing is canceled and a new vehicle interval timing initiated. This process is repeated for each additional vehicle detection until: • Gap-out occurs (the gap between detections is greater than the vehicle interval or a present minimum gap). • Max-out occurs (the interval timing reaches a preset maximum and a pedestrian or a vehicle call has been placed for another phase). In either of these 2 cases, the timing of a yellow change interval is initiated and the phase terminated. If the vehicle interval is not completely timed out (because of the maximum override), then a recall situation is set and the timing will return to this phase at the first opportunity. Figure 3-15 illustrates the situation where: • Successive actuations occurred. • Gaps shorter than passage time interval. • Preset maximum green interval reached. **Long loop presence detection:** Set passage time interval close to zero because the signal controller continuously extends the green as long as loop is occupied. In this case, critical time gap is time required for a vehicle to travel a distance equal to the loop length plus the vehicle length. For a series of short loops, treat them as a long loop, provided that the distance between loops is less than the vehicle length; otherwise, use a short vehicle interval to produce the equivalent effect of a single long loop.
Maximum Green (Total green time or vehicle extension limit)	Maximum length of time a phase can hold green in presence of conflicting call	Normal range between 30 and 60 seconds depending on traffic volumes

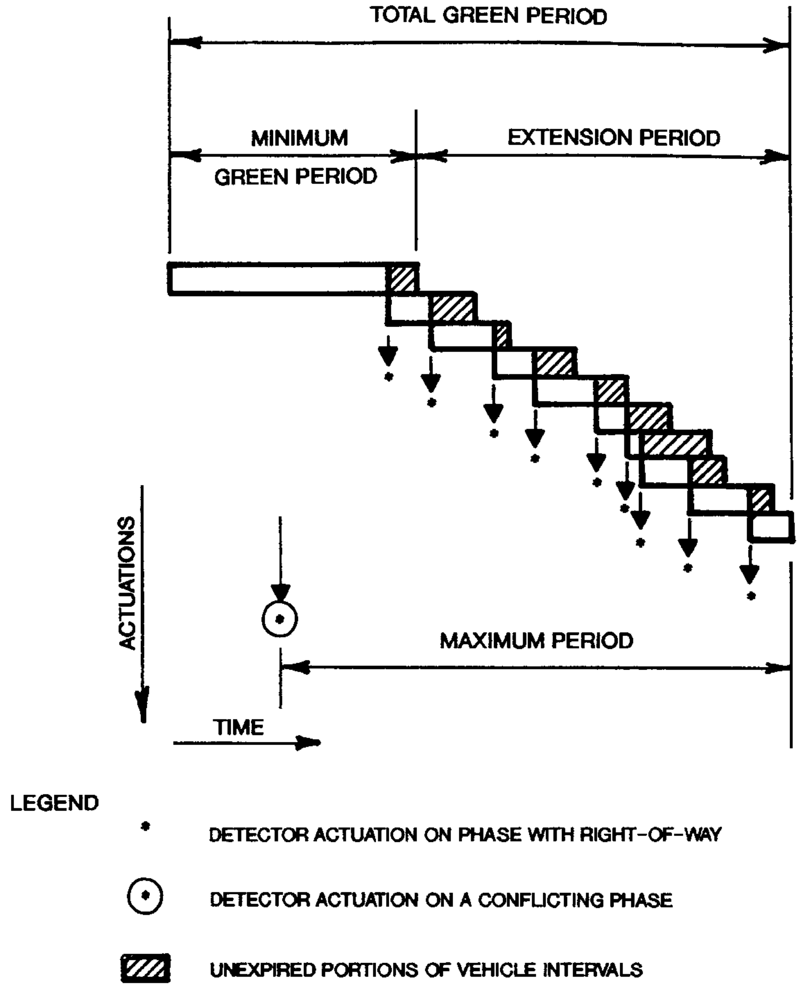


Figure 3-15. Schematic of actuated phase interval

Table 3-10. Webster delay equation.

$$d = \frac{C(1- l)^2}{2(1- lX)} + \frac{X^2}{2q(1-X)} - 0.65\left(\frac{c}{q^2}\right)^{\left(\frac{1}{3}\right)} X^{(2+5l)} \tag{3.13}$$

Where:

D	=	Average delay per vehicle on the intersection approach under consideration
C	=	Cycle length
λ	=	Proportion of the cycle effectively green for the phase under construction
q	=	Flow rate
S	=	Saturation rate (1800 v/hr)
X	=	q/S = The degree of saturation. This the ratio of actual to maximum flow that can pass through the intersection from this approach.

Table 3-11. Optimum cycle length formulas.

Pretimed	Actuated
$C_o = \dfrac{\dfrac{1.5L+5}{n}}{1-\sum\limits_{i=1} Y_i}$ (3.14)	$C = \dfrac{\dfrac{1.3L}{n}}{1-\sum\limits_{i=1} Y_i}$ (3.15)

Where:

C_o = Optimum cycle length, in seconds
L = nl + R (total lost time per cycle)
n = Number of phases
l = Average lost time per phase, in seconds
R = Time during each cycle when all signals display red simultaneously, in seconds
Y_i = Critical lane flow (with phase, v/hr) saturation flow (v/hr)

Refer to Chapters 6 and 7 of this Handbook for a discussion of:

- Types of detectors and controllers, and
- Proper design and operation.

To perform a simple check on traffic-actuated controller performance, for a given amount of green time during peak periods, observe:

- Cycle lengths, and
- Number of cars moved.

Traffic performance can probably be improved if:

Table 3-12. Calculation of green time for a 2-phase pretimed intersection.

DG_t *(effective green time)* $= C_o - nl$ (3.16)

Where:

C_o = Optimum cycle length, in seconds
n = Number of phases
l = Lost time per phase, in seconds

- Cycle lengths prove excessive (100 seconds or greater), and
- The cycle makes inefficient use of green time.

This improvement may require:

- Revised design,
- Timing changes,
- Equipment repair, or
- Geometric or channelization changes.

Other Considerations

Methods are available for developing timing plans other than those previously discussed. References on this subject include:

- *Traffic Engineering Handbook* (11),
- *Manual on Uniform Traffic Control Devices* (5),
- *Manual of Traffic Signal Design* (6), and
- *Traffic Engineering Theory and Practice* (18).

In addition to cycle length and split calculations, the traffic engineer should consider several other important factors in developing timing plans for signal control.

Pedestrian movement often governs a timing plan. The engineer must provide sufficient green for pedestrians to cross the traveled way (see Reference

Table 3-13. Example of Webster's methods.

Assume saturation flow of 1800 v/hr, and lost time per phase of 5.2 seconds

$$Y_i = \frac{observed\,flow}{saturated\,flow}$$

$$Y_1 = \frac{600}{1{,}800} = 0.333$$

$$Y_2 = \frac{400}{1{,}800} = 0.222$$

$$\sum Y_i = 0.333 + 0.222 = 0.555$$

$$C_o = \frac{1.5\,L + 5}{1 - \sum Y_i} \qquad (3.14)$$

$$C_o = \frac{1.5\,(2)\,(5.2) + 5}{1 - 0.555} = 46.3\ sec$$

Use C_o = 46 seconds

$$G_t = C_o - nl \qquad (3.16)$$

$$G_t = 46 - 10.4 = 35.6$$

Critical lane volumes = 600 + 400 = 1,000

$$G_1 = \frac{600}{1{,}000}\,(35.6) = 21.4\ sec$$

$$G_2 = \frac{400}{1{,}000}\,(35.6) = 14.2\ sec$$

Signal timing becomes:

Phase 1 Green = G_1 – Yellow + lost time
= 21.4 - 4 + 5.2 = 22.6 seconds

Phase 2 Green = G_2 – Yellow + lost time
= 14.2 - 4 + 5.2 = 15.4 seconds

Cycle Length = Phase 1 + Phase 2 + A1 + A2
= 22.6 + 15.4 + 4 + 4 = 46 seconds

A_1 = Yellow time on Phase 1, in seconds
A_2 = Yellow time on Phase 2, in seconds

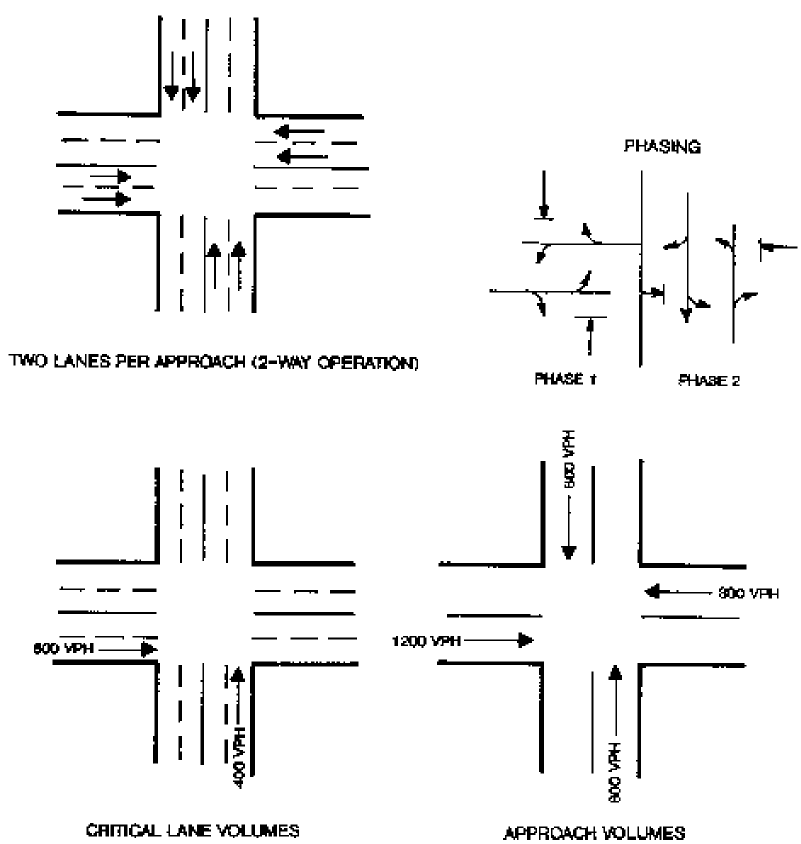


Figure 3-16. Example intersection.

11 for example). Where equipment permits, the pedestrian phase should be activated when the pedestrian phase interval exceeds the vehicle interval.

Another important consideration is the length of the phase-change period. This period may consist of only a yellow change interval or may include an additional all red clearance interval. The yellow interval warns traffic of an impending change in the right-of-way assignment. For a detailed discussion of these intervals refer to the *Traffic Control Devices Handbook* (7).

In considering control concepts and strategies for isolated signalized intersections, the engineer must consider:

- Traffic flow fluctuations, and
- The random nature of vehicle and pedestrian arrivals.

The daily patterns of human activity influence traffic flow; it usually exhibits three weekday peak periods (A.M., midday, P.M.). Drew (15) has shown that even within a peak hour the five-minute flow rates can prove as much as 15 to 20 percent higher than the average flow rate for the total peak hour period. He has further shown that a Poisson distribution best predicts vehicle arrivals for isolated intersections, indicating that considerable variation in arrival volume can occur on a cycle-to-cycle basis. Drew presents a comprehensive treatment of the design and signalization of intersections.

Available Computer Software

Manual design techniques for intersection signal timing can prove useful, but inefficient for conducting comprehensive analyses and evaluation of alternative timing plans for a set of geometric and traffic conditions. Since the early 1960's, computer models have assisted the traffic engineer in developing cost-effective operational improvements.

Well-documented computer models for intersection signal timing include:

- WHICH (contains several programs including SOAP),
- EVIPAS, and
- PASSER.

Table 3-14 presents a brief overview of these models.

Intersection Capacity Analysis

Certain signalized intersections experience long delays during recurring peak periods. As a rule of thumb, an intersection reaches capacity when:

- More than 15% of the peak hour traffic cannot clear the intersection in one cycle, and
- Any vehicle must wait more than two cycles.

As shown in Figure 3-17, increasing the cycle length beyond 80 seconds does not provide a great deal of throughput and significantly increases delay.

Under these conditions, the engineer should perform a study using the *"Highway Capacity Manual"* (17) or related computer models to determine what geometric changes the intersection needs.

The *1994 Highway Capacity Manual* is the current edition. The Transportation Research Board (TRB) Committee on Highway Capacity and Quality of Service has approved in principle revisions to the chapter involving capacity of intersections under traffic signal control.

3.8 Arterial Street Control

Basic Considerations

Arterial street control gives preference to *progressive* traffic flow along the arterial. In contrast with isolated intersections, the signals must operate as a system.

Arterial street signal systems form an *open* network, as compared to a *closed* network, as illustrated in Figure 3-18. Arterial street control recognizes that a signal releases *platoons* which travel to the next signal. To maintain the flow of these platoons, the system must coordinate timing of adjacent intersections. The system accomplishes this by establishing a time relationship between the beginning of arterial green at one intersection and the beginning of arterial green at the next intersection. By doing this, static queues receive a green indication on their approach in advance of arriving platoons. This permits continuous traffic flow along an arterial street and reduces delay.

Basic factors that indicate the need to operate signals as a single system to maximize progressive movement include:

- Distance between signalized intersections - The spacing of signalized intersections on an arterial street may range from 150 ft. to more than 5,000 ft. The need to operate the signals as a system generally increases as the:
  - Distance between signals decreases, and
  - Friction along the arterial decreases.

Table 3-14. Intersection signal timing computer models.

Model	Developer	Purpose	Capabilities/Functions	Additional Information
SOAP-84 (Signal Operations Analysis Package, component of WHICH)	State of Florida and University of Florida Transportation Research Center for the Federal Highway Administration	Develops signal timing plans for isolated intersections. Can evaluate a wide range of control alternatives including pretimed or multiphase-actuated control. Typical condition is a 4- legged intersection with left-turns, through traffic and right-turns	Determines optimum signal timing and phasing by 3 computational functions: • Design • Analysis • Evaluation **Design:** • Examines all legitimate sequences for an intersection configuration and traffic conditions. • Selects one that uses minimum queue time • User decides number of traffic patterns and assigns them to appropriate dial. • Assigns unassigned patterns based on traffic demands. No assignments made for traffic-actuated control. • Determines optimum cycle length to minimize total delay subject to queue constraints. Allocates green based on critical movement analysis (6). **Analysis:** • Computes MOEs: - delay - stops - fuel consumption - volume-to-capacity ratio - left-turn conflicts • Quantifies effects of design or other timing schemes **Evaluation:** • Produces comparisons of different design schemes	References 19-21
EVIPAS (Enhanced Value Iteration Process Actuated Signals)	Originally developed by PennDOT, later enhanced by Viggen Corp.	Analyzes and develops optimal timing plans for a wide range of geometric and detector designs.	Provides MOEs: • Delay • Operating costs • Fuel consumption • Emissions	Reference 21

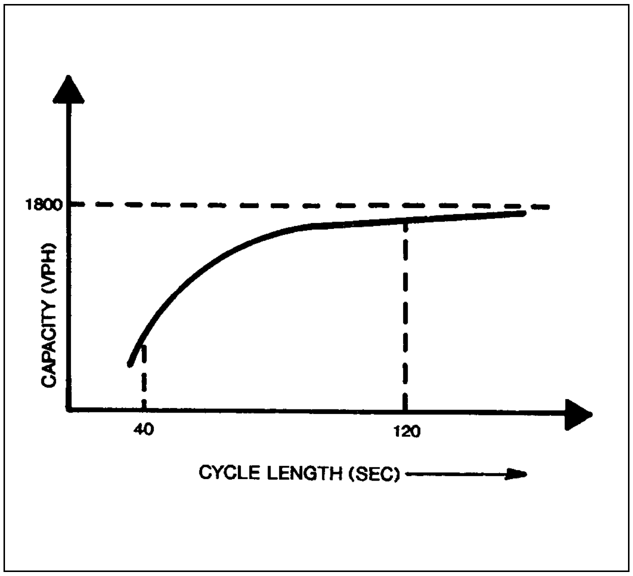


Figure 3-17. Cycle length relationship to Capacity.

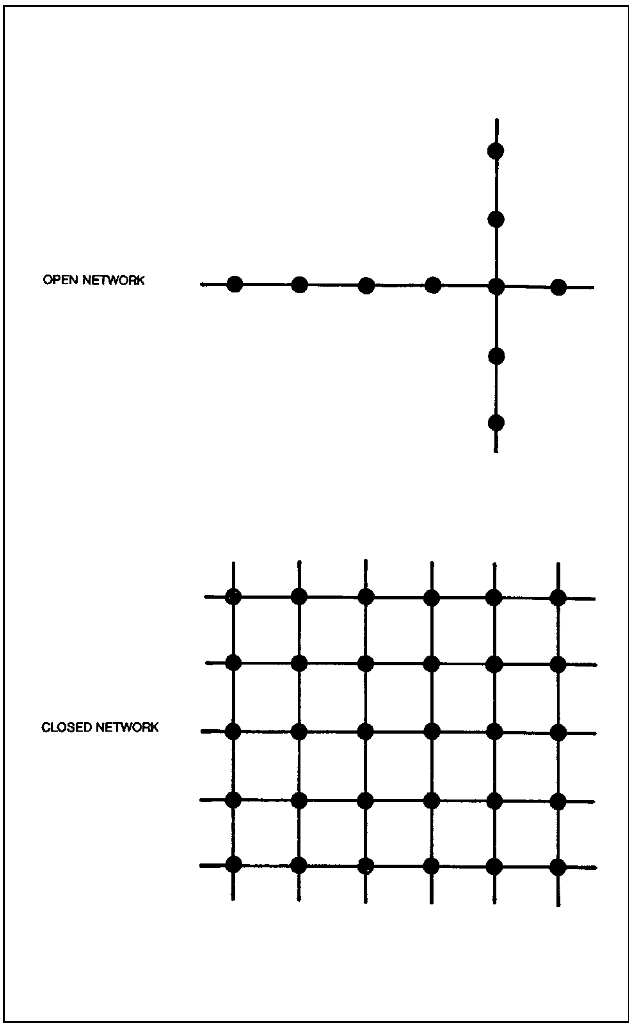


Figure 3-18. Signal networks.

Section 3.9 describes the effect of spacing and friction on platoon structures.

As a general criterion, interconnect adjacent traffic signals when the distance is less than approximately 70 times the desired average speed in feet per second (22).

- Street operation - One-way vs. two-way - One-way street operation greatly facilitates progressive movement and increases effectiveness of system control.
- Signal phasing - The phasing requirements for the type of intersection under control also influences system control. Some arterials have simple two-phase intersections, while others require multiple left-turn phases. The phase sequence for multiphase intersections with left-turn phase sequences could be any of those shown in Figures 3-10 and 3-11. Depending on the type intersection control, the left-turn phase sequence could be changed as the cycle length changes.
- Arrival characteristics - The arrival characteristics of traffic at the signalized intersections also prove important. Conditions which create random, unplatooned vehicle arrivals and hence reduce system effectiveness include:
  - Excessive distance between signalized intersections.
  - High volume of traffic turning onto the arterial from unsignalized minor streets or access points (e.g., shopping center) between two signalized intersections.
  - High volumes turning into the arterial from the minor street approaches at the signalized intersections.
- Traffic fluctuations with time - The arrival characteristics and traffic flow conditions can vary greatly during the daily time period. Peak period conditions may strongly indicate the need for system operation, but off-peak conditions may best be handled with isolated or flashing control.

Time-Space Diagram

Figures 3-19(a) and 3-19(b) show this traffic flow control concept via a *time-space diagram*. Definitions used in the diagram include:

- Green band - The space between a pair of parallel speed lines which delineates a progressive movement on a time-space diagram.
- Band speed - The slope of the green band

representing the progressive speed of traffic moving along the arterial.

- Bandwidth - The width of the green band in seconds indicating the period of the time available for traffic to flow within the band.

The use of 1- or 2-way operation proves a major consideration in developing timing plans for an arterial street. If the street is:

- 1-way, the system can obtain full use of the green band for progressive movement, or
- 2-way, progression in both directions proves more difficult.

Good 2-way progression depends on *signal spacing* which, ideally should:

- Be approximately equal for all intersections, and
- 900 to 1,300 feet or greater *depending on the progression speed selected.*

These conditions rarely exist, and compromises must be made in the bandwidth and progression speed achieved.

Timing Plan Elements

To operate a control system for an arterial street (or open network), requires a *timing plan* for all signals in the system, consisting of the following elements:

- Cycle length - This normally is the same (or some multiple) for all signals in the system or *section* (subset of a system). The intersection with the longest cycle length requirements (as calculated via methods in Section 3.7) usually governs the system cycle length.
- Splits - The length of the various signal phases must be calculated for each intersection. Phase lengths (splits) may vary from intersection to intersection.
- Offset - An offset value must be calculated for each intersection. One definition of offset is the start time of main street green relative to the green interval start for a master intersection in the system.

Figures 3-19(a) and 3-19(b) depict an idealized case of equal intersection spacing and splits at all intersections. When this does not occur, the bandwidth becomes narrower than the green interval at some or all signals, as shown in Figure 3 -20 (11).

Traffic Flow Variations

A timing plan is developed for a specific set of traffic conditions. When these change substantially, the timing plan loses effectiveness.

Two basic types of traffic flow variations can occur:

- Traffic flow at individual intersections - Volumes can increase or decrease at one or more signal locations. These changes can alter the cycle length or split requirements at the affected intersections.
- Traffic flow direction - Flow volume can vary directionally on a two-way arterial. Table 3-15 shows the three basic conditions, their normal times of occurrence and associated timing plans.

Early control techniques often provided at least three timing plans (A.M., off-peak, P.M.), selected on a *time-of-day* basis. *Traffic-responsive* control systems can now automatically adjust timing plans at shorter intervals based on measured traffic flow and select from a greater number of plans.

Timing Plan Development

Three basic techniques for developing timing plans are:

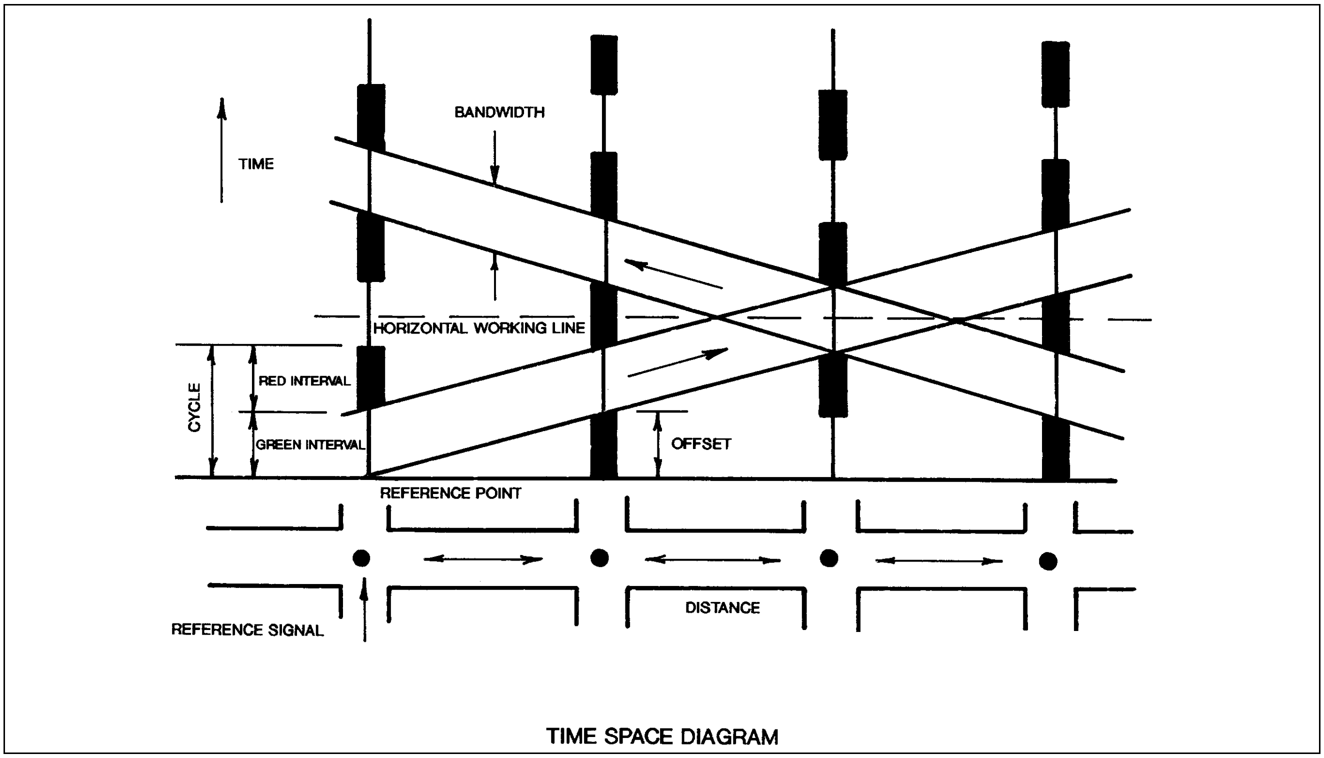
- *Manual* calculations and/or graphical analysis determine cycle lengths, splits, and offsets.
- *Off-line computer* software models make required calculations. *Off-line* indicates that timing plans are generated from traffic data collected earlier. Plans are stored for use during an appropriate time of day or may be selected on a traffic responsive basis using data from traffic system detectors.
- *On-line computer* techniques use a computer traffic control system to:
    - Collect data on traffic flow conditi ons,
    - Make calculations to determine a desired timing plan, and
    - Implement or adjust the timing plan in short time intervals such as each cycle or every five minutes.

This provides a traffic-responsive system with dynamic or real-time timing plan g eneration.

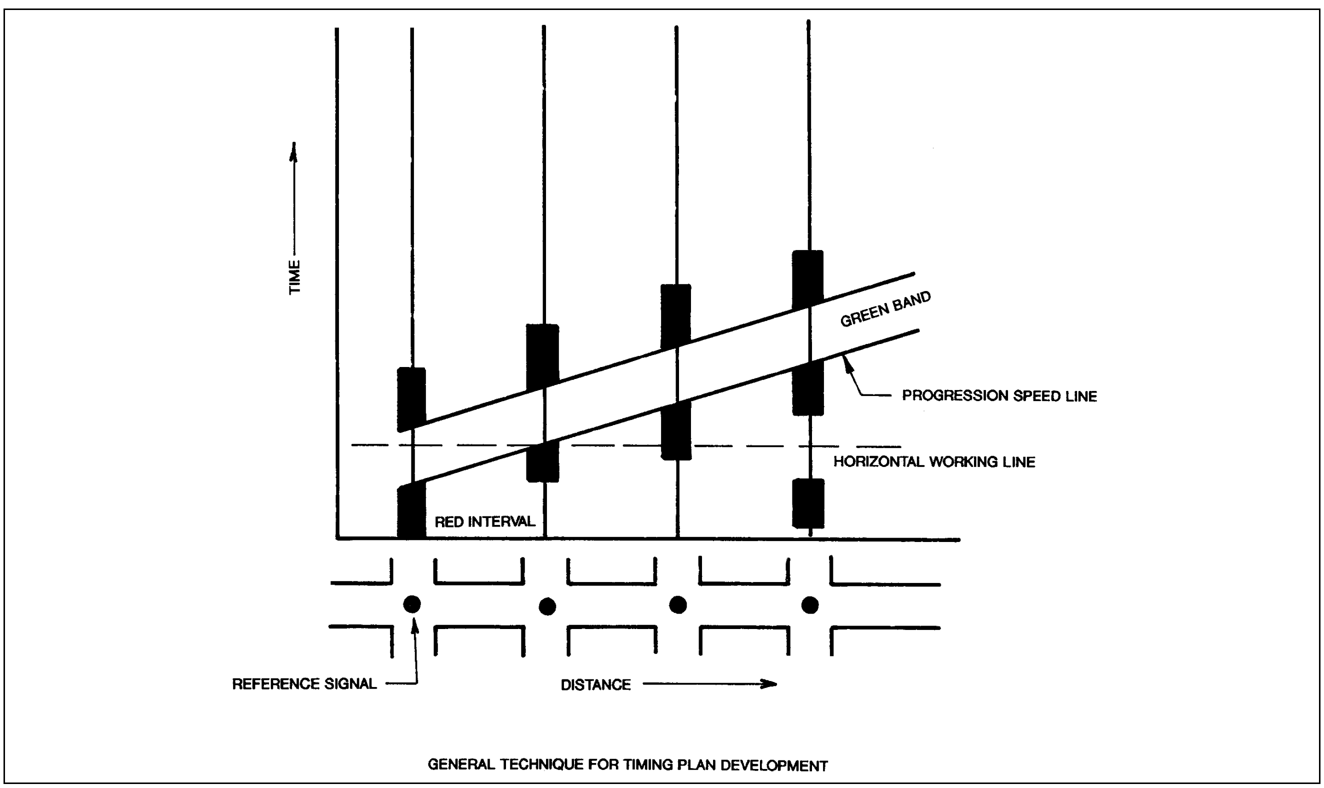
The following paragraphs present pertinent elements of these three techniques.

Manual Techniques

Developing an arterial signal system timing plan, requires collecting the following data:



(a). Time-space diagram.



(b). General technique for timing plan development.

Figure 3-19. Time-space diagram and graphic technique.

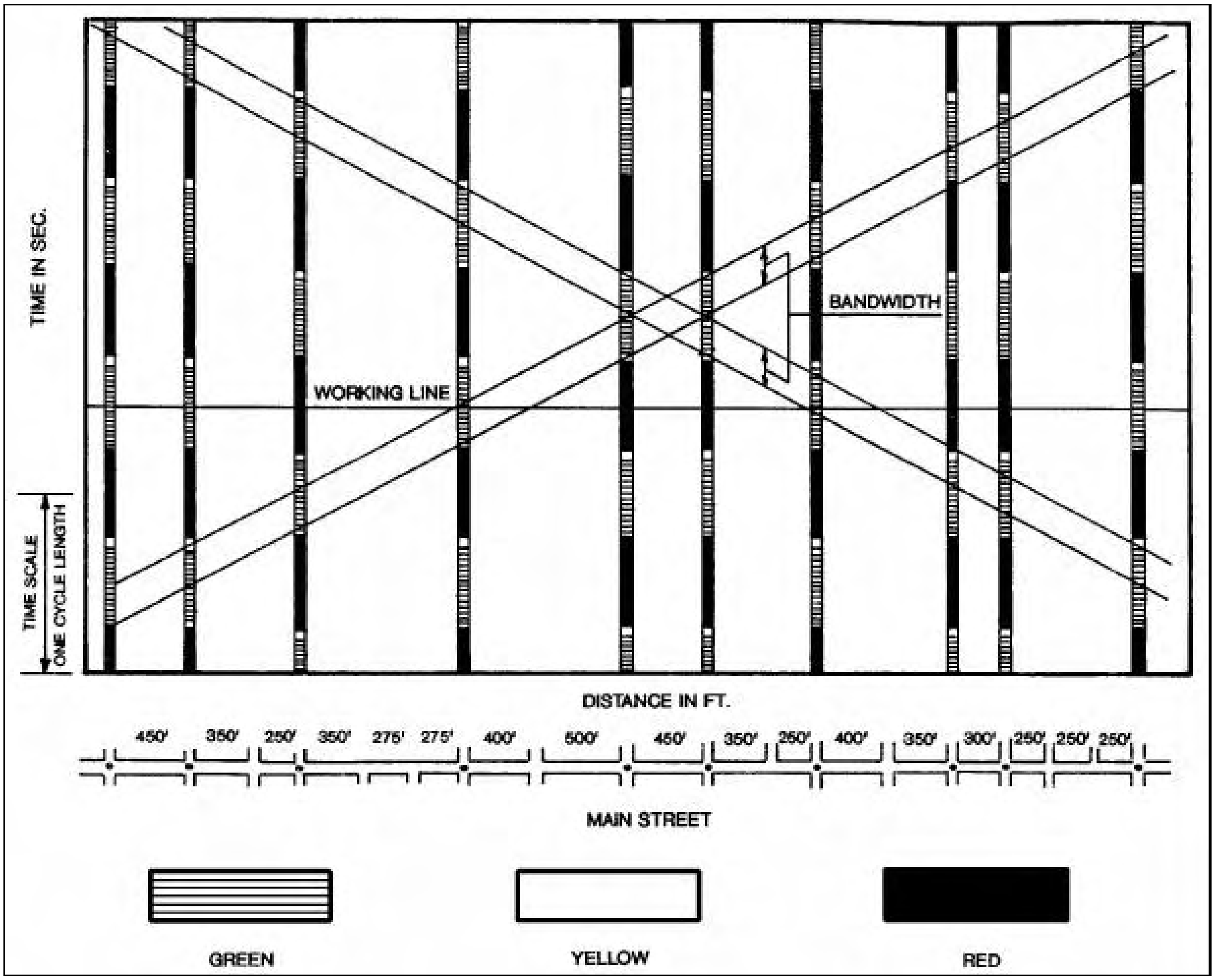


Figure 3-20. Typical time-space diagram.

Table 3-15. Directional flow conditions.

Condition	Normal Time of Occurrence	Timing Plan Progressive Movement
Inbound flow exceeds outbound flow	a.m. peak	Inbound
Inbound flow approximates outbound flow	Off-peak	Inbound and outbound equally
Outbound flow exceeds inbound flow	p.m. peak	Outbound

- Geometric
  - Intersection spacing (stopline to stopline), and
  - Street geometrics (width, lanes, and approaches).
- Traffic flow
  - Volumes including turning movement counts,
  - Flow variations, and
  - Speed limitations.

Table 3-16 shows a series of steps leading to manual development of a timing plan.

As a general rule, the time-space diagram resulting from Table 3-16 will have the beginning of green occurring at:

- Every other signal, i.e., *single alternate*, or
- Two adjacent intersections, i.e., *double alternate*, or
- At three adjacent intersections, i.e., *triple alternate.*

The beginning of greens may not exactly coincide but will usually approximate one of the three patterns. Figure 3-19(a) shows signal alternate offset timing.

Consider the manual method in Table 3-16 as a trial and error procedure. For example, if the resulting progression speeds prove too slow or fast, adjust the system cycle length. A 15% decrease or 25% increase may provide the desired progression speed without significantly increasing delay. Also, modify phase timing to favor straight through movements. A protected-permissive left-turn operation may reduce the time initially calculated for protected only left-turn phases. The modified timing plan may produce better results.

Table 3-16. Manual timing plan development.

1. Prepare a graphic display of the signal system, similar to figure 3-19 or 3-20.

2. For each timing plan, examine flow conditions at each intersection and evaluate cycle length and split. Use the methods discussed under isolated intersections.

   Consider increasing volumes to account for seasonal differences and increases in the next 3 to 5 years. Five (5) percent typically accounts for seasonal differences.

   Calculate optimum cycle length and phase interval for each signal. The longest cycle length usually becomes the system cycle.

3. Conduct a graphic analysis to determine offsets for each timing plan. The graphical analysis proceeds as follows (refer to figure 3-19):

   (a) Identify the signal with the smallest main street green phase split.

   (b) Draw a progression speed line and provisional green band beginning at the start of main street green at this signal. This speed line will have a slope representing the desired progression speed.

   *(c) Draw a horizontal working line through the center of either a red or green interval for the reference signal.

   *(d) Center either a red or green signal interval on the horizontal working line (as required to obtain the greatest width of the green bands) to achieve an equal bandwidth for each flow direction.

   *(e) Usually the provisional green band defined by the progression lines plotted in step (b) will not pass through all green phase intervals plotted in step (d).

   For this case, adjust the provisional green band by drawing progression lines parallel to the original lines. Space these lines to define the widest bandwidth remaining within the green phase of all signals.

   *(f) Modestly alter the progression line slope about the signal identified in step (a) to determine whether small changes can increase bandwidth.

   *(g) The preceeding step results in a timing plan that provides equal bandwidths for each flow direction. If desired, modify this result to favor 1 flow direction.

Applies to 2-way progression shown in figures 3-19 (a) and 3-20.

Off-Line Computer Techniques

Techniques using computers can calculate timing plans *off-line* for arterial signal systems.

Two basic approaches to computing arterial timing are:

- Maximize the bandwidth of the progression, and
- Minimize overall delay and stops.

Maximizing bandwidth has seen much use with considerable research performed (23, 24, 25, 26, 27, 28, 29). Wagner, et al. (30) summarized developments in arterial signal timing. Traffic engineers commonly use the following arterial signal timing programs available from transportation software distribution centers (21, 31).

- MAXBAND,
- MULTIBAND,
- PASSERII-90,
- AAPEX, and
- PASSER IV.

Table 3-17 summarizes features of these programs.

The second approach uses models that seek to minimize delay, stops, or other measures of disutility (32, 33, 34).

TRANSYT has become the most popular of these models. TRANSYT-7F (34) is the version suitable for the U.S. traffic engineering community. It applies to both open network (arterial) and closed network system (see Section 3.9).

Computer Assistance

The user can obtain additional assistance on the use of these models from two key resources:

Methodology for Optimizing Signal Timing (MOST) covers signal timing and analysis in five volumes. It includes discussions on the use of the Arterial Analysis Package (AAP), PASSER II-90 and TRANSYT-7F computer models (21).

Computer models such as MAXBAND, PASSER II-90, and TRANSYT-7F are designed for use with pre-timed controllers. The document "*Progression Through a Series of Intersections with Traffic Actuated Controllers*" (21) provides guidelines on how to apply actuated signal timing to the three models noted above and how to select the type of signal control at an intersection.

Passer III-90

Passer III-90 is a computer program designed to assist transportation engineering professionals in the analysis of pre-timed or traffic-responsive, fixed sequence signalized diamond interchanges. Table 3-18 describes Passer III-90 features while Table 3-19 summarizes inputs and outputs. Passer III-90 can also evaluate the split diamond freeway interchange (Figure 3-22) with the phasing options shown in Figure 3-23.

Passer III-90 can use IBM compatible microcomputers with at least 512K of random access memory (RAM), a DOS 2.0 or higher version operating system. The basic program is written in FORTRAN-77 and the interactive input-output routines in TURBO PASCAL. This model is maintained by the Texas Department of Highways and Public Transportation.

On-Line Control Techniques

A computer based signal system exercises control by two basic methods, *time-of-day* and *traffic responsive*, summarized in Table 3-20. Table 3-21 summarizes on-line systems used primarily for arterial control.

3.9 Network Control

Basic Considerations

Where two arterials cross at an intersection, for progression along both arterials a signal timing *interlock* must occur. Both arterials must use the same cycle length and the timing plans must use as a reference point the timing at that intersection.

Signal timing in networks conventionally features a common cycle length. The closed topology of the network requires a constraint on the offsets, however. The sum of offsets around each loop in the network must sum to an integral number of cycle lengths. Figure 3-25 provides the node definitions for the following relationships:

$$D_{AB} + D_{BC} + D_{CF} + D_{FE} + D_{ED} + D_{DA} = n_1 C \quad (3.17)$$
$$D_{AB} + D_{BE} + D_{ED} + D_{DA} = n_2 C \quad (3.18)$$
$$D_{BC} + D_{CF} + D_{FE} + D_{EB} = (n_1 - n_2) C \quad (3.19)$$

Where:

D_{AB} = Offset between signals B and A
C = Cycle length
n_1 and n_2 are positive integers

Table 3-17. Aterial signal timing programs.

Name	Purpose	Capabilities/Functions	Additional Information
MAXBAND	Develops signal timing plans for arterials and triangular networks	Bandwidth optimization model based on mixed integer programming formulation **Features include:** • Cycle length treated as continuous variable within specified range • Design speed can vary within specified limits • Best phase sequence at each intersection automatically selected from a specified set • Queue clearance time allowed to permit secondary flow accumulated during red to discharge before platoon arrival • Model accepts user-specified weights for green band in each direction **Basic inputs include:** • Range of cycle lengths • Link geometry • Flow rates • Saturation flow rates • Permitted phase sequences • Queue clearance times • Range of speeds **Outputs include:** • Data summary report • Solutions report containing: - cycle length - bandwidths - selected phase sequencing - splits - offsets - link speed - travel time Can run on PC	References 21, 29, 35, 36-38

Table 3-17. Aterial signal timing programs (continued).

Name	Purpose	Capabilities/Functions	Additional Information
MULTIBAND	Provides bandwidth within each link based on needs within that link	Can tailor progression to different flow patterns within network. Tailors bandwidth to a platoon altered by turning movements. See figure 3-21 for MULTIBAND time-space diagram. Currently being incorporated into a new version of MAXBAND.	References 35, 39
PASSER II-90 (Progression Analysis and Signal System Evaluation Routine)	Optimizes progression considering various multiphase sequences	Combines Brook's Interference Algorithm with Little's Optimized Unequal Bandwidth Equation. Extends them to multiphase arterial signal operations. Model inputs for each intersection include: • Turning movements including lead/lag and dual- left combinations • Saturation capacity flow rates • Distances between intersections • Average link speeds • Queue clearance intervals • Permissible phasing sequences • Minimum green time Program first determines optimal demand-to-capacity ratios and uses them to determine splits. To determine optimal timing that maximizes progression bandwidth, program varies: • Cycle lengths • Phase • Phase sequences • Offsets Can handle up to 20 signalized intersections along a single arterial, with up to 4 phase sequences per intersection. New graphics simulator permits user to analyze operational effects and visualize arterial signal coordination. Designed for use on IBM PC or compatible microcomputers. Written in FORTRAN.	Reference 40

Table 3-17. Aterial signal timing programs (continued).

Name	Purpose	Capabilities/Functions	Additional Information
AAPEX (Arterial Analysis Executive Package)	Provides access to PASSER-II and TRANSYT-7F programs. Contains other signal design and analysis programs.	Uses a common database and input and output formats (some interactive) for the component models to facilitate use as an integrated system. User can compare outputs from TRANSYT and PASSER. User can use output from one model as input to the second model for further comparison. AAPEX may be obtained from McTrans (21).	References 21, 41
PASSER IV	Optimizes signal timing in grid networks, based on maximizing platoon progression	PASSER IV has evolved from MAXBAND. Optimal efficiency has been enhanced by implementation of the following techniques: • Two-step heuristic method producing a maximum bandwidth solution • Three-step heuristic method - faster than 2-step method - does not guarantee absolute maximum bandwidth solution The 3-step method is generally a best possible solution. • Explicitly models PASSER IV, therefore the size and complexity of the mixed integer linear programming (MILP) formulation is reduced. This results in: - reduced central processing unit (CPU) time - production of wider bands • Tighter bounds for link synchronization variables. This results in: - reduced search region - elimination of repeating integer variables with same lower and upper bands The MILP developed in PASSER IV is less complex than in MAXBAND, resulting in production of a much faster solution.	Reference 42

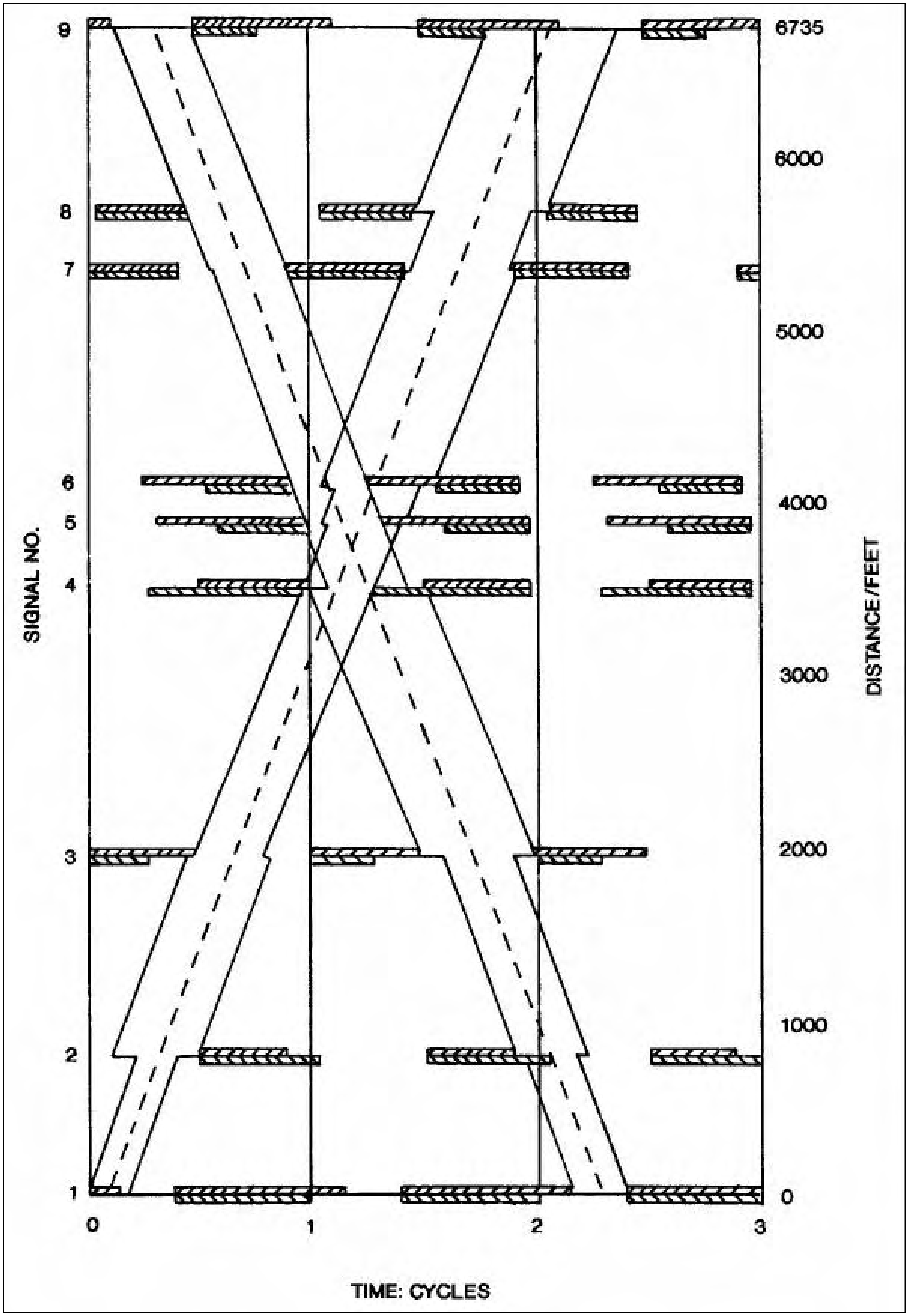


Figure 3-21. Example of MULTIBAND time-space diagram.

Table 3-18. PASSER III-90 features.

- Evaluates existing or proposed signalization strategies
- Determines signalization strategies to reduce the average delay per vehicle
- Calculates signal timing plans for interconnecting a series of interchanges along continuous 1-way frontage roads
- *Isolated interchange* analysis
  - analyzes 5 identified phasing patterns which include the 4-phase, 2-overlap sequence and different variations of the 3-phase sequence
- *Progressive* analysis determines optimal cycle length to increase progression bandwidth
  - progression may be 1- or 2-way (with or without preference to one direction)
- Provides an assistance screen to calculate saturation flow rate for the 18 possible movements at a diamond interchange (simply an automatic manual procedure)
- Evaluates effectiveness of various geometric design alternatives:
  - lane configurations
  - U-turn lanes
  - channelization (43)
- Evaluates the number of lanes at signalized freeway/street interchanges

Network signal control systems may adjust signal timing via:

- Selection of precomputed timing plans according to time of day,
- Selection of timing plans from a precomputed library of alternatives using traffic detectors, and
- Real-time generation of timing plans using traffic detectors.

The first two methods require the traffic engineer to develop *off-line* timing plans. Engineers commonly use two classes of techniques: *progression based* and *optimization.*

Table 3-19. PASSER III-90 inputs and outputs

Inputs

- **Signal-Phasing Data:** Basic interchange and signal-phasing data
- **Movement-Interchange Data:** Traffic volumes, saturation flows, and minimum green time
- **Progression-Link Geometry Data:** Link geometry, speeds, and distances for a frontage road

Outputs

- Data summary report
- Phase-interval report
- Optimal progression solution report
- General signalization information
- Frontage road progression information
- Time-space plot
- Provides 12 options for viewing either a portion or entire output file

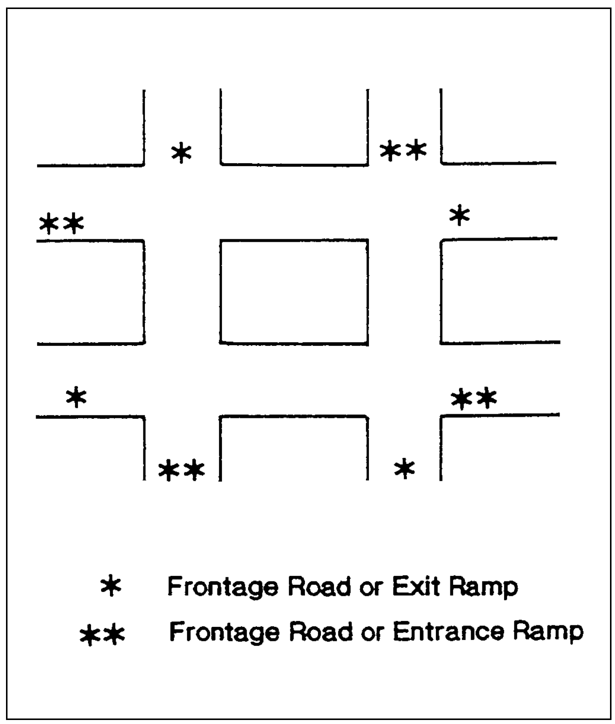


Figure 3-22. Split-diamond interchange design.

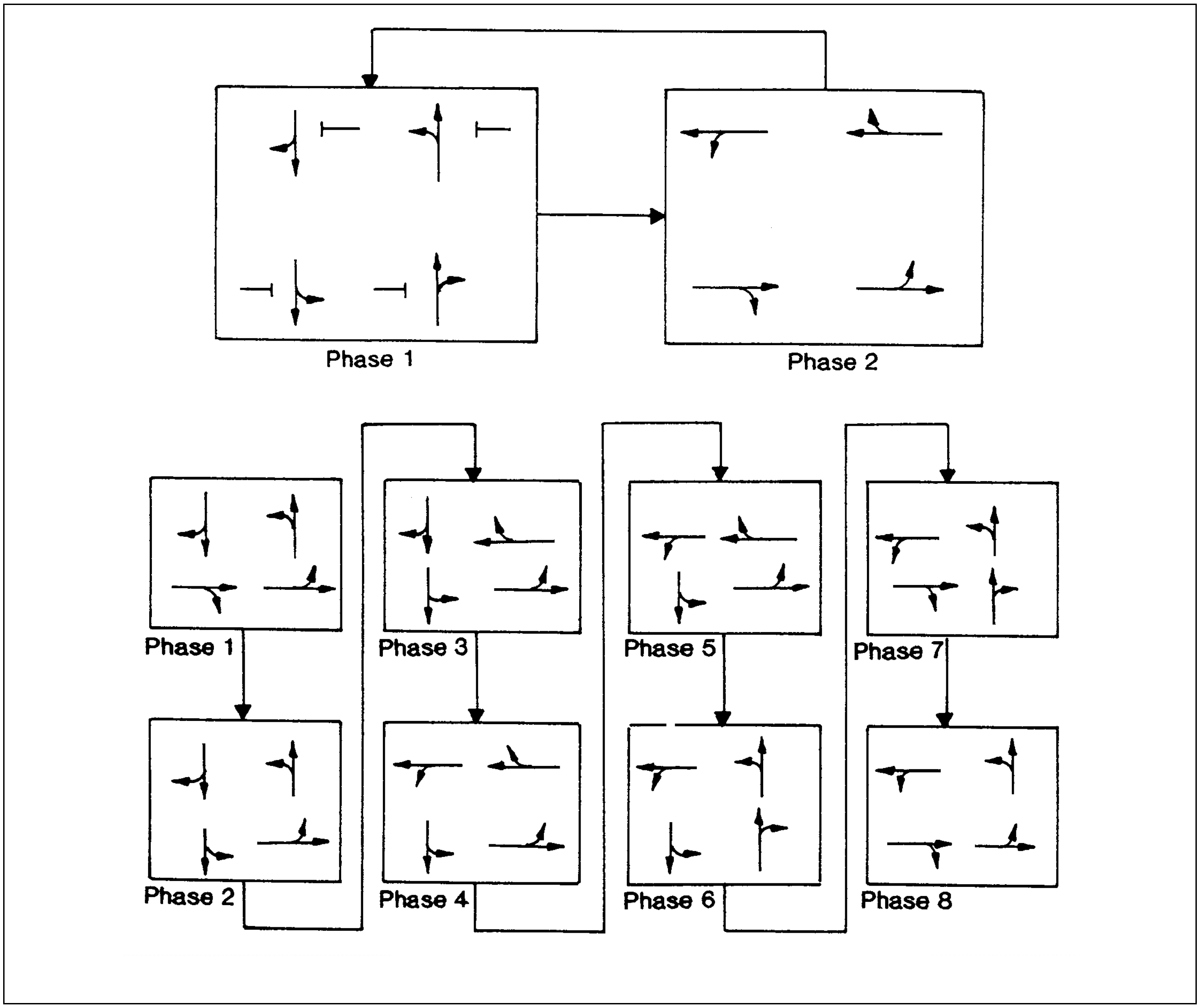


Figure 3-23. Split-diamond interchange phasing options.

OffLine Timing Plan Techniques

Progression-Based

Manual progression based techniques establish green bands as discussed in Section 3.8.

Graphical trial and error bandwidth techniques can prove difficult for developing timing plans in a closed network. To consider flow in all directions at the intersections requires a three -dimensional time -space diagram.

Decomposing the (closed) network into a series of *open* networks or arterials as illustrated in Figure 3-26 can often resolve this difficulty. The techniques described in Section 3.8 can then time these individual arterials.

If the signal network consists of a regular grid pattern often found in a city's central business district (CBD), and the street spacing and directional flow configuration proves appropriate, the types of timing plans in Table 3-22 may be considered.

The simple timing plans summarized in Table 3-22 depend on grid network geometrics (specifically block length) and are inflexible. The only variables are cycle length or type of plan (single alternate, double alternate, etc.).

Optimization

This concept develops plans which optimize the timing according to some performance index. Engineers commonly use the sum of *delays and weighted stops* at all intersection approaches. Optimally timed signals then minimize this performance index.

Table 3-20. Online control techniques.

Method	Definition	Timing Plan Selection/Computation	Features
Time-of-Day	Timing plan that operates at a given time-of-day	Responds to 3 or 4 basic time periods such as: • a.m. peak (7:00 to 9:00 a.m.) • Off-peak (9:00 a.m. to 4:00 p.m.) and (6:00 p.m. to 7:00 a.m.) • p.m. peak (4:00 to 6:00 p.m.) or to more time periods	Where traffic demand remains reasonably predictable, coordinated pretimed controllers can provide satisfactory operations. Where 1 or more intersections require multiphase operation, full-actuated controllers can be incorporated into the coordinated system. Traffic signal manufacturers currently supply such systems. A typical system provides up to: • Four cycle lengths • Three offsets • Three split/signal sequence combinations per cycle length Hardware technology now enables traffic pattern changes by downloading new patterns from a central system master. A local controller then stores these patterns. Chapters 7 and 8 discuss local controllers and system masters, respectively.
Traffic-Responsive	Timing plan based on traffic conditions measured by a detection system. Timing plan can be updated as often as every cycle.	Three general traffic-responsive strategies in use (sometimes in combination) are: • Select a background signal timing plan based on detector data. • Online computation of a background timing plan. The computation time interval may range from one cycle length to several minutes. • Change of one or more signal parameters within a cycle length.	In most cases, systems may operate either on a time-of-day or traffic-responsive basis. This flexibility permits: • Initial time-of-day control when the traffic patterns remain predictable • Conversion to traffic-responsive when traffic patterns are no longer sufficiently predictable for time-of-day control because of: - construction - addition of major traffic generators - frequent incidents - split shifts - flex time

Table 3-21. Online arterial control systems.

Name	Purpose	Capabilities/Functions	Additional Information
DARTS **(Dynamic Artery Responsive Traffic System)**	Allows each intersection to function in its normal isolated full-actuated mode until a platoon is detected	Consists of a series of NEMA full-actuated controllers, each with an external logic modular dynamic coordination unit. Once a platoon is detected, the upstream intersection controller advises the adjacent downstream intersection controller that a platoon is on the way. Through the use of 3 timers, the adjacent downstream controller coordination unit permits the cross-street and opposing left-turn phases (if there is a demand) and then forces off these phases in time for the arterial street platoon to pass through the intersection. If the cross-street and/or left-turn demand is not serviced for a period of time, then the coordinated system drops this intersection for 1 cycle to permit clearance of traffic on all phases. The system uses 2 pairs of wires between intersections, 1 pair for each traffic direction. The system is commercially available.	Reference 44
ACS **(Arterial Control System)**	Developed for: • Arterial highways • Freeway frontage roads • Complex freeway interchanges involving traffic signals • Small grid networks	Operates as a 3 level distributed microcomputer-based traffic data and control system shown in figure 3-24 The Local Control Unit (LCU) gathers system detector data 30 times each second and transmits assembled volume and occupancy information to the System Control Unit (SCU) each 20 seconds The SCU determines the control pattern to be implemented and advises the LCU The SCU also advises the operator at the Manager (a standard IBM compatible computer) of the plan implemented. The system can implement an alternate plan if desired. Each SCU can control 68 signalized intersections assigned to 6 subsystems. Additional intersections can be controlled by coordinating SCUs. Each SCU can provide up to 256 plans. The LCU uses NEMA hold, phase omit, and force-off inputs to provide any desired left-turn sequence. Use of these command functions also allocates unused time from the actuated cross-street and left-turn phases to the main street and side street phases to improve overall intersection operation and arterial street progression. A 1-1/2-generation system control has been developed for the arterial street design using the PASSER II-90 model for plan development. Section 3.9 discusses the 1-1/2-generation control concept.	

Table 3-21. Online arterial control systems (continued).

Name	Purpose	Capabilities/Functions	Additional Information
ACS (continued)		The ACS is also used as the Signal Control System (SCS) module in an integrated freeway corridor traffic management system that includes 2 additional surveillance and control modules: • One for a dedicated HOV lane • One for the freeway general purpose lanes	
Actuated Controllers with Background Cycle	Obtain good progression and retain traffic-responsive control at each intersection	Uses interconnected actuated controllers with background cycle. Uses detectors on side streets and left-turn lanes at each intersection. Uses force-off inputs to permit side streets and left-turns to receive a green indication only when it will not interfere with progressive movement on the major arterial. Provides for predetermined minimum green band along the coordinated arterial by establishing a preset point (yield point) in the background cycle when vehicle calls on the side street can be serviced. In the absence of demand on the side streets and left-turns (as measured by detectors), the green assignment will remain on the major arterial.	
Field Master Based Systems	Selects cycle, split, and offset based on detector data	Assigns certain detectors to cycle length selection. Compares detector outputs to established thresholds which define the boundaries of cycle length selections. Detectors select offset by comparing detector volumes in each arterial direction to ranges of pre-established ratios or values. Splits selected by comparing arterial and cross-street data at a few key intersections Systems of this type often implemented by field microprocessor computers that serve as on-street master controllers. Master controllers process detector data and select cycle, split, and offset settings on the field controllers. Various techniques described in chapter 9 are used to communicate between field master and intersection controllers.	Section 8.2
Closed-Loop Systems	Selects cycle, split, and offset based on detector data	In recent years, adding a computer (usually a PC) located in a traffic operations center or the traffic engineer's office to a field master-based system provides the capability to monitor traffic conditions and change timing plans and other control parameters by downloading this information to the field master controller and thence to local controllers. Section 8.2 describes these systems termed *closed-loop systems*.	Section 8.2

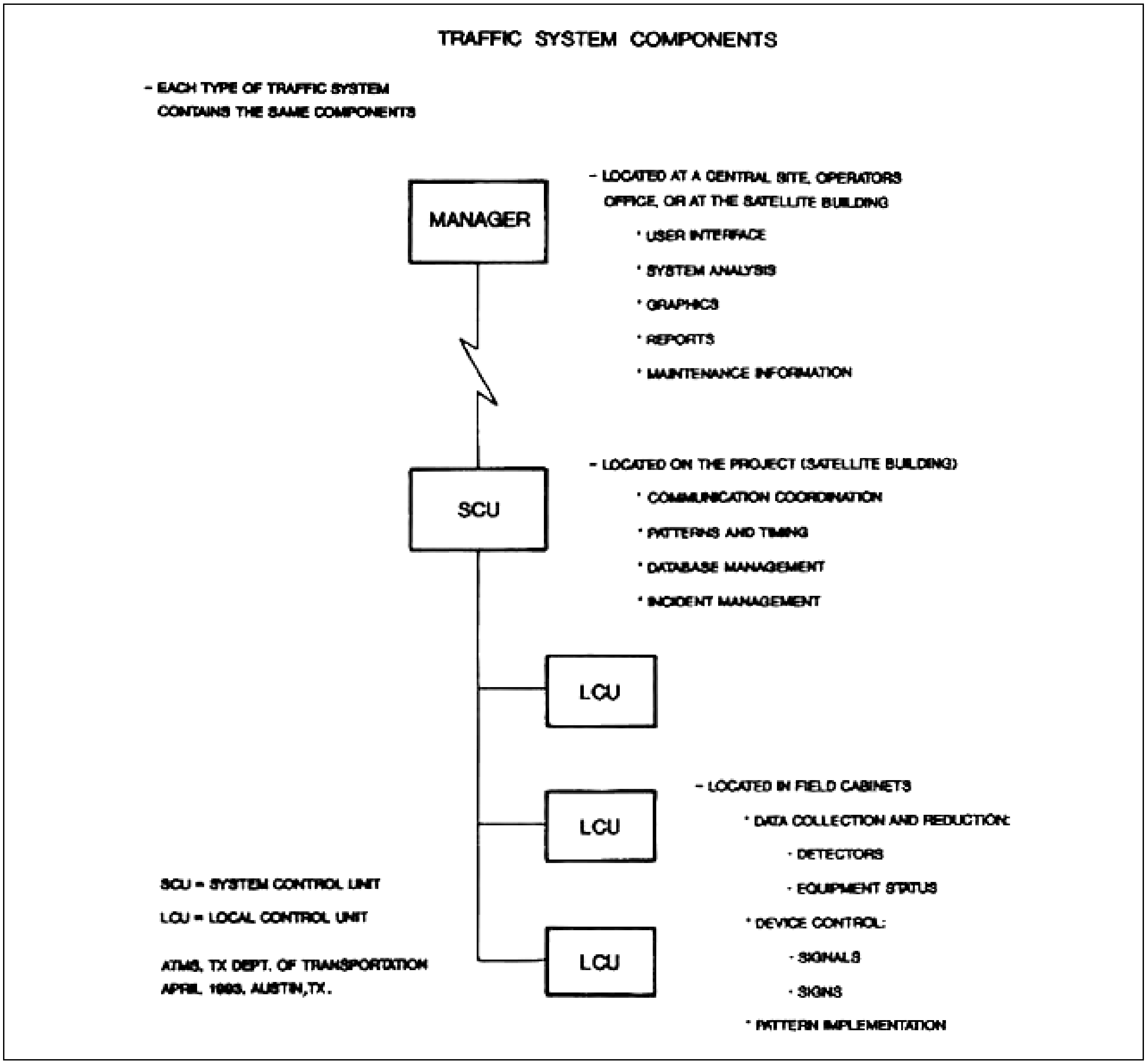


Figure 3-24. Three level distribution system development by Texas Department of Transportation.

Optimization techniques use computer programs to calculate the timings. TRANSYT-7F (44) has proved the program most widely used for this purpose.

TRANSYT Model

The Traffic Network Study Tool (TRANSYT) has become one of the most widely used models in the United States and Europe for signal network timing. It was developed in 1968 by Robertson of the UK Transport and Road Research Laboratory (TRRL), which has since released several versions. This handbook discusses TRANSYT-7F (34), where "7" denotes the seventh TRRL version, and "F" symbolizes the Federal Highway Administration's version using North American nomenclature for input and output (34).

TRANSYT-7F is a signal timing optimization program and a powerful traffic flow and signal timing design tool. Using standard traffic data timing parameters as input, it can both *evaluate* existing timing and *optimize* new plans to minimize either:

- A linear combination of weighted delays, stops, and queue spillback, or
- Total operating cost.

The TRANSYT model is based on the dispersion of a vehicle platoon departing from a signalized inter-

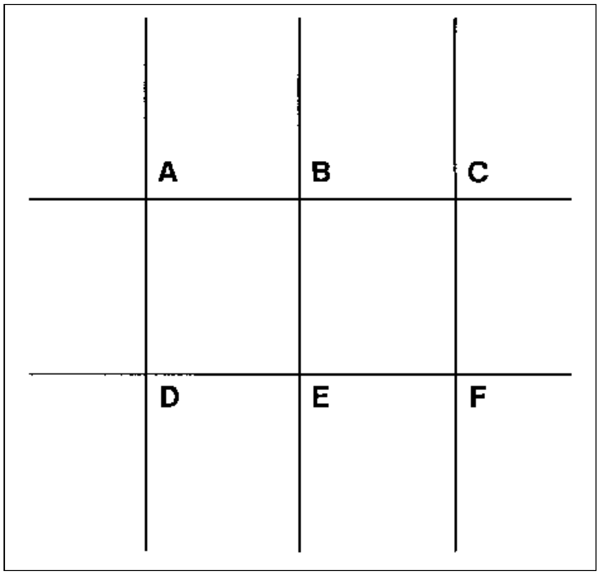


Figure 3-25. Closed network node definitions.

section as illustrated in Figure 3 -27 (45). The figure also shows percentage saturation (a measure of volume) as a function of time at three points along the roadway when no downstream queue is present.

TRANSYT assumes that the average flow demand at an approach remains constant, i.e., the flow patterns for each cycle repeat. For each computation time interval **t**, Table 3-23 (46) gives the analytical model for the arrival flow at the downstream stopline. Table 3-24 (44) shows recommended values of platoon dispersion factor (PDF).

TRANSYT-7F has an executive menu and file processing program for the microcomputer version, called McT7F.

TRANSYT-7F quantifies perceived progression by *progression opportunities* (or PROS), which simply represent opportunities to get through consecutive intersections on green. Thus, signal timing may be designed for PROS alone, in which case splits remain fixed, or the PROS/DI policy yields a combination of wide bands, while still trying to minimize the disutility index. With PROS, the user can request an explicit time -space type design.

The TRANSYT-7F program has a modular structure and contains over 50 subroutines. Each subroutine falls into one of the major functional areas summarized in Table 3 -25.

TRANSYT-7F has a number of user controlled options, some of which are described in Table 3 -26.

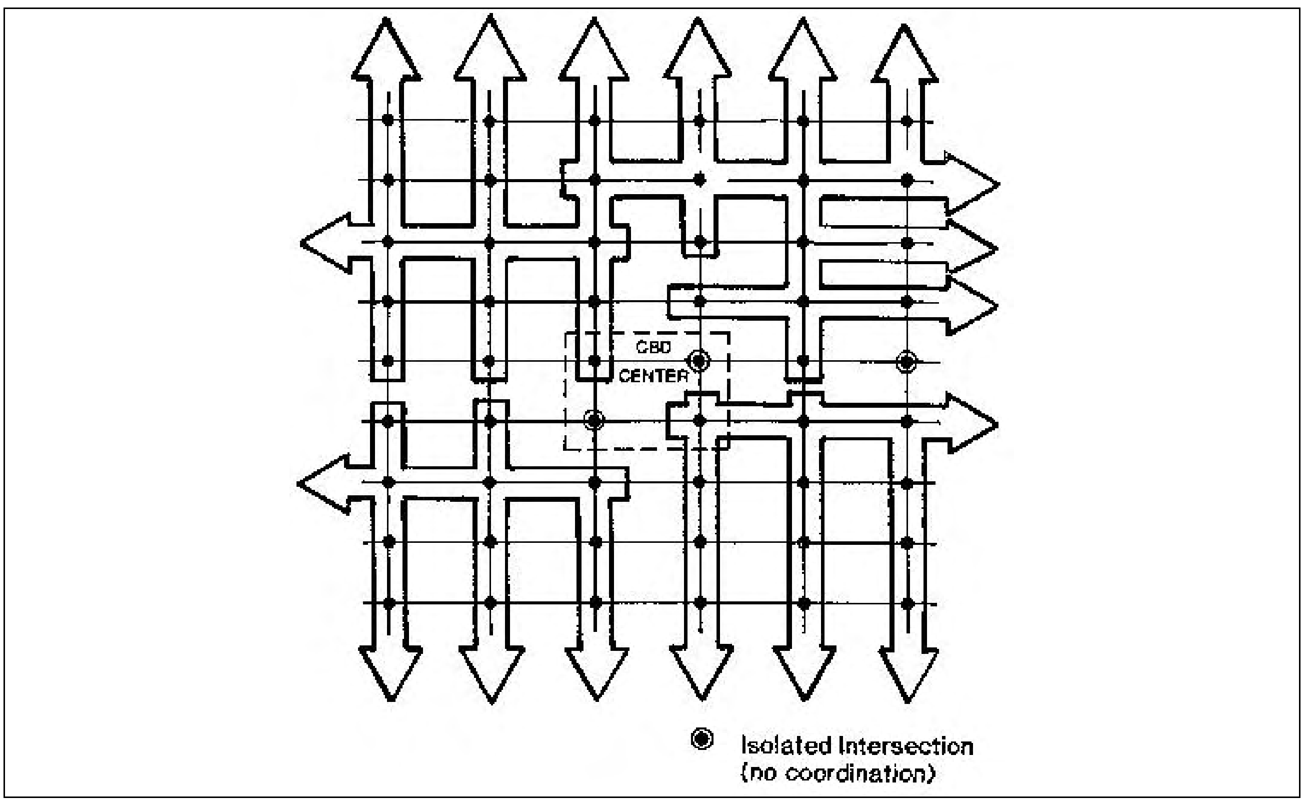


Figure 3-26. Decomposition of closed network into arterials and “open” networks with preferential flow.

Table 3-22. Network timing plan types.

Type	Definition	Application
Single Alternate	Half-cycle offsets alternated at each intersection	Works well if block lengths and/or cycle length permit use of half-cycle offset. For example, with a 60-second cycle and a half-cycle offset, offset is 30 seconds. If the block length is 900 ft (274 m), a progression speed of 900/30 or 30 ft/sec (274/30 or 9.1 m/sec) results.
Double Alternate	Variation of single-alternate. 2 adjacent signals have same offset and a half-cycle offset occurs every 2 signals.	Often used with a half-cycle offset for block lengths in the range of 450 ft (137 m). Width of through-band reduced to one-half of a single-alternate system. If block lengths are shorter, use a triple-alternate system.
Quarter-Cycle	Adjacent signals offset by one-quarter of cycle length	Used on 1-way grids Works well with block lengths of or greater than 450 ft (137 m). For example, with a cycle length of 60 seconds, a progression speed of 450/15 or 30 ft/sec (137/15 or 9.1 m/sec) results.
Simultaneous Offset	All signals turn green at same time	Used with relatively long cycle lengths under congested conditions

The TRANSYT-7F model is written in FORTRAN IV and is available for most microcomputers. A program user's manual assists users in operation.

TRANSYT Experience

The TRANSYT-7F model represents the state-of-the-art. A number of states have adopted TRANSYT-7F to improve signal timing on a statewide basis. During 1981, TRANSYT-7F was tested in 11 U.S. cities and produced optimal timing plans for 520 intersections in coordinated signal systems.

One hundred and fifty U.S. cities have invested more than $35 million in using TRANSYT -7F to improve signal timing. Since 1983, California has implemented the Fuel-Efficient Traffic Signal Management (FETSIM) program and widely used TRANSYT-7F to optimize signal timing. Estimated benefits (47) from the new signal timing in 61 California cities and one county show reduction in:

- Vehicle delay (15%),
- Stops (16%), and
- Overall travel time (7.2%).

Many cities, under contract with the FHWA, optimized timing in a portion of their network and evaluated the effectiveness of the optimized plans. Cities reported unanimous agreement on the positive value of the TRANSYT-7F model for retiming traffic signal systems.

On-Line Network Traffic Control Techniques

UTCS Control

Starting in the 1970's, a large number of U.S. cities implemented computer traffic systems using technology developed by the FHWA (under a number of related research programs) (48, 49, 50, 51, 52) and termed the Urban Traffic Control System (UTCS). FHWA established a testbed in Washington, DC which served as the prototype for many later systems. UTCS systems implemented in the 1970's and through much of the 1980's possessed the following characteristics:

- Minicomputer based central computer controls signals with commands for discrete signal state changes. Timing for commands provided at intervals of approximately one second.
- Signal timing plans stored in the central computer. Timing plan changes may result from:
  - Traffic responsive operation (based on detector inputs from the field),
  - Time-of-day selection, or
  - Operator commands (manual).

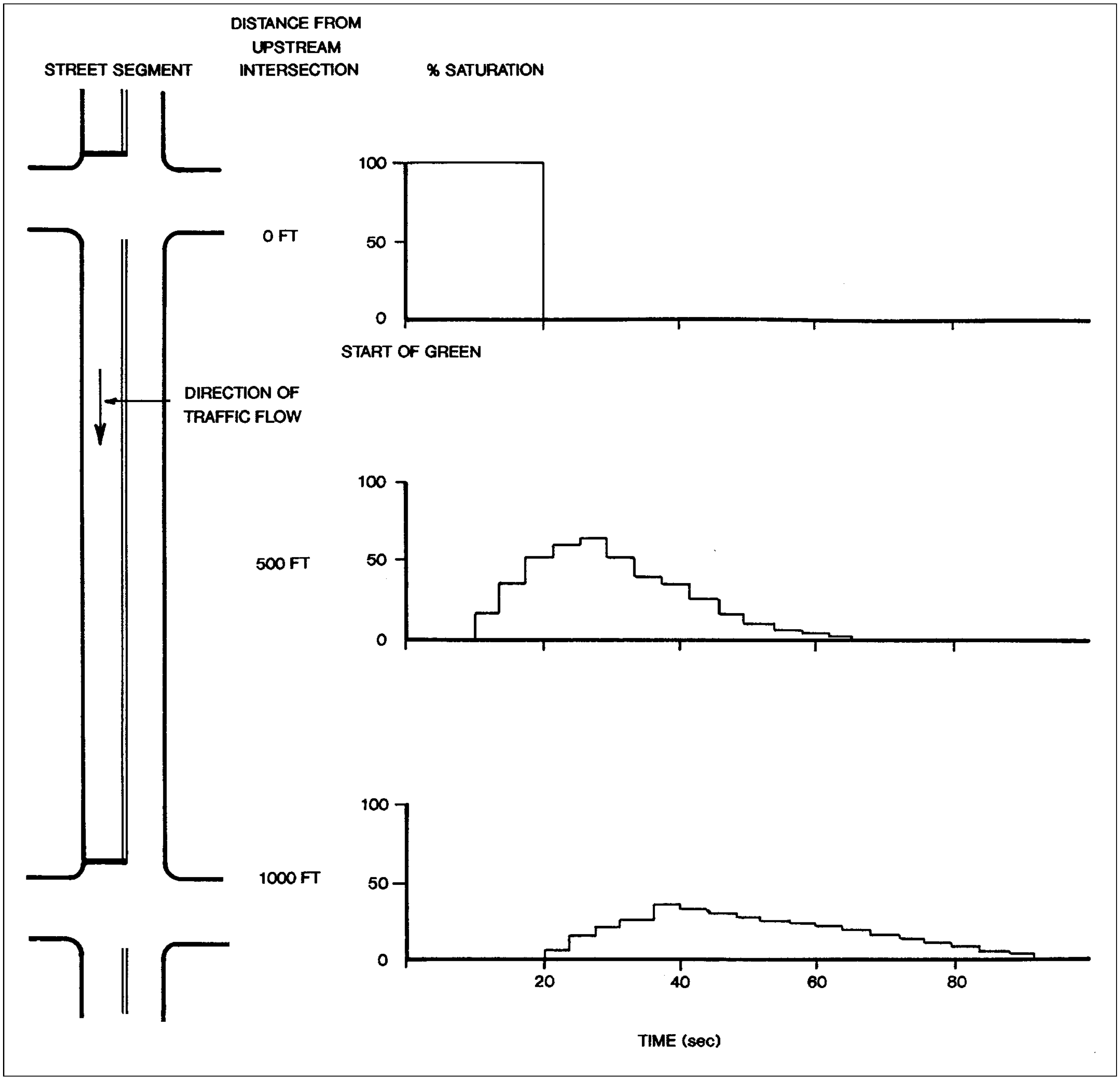


Figure 3-27. Simple case of platoon dispersion.

Table 3-23, TRANSYT analytical model.

$$q'(t + T) = F * q_t + [(1-F) * q'(t + T-1)] \qquad (3.20)$$

Where:

$q'(t + T)$	=	Predicted flow rate (in time interval t + T) of the predicted platoon, where T is defined below:
q_t	=	Flow rate of the interval platoon during interval t
T	=	0.8 times the cruise travel time on the link
F	=	A smoothing factor where:
		$F = 1/(1 + aT)$ (3.21)
		And "a" is a constant, called the platoon dispersion factor (PDF).

Table 3-24. Recommended values of platoon dispersion factor (PDF).

PDF Value	Roadway Characteristics	Conditions
0.5	Heavy friction	Combination of parking, moderate to heavy turns, moderate to heavy pedestrian traffic, narrow lane width. Traffic flow typical of urban CBD.
0.35	Moderate friction	Light turning traffic, light pedestrian traffic, 11 to 12 ft (3.4 to 3.7 m) lanes, possibly divided. Typical of well-designed CBD arterial.
0.25	Low friction	No parking, divided, turning provisions 12 ft (3.7 m) lane width. Suburban high type arterial.

- Computation of volume and occupancy and data distribution of the general form is shown in Figure 3-28 (4).
- A *first generation* traffic responsive control algorithm for changing *background* timing plans. Table 3-27 explains the UTCS first generation traffic responsive control algorithm.

Reference 4 provides a more detailed discussion of the UTCS control algorithms.

Critical Intersection Control (CIC) Algorithm

With flow conditions near or at saturation for a limited number of intersections in the subnetwork, the traffic engineer may designate use of a *critical intersection control* algorithm. This type of control requires detection of all critical approaches or movements.

The CIC algorithm adjusts split at critical intersections in accordance with phase demand. It computes phase demand using the deterministic (non-random) component of detector data, i.e., filtered data as shown in Figure 3 -28. Thus, the CIC does not respond to total instantaneous cyclic demand like a conventional fully -actuated controller (Section 7.7) or OPAC controllers discussed later.

Table 3-28 describes the UTCS CIC operation.

Researchers tested the CIC algorithm under NCHRP Project 3-38 (3). That study reported "limited conditions exist for which the evaluated CIC algorithm will provide improved performance. These conditions can only be satisfied when the underlying trends are significant in comparison with the random fluctuations in traffic demand" (54).

Evolution of UTCS

Subsequent to the initial introduction of UTCS, FHWA sponsored development of two additional software versions known as Extended UTCS Software (51) and Enhanced UTCS Software (52).

These versions added the following features:

- Interfaces with NEMA type controllers,
- Improved traffic signal state feedback,
- Improved database management,
- More user friendly data entry capability,
- Cycle locking of adjacent sections,

Table 3-25. TRANSYT-7F major functional areas.

- **Preprocessor**
  Input processing
- **Simulation Model**
  A macroscopic, deterministic traffic flow model used to compute the value of a specified performance index for a given signal network and a given set of signal timings. The performance index is a linear combination of MOE specified by the user.
- **Optimization Model**
  A hill-climbing optimization procedure that makes changes to signal timing (splits and offsets) and determines whether or not the performance index is improved.
- **Postprocessor**
  Output processing

Table 3-26. TRANSYT-7F options.

- Modeling buses separately by including bus links. These can represent either separate or shared lanes.
- Modeling RT/LT delays caused by pedestrians.
- Subdivision of large networks into sections (i.e., 50 nodes and 250 links) that the program can handle. The boundary nodes remain fixed from section to section so that their timings do not change in subsequent analyses. The user can also expand program dimensional arrays to accommodate a larger network.
- Modeling bottlenecks and unsignalized intersections controlled by stop signs on the cross streets
- Computing an es timate of network fuel consumption based on total travel, stops, an delay. The fuel consumption value includes fuel consumed at cruise, idle, and acceleration or deceleration. The program calculates fuel consumption estimates for each link and sums for the entire network.
- A PPD program can produce Platoon Progression Diagrams that show traffic density at all points in time and distance. It combines the best features of the time-space diagram and TRANSYT-7F flow profile plots.

- Improved map display capabilities, and
- Increased use of FORTRAN.

During the 1970's and 1980's a number of system suppliers developed proprietary central computer based systems which retained the fundamental UTCS characteristics. However, these systems provided unique features including graphics displays and user friendly database entry. Section 8.3 describes the current generation of supplier's systems.

In addition to the UTCS First Generation control just described, FHWA also sponsored development of traffic control software known as UTCS Second Generation and Third Generation Control (55). This software, however, did not become widely used.

UTCS 1-1/2 Generation Control

Cities using 1-GC face the problem of developing a full complement of suitable timing plans to accommodate various traffic patterns in each control section. This requirement often proves burdensome; the city may need several hundred timing plans for the number of control sections and different traffic patterns.

Many cities use versions of TRANSYT for timing plan generation, but collecting, assembling and inputting data can prove complex and burdensome. Therefore, many computer-supervised signal systems function with small numbers of timing plans and possibly outdated plans. Often these plans were developed shortly after system implementation, and have not undergone revision for a long time.

To overcome inadequate and improperly maintained timing plans, requires a simple procedure for generating and maintaining a library of appropriate plans. A *timing plan generator* can accomplish this using data collected by the system and analyzed off-line, followed by automated loading of the generated plans into the traffic control system.

This concept has been referred to as *1-1/2 Generation* control. The FORCAST model (55) developed by Computran Systems Corporation implements this concept. FORCAST provides signal timing plans for an arterial or open grid network, and Table 3-29 summarizes its features. The overall impact of using FORCAST along with 1-GC in the Winston-Salem signal system has made city staff more able to contend with normal problems inherent in long-term control system operation (55). The City of Bellevue, Washington reports (56) that although FORCAST has certain operational limitations, it provides a powerful capability towards the automation of timing plan development.

SCOOT (Split, Cycle and Offset Optimization Technique) (57-60)

The Transport and Road Research Laboratory (TRRL) in Great Britain developed SCOOT in beginning 1973, and by 1979 implemented it on a full-scale trial in Glasgow.

Based on detector measurements upstream of the intersection, the SCOOT traffic model computes the cyclic flow profile for every traffic link every four seconds (Figure 3-29). SCOOT projects these profiles to the downstream intersection using the TRANSYT dispersion model (Equations 3.20 and 3.21 in Table 3-23). Table 3-30 summarizes the SCOOT optimization process.

SCOOT contains provisions for weighting capabilities in the signal optimizers to give preference to specific links or routes.

Recent additions to SCOOT have enhanced its performance under congestion and saturation conditions. Table 3-31 describes the enhanced

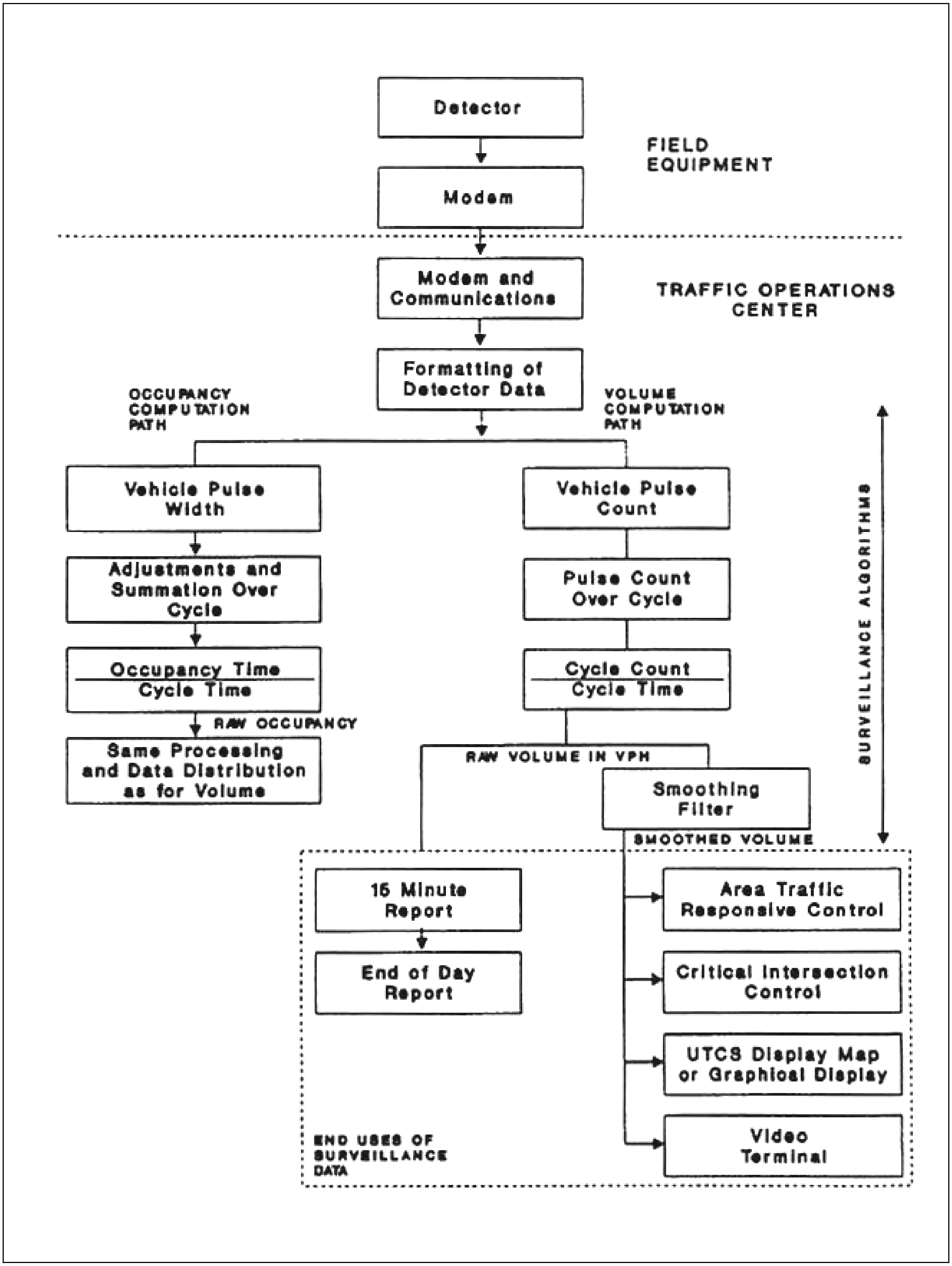


Figure 3-28. Typical UTCS surveillance data flow.

Table 3-27. UTCS first generation traffic-responsive control algorithm.

Signature

The basic concept of the traffic-responsive control law associates each prestored timing plan with one or more *traffic signatures*. This signature comprises an array of numbers, one for each system detector in the subnetwork or *section.* Each number represents a linear combination of volume and occupancy data for the detector. A column matrix or vector can represent these numbers if ordered in a vertical array. Equation 3.22 represents the vector equation for the signature.

$$\overline{VPLUSKO}\,(SIG) = \overline{VS}\,(SIG) + KWT\,(\overline{OS}\,(SIG)) \qquad (3.22)$$

Where:

$\overline{VS}$ = Vector representative of the volumes for stored signature SIG
OS = Similar vector for occupancy
KWT = Weighing factor

With 2 detectors present (denoted by subscripts 1 and 2), the corresponding scalar equations become:

$$VPLUSKO_1\,(SIG) = VS_1\,(SIG) + KWT\,(OS_1\,(SIG)) \qquad (3.23)$$
$$VPLUSKO_2\,(SIG) = VS_2\,(SIG) + KWT\,(OS_2\,(SIG)) \qquad (3.24)$$

Match

The algorithm then *matches* real-time traffic data from each subnetwork detector against the signatures and selects the timing plan corresponding to the best match. Matching identifies the signature, which minimizes the sum of absolute values of the difference in each detector's match.

Equation 3.25 represents this mathematically:

$$\overline{ERR}\,(SIG) = \overline{VPLUSKO}\,(SIG) - \overline{VF} - KWT * \overline{OF}$$

Where:

VF = Current smoothed volume
OF = Current smoothed occupancy

The components of the error vector for each signature are summed and the timing plan associated with the signature having the smallest error sum is selected.

UTCS permits a limited number of signatures (often 3 or 4) to be matched at any time of day *(window)*. This ensures selection of a viable timing plan.

Many UTCS can adjust the test frequency, with the usual period ranging from 4 to 15 minutes.

Sometimes, error values relative to each of 2 stored signatures may be close. In this case, random components in the traffic data may cause frequent changes in timing plans. To reduce this *oscillation*, UTCS permits implementation of a new timing plan only when it provides a significantly lower error than the current signature, i.e., it must show at least a *threshold level* of error improvement.

Table 3-28. UTCS CIC opration.

Cycle length, split and offset

Cycle length equals section cycle length

Offset for one (and only one) critical phase can coordinate with another intersection

Split obtained by computing phase demand for critical phases and appropriating green proportionally (within phase minimum constraints)

Phase Demand

Many UTCS contain the following equation for phase demand. Reference 49 discusses its derivation:

$$GDP = Kr\left(KK_1(OF) + KK_2(VF)\frac{C}{3600} + KK_3\frac{C}{3600}(VF)(OF) \right) \tag{3.26}$$

Where:

GDP	=	Phase demand in vehicles per cycle
Kr	=	Vehicle release rate
C	=	Cycle length, in seconds
VF	=	Smoothed volume and
OF	=	Smoothed occupancy

Reference 49 describes a typical set of coefficients for KK_1, KK_2, and KK_3.

Equation 3.27 represents an alternative expression for green demand used in Extended UTCS software (52).

$$GDP = ST + \frac{(VF)(C)(RR)}{3600} \tag{3.27}$$

Where:

RR	=	Vehicle release rate, in seconds
ST	=	Vehicle starting delay, in seconds

Split Calculation

UTCS CIC sets the ratio of actual green time on a phase equal to the ratio of green time demand on all phases.

Mathematically:

$$GP = \frac{GDP}{\sum GDP} * (GT) \tag{3.28}$$

Where:

GP	=	Calculated green time for critical Phase, P
GDP	=	Green time demand for Phase, P
GT	=	Total available green time for all critical phases

UTCS CIC performs this computation once each traffic cycle

The actual green time for each critical phase must not decrease below the prescribed minimum value in effect for the current timing plan. If GP falls below this value, the actual green time will be set equal to the minimum and the remaining green time allocated proportionally among the unconstrained phases.

Table 3-29. FORCAST features.

• Permits an interactive search for optimum timing plans over a range of cycle lengths • Examines each permitted cycle length and develops a best timing plan for this cycle • In accordance with controller settings, input specifies: - phase sequences - green times - change times - clearance times • Logic involves sequential threading of prescribed movements through the network using a priority listing of demands to be accommodated • Adjusts in a priority manner individual splits and offsets of each intersection to accommodate defined movements throughout the network • Timing plan for solution output for intersection in form of: - cycle length - offset - interval time • Time-space diagrams for selected timing plan produced on user request • System user evaluates suitability of generated plan based on output measures of effectiveness and time-space diagrams. If the resultant output is acceptable, the timing plan can be loaded into the system library.

SCOOT features. Section 8.4 describes SCOOT benefits, SCOOT detector deployments and additional application information.

SCATS (Sydney Coordinated Adaptive Traffic Control System) (61, 62)

The Sydney Coordinated Adaptive Traffic System (SCATS) was developed by the Roads and Traffic Authority (RTA) of New South Wales, Australia. A real-time area traffic control system, it adjust s signal timing in response to variations in traffic demand and system capacity, using information from vehicle detectors, located in each lane immediately in advance of the stopline.

SCATS uses two levels of control: *strategic* and *tactical*. Strategic control determines suitable signal timings for the areas and sub -areas based on average prevailing traffic conditions. Tactical control refers to control at the individual interaction level. Table 3-32 describes the functions of each control level.

SCATS has seen application in many cities throughout the world. Recently, it has been applied together with Autoscope machine vision detection in Oakland County, Michigan, in the FAST -TRAC project. This represents the first North American implementation of SCATS. The initial installation consisted of 28 intersections, 23 equipped with video processor detection for vehicle detection. The system will expand to 95 intersections, and the long-term goal includes 800 SCATS intersections by 1996.

SCATS distributes computations between a computer at the traffic operations center and the field controller. Implementation in the US therefore requires special adaptation of NEMA and Model 170 controllers to incorporate the SCATS field processing functions.

RTA simulated a comparison of SCATS with a TRANSYT optimized fixed time system (63) and claims the following benefits:

- In the A.M. peak period, with traffic flow not deviating about the average, SCATS shows little improvement in delay and approximately 7 -8% fewer stops.
- In the A.M. peak period, when traffic flows fluctuate 20% to 30% from the average, SCATS shows improvements as follows:
    - 8% in total vehicle stops along main roads,
    - 3% in total traffic delay,
    - 3% in total fuel consumption, and
    - 3 to 6% reduction in pollutant emission (CO, HC and NOx).

Major operational advantages of SCATS include:

- The ability to automatically generate timing plans thus saving the operating agency the effort of performing this task, and
- The ability to automatically calibrate detectors, thus avoiding this task during system test and grooming.

Section 8.4 provides additional application information on SCATS.

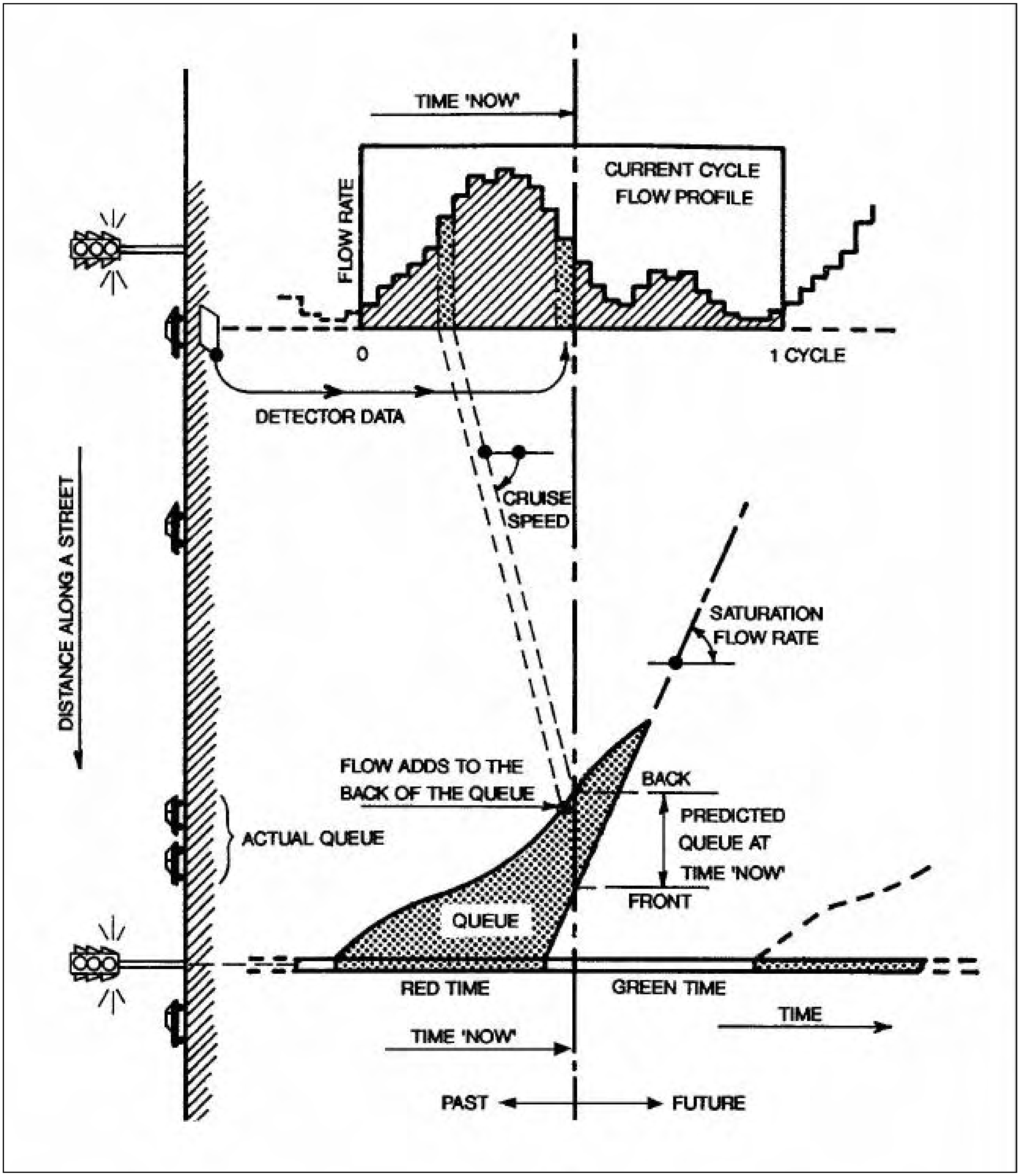


Figure 3-29. Principles of the SCOOT traffic model.

Table 3-30. SCOOT optimization process.

Timing Parameter	Process
Offset	A few seconds before every phase change, SCOOT determines whether it is better to: • Advance or retard the scheduled change by up to 4 seconds, or • Leave it unaltered.
Split	Once per cycle, SCOOT determines whether the performance index (PI) can be improved by reducing or increasing each offset by 4 seconds. The PI is usually a weighted sum of stops and delays.
Cycle	SCOOT varies the cycle time by a few seconds every few minutes to try, if possible, to keep the maximum degree of saturation below 90 percent on the most heavily loaded phase.

Saturated Flow Conditions

A *saturated* flow condition develops when demand at a point (or points) in a network exceeds capacity for a sustained period. This condition manifests itself at an intersection through the development of long queues which may reach from one intersection to another.

When this condition occurs, traffic cannot move even when it receives a green light, and jam conditions develop.

To clear traffic when jam conditions develop requires a different concept of control. In a network two levels of saturated flow can occur:

- Saturated flow at a limited number of signalized intersections, and
- Widespread saturation.

The following control concepts deal with these two types of saturated flow.

Table 3-31. Enhanced SCOOT features.

Feature	Description
Congestion Offsets	Under *congestion* conditions, the best offset may facilitate a particular movement (to prevent spillback across an intersection or for other reasons). Under *congestion situations*, SCOOT provides congestion offsets that replace the criterion for optimizing the PI with a specially designed offset. Information from another link may also be used to implement offsets under congestion conditions.
Gating Logic	*Gated* links are designated to store queues that would otherwise block bottleneck links. Thus, green time can be reduced on a gated link as a function of saturation on a remote bottleneck link.
Automatic Calibration of Saturation Occupancy	Early versions of SCOOT required the system operator to supply the appropriate value of *saturation occupancy*. The latest version of SCOOT provides this capability automatically, which: • Eliminates a calibration effort, and • Improves response to the real-time changes of this value as a function of temporary conditions.

Saturated Conditions at a Limited Number of Signalized Intersections

Under NCHRP-sponsored Project 3-18 (3) researchers at Polytechnic University developed guidelines for improving traffic operations on oversaturated street networks and documented them in NCHRP Report 194, *Traffic Control in Oversaturated Street Networks* (64). The researchers used simulation and analytical studies, field tests, and national surveys to develop the guidelines. The report enumerates several candidate treatments:

- Minimal response signal remedies -intersection,

Table 3-32. SCATS control levels.

Level	Description
Strategic	• A number of signals (from 1 to 10) group together to form a subsystem. • Up to 64 subsystems can link together for control by a regional computer. • Each traffic signal in a subsystem shares a common cycle time, which is updated every cycle to maintain the degree of saturation around 0.9 (or a user-definable parameter) on the lane with the greatest degree of saturation. Degree of saturation corresponds to an occupancy value measured by the detector. • Cycle time can normally vary up to 6 seconds each cycle, but this limit increases to 9 seconds when a trend is recognized. • Phase splits vary up to 4 percent of cycle time each cycle to maintain equal degrees of saturation on competing approaches, thus minimizing delay. • Offsets selected for each subsystem (i.e., offsets between intersections within the subsystem) and between subsystems linked together.
Tactical	• Operates under the strategic umbrella provided by the regional computer. • Provides local flexibility to meet cyclic demand variation at each intersection. For example, any phase (except the main street phase) may be: - omitted - terminated earlier - extended • Time saved during the cycle as a result of other phases terminating early or being skipped may be: - used by subsequent phases - added to the main phase to maintain each local controller at the system cycle length

- Minimal response signal remedies -system,
- Highly responsive signal control,
- Enforcement and prohibition,
- Turn-bays and other non-signal remedies,
- Major lane assignments, and
- Disruptions to the traffic.

Another strategy for this condition uses signal timing designed for saturated conditions including:

- The CIC algorithm previously discussed, and
- Control strategies such as OPAC and MOVA (Section 3.13).

In the latter two strategies, the saturated intersection operates as a non-coordinated intersection, with the non-saturated intersections separately coordinated.

When demand exceeds intersection capacity, one strategy delays the onset of queue spillback or eliminates it by fully using vehicle storage capacity on all approaches through an appropriate control law (65).

Widespread Saturation in the Network

Arterial and network signal timing programs such as PASSER and TRANSYT optimize flow primarily on unsaturated arterials and networks. These concepts provide progressive greenbands for vehicles and minimize a network performance index such as delays and stops.

However, widespread network saturation requires special coordination techniques (64, 66, 67). Quinn (66) expresses the coordination principles:

> *"A common feature of the strategies is a change in the basic concept of what the offset between*

signals is supposed to accomplish. Instead of providing for forward progression of vehicle platoons, the signal timings at an upstream junction are determined by the start of green downstream, and the time taken for the front of a queue to move upstream and clear the upstream intersection. Thus, the order of calculation of signal timings is opposite to the flow of congested traffic, so that the term 'reverse offsets' is sometimes used. The principle is illustrated in Figure 3-30."

Using these principles, Rathi (67) discusses a scheme for timing midtown Manhattan's congested network. The network generally consists of major one-way north-south arterials and narrower one-way east-west cross streets. A number of factors inhibit movement on cross streets. Queue extension and spillback from the cross streets impacts arterial movement. Figures 3-31 and 3-32 show the timing plan developed by Rathi where the cross streets feature a reverse offset. The splits *flare* (increase in the direction of the network periphery) to provide increasing capacity for vehicles entering from the arterials. A simultaneous progression is provided for the arterials. Rathi termed this type of control *internal metering.*

The NCHRP 3-38 (68) study broadened these concepts. Reference 72 describes the basis for developing signal timing plans and strategies along with examples. The reference also describes other forms of metering such as *external metering* (Figure 3-33) and *release metering* (controlled rate of discharge from parking facilities).

Where widespread saturation exists, one perspective views the area as possessing a capacity to contain vehicles, and manages entry flow to this capacity.

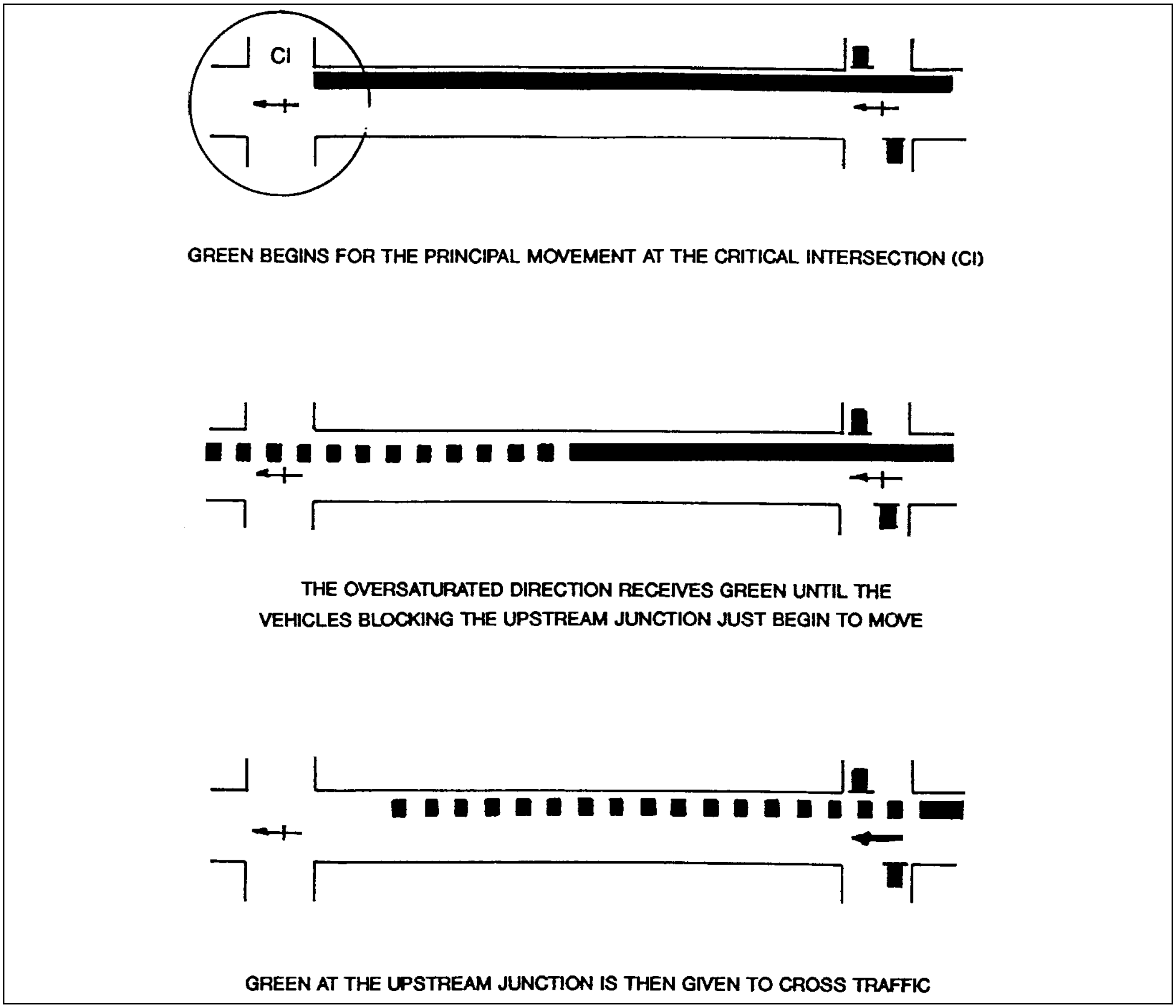


Figure 3-30. Reverse progression signal offset.

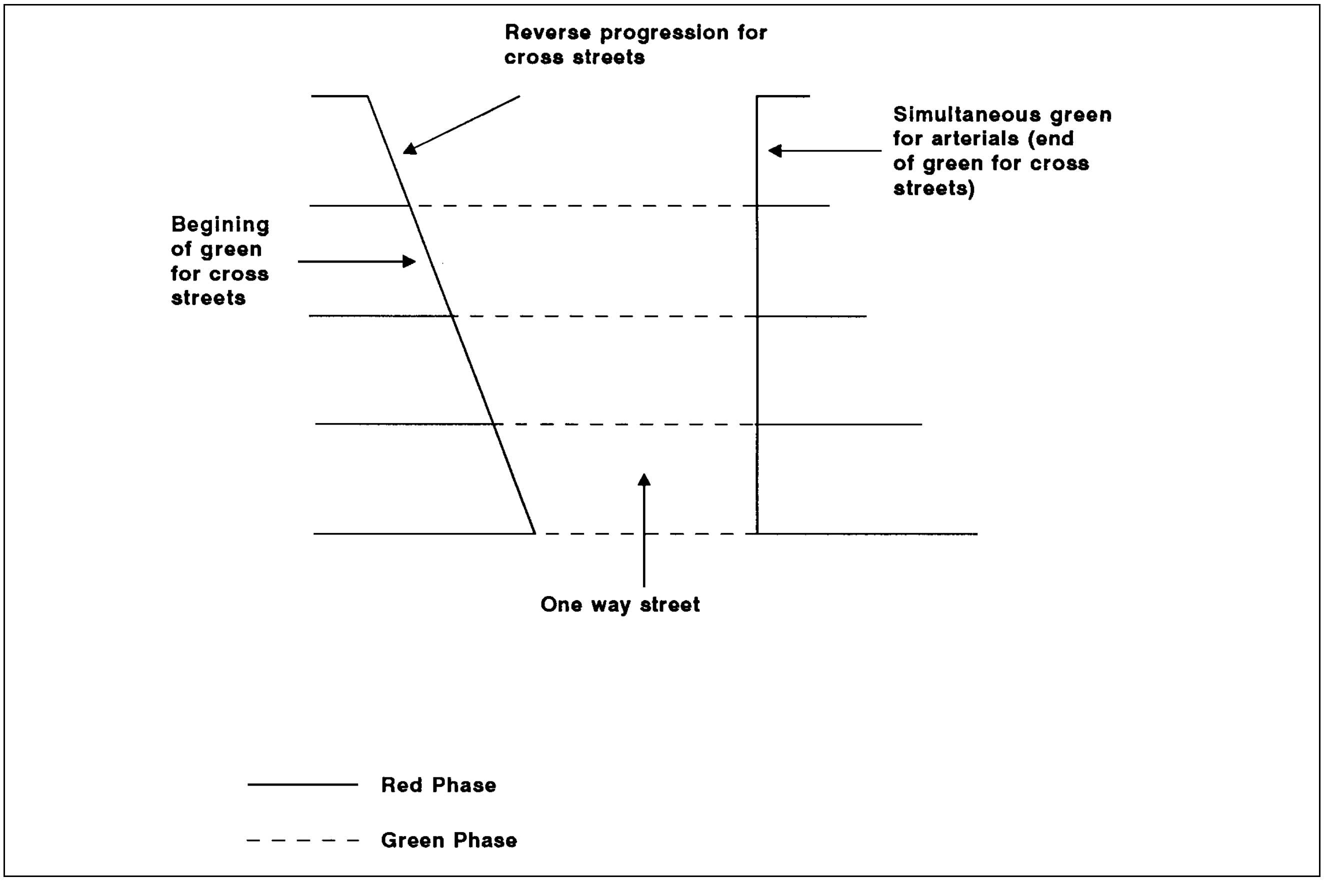


Figure 3-31. General "flared" signal pattern for cross streets.

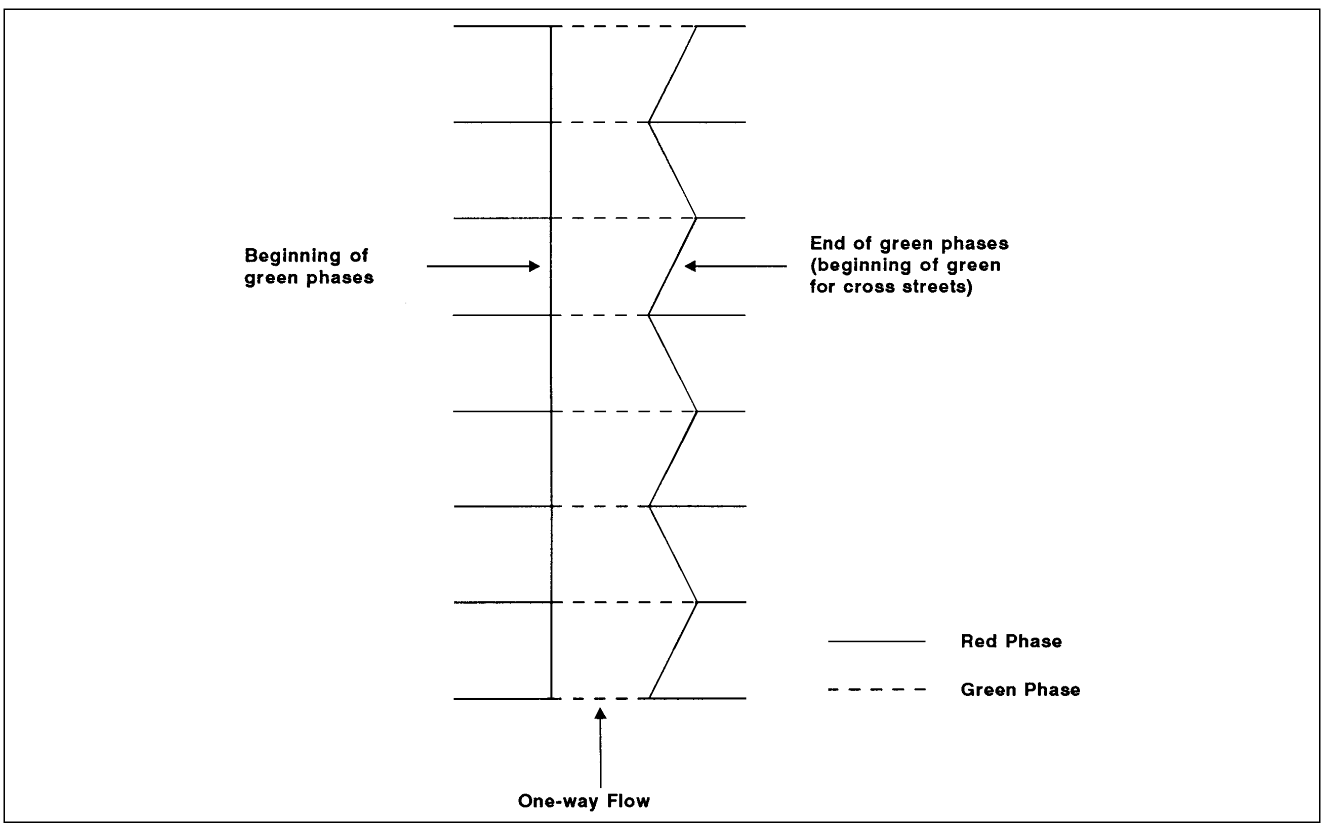


Figure 3-32. General signal timing pattern along arterials.

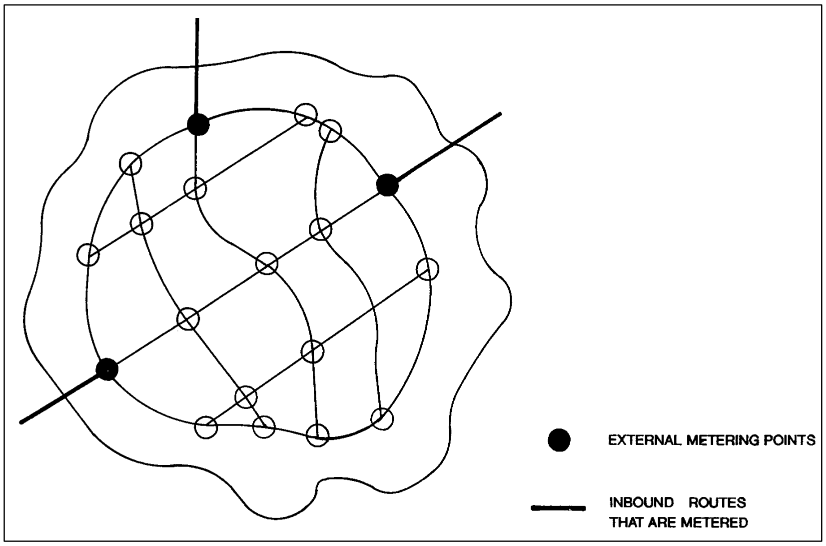


Figure 3-33. External metering.

Smeed (69) provides equations to determine the capacity. Godfrey (70) illustrates the relationships among:

- Number of vehicles in the network,
- Throughput of the network in vehicle miles per hour, and
- Average vehicle speed.

Figures 3-34 and 3-35 illustrate the relationship for the town center of Ipswich, England (70). The figures show that current operation provides less than maximum potential throughput at an average speed of 7.4 mph. The shape of Figure 3-34 resembles the freeway speed versus density relationship and the shape of Figure 3-35 resembles the freeway volume versus speed relationship (Section 3.4). These curves suggest improvement of network utilization and travel speed through a combination of external and release metering to limit the number of vehicles accessing the network to the number which represents a maximum throughput condition.

Network Simulation

TRAF -NETSIM Model

TRAF-NETSIM is an interval-based, microscopic, stochastic simulation model that simulates the operational performance of vehicles traveling on a network of surface streets (71). The model was developed from the UTCS-1 (Urban Traffic Control System) model, and represents one of the major component models in TRAF (Integrated Software System). The vehicles in this model are simulated individually and their operational performance is determined uniquely every second. Also, each vehicle is identified by category (auto, car, pool, truck, bus), by type (up to 16 different types of vehicles, with different operating and performance characteristics), and by the distribution of driver behavior characteristics (passive, normal, aggressive). The driver vehicle characteristics, turning movements, free-flow speed, queue discharge headway, lane-switching, and acceptable gap are all assigned stochastically in this model.

TRAF-NETSIM can simulate the effects of traffic control ranging from *STOP* or *YIELD* sign to actuated traffic control systems. Signal controllers may be either pre-timed or actuated and bus operations can be analyzed. The output of the TRAF-NETSIM model includes speed, volume, density, delay, spillback, queuing, turning movements, and estimates of fuel consumption and emissions (71).

The TRAF-NETSIM network is configured in terms of links and nodes. Links are unidirectional segments of streets. Nodes usually represent the intersections of streets. The links are defined in terms of the nodes at each end. A buffer node is normally placed between the entry and exit nodes, and the node at the intersection. The buffer node, referred to as a dummy node, improves the simulation performance and allows the collection of statistics on the traffic approaching and exiting the nodes on the periphery of the network. The geometries of the streets, the traffic volume, and the turning movements are specified with reference to the links. The traffic control used at the intersection is specified with reference to the nodes. Information obtained from the TRAF-NETSIM simulation can be viewed in a static graphic format or in an animated format using the interactive display postprocessors in GTRAF. The soon to be released TRAF-NETSIM version 5.0 has the additional capability to model urban interchanges (72).

Future work includes the introduction of a real -time dynamic traffic assignment model to provide the TRAF-NETSIM model with Advanced Traffic Management System (ATMS) control strategies to be evaluated (72). Also, through the use of interface links, TRAF-NETSIM has been linked to the Freeway Simulation (FRESIM) model and adjacent freeways can be modeled (73). The model resulting from the interface of TRAF-NETSIM with FRESIM is called the Corridor Simulation (CORSIM) model. To date, CORSIM is still in the developmental stage but should be released in the near future.

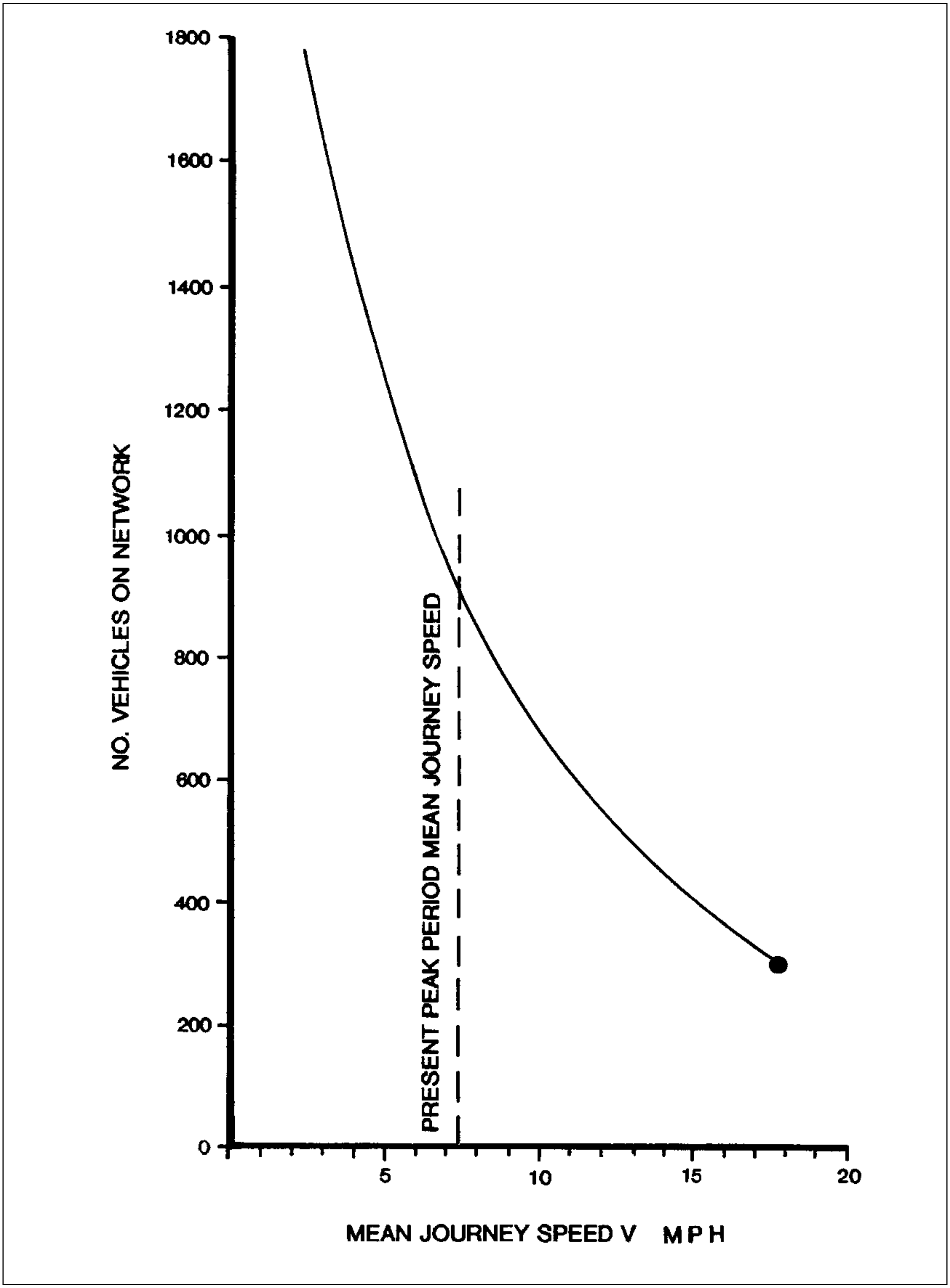


Figure 3-34. Relationship between mean journey speed and number of vehicles on town center network.

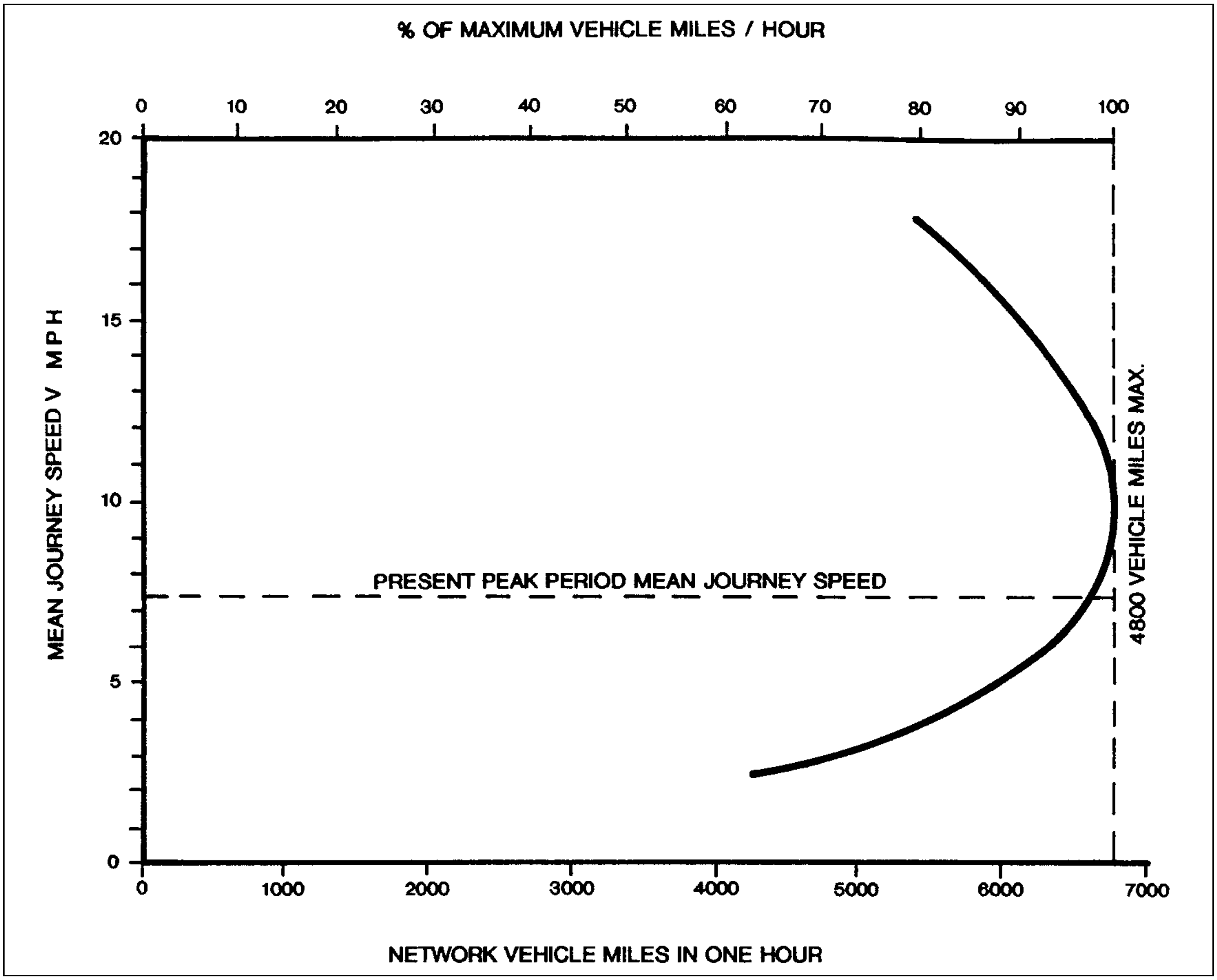


Figure 3-35. Relationship between mean journey speed of vehicles and total vehicle mileage on network.

NETFLO Level 1

NETFLO 1 is an event based urban network simulator of traffic operations. Each vehicle on the network is treated as an identifiable entity in the traffic stream. Vehicles are identified by type (auto, carpool, truck or bus) and driver characteristics (passive or aggressive). Turning movements, free -flow speed, queue discharge headway and other behavioral attributes are determined stochastically. Actuated signal control and the interaction between buses and autos can also be modeled. The program logic is such that vehicle position (lateral and longitudinal) on a network link is determined relative to other vehicles nearby for every individual vehicle movement.

The major difference in the macroscopic NETFLO 1 model and the microscopic TRAF -NETSIM model is that no car-following logic is employed by NETFLO 1. NETFLO 1 moves each vehicle whenever an event occurs. Events refer to interruption in the flow of vehicles, for example, a change of direction at an intersection. From one event to the next the vehicle is moved downstream, as far as possible, within the traffic flow constraints of the particular roadway. Therefore, detailed vehicle trajectories cannot be generated. The MOE output produced by NETFLO 1 includes speed, volume, density, delay, spillback, queuing, turning movements, and estimates of fuel consumption and emissions (71).

Through the use of interface links NETFLO 1 can be linked to the Freeway Flow (FREFLO) model to simulate adjacent freeway operations. The resulting model is called the Corridor Flow (CORFLO) model.

NETFLO Level 2

NETFLO Level 2 was adapted from the TRANSYT flow model. The TRANSYT inputs were simplified and the ability to handle time varying traffic flow and multiple cycle lengths were added. Link-specific statistical flow histograms are used to describe the platoon structure of the traffic stream on each network link. Five types of histograms are generated to represent the traffic flow on each link for every time interval. The histograms are described as follows:

- An entry histogram which describes the platoon flow at the upstream end of the link. It is an aggregation of the output turn movement histogram of all links that feed this specific link.
- An output histogram which describes the pattern of traffic discharging from the subject link. Each input histogram interacts with an associated service histogram and is transformed into an output histogram by the control applied to the subject link. Each output histogram is then applied to the entry histogram of its receiving link.
- An input histogram which describes the platoon flow pattern arriving at the stopline. These histograms are obtained by disaggregating the entry histograms into turn movement specific histogram components, then modifying these components to account for platoon dispersion along the link.
- A service histogram which describes the history of discharge service rates for each turn movement component of traffic and reflects the control device applied at the intersection.
- A queue histogram which describes the history of queue length over time for each turn movement component of traffic.

This model treats buses as separate entities, and their time along each link is computed by employing kinematic relations and includes the effect of dwell time at stations. Also, traffic congestion is treated explicitly, along with blockage due to spillback and the intersection of buses with general traffic. Trucks and carpools are not modeled explicitly. However, the effect of trucks is accounted for by adjusting queue discharge rates based on the impedance of traffic flow. The MOE output produced by NETFLO 2 is similar to NETFLO 1 and NETSIM and includes speed, volume, density, delay, spillback, queuing, turning movements, and estimates of fuel consumption and emissions (71).

Through the use of interface links NETFLO 2 can be linked to the Freeway Flow (FREFLO) model to simulate adjacent freeway operations. The resulting model is called the Corridor Flow (CORFLO) model.

3.10 Special Controls

Special controls for traffic management include:

- Directional Controls,
- High Occupancy Vehicle (HOV) Priority Systems,
- Preemption/Priority Systems,
- Television Monitoring, and
- Overheight Vehicle Control Systems.

Directional Controls and Lane Control Signals

To best use existing facilities, consider unbalanced and/or reversible-lane flow. This requires special traffic controls to effect the desired movements. Two basic types of operations using surface street directional controls include:

- Reversible Flow - Dynamically operating a street as one-way inbound, one-way outbound, or two-way. Applications may include:
  - Heavy imbalance of directional traffic flow for relatively short periods such as in and out of central business districts,
  - No alternate solutions such as one-way pair or street widening,
  - Severe congestion and need to increase directional capacity, and
  - Nearby parallel street capable of handling minor directional flow during peak one-way operation.

- Off-center lane movement - Partial reversal of traffic flow where only one or two lanes are reversed. Applications are similar to reversible flow.

Current techniques for controlling directional movement uses signs or a combination of signs and lane control signals. Change of operational mode is usually on a time-of-day basis.

Directional control is often used in tunnel and bridge operations for the following purposes:

- Assignment of roadway lanes to prevailing directional traffic flow requirements,
- Balancing of traffic flow during maintenance operations, and
- As an element in incident response plans (Section 4.5).

According to the MUTCD (5), *lane control signals are special overhead signals having indications used to permit or prohibit the use of specific lanes of a street or highway or to indicate the impending prohibitions of use. Installations are distinguished by the placement of these special signals over a certain lane or lanes of the roadway and by their distinctive shapes and symbols. Supplementary signs are often used to explain their meaning and intent.*

Reversible lane control has proven the most common use for lane control signals (LCS). Examples include (75, 76):

- Toll booths,
- HOV lanes,
- Reversible transitways on freeways,
- Arena traffic, and
- Parking control

Other applications include:

- Restriction of traffic from certain lanes at certain hours to facilitate merging traffic from a ramp or other freeway, and
- Lane use control for:
  - Tunnels,
  - Bridges, and
  - Freeways.
- Indication of the use of the shoulder lane during peak hours. For example, Interstate 66 in Virginia uses the left most lane as an HOV lane during the peak periods; therefore, to provide the same number of lanes to non-HOV traffic the shoulder lane is used during this period. Lane control signals are used to indicate when the shoulder lane can be used.

The MUTCD further defines the signal displays and meaning of indications as described in Table 3-33.

Supplementary signing may prove particularly useful with the yellow X since studies have shown varied and ambiguous interpretation of this display (76, 77).

Other countries have used different symbols with their freeway LCS, including (76-84):

- Additional downward diagonal arrows,
- Additional road work symbols, or
- Alternative symbols for the red X.

Some state agencies are experimenting with alternative or additional lane-use control signal indications. The MUTCD has permitted

Table 3-33. Definitions of lane control signal displays.

Display	Definition
Steady Downward Green Arrow	Driver permitted in the lane over which the arrow signal is located.
Steady Red X	Driver not permitted in the lane over which the signal is located.
Steady Yellow X (Optional)	Driver should prepare to vacate the lane over which the signal is located.
Flashing Yellow X (Optional)	Driver permitted to use a lane over which the signal is located for a left-turn. Driver further cautioned that lane may be shared with opposite flow left-turning vehicles.

experimentation with steady and flashing downward yellow arrows and both Texas and Minnesota DOTs have done so. Arizona DOT is experimenting with yellow arrows pointing in downward 45 degrees (diagonal) directions.

The MUTCD further defines other characteristics of LCS including:

- Display shape and size,
- Visability distance and angle,
- Separate or superimposed display units,
- Positioning of LCS over lane,
- Longitudinal spacing of LCS over length of controlled roadway, and
- LCS display sequencing and operations.

An ITE equipment and materials standard also exists for LCS (85). It further defines a number of other characteristics including:

- Construction,
- Lens color definitions, and
- Arrow and X shape guidelines.

Many of the factors that govern visibility of CMS messages also apply to LCS. An Ontario Ministry of Transportation series of studies compared various manufacturer's LCS products (80).

The most common types of LCS are:

- Fixed-grid fiberoptic, and
- Fixed-grid LED light emitting.

Refer to Section 10.3 for a description of these technologies with regard to CMS.

Figure 3-36 shows an example of lane control signals for reversible-lane control. Lane control signals a re not mandatory for reversible lanes or other purposes; signing often can suffice in these applications. However, properly designed and operated lane control signals generally prove more effective and their use is steadily increasing.

Lane control signals are discussed further in Section 7.3.

HOV Priority Systems

Conditions may warrant special assignment of right-of-way at a signalized intersection. This is accomplished by priority systems.

High Occupancy Vehicle (HOV) Priority

To facilitate person movement rather than vehicle movement, priority can be assigned to high-occupancy vehicles including:

- Buses,
- Vans, and
- Carpools.

Average occupancy of an automobile often approximates 1.2 persons per vehicle, while HOV may have many times this value. Thus, assigning priority to HOV over Single Occupant Vehicles (SOV) emphasizes person rather than vehicle movement. This section describes techniques for HOV priority control on urban networks, while section 4.7 describes HOV techniques for freeway control.

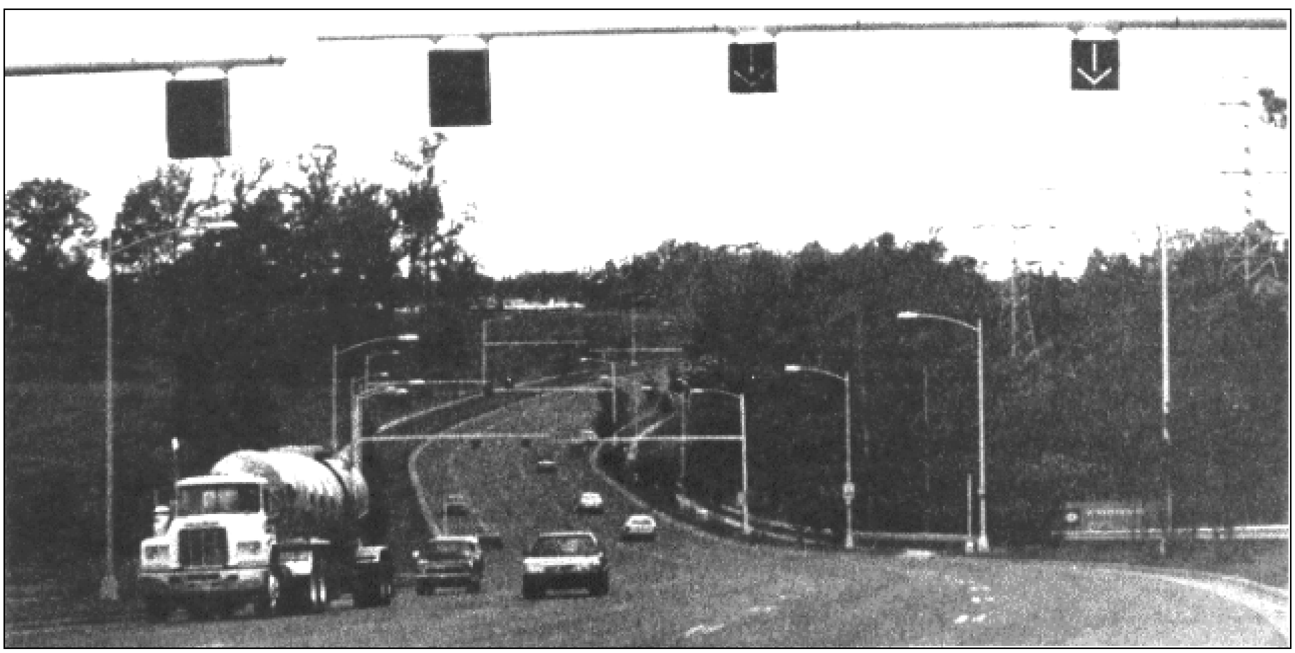
Priority techniques for buses on surface streets include:

Exclusive (diamond) lanes which give buses exclusive right-of-way except for vehicles making right turns,
Exclusive contra-flow lanes on one-way streets, and
Exclusive left-turn movements.

Preemption/Priority Systems

Preemption Systems

Preemption of the normal cycling of traffic signals may apply:



Courtesy C.J. Hood Company, Inc.

Figure 3-36. Fiber optic reversible lane, lane-use signals.

- Where a signalized intersection is adjacent to a railroad track; right-of-way may be given to phase(s) not crossing the track,
- To permit assignment of right-of-way to fire fighting equipment or other emergency vehicles, and
- To provide right-of-way to transit vehicles.

In railroad preemption, detectors sense the approach of a train and trigger an all red, flashing red, etc., which lasts until the train clears the intersection. Some traffic control systems provide a special traffic plan for a period after preemption. This plan dissipates the queue developed during preemption.

Fire fighting vehicles may use two preemption schemes:

- Route Preemption -- The traffic signal system can provide pre-planned fire fighting equipment routes. Green signal indications are displayed at signals along the appropriate route, often selected at a control panel in the central fire station. The signals are switched back to normal operation after the reported passage of the emergency vehicle(s) - often at a pre-specified time.

  Flashing yellow signal indications may be used instead of the green band to reduce delay by allowing some vehicles to proceed through with caution.

- Local Signal Preemption -- A transmitter located on emergency vehicles emits an optical or radio signal detected by a receiver at the intersection. Section 6.2 further discusses this equipment.

  When the vehicle is detected approaching the intersection, a special signal control procedure assigns right-of-way to the vehicle. After a pre-determined time period, the signal returns to normal operation.

Signal Priority Systems

Bus delays at traffic signals usually represent 10 to 20 percent of overall bus trip times and nearly one -half of all delays (86). Other authors have come to similar conclusions (87 - 90); thus, signal priority treatment for buses may be warranted in many cases. Minimizing bus delays often results in reducing total person delay for all persons using the roadway, whether in buses or private vehicles.

Signal priority may be accomplished as follows:

- *Conditional Signal Priority* - Gives priority to transit vehicles at an intersection if they can effectively use the additional green time.

  Some control techniques available under conditional signal priority include (87, 88, 91-94):

  - *Phase/green extension*: desired phase green is lengthened by a maximum time. This proves helpful when the transit vehicle is detected near the end of the green and no near side bus stop is present. By extending the green a few seconds, the transit vehicle avoids stopping at the signal.
  - *Phase early start* or *red truncation*: desired phase green is started earlier. This is helpful if the transit vehicle is detected during the desired phase red. Starting the desired phase green a few seconds earlier will save a few seconds of delay.
  - *Red interrupt* or *special phase*: a short special green phase is injected into the cycle. This is especially helpful with near side stops serviced from a shoulder. The special phase will permit a *queue jump*. Buses get a special advance phase display which allows them to get through the intersection smoothly and get back into a regular lane of travel easily.
  - *Phase suppression/skipping*: logic is provided so that fewer critical phases are skipped. This can be used with logic that assesses congestion on the approaches to the skipped phase.
  - *Compensation*: non-priority phases are given some additional time to make up for the time lost during priority. Other compensation techniques include limiting the number of consecutive cycles in which priority is granted.
  - *Window stretching*: non-priority phases are given a core time, which must be serviced every cycle, and a variable timer which could be taken away for priority purposes. Flexible window stretching differs in that the core time is not fixed in position relative to the cycle.

A number of traffic equipment manufacturers offer NEMA controllers with some of these features. This type of control requires detection of the transit vehicle at the appropriate location. Detectors based on optical or microwave technology (as used for emergency vehicle preemption), inductive loop technology or AVI/ETTM technology may suit this purpose (see Section 6.2).

While signal priority techniques generally emphasize travel time reduction, signal priority may also improve adherence to bus schedules (95). The tendency of buses to bunch is well known (96, 97, 98), resulting in the additional passenger waiting time as shown in Figure 3-37 (95), and uneven passenger loadings. Gordon (95) expresses this irregularity in terms of control system stability theory and describes an algorithm based on control of traffic signals which removes the instability and improves schedule conformance.

- *Signal Timing Plan Priority* - TRANSYT 7F (Section 3.9) can generate signal timing plans to favor buses (44) and includes the following features (34):

  - Accounts for bus dwell times,
  - Can simulate buses either in priority lanes or general traffic lanes by assigning separate links to the buses,
  - Gives priority to buses by applying high weights to delay and/or stops on bus links, and
  - Can similarly model carpools that are assigned separate lanes.

Selection of Signal Priority Approach

The selection of the signal priority approach depends on:

- Number of buses which are candidates for priority,
- Number of buses adversely affected by priority,
- Impact of priority on general traffic and pedestrian flow, and
- Additional concurrent bus priority measures.

Conditional signal priority (priority when transit vehicles can make use of added green time) can prove effective when bus flow and passenger traffic lies within the range of values shown in Table 3 -34 (85). When bus flow exceeds the maximum shown in the table, signal timing plan priority may become more effective.

Each candidate transit priority project must be carefully evaluated with respect to:

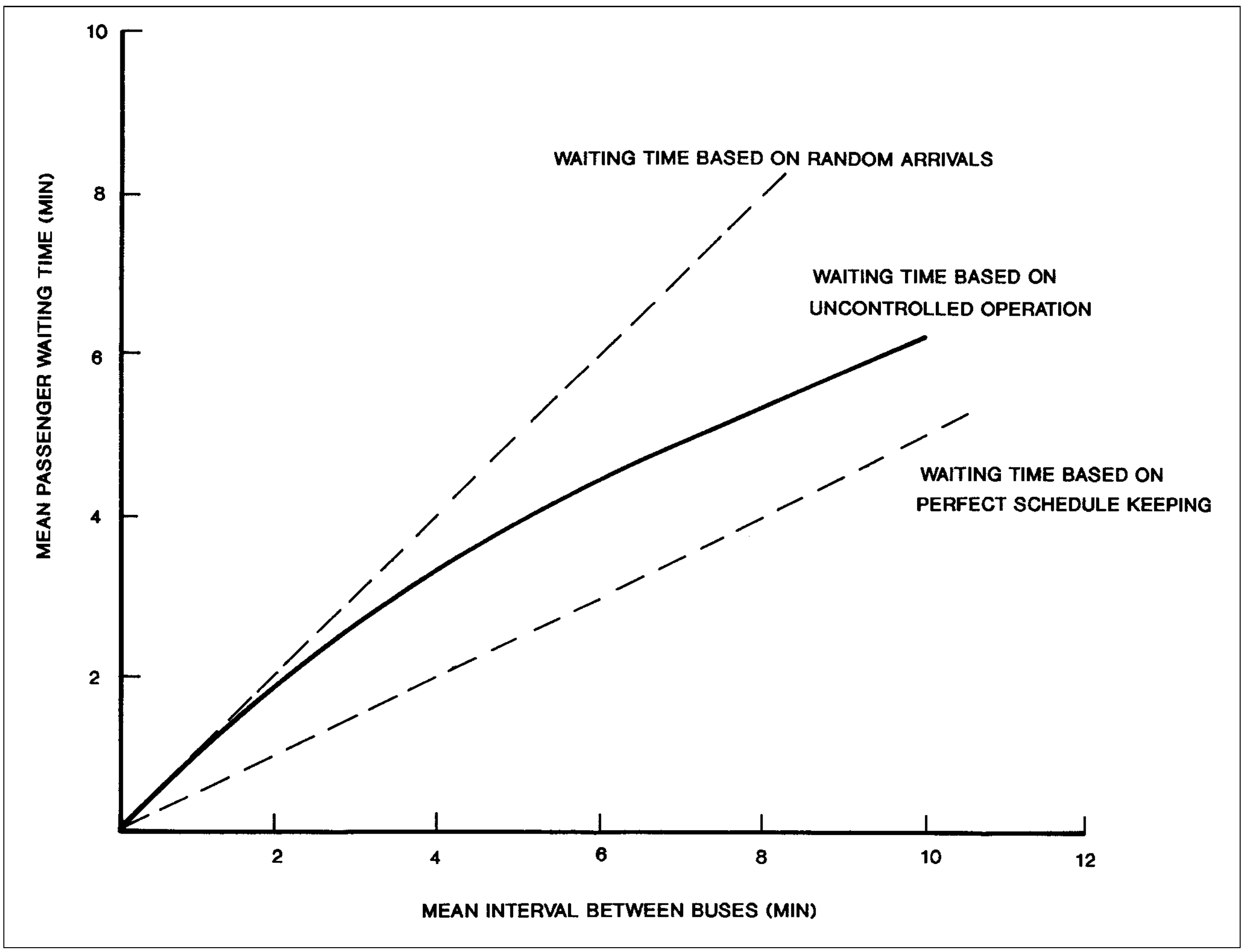


Figure 3-37. Passenger waiting time versus mean headway.

Table 3-34. Bus flow requirements for conditional signal priority.

- **Minimum Daily Bus Volume**
  100 Buses
- **Minimum Peak Hour Requirements**
  10 to 15 buses
  400 to 600 people
- **Maximum Peak Hour Bus Volume**
  Approximately half the number of hourly traffic cycles

- Overall traveler benefits,
- Impacts and constraints on general traffic and pedestrian flow, and
- Community acceptance.

Signal Transit Priority Experience

Table 3-35 (98) describes a number of locations, mostly in North America which have applied traffic signal priority. Table 3-36 (99) provides information on five European locations. The greater success of priority in Europe results from (99):

Greater emphasis on transit, and
Institutional emphasis on reducing transit delays and encouraging transit ridership.

One success story in North America is in Charlotte, North Carolina (99). The city provides priority for express buses at eleven intersections. Bus delay at signals has been reduced by 67% and ridership has substantially increased.

Chicago and Toronto have embarked on projects of significant scope to introduce priority systems.

Television Monitoring

Although CCTV has been applied in the United States mainly to freeway monitoring and control projects (see Section 4.5), it has been used for urban streets in Columbus, Ohio (101) and Overland Park, Kansas (102). Other installations include Los Angeles, California and Oakland County, Michigan, and several Texas cities.

In these systems, cameras are usually placed at critical intersections in the network. This allows the operator to quickly determine:

- Nature and time of occurrence of traffic incidents (accidents, stalled vehicles, debris on the road, parking violations, etc.),
- Type of response required, and
- Effect on the upstream network.

Overheight Vehicle Control Systems

Overheight vehicle control systems prevent damage to vehicles and highway structures resulting from vehicles too high for the structures. Systems of this type see use on:

- Approaches to tunnel portals,
- Entry ramps leading to tunnels, and
- Approaches to restricted height garages.

A system consists of two elements:

- Overheight vehicle detectors, and
- Warning message devices.

The overheight vehicle detector system typically consists of:

- Pole mounted infrared light emitting diode transmitter mounted at an appropriate height, and
- Receiver mounted across the protected roadway.

Interruption of the light beam by an overheight vehicle causes the detector system to output a signal.

The presence of two-way traffic on the same roadway can require two units. The time sequence of output signals establishes the vehicle's direction. Warning message devices include:

Blank-out signs,
Static sign with flashers, and
Audible warning devices.

3.11 Benefits

A successful traffic control system improves levels of service on the urban network. The degree of success is usually measured by reduction in:

- Accidents,
- Travel time,
- Delay,
- Stops, and

Increases in average speed can also result.

These, in turn, directly influence:

Table 3-35. Traffic signal transit priority projects.

Location	Year Documented	Mode	Priority Methods	Actuation Technology	No. of Signals	Traffic Control Strategy	Evaluation Results	Current Status
Leicester, England	1972	Bus	Truncation, compensation, inhibition	Passive transponder	1	Isolated	Average bus delay reduced by 10 seconds	Unknown
Louisville, KY	1972	Express Bus	Extension, truncation	Optical detectors	8	Isolated	15 to 19 percent reduction in p.m. travel time	Discontinued
Woking, England	1976	Bus	Truncation, phase skipping	Loop detector in bus-only lane	1	Isolated	Average bus delay reduced by 7 seconds	Unknown
Miami, FL	1977	Express Bus	N/A	N/A	37	Various	23 percent reduction in travel time	Discontinued
Concord, CA	1978	Bus	Extension, truncation	Optical detectors	12	Isolated and fixed time	10 percent reduction in bus travel time	Discontinued
Melbourne, Australia	1978	Bus	Extension, truncation, compensation, inhibition	Passive transponder	1	Isolated	Significant reduction in bus delays	Unknown
Santa Clara, CA	1978	Bus	N/A	Optical emitters	60	N/A	System worked well but abuse and high maintenance costs degraded benefits	Discontinued

Table 3-35. Traffic signal transit priority projects (continued).

Location	Year Documented	Mode	Priority Methods	Actuation Technology	No. of Signals	Traffic Control Strategy	Evaluation Results	Current Status
Dallas, TX	1982	Bus	Extension, truncation, phase skipping inhibition	Active transponder	N/A	Isolated	5 percent reductions in bus travel time, peak direction	Discontinued
Memphis, TN	1982	Express Bus	Extension, truncation, phase skipping	Optical detectors	24	Isolated	47 to 72 percent reduction in p.m. express bus signal delay	Discontinued
S. Hertogenbosch, Netherlands	1982	Bus	N/A	Passive transponder	28	N/A	10 percent reduction in bus travel time	Unknown
Los Angeles, CA	1986	Bus	Extension, truncation	Optical emitters	49	Various	4.2 percent travel time reduction	Operational (1)
Minneapolis, MN	1989	Local Bus	Extension, truncation, phase skipping	Signature recognition	20	Fixed time	Signature recognition reliable but limited to one specific type of bus	Operational (2)
Zurich, Switzerland	1989	Bus	Extension, truncation	Active transponder	217	N/A	N/A	Unknown
Ottawa, Ontario	N/A	Bus	Special phase	Four microloops	3 or 4	N/A	N/A	Operational

N/A = Not Available
(1) System not operating pending software modifications
(2) System not operating pending purchase of new computer hardware and software
SOURCE: TORONTO TRANSIT COMMISSION

Table 3-36. Selected European traffic signal transit priority projects.

Elements/Cities	London	Stuttgart	Zurich	Nancy	Angouleme
Traffic Control System					
Central Control	✓		✓		
Isolated		✓		✓	✓
UTC System	✓			✓	Future
Associated Priority Facilities					
With Bus Lanes	✓		✓	✓	
Without Bus Lanes	✓	✓	✓	✓	✓
Relation to AVL System					
Combined with AVL		Future		✓	✓
Not Combined with AVL	✓	✓	✓		
Strategies Employed					
Green Extension	✓	✓	✓	✓	✓
Red Truncation	✓	✓	✓	✓	✓
Red Interruption		✓	✓		
24-hour Priority	✓	✓	✓	✓	✓
Priority Cut-off		✓	✓	✓	✓
Compensation Following Priority					
Green Extension		✓	✓		
Red Extension	✓				
Conditions of Priority					
Reduced Delay	✓				
Full Priority		✓	✓		✓
Late Buses Only				✓	Future
Technology Employed					
Loops	✓	✓	✓		
Beacons		✓			
Radio		✓		✓	✓
Selection Procedure					
Individual Intersection Analysis			✓	✓	✓
Full Line Implementation		✓	✓		
System Implementation					
Area Implementation	✓		✓		

- Fuel consumption,
- Vehicle emissions, and
- Highway user costs.

FHWA, ITE and the American Automobile Association have performed much research and data collection on fuel consumption, vehicle emissions and user costs.

Estimating Fuel Consumption (11)

Vehicle fuel consumption represents a major operating expense and is strongly influenced by road and traffic conditions. Table 3-37 shows the fuel consumption rate of passenger cars operating at various speeds on level and gradient roads. Table

Table 3-37. Fuel consumption as affected by speed and gradient, passenger cars.

Uniform Speed		Gasoline Consumption on Upgrades (gal/mi (L/km))											
		Level		2%		4%		6%		8%		10%	
mi/hr	km/hr	gal/mi	L/km	gal/mi	L/km	gal/mi	L/km	gal/mi	L/km	gal/mi	L/km	gal/mi	L/km
10	16	0.072	0.169	0.087	0.205	0.103	0.242	0.121	0.284	0.143	0.336	0.179	0.421
20	32	0.050	0.118	0.070	0.165	0.086	0.202	0.104	0.244	0.128	0.301	0.160	0.376
30	48	0.044	0.103	0.060	0.141	0.078	0.183	0.096	0.226	0.124	0.291	0.154	0.362
40	64	0.046	0.108	0.062	0.146	0.078	0.183	0.096	0.226	0.124	0.291	0.156	0.367
50	80	0.052	0.122	0.070	0.165	0.083	0.195	0.104	0.244	0.130	0.306	0.162	0.381
60	97	0.058	0.136	0.076	0.179	0.093	0.219	0.112	0.263	0.138	0.324	0.170	0.400
70	113	0.067	0.158	0.084	0.197	0.102	0.240	0.122	0.263	0.148	0.348	0.180	0.423

The composite passenger car represented here reflects the following vehicle distribution: large cars, 20 percent; standard cars, 65 percent; compact cars, 10 percent; small cars, 5 percent.

The values in this table are for a tangent, high-type pavement and free-flowing traffic. They should be increased by about 20 percent for speeds of 30 mi/hr (48.3 km/hr) and 50 percent for speeds of 50 mi/hr (80.5 km/hr) when operation is on badly broken and patched asphalt pavement. They should also be increased for operation on horizontal 5-degree curves; increase by about 3 percent at 30 mi/hr (48.3 km/hr) and 30 percent at 60 mi/hr (96.5 km/hr); on 10-degree curves, increase by about 20 percent at 30 mi/hr (48.3 km/hr) and 100 percent at 50 mi/hr (80.5 km/hr).

3-38 shows the fuel consumption of passenger cars for stop-and-go and speed-change cycles in excess of that for continued operation at the given running speeds. This table does not include fuel consumption for stopped delays. Fuel consumption for stopped delays may be computed by using a passenger car idling fuel consumption rate of 0.58 gal/hr.

Estimating Vehicle Emissions (102)

Air pollution from transportation creates a significant burden for urban areas. Emissions from cars, trucks, and buses prove major contributors to unhealthful levels of carbon monoxide and ozone. Nationwide, in 1989, highway vehicles emitted:

- 54% of the carbon monoxide,
- 28% of the hydrocarbons, and
- 30% of the nitrogen oxide.

In many urban areas mobile sources accounted for more than 90% of all carbon monoxide and 50% of hydrocarbon emissions. As vehicle-related pollution increases, the Clean Air Act of 1990 requires transportation conformity, with renewed emphasis on automobile pollution.

Table 3-39 shows the National Ambient Air Quality Standards while Table 3-40 indicates how vehicle emissions standards have become more stringent over the past twenty years.

Technological changes mandated by federal legislation have significantly reduced actual average emissions per mile traveled. For example, hydrocarbon emissions from the average car have fallen from approximately 13 grams/mile (gpm) in 1970 to less than 4 gpm in 1990. The Clean Air Act of 1990 is expected to reduce average vehicle hydrocarbon emissions from 4 gpm in 1990 to 1.32 gpm by the year 2000 and to 0.63 gpm by 2015.

Several software packages can:

- Estimate vehicle emissions, and
- The impacts of vehicle pollution.

MOBILE5C, CALINE3 and CALQHC are the three software packages approved by the Environmental Protection Administration (EPA) to analyze transportation emissions and their air pollution impacts.

Table 3-38. Excess fuel consumption for stop and slowdown cycles, passenger cars.

Running Speed		Excess Gasoline Consumed by Amount of Speed Reduction Before Accelerating Back to Speed (mi/hr (km/hr))											
		10 (mi/hr)		20 (mi/hr)		30 (mi/hr)		40 (mi/hr)		50 (mi/hr)		60 (mi/hr)	
mi/hr	km/hr	gal	L	gal	L	gal	L	gal	L	gal	L	gal	L
10	16	0.0016	0.0061	---	---	---	---	---	---	---	---	---	---
20	32	0.0032	0.0121	0.0066	0.0250	---	---	---	---	---	---	---	---
30	48	0.0035	0.0056	0.0062	0.0235	0.0097	0.0367	---	---	---	---	---	---
40	64	0.0038	0.0144	0.0068	0.0257	0.0093	0.0352	0.0128	0.0484	---	---	---	---
50	80	0.0042	0.0159	0.0074	0.0280	0.0106	0.0401	0.0140	0.0530	0.0168	0.0636	---	---
60	97	0.0046	0.0174	0.0082	0.0810	0.0120	0.0454	0.0155	0.0587	0.0190	0.0719	0.0208	0.0787

The composite passenger car represented here reflects the following vehicle distribution: large cars, 20 percent; standard cars, 65 percent; compact cars, 10 percent; small cars, 5 percent.
Excess fuel consumption for stop-go cycles at given running speeds.

Table 3-39. National ambient air quality standards (NAAQS).

Pollutant	Averaging Time	Federal Primary	Federal Secondary	Objective
Carbon Monoxide	8 hour	10 mg/m^3 (9 ppm)	None	Limit carboxyhemoglobin
	1 hour	40 mg/m^3 (35 ppm)	None	
Nitrogen Dioxide	Annual	100 µg/m^3 (0.053 ppm)	Same	Prevent health risk and improve visibility
	1 hour	None	None	
Ozone	1 hour	235 µg/m^3 (0.12 ppm)	Same	Prevent eye irritation, breathing difficulties
Sulfur Dioxide	Annual	80 µg/m^3 (0.03 ppm)	None	Prevent increase in respiratory disease, plant damage and odor
	24 hour	365 µg/m^3 (0.14 ppm)	None	
	3 hour	None	1310	
	1 hour	None	None	
PM-10	Annual	50 µg/m^3	Same	Improve visibility and prevent health effects
Lead	24 hour	150 µg/m^3	Same	Prevent health problems
	1 month	None	None	
	3 months	1.5 µg/m^3	Same	

*** California also has air quality standards for hydrogen sulfide (42mg/m3, 1 hour), vinyl chloride (26mg/m3, 24 hour), and ethylene (0.1 parts per million, 8 hour; 0.5 parts per million, 1 hour)**

Table 3-40. Emissions standards for passenger vehicles.

Year(s)	Hydrocarbons		Carbon Monoxide		Nitrogen Oxides	
	g/mi	g/km	g/mi	g/km	g/mi	g/km
Pre-1968	8.2	5.1	90.0	55.9	3.4	2.1
1968-1971	4.1	2.5	34.0	21.1	0.0	0.0
1972-1974	3.0	1.8	28.0	17.4	3.1	1.9
1975-1976	1.5	0.93	15.0	9.3	3.1	1.9
1977-1979	1.5	0.93	15.0	9.3	2.0	1.2
1980	0.41	0.25	7.0	4.4	2.0	1.2
1981	0.41	0.25	3.4	2.1	1.0	0.62
1994 (begin phase-in)	0.25	0.16	3.4	2.1	0.4	0.25
2003 (may be required)	0.13	0.08	1.7	1.1	0.2	0.12

MOBILE5C

MOBILE5C represents an EPA promulgated computer program developed in the 1970's and since modified. MOBILE5C generates emission factors for input data to the models CALINE3 and CAL2QHC. MOBILE5C calculates emissions factors (EFIS) for eight vehicle types based on the variables:

- Calendar year,
- Ambient temperature,
- Average speed, and
- Engine operating temperature at start -up.

Based on the vehicle fleet mix, MOBILE5C also calculates a weighted average EF (a composite EF) generally used in the air quality modeling process.

The user can create input files using any edit, spreadsheet, or word-processing package that can generate an ASCII file. All the inputs contain three main sections:

- Control - sets *flags* to control computer run,
- One time - data entered only once; applies to all modeled site-specific scenarios, and
- Scenario - allows evaluation of various scenarios.

MOBILE5C contains a large database controlled by a FORTRAN program. A user's manual can assist the analyst in running the program.

CALINE3

CALINE3 was developed by Paul Benson of the California Department of Transportation. It calculates concentrations of non-reactive air pollutants near highways. The program can calculate CO concentrations for nearby receptors given:

- An average emissions factor (such as output from MOBILE5C),
- Site geometry,
- Local meteorology, and
- Traffic flow rate.

The present CALINE3 version handles up to 20 roadway links and 20 receptors, and a large number of meteorological conditions. CALINE3 has proven a powerful tool for analyzing air pollution effects of a roadway with vehicles moving at constant speed (at intersections, CAL3QHC is the primary choice, see CAL3QHC section). The input data for the CALINE3 model includes:

- Average time,
- Surface roughness,
- Settling velocity and deposition velocity,
- Number of receptors,
- Position of receptors,
- Number of links,
- Number of meteorological conditions,

- Type of roadway,
- Vehicle volume,
- Average emission factors,
- Wind speed and direction, and
- Ambient background conditions.

The output will be the parts-per-million by volume (PPM) listed for each modeled receptor location. CALINE3 is written in FORTRAN and can be operated on any IBM compatible PC.

CAL3QHC

CAL3QHC is the model preferred by EPA to analyze air pollution at intersections where both idle and steady motion take place.

CAL3QHC assumes that vehicles move on a road at constant speed with a related emission factor calculated by MOBILE5C. Queue lengths and vehicles in the idle mode due to intersection delay are calculated using the 1985 Highway Capacity Manual methodology.

The input file for CAL3QHC resembles CALINE 3. In addition to the data required by CALINE3, CAL3QHC also requires:

- Queuing lanes,
- Idle emission rates,
- Saturation flow rates,
- Arrival type, and
- Intersection timing plan.

The output for CAL3QHC will be parts-per-million by volume (PPM) listed for each modeled receptor location.

Estimating Highway User Costs (11)

Highway user costs are the total of:

- Vehicle operating costs,
- Travel time, and
- Accident costs.

Table 3-41 lists passenger car operating costs in the United States from 1950 to 1990. Demonstrating the nation's reliance on highway transportation, in 1986 over 158.5 million U.S. drivers drove over 1.86 trillion vehicle-miles in over 172 million regulated vehicles. In the same year, highway accidents killed 47,000 people, a rate of 2.57 deaths/100 million vehicle-miles. Tables 3-42 and 3-43 provide information on vehicle travel and accidents in 1990. Based on National Safety Council data, Table 3-44 shows accident cost rates for 1977, 1983 and 1988.

Impacts of Traffic Signal System Improvement (47)

About 240,000 urban signalized intersections exist in the USA; 148,000 need upgrading of physical equipment and signal timing optimization, while another 30,000 need signal timing optimization only.

The States of Texas, California, Virginia, North Carolina and others have conducted comprehensive traffic signal system improvement programs. Percent improvement in overall average travel time, delay, or fuel consumption was the basis for evaluating the effectiveness of these projects.

Table 3-45 summarizes MOE improvement for the TLS (Traffic Light Synchronization) programs in Texas and the FETSIM (Fuel Efficient Traffic Signal Management) Program in California.

Project Level Impacts

The degree of improvement in overall traffic performance resulting from a given traffic signal improvement project depends, to a large extent on the control methods before project implementation. The more primitive the level and quality of the base condition, the greater the potential for improvement.

Fambro in cooperation with the Texas Governor's Energy Office and the U.S. Department of Energy (47) conducted an extensive evaluation of traffic signal improvement projects in Texas. Table 3-46 shows the overall MOE improvement. The evaluation shows that commitment to high quality signal timing efforts, including periodic updating of timing plans proves essential in all signal systems from the basic to the most advanced. The *set it and forget it* policy results in significant waste of the resources invested in traffic control systems.

Network Impacts

Improving traffic signal operations, particularly on arterial streets, has powerful areawide impacts. With 166 projects completed in 8 large, 7 medium and 19 small cities, the Texas TLS Program realized benefits during the first year as shown in Table 3-47 (47).

Table 3-41. Passenger car operating costs, United States. [(a)]

	1950		1960		1970		1979		1986		1989	
Variable costs (cents/mi (cents/km))												
Gas and oil	2.14	(1.33)	2.62	(1.63)	2.76	(1.71)	4.11	(2.55)	4.48	(2.78)	5.20	(3.23)
Maintenance	0.68	(0.42)	0.79	(0.49)	0.68	(0.42)	1.10	(0.68)	1.37	(0.85)	1.90	(1.18)
Tires	0.46	(0.29)	0.49	(0.30)	0.51	(0.32)	0.65	(0.40)	0.67	(0.42)	0.80	(0.50)
TOTAL	3.28	(2.04)	3.90	(2.42)	3.95	(2.45)	5.86	(3.63)	6.52	(4.05)	7.90	(4.91)
Fixed costs ($/year)												
Fire and theft insurance [(b)]	15.79		30.38		44.00		74.00		86.00		109.0	
Collision insurance [(c)]	---		---		102.00		168.00		191.00		245.00	
Property damage and liability insurance [(d)]	59.71		109.76		154.00		241.00		232.00		309.00	
License and registration	15.47		22.40		24.00		90.00		130.00		151.00	
Depreciation [(e)]	442.05		646.00		729.08		942.00		1320.00		2094.00	
Finance charge	---		---		---		296.00		637.00		626.00	
TOTAL	533.02		808.54		1053.08		1811.00		2596.00		3534.00	
Total variable and fixed costs ($)												
At 10,000 mi/year (16,090 km/year) [(f)]	861.02		1198.54		1448.08		2397.00		2959.00		3820.00	
At 20,000 mi/year (32,180 km/year) [(e)]	1189.02		1588.54		1843.08		3188.00		4239.00		5588.00	
Cost (cents/mi (cents/km))												
At 10,000 mi/year (16,090 km/year)	8.61	(5.35)	11.99	(7.45)	14.48	(8.99)	23.97	(14.89)	29.60	(18.39)	38.20	(23.73)
At 20,000 mi/year (32,180 km/year)	5.95	(3.70)	7.94	(4.93)	9.22	(5.73)	15.94	(9.90)	21.20	(13.17)	27.90	(17.33)

(a) Cars specified: 1950, "car in $2,000 price class"; 1960, Chevrolet, 8-cylinder, Bel-Air 4-door sedan: 1970, Chevrolet, 8-cylinder, Impala 4-door hardtop; 1979, Chevelle, 8-cylinder, Malibu Classic 4-door hardtop; 1986 and 1989, Chevrolet Celebrity, 6-cylinder, 4-door sedan.

(b) $100 deductible in 1979 and later years.

(c) $100 deductible through 1979; $250 deductible in later years.

(d) Property damage and liability insurance coverage; 1950, $15,000/$30,000; 1960, $25,000/$50,000; 1970 to date, $100,000/$300,000.

(e) Depreciation based on 4-year/60,000-mi (96,600-km) retention cycle; for mileage in excess of 15,000, an additional depreciation allowance of $41.00 per thousand in 1979; $68.00 per thousand in 1986; $95.00 per thousand in 1989.

(f) For 1986 and later years, depreciation based on 6-year/60,000-mi (96,600-km) retention cycle.

SOURCE: American Automobile Association, "Your driving Costs," various issues.

Table 3-42. Motor vehicle traffic fatalities and injuries – 1990.

State	Public Road Mileage	Annual Vehicle Miles (Millions)	AADT Per Mile	Injury Accidents				Persons Injured				Pedestrians Injured			
				Fatal		Nonfatal		Fatal		Nonfatal		Fatal		Nonfatal	
				Number 1/	Rate 2/	Number	Rate 2/	Number 1/	Rate 2/	Number	Rate 2/	Number 1/	Rate 2/	Number	Rate 2/
ALABAMA	90,672	42,347	1,280	981	2.32	30,245	71.42	1,118	2.64	44,640	105.41	93	0.22	724	1.71
ALASKA	13,485	3,979	808	90	2.26	3,921	98.54	95	2.39	5,761	144.79	7	0.18	155	3.90
ARIZONA	51,612	35,456	1,882	784	2.21	37,609	106.07	869	2.45	60,747	171.33	133	0.38	1,444	4.07
ARKANSAS 3/	77,085	21,011	747	521	2.48	11,686	55.62	604	2.87	21,583	102.72	59	0.28	719	3.42
CALIFORNIA	163,574	258,926	4,337	4,682	1.81	236,542	91.36	5,189	2.00	365,758	141.26	986	0.38	18,419	7.11
COLORADO	77,680	27,178	959	492	1.81	25,564	94.06	544	2.00	39,183	144.17	47	0.17	951	3.50
CONNECTICUT	19,991	26,303	3,605	357	1.36	29,644	112.70	384	1.46	42,020	159.75	65	0.25	1,368	5.20
DELAWARE	5,444	6,548	3,295	121	1.85	5,304	81.00	138	2.11	8,427	128.70	21	0.32	224	3.42
DIST. OF COLUMBIA	1,102	3,407	8,470	46	1.35	9,492	278.60	48	1.41	13,219	388.00	19	0.56	1,289	37.83
FLORIDA	108,085	109,997	2,788	2,587	2.35	130,589	118.72	2,892	2.63	214,209	194.74	583	0.53	7,480	6.80
GEORGIA	109,601	72,746	1,818	1,410	1.94	63,403	87.16	1,562	2.15	98,864	135.90	181	0.25	2,602	3.58
HAWAII	4,099	8,066	5,391	155	1.92	8,625	106.93	177	2.19	12,424	154.03	31	0.38	600	7.44
IDAHO	62,435	9,849	432	210	2.13	8,046	81.69	244	2.48	11,236	114.08	21	0.21	200	2.03
ILLINOIS	135,944	83,334	1,679	1,430	1.72	106,274	127.53	1,589	1.91	157,763	189.31	272	0.33	10,151	12.18
INDIANA	91,908	53,697	1,601	929	1.73	52,269	97.34	1,050	1.96	74,416	138.59	102	0.19	1,963	3.66
IOWA	112,541	22,993	560	404	1.76	20,577	89.49	465	2.02	30,233	131.49	32	0.14	825	3.59
KANSAS	133,578	22,849	469	391	1.71	20,069	87.83	444	1.94	30,254	132.41	36	0.16	1,184	5.18
KENTUCKY	69,668	33,639	1,323	752	2.24	35,670	106.04	846	2.51	54,832	163.00	70	0.21	1,393	4.14
LOUISIANA	58,620	37,667	1,760	831	2.21	46,835	124.34	956	2.54	78,182	207.56	135	0.36	1,629	4.32
MAINE	22,389	11,871	1,453	196	1.65	10,017	84.38	213	1.79	16,383	138.01	22	0.19	399	3.36
MARYLAND	28,752	40,536	3,863	639	1.58	48,940	120.73	682	1.68	80,410	198.37	123	0.30	4,167	10.28
MASSACHUSETTS	34,076	46,130	3,709	546	1.18	73,122	158.51	605	1.31	91,563	198.49	124	0.27	3,421	7.42
MICHIGAN	117,449	81,091	1,892	1,399	1.73	97,478	120.21	1,566	1.93	148,972	183.71	224	0.28	3,792	4.68
MINNESOTA	129,397	38,946	825	501	1.29	27,958	71.79	566	1.45	44,634	114.60	65	0.17	1,499	3.85
MISSISSIPPI	72,520	24,398	922	626	2.57	13,980	57.30	746	3.06	26,577	108.93	69	0.28	588	2.41
MISSOURI 3/	120,527	50,883	1,157	943	1.85	41,686	81.93	1,097	2.16	66,138	129.98	101	0.20	2,055	4.04
MONTANA	71,387	8,332	320	190	2.28	5,520	66.25	212	2.54	8,280	99.38	11	0.13	159	1.91
NEBRASKA	92,403	13,958	414	220	1.58	15,501	111.05	262	1.88	23,288	166.84	26	0.19	653	4.68

1/ Fatal accident and fatality numbers have been adjusted to agree with State totals obtained from the Fatal Accident Reporting System (FARS) as of June 1, 1991.

2/ Per 100 million vehicle miles (161 million vehicle kilometers) of travel.

3/ Estimates of nonfatal injury crashes and nonfatally injured persons and pedestrians were made by the FHWA based on State-reported 1989 data.

Table 3-42. Motor vehicle traffic fatalities and injuries – 1990 (continued).

State	Public Road Mileage	Annual Vehicle Miles (Millions)	AADT Per Mile	Injury Accidents				Persons Injured				Pedestrians Injured			
				Fatal		Nonfatal		Fatal		Nonfatal		Fatal		Nonfatal	
				Number 1/	Rate 2/	Number	Rate 2/	Number 1/	Rate 2/	Number	Rate 2/	Number 1/	Rate 2/	Number	Rate 2/
NEVADA	45,524	10,215	615	300	2.94	12,552	122.88	343	3.36	19,193	187.89	57	0.56	691	6.76
NEW HAMPSHIRE /3	14,836	9,844	1,818	140	1.42	3,381	34.35	158	1.61	6,982	70.93	14	0.14	516	5.24
NEW JERSEY	34,252	58,923	4,713	817	1.39	102,950	174.72	886	1.50	162,574	275.91	202	0.34	7,332	12.44
NEW MEXICO	54,736	16,148	808	440	2.72	15,892	98.41	499	3.09	24,796	153.55	83	0.51	995	6.16
NEW YORK 3/	111,242	106,902	2,633	2,032	1.90	200,301	187.37	2,212	2.07	296,933	277.76	590	0.55	22,283	20.84
NORTH CAROLINA	94,690	62,707	1,814	1,250	1.99	248,625	396.49	1,385	2.21	117,973	188.13	187	0.30	2,873	4.58
NORTH DAKOTA	86,517	5,910	187	104	1.76	3,164	53.54	112	1.90	4,629	78.32	13	0.22	106	1.79
OHIO 3/	113,600	86,972	2,098	1,479	1.70	120,195	138.20	1,636	1.88	201,716	231.93	198	0.23	4,475	5.15
OKLAHOMA	111,765	33,081	811	557	1.68	24,674	74.59	640	1.93	38,582	116.63	54	0.16	652	1.97
OREGON	94,969	26,738	771	500	1.87	22,412	83.82	579	2.17	35,201	131.65	66	0.25	478	1.79
PENNSYLVANIA	116,508	85,708	2,015	1,514	1.77	92,617	108.06	1,646	1.92	142,945	166.78	265	0.31	6,684	7.80
RHODE ISLAND	6,111	7,024	3,149	79	1.12	8,047	114.56	84	1.20	11,734	167.06	14	0.20	200	2.85
SOUTH CAROLINA	64,046	34,376	1,471	884	2.57	29,776	86.62	979	2.85	48,337	140.61	108	0.31	1,137	3.31
SOUTH DAKOTA	74,696	6,989	256	139	1.99	4,820	68.97	153	2.19	7,261	103.89	15	0.21	138	1.97
TENNESSEE 3/	84,639	46,710	1,512	1,044	2.24	46,805	100.20	1,176	2.52	72,254	154.69	107	0.23	1,950	4.17
TEXAS	305,951	162,232	1,453	2,881	1.78	162,424	100.12	3,241	2.00	262,576	161.85	484	0.30	5,664	3.49
UTAH	43,244	14,646	928	236	1.61	14,941	102.01	272	1.86	22,650	154.65	34	0.23	1,870	12.77
VERMONT	14,121	5,838	1,133	82	1.40	3,617	61.96	88	1.51	5,581	95.60	10	0.17	232	3.97
VIRGINIA	67,700	60,178	2,435	952	1.58	51,754	86.00	1,077	1.79	76,436	127.02	119	0.20	2,220	3.69
WASHINGTON	81,299	44,695	1,506	726	1.62	51,713	115.70	825	1.85	76,064	170.18	80	0.18	1,783	3.99
WEST VIRGINIA	34,592	15,418	1,221	407	2.64	18,138	117.64	481	3.12	27,997	181.59	38	0.25	552	3.58
WISCONSIN	109,876	44,277	1,104	678	1.53	42,394	95.75	769	1.74	62,530	141.22	64	0.14	2,180	4.92
WYOMING	39,213	5,833	408	105	1.80	3,409	58.44	125	2.14	5,367	92.01	8	0.14	99	1.70
TOTAL	3,880,151	2,147,501	1,516	39,779	1.85	2,501,167	116.47	44,529	2.07	3,600,307	167.65	6,468	0.30	135,163	6.29

1/ Fatal accident and fatality numbers have been adjusted to agree with State totals obtained from the Fatal Accident Reporting System (FARS) as of June 1, 1991.

2/ Per 100 million vehicle miles (161 million vehicle kilometers) of travel.

3/ Estimates of nonfatal injury crashes and nonfatally injured persons and pedestrians were made by the FHWA based on State-reported 1989 data.

SOURCE: U.S. Department of Transportation Federal Highway Administration statistics, 1990.

Table 3-43. Motor vehicle accidents by highway system – 1990.

Highway Category	Public Road Mileage	Annual Vehicle-Miles (Millions)	Injury Accidents				Persons Injured				Pedestrians Injured			
			Fatal		Nonfatal 1/		Fatal		Nonfatal 1/		Fatal		Nonfatal 1/	
			Number 2/	Rate 3/	Number	Rate 3/	Number 2/	Rate 3/	Number	Rate 3/	Number 2/	Rate 3/	Number	Rate 3/
RURAL SYSTEMS														
INTERSTATE	33,547	200,573	2,258	1.13	43,911	21.89	2,713	1.35	72,921	36.36	206	0.10	716	0.36
OTHER PRINCIPAL ARTERIALS														
OTHER FEDERAL-AID PRIMARY	83,085	173,737	3,862	2.22	87,318	50.26	4,625	2.66	150,445	86.59	346	0.20	1,536	0.88
NON-FEDERAL-AID	717	1,645	156	9.48	1,222	74.29	192	11.67	2,170	131.91	6	0.36	9	0.55
SUBTOTAL	83,802	175,382	4,018	2.29	88,540	50.48	4,817	2.75	152,615	87.02	352	0.20	1,545	0.88
MINOR ARTERIALS														
OTHER FEDERAL-AID PRIMARY	142,993	155,289	4,341	2.80	114,030	73.43	5,037	3.24	191,956	123.61	351	0.23	2,076	1.34
NON-FEDERAL-AID	1,742	555	38	6.85	866	156.04	52	9.37	1,503	270.81	6	1.08	24	4.32
SUBTOTAL	144,735	155,844	4,379	2.81	114,896	73.73	5,089	3.27	193,459	124.14	357	0.23	2,100	1.35
MAJOR COLLECTORS														
FEDERAL-AID PRIMARY	399,974	187,011	5,898	3.15	166,172	88.86	6,737	3.60	264,968	141.69	484	0.26	4,052	2.17
NON-FEDERAL-AID	36,391	4,291	189	4.40	4,641	108.16	209	4.87	8.039	187.35	16	0.37	115	2.68
SUBTOTAL	436,365	191,302	6,087	3.18	170,813	89.29	6,946	3.63	273,007	142.71	500	0.26	4,167	2.18
MINOR COLLECTORS	293,912	50,462	1,699	3.37	60,610	120.11	1,875	3.72	90,243	178.83	105	0.21	1,405	2.78
LOCALS	2,130.427	96,846	3,956	4.08	189,870	196.05	4,339	4.48	282,541	291.74	308	0.32	8,846	9.13
TOTAL - ALL RURAL SYSTEMS	3,122,788	870,409	22,397	2.57	668,640	76.82	25,779	2.96	1,064,786	122.33	1,828	0.21	18,779	2.16
URBAN SYSTEMS														
INTERSTATE	11,527	278,404	1,965	0.71	120,668	43.34	2,228	0.80	187,509	67.35	452	0.16	1,889	0.68
OTHER PRINCIPAL ARTERIALS FREEWAYS & EXPRESSWAYS														
OTHER FEDERAL-AID PRIMARY	6,464	119,826	884	0.74	72,727	60.69	969	0.81	111,551	93.09	175	0.15	1,954	1.63
FEDERAL-AID URBAN	759	5,313	64	1.20	8,060	151.70	68	1.28	13,096	246.49	12	0.23	350	6.59
NON-FEDERAL-AID	447	2,292	43	1.88	2,516	109.77	46	2.01	4,260	185.86	13	0.57	50	2.18
SUBTOTAL	7,670	127,431	991	0.78	83,303	65.37	1,083	0.85	128,907	101.16	200	0.16	2,354	1.85

1/ Estimates of nonfatal accidents and nonfatally injured persons and pedestrians were made by the FHWA based on 1989 data reported by Arkansas, Missouri, New Hampshire, New York, Ohio, and Tennessee

2/ Fatal accident and fatality numbers have been adjusted to agree with State totals obtained from the fatal accident report system (FARS) as of June 1, 1991.

3/ Per 100 million vehicle miles (161 vehicle kilometers) of travel.

SOURCE: U.S. Department of Transportation Federal Highway Administration Statistics, 1990.

Table 3-43. Motor vehicle accidents by highway system – 1990 (continued).

Highway Category	Public Road Mileage	Annual Vehicle-Miles (Millions)	Injury Accidents				Persons Injured				Pedestrians Injured			
			Fatal		Nonfatal 1/		Fatal		Nonfatal 1/		Fatal		Nonfatal 1/	
			Number 2/	Rate 3/	Number	Rate 3/	Number 2/	Rate 3/	Number	Rate 3/	Number 2/	Rate 3/	Number	Rate 3/
URBAN SYSTEMS (continued)														
NON-FREEWAYS AND EXPRESSWAYS														
OTHER FEDERAL-AID PRIMARY	26,352	262,952	2,617	1.00	221,346	84.18	2,877	1.09	353,572	134.46	685	0.26	9,689	3.68
FEDERAL-AID URBAN	24,864	69,430	3,494	5.03	281,669	405.69	3,725	5.37	446,633	643.29	1,140	1.64	19,190	27.64
NON-FEDERAL-AID	771	3,305	32	0.97	3,420	103.48	32	0.97	5,589	169.11	13	0.39	165	4.99
SUBTOTAL	51,987	335,687	6,143	1.83	506,435	150.87	6,634	1.98	805,794	240.04	1,838	0.55	29,044	8.65
SUBTOTAL	59,657	463,118	7,134	1.54	589,738	127.34	7,717	1.67	934,701	201.83	2.038	0.44	31,398	6.78
MINOR ARTERIALS														
OTHER FEDERAL-AID PRIMARY	1,379	121,982	215	0.18	19,884	16.30	235	0.19	32,700	26.81	70	0.06	546	0.45
FEDERAL-AID URBAN	66,486	105,814	3,378	3.19	333,313	315.00	3,590	3.39	514,752	486.47	871	0.82	22,517	21.28
NON-FEDERAL-AID	6,791	7,240	141	1.95	16,314	225.33	154	2.13	25,788	356.19	32	0.44	1,641	22.67
SUBTOTAL	74,656	235,036	3,734	1.59	369,511	157.21	3,979	1.69	573,240	243.89	973	0.41	24,704	10.51
COLLECTORS														
FEDERAL-AID URBAN	55,571	92,090	1,087	1.18	123,519	134.13	1,158	1.26	180,999	196.55	256	0.28	11,919	12.94
NON-FEDERAL-AID	22,677	11,666	222	1.90	28,113	240.98	234	2.01	40,884	350.45	45	0.39	2,013	17.26
SUBTOTAL	78,248	103,756	1,309	1.26	151,632	146.14	1,392	1.34	221,883	213.85	301	0.29	13,932	13.43
LOCALS	533,275	196,778	3,240	1.65	600,978	305.41	3,434	1.75	618,188	314.16	876	0.45	44,461	22.59
TOTAL — ALL URBAN SYSTEMS	757,363	1,277,092	17,382	1.36	1,832,527	143.49	18,750	1.47	2,535,521	198.54	4,640	0.36	116,384	9.11
ALL SYSTEMS														
INTERSTATE	45,074	478,977	4,223	0.88	164,579	34.36	4,941	1.03	260,430	54.37	658	0.14	2,605	0.54
OTHER FEDERAL-AID PRIMARY	260,273	833,786	11,919	1.43	515,305	61.80	13,743	1.65	840,224	100.77	1,627	0.20	15,801	1.90
FEDERAL-AID URBAN	147,680	272,647	8,023	2.94	746,561	273.82	8,541	3.13	1,155,480	423.80	2,279	0.84	53,976	19.80
FEDERAL-AID SECONDARY	399,974	187,011	5,898	3.15	166,172	88.86	6,737	3.60	264,968	141.69	484	0.26	4,052	2.17
NON-FEDERAL-AID	3,027,150	375,080	9,716	2.59	908,550	242.23	10,567	2.82	1,079,205	287.73	1,420	0.38	58,729	15.66
TOTAL STATEWIDE	3,880,151	2,147,501	39,779	1.85	2,501,167	116.47	44,529	2.07	3,600,307	167.65	6,468	0.30	135,163	6.29

1/ Estimates of nonfatal accidents and nonfatally injured persons and pedestrians were made by the FHWA based on 1989 data reporte d by Arkansas, Missouri, New Hampshire, New York, Ohio, and Tennessee

2/ Fatal accident and fatality numbers have been adjusted to agree with State totals obtained from the fatal accident report system (FARS) as of June 1, 1991.

3/ Per 100 million vehicle miles (161 vehicle kilometers) of travel.

SOURCE: U.S. Department of Transportation Federal Highway Administration Statistics, 1990.

Table 3-44. Cost per accident.

Type	Year		
	1977	1983	1988
Fatal Accidents	$ 137,000	$ 210,000	$ 1,500,000
Injury Accidents	7,500	8,600	11,000
Property Damage Only	670	1,150	3,000

Table 3-45. Benefits of signal system improvement.

Program/Items	Year	Fuel Reduction	Delay Reduction	Stop Reduction
TLS	1992	9.1%	24.6%	14%
FETSIM	1987	8.1%	14%	14%

Table 3-46. Annual benefits from optimization on arterial.

Coordination / Equipment Status	Percent Stops (%)	Percent Delay (%)	Percent Fuel Consumption (%)
Uncoordinated arterial with existing equipment	10	24	8
Uncoordinated arterial with new equipment	18	21	14
Partially coordinated arterial with existing equipment	6	9	3
Partially coordinated arterial with new equipment	15	18	3
Coordinated arterial with existing equipment	16	23	17
Coordinated arterial with new equipment	14	23	12

Table 3-47. Texas TLS program annual benefits and costs.

Size	Stops	Delay (hrs.)	Fuel		Savings ($)	Cost ($)
			gal	L		
Large Cities	1,283,099,850	30,621,657	22,180,341	83,952,590	346,360,309	2,885,302
Medium Cities	239,633,625	6,926,904	4,481,237	16,961,482	77,106,148	4,032,313
Small Cities	198,936,150	5,696,696	3,409,346	12,904,375	63,171,212	972,264
TOTAL	1,721,669,625	43,245,357	30,080,724	113,855,540	486,637,668	7,889,879

As expected, the bulk of benefits occurred in large cities with the highest population and traffic volumes. However, substantial benefits also occurred in medium and small cities; the benefit/cost (B/C) ratio for small cities was 65:1. High value of B/C are obtained when capital expenditures for improvements are minimal.

The benefits for each intersection improvement depend on the before condition. For example, coordinating a series of isolated intersections generally produced greater benefits than retiming an existing coordinated system. Finally, note that signal timing optimization can increase delay or fuel consumption on side streets to improve flow along the arterial network. However, these increases in delay or fuel consumption often prove negligible in terms of total network improvement. Table 3-48 shows network improvement data from the TLS Program (47).

Cost Effectiveness Comparisons

Traffic signal system improvements rank as one of the most cost-effective urban transportation improvement actions. The following presents results of cost-effectiveness analyses of four different signal optimization programs at different locations and time periods.

- TLS Program (Traffic Light Synchronization) in 1992:The TLS Program expended $7.9 million, approximately $3500/intersection (equipment purchase). It resulted in annual reductions in fuel consumption, delay, and stops of 9.1% ($30 million), 24.6% (43 million hours), and 14.2% (1.7 billion stops), respectively. The total savings to the public in the form of reduced fuel, delay, and stops was approximately $485 million in 1993. The benefit/cost ratio is about 62:1 (47).
- FETSIM (Fuel Efficient Traffic Signal Management) in 1987: The FETSIM Program has an average cost per intersection of $1,500. First year reduction shows reductions of 14% in stops and delay, 7.5% in travel time, and 8.1% in fuel consumption. The benefit/cost ratio is about 58:1 (47).
- SSOS (Statewide Signal Optimization Squad) in North Carolina 1987:
    - The SSOS Program average cost per retimed signalized intersection is $481,
    - Each intersection annually saved 13,500 gallons of fuel, and $51,815 of operating costs, and
    - The benefit cost ratio is about 108:1 (103).National Signal Timing Optimization (NSTO) Project by FHWA 1981: The NSTO Project cost $456 per intersection. At an average intersection each year, 15,470 vehicle-hours of delay were reduced, 455,921 vehicle stops were eliminated and 10,526 gallons of fuel were saved. The benefit/cost ratio is 63:1 (104).

Table 3-48. Annual benefits from optimization on network.

Coordination / Equipment Status	Percent Stops (%)	Percent Delay (%)	Percent Fuel Saving (%)
Uncoordinated network with existing equipment	8	18	8
Uncoordinated network with new equipment	11.2	16.3	8.8
Partially coordinated network with existing equipment	4.4	20.5	8.7
Partially coordinated network with new equipment	16	26	11
Coordinated network with existing equipment	15	22	12
Coordinated network with new equipment	15	27	9

3.12 Measures of Effectiveness (MOE)

Any new or modified traffic control system should satisfy a goal or set of goals. The goal may explicitly state: *reduce congestion in the core area of a city by minimizing stops and delays* or pledge *increase accessibility to downtown business.* Goals may be easy to state, but difficult to measure.

Measures of effectiveness (MOE) provide a quantitative basis for determining the capacity of traffic control systems and their strategies to attain the desired goals. To successfully determine goal attainment, the MOEs must relate to the goals. Also, with no comparative analyses, measures must be compared with baseline values to determine the quality of goal attainment. Other desirable criteria for selecting MOEs include:

- Simplicity within the constraints of required precision and accuracy,
- Sensitivity to relatively small changes in control strategy implementation, and
- Measurability on a quantitative scale within reasonable time, cost, and manpower budgets.

Common measures of effectiveness include:

- Total travel time,
- Total travel,
- Number and percentage of stops,
- Delay,
- Total minute-miles of congestion,
- Average speed,
- Accident rate, and
- Throughput.

These measures of effectiveness indicate the improvement in efficiency of traffic flow resulting from control.

Table 3-49 describes these MOEs and their calculation.

Several other important MOEs can be derived from those in the Table. Gasoline consumption and emissions, for example, can be computed from total travel time, stops, and delay (107).

In many cases, these MOE are measured independently of traffic control system data. Box and Oppenlander (105) provide techniques and sample size requirements for performing many of these studies.

In some cases, these studies may use data generated by the traffic system. It then becomes important to:

- Identify the measurement error for these variables, and
- Specify and collect a sample size which assures statistically significant results.

Evaluation procedures must also consider the *demand* element. The evaluation must account for:

- Changing traffic demands between the *before* and *after* period,
- Other factors such as weather.

3.13 A Look to the Future

The next decade is likely to witness improvements in traffic control concepts in the following areas:

- Improved estimation of traffic variables,
- Improved traffic control strategies, and
- Improved incident detection on urban streets.

The following sections describes each of these areas.

Improved Estimation of Traffic Variables

Since accurate traffic variable estimates provide the basis for the implementation of real-time control strategies, improvements in these estimates will improve control results. It is expected that improvements in traffic variable estimates will result from:

- Prediction through real-time on-line modeling using such techniques as artificial neural networks (ANN) (110).
- Use of *multipoint* and *continuous* detector data. Traditional traffic detectors such as loops are point detectors, thus limiting the ways in which traffic variables may be estimated. Multipoint and continuous traffic detectors (Section 6.5) can provide more accurate estimates of such variables as stops, delay and queues, as well as provide variables such as turning movements which cannot be sensed with point detectors.
- Use of vehicle probe data (111) to obtain control variables and MOE data such as travel times, delays and real-time origin/destination data.

Table 3-49. Measures of effectiveness (MOE).

MOE	Description	Calculation
Total Travel Time	A primary MOE for evaluating freeway and urban street control systems and strategies. Expressed in vehicle-hours (veh-hr), it represents the product of the total number of vehicles using the roadway during a given time period and the average travel time of the vehicles.	The average travel time, tt_j, in hours over a roadway section is: $tt_j = \frac{X_j}{u_j}$ (3.29) Where: X_j = Length of roadway section, in mi (km) and u_j = Average speed of vehicles over roadway section j, in mi/hr (km/hr) Total travel time, TTT_j, in veh-hr over section j is: $TTT_j = N_j\ tt_j = \frac{N_j X_j}{u_j}$ (3.30) Where: N_j = Number of vehicles traveling over section j, during time period, T tt_j = Average travel time of vehicles over roadway section j, in hr Total travel time, TTT, in veh-hr, for all sections of a roadway is: $TTT = \sum_{j=1}^{K} TTT_j$ (3.31) Where: TTT_j = Total travel time for section j, in veh-hr K = Number of roadway sections

Table 3-49. Measures of effectiveness (MOE) (continued).

<table>
<tr><th>MOE</th><th>Description</th><th>Calculation</th></tr>
<tr><td>Total Travel</td><td>Another common MOE used to evaluate traffic operations. Expressed in units of vehicle-miles (veh-mi) (vehicle-kilometers (veh-km)), it represents the product of the total number of vehicles using the roadway during a given time period and the average trip length of the vehicles.</td><td>The total travel, TT_j, in veh-mi, over a roadway section j is:

$TT_j = X_j N_j$ (3.32)

Where:

X_j = Length of roadway section j, in mi (km)
N_j = Number of vehicles traveling over section j during time period, T

Equations 3.30 and 3.32 suggest that the total travel, TT_j, in veh-mi (veh-km), over a roadway section j can be derived from total travel time and average speed for section j, as follows:

$TT_j = TTT_j V_j$ (3.33)

Where:

$TTTj$ = Total travel time for section j during time period, T, in veh-hr, and
Vj = Average speed of vehicles over section j during time period, T, in mi/hr (km/hr)

Total travel, TT, in veh-mi (veh-km), for all sections of a roadway is:

$TT = \sum_{j=1}^{K} TT_j$ (3.34)

Where:

K = Number of roadway sections</td></tr>
</table>

Table 3-49. Measures of effectiveness (MOE) (continued).

MOE	Description	Calculation
Number and Percentage of Stops	Evaluates the quality of flow on urban streets. Stops may be obtained by floating vehicle methods or by direct observation of the intersection. Traffic control systems may have the capability to compute stops.	The calculation of the number of stops on an approach to an intersection is determined by the relationship between detector actuations and signal timing. A typical time-space diagram for number of stops computations is presented in Figure 3-38. The number of stops per cycle is the number of detector actuations that occur between T_{gc} and T_{rc}. T_{rc} is the last time that a vehicle can cross the detector during the green interval and still clear the intersection without stopping. The values for T_{gc} and T_{rc} are based on predetermined vehicle trajectories between the detector and the intersection. In some algorithms for computing number of stops, these trajectories remain the same for all vehicles, while in others they vary according to the number of vehicles already stopped between the detector and intersection.
Delay	Widely used MOE in traffic control. On urban arterials, delay is defined as the increase beyond a travel time corresponding to a baseline speed (a speed below which travel would be considered delayed). For urban intersections, delay is commonly defined as the time lost at the intersection by those vehicles that are stopped. Box and Oppenlander describe a technique for manually obtaining stopped delay (106).	For urban arterials, baseline travel time subtracted from measured total travel time for the same time period. Where computer traffic control systems compute delay, figure 3-38 illustrates the computation of stopped-vehicle delay. Assuming all stopped vehicles clear the intersection on the next green, the delay Di, in seconds, for the ith stopped vehicle is determined. $Di = R - (tc_i - T_r) + (td_i - T_g)$ (3.35) Where: R = Length of the red interval, in seconds T_r = Time at which the red interval begins, in seconds tc_i = Predicted time at which the ith vehicle would have reached the intersection if it had not been stopped, in seconds T_g = Time at which the next green interval beings, in seconds td_i = Predicted time at which the ith vehicle clears the intersection, in seconds

Table 3-49. Measures of effectiveness (MOE) (continued).

MOE	Description	Calculation
Delay (continued)		Time, tc_i, is determined from the time, ta_j, at which the ith vehicle actuates the detector and a predetermined approach trajectory. Time, td_j, is determined from time, T_g, at which the next green interval begins and a predetermined departure trajectory. Some algorithms used to compute stopped-vehicle delay provide for varying the predetermined approach and departure trajectories according to the number of vehicles already stopped. Assuming all stopped vehicles clear the intersection on the next green, total stopped-vehicle delay, D, in seconds, for a cycle is determined by: $$D = \sum_{i=1}^{n} D_i \quad (3.36)$$ Where: D_i = The delay of the ith vehicle stopped during the cycle, in seconds n = The number of vehicles stopped during the cycle Algorithms based on these concepts may be subject to the following additional sources of error: • Vehicles making right-turns-on-red may not be properly accounted for • The algorithm might not properly handle saturated intersections

Table 3-49. Measures of effectiveness (MOE) (continued).

MOE	Description	Calculation
Total Minute-Miles (Minute-Kilometers) of Congestion	Developed by the Chicago Area Expressway Surveillance Project to evaluate freeway operations (107). Indicates the extent of freeway congestion in both time and space.	Assign each mainline detector a section of freeway that covers half of the distance between the adjacent mainline detector on either side. Minute-miles (minute-kilometers) of congestion at each detector equals the product of the minutes of congestion at the detector and the distance, in mi (km), assigned to the detector. The sum of minute-miles (minute-kilometers) of congestion of all detectors represents total minute-miles (minute-kilometers) of congestion. The calculation of this measure of effectiveness requires a quantitative definition of congestion such as a 5-minute lane occupancy of 30 percent or more. Analysis shows that total travel time correlates with total minute-miles (minute-kilometers) of congestion. However, it is more readily obtainable, primarily because of less sensitivity to detector accuracy.
Average Speed	One of the most descriptive variables of freeway traffic flow. Point samples of average stream speeds or the speed traces of individual vehicles can locate problem areas and provide useful data for developing other performance measures (108). For example, the evaluation of the INFORM (Information For Motorists) System on Long Island Expressway strongly relied on the average speed to determine the degree of freeway congestion, fuel consumption, and travel time (109).	Manually, by radar or laser guns. See table 3-2 for calculations from system detectors.

Table 3-49. Measures of effectiveness (MOE) (continued).

MOE	Description	Calculation
Accident Rate	Accident rate improvement is a common goal for traffic control systems. Rates for intersections usually are expressed in terms of accidents per million entering vehicles. Freeway accident rates are often expressed in accidents per 100 million vehicle miles.	Box and Oppenlander describe techniques for determining the statistical significance of accident data (106).
Throughput (110)	Although its dimension is equivalent to speed, throughput is usually used in a somewhat different way. Figure 3-39 shows plots of throughput for a baseline system (curve A) and an improved traffic control system (curve B). These plots represent a best mathematical fit of the data represented by individual sets of measurements. Throughput is represented by the slope of the line to a point on the curves. As traffic demand increases, the throughput begins to decrease. This approach enables the traffic engineer to more precisely measure results relative to goals. For example, if the goal is to improve congested traffic conditions, examination of curve B in the congested region indicates only marginal improvement. This might lead the traffic engineer to consider strategies to specifically target to this region (section 3.9).	$Throughput = \frac{Vehicle\ mi\ (km)\ per\ unit\ of\ time}{Vehicle\ hours\ per\ unit\ of\ time}$ for one or more traffic conditions

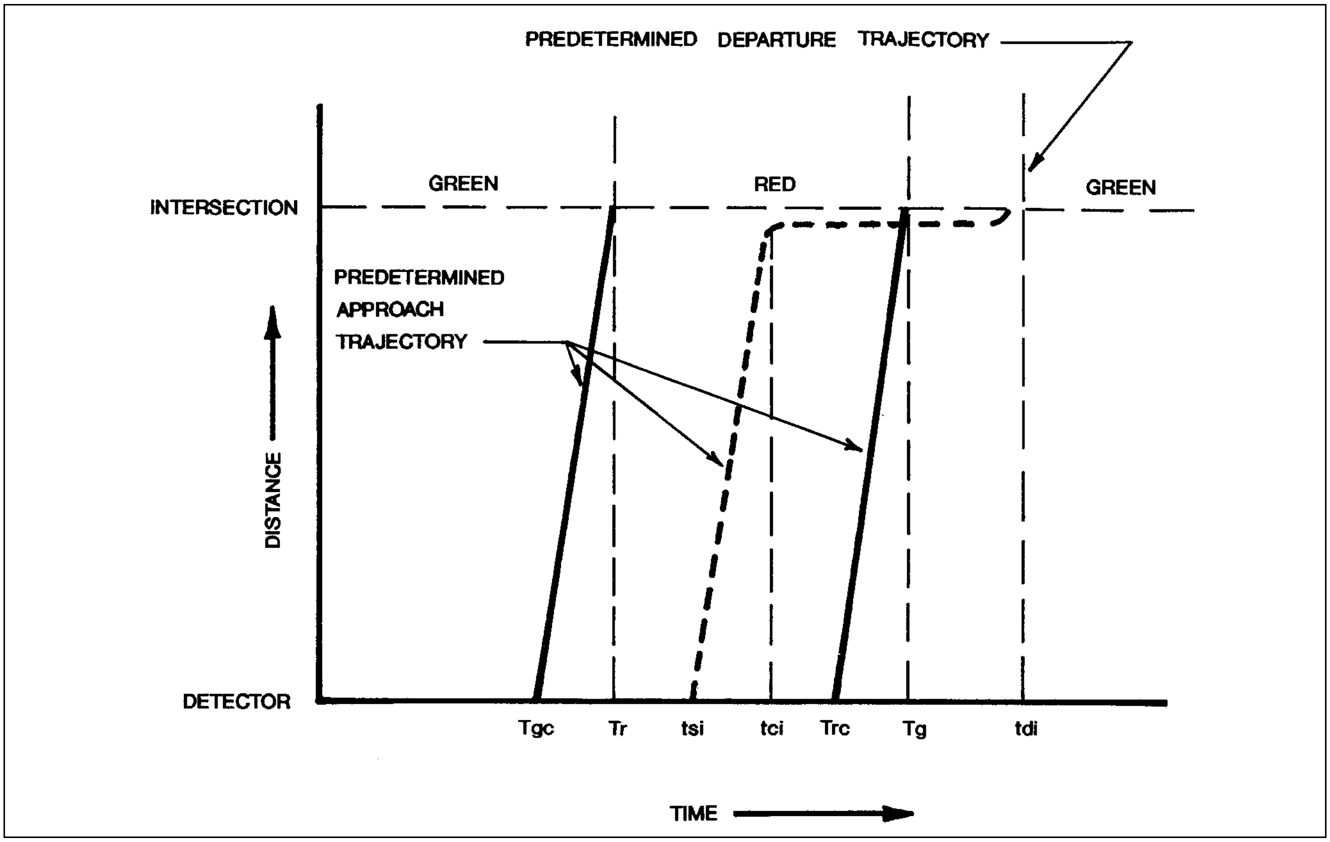


Figure 3-38. Time-space diagram for stop and delay computations for urban street control.

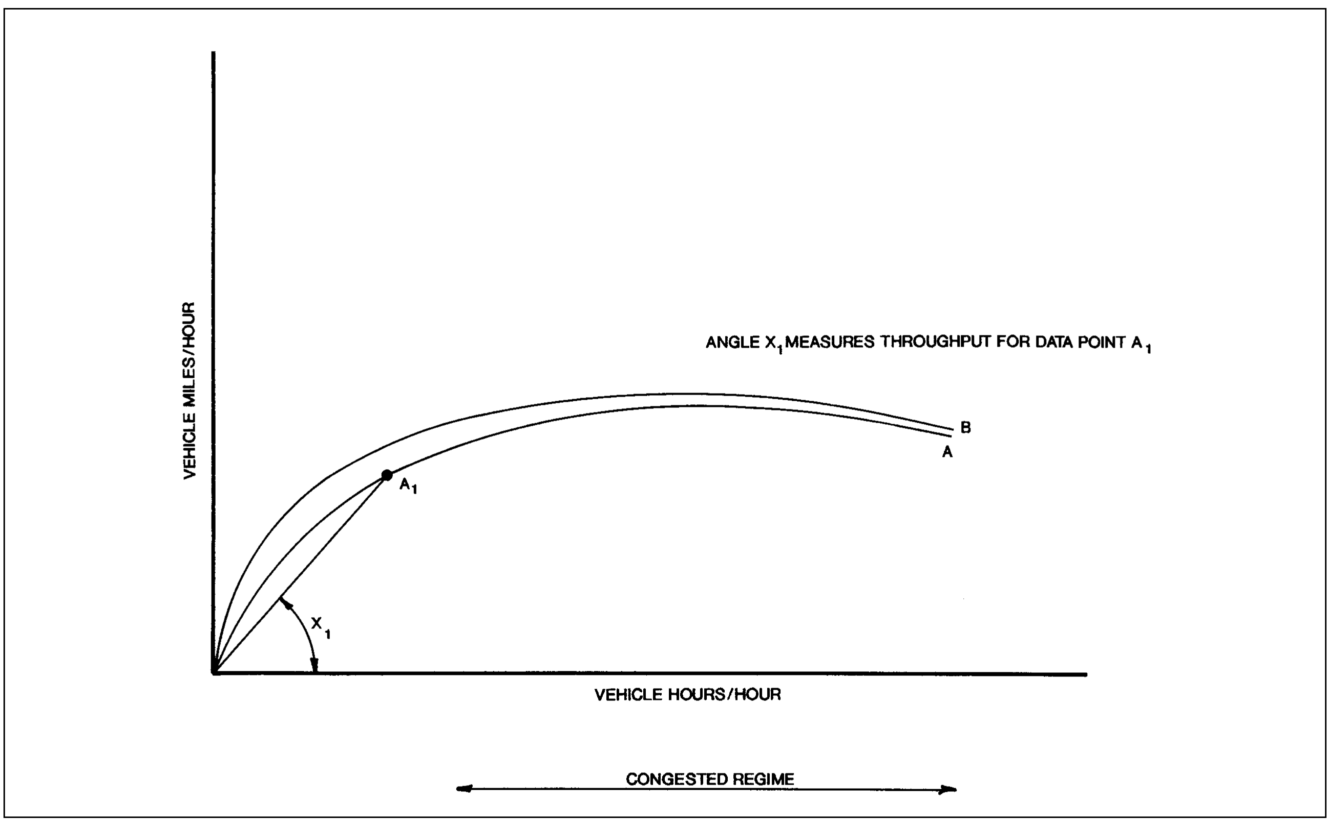


Figure 3-39. Throughput and component MOEs.

Improved Traffic Control Strategies

It is expected that advances will be made in the following areas:

- Isolated Intersection Control Strategies

  These strategies provide an improved level of control by using better modeling of traffic variables and improved control algorithms. The Microprocessor Optimized Vehicle Actuation (MOVA) system in the United Kingdom has been in operation for some time. The Optimized Policies for Adaptive Control (OPAC) strategy has recently undergone testing in the U.S. Table 3-50 describes these strategies.

  The use of knowledge based expert system traffic controllers has been researched and shows promising results (117).

- Coordinated Signal Control Strategies

  Current existing strategies such as SCOOT will continue to be improved through the use of improved traffic variable modeling and the use of probe data (118).

  An FHWA project, *Real-Time Traffic Adaptive Control Strategies* (RT-TRACS), includes the development and evaluation of a number of strategies, and the incorporation of suitable strategies into the system (119).The traffic control and management techniques implemented by current systems are not generally designed to deal with widespread saturation in the network. Systems such as SCOOT are being modified to address this requirement (120). Unique signal timing and metering approaches for control of this condition were described in Section 3.9; however, the implementation of techniques such as these has to date been extremely limited. It is likely that these and other techniques will see greater application in the future.

Incident Detection for Urban Intersections

Requirements for the detection and monitoring of incidents in signal networks appears to be increasing. The following techniques are receiving increasing emphasis:

- Artificial Neural Networks (121), and
- Statistical Techniques such as Discriminate Analysis (122).

Table 3-50. MOVA and OPAC control strategies.

Model	Developer	Purpose	Capabilities/Functions	Additional Information
MOVA (Microprocessor Optimized Vehicle Actuation)	United Kingdom	Provides self-optimized control of signal timing at isolated intersections with 8 or fewer phases	Checks if vehicles are clearing at saturation flow rate at end of minimum green interval. Compares time for extending green with delay time lost by vehicles waiting for their green intervals. Determines appropriate green by balancing these 2 factors. Provides special routine when one or more approaches found over-saturated Delay saving obtained with MOVA compared with current vehicle actuated controllers shown in table 3-51. Delay savings averaged 13 to 14 percent. Two detectors placed in each through lane as shown in figure 3-40. One set of detectors located 8 seconds travel time upstream of intersection. Second set placed 3 seconds in advance. Third detector may instrument turn lane.	Reference 113
OPAC (Optimized Policies for Adaptive Control)	N. Gartner, University of Massachusetts at Lowell	Self-optimizes control at isolated intersections Mutually coordinates adjacent traffic signals Serves as part of interconnected system	Compares savings in not stopping flow during green phase with total delay time of vehicles stopped on red. Signal switched when warranted to lessen overall delay. Detectors placed at least 10 to 15 seconds travel time upstream of stopline Has been field tested in isolated mode. Currently under test in system interconnect mode.	References 114-117

Table 3-51. Delay savings with MOVA compared with D-System (prior standard U.K. vehicle-actuated controller).

Survey Site	A.M. Peak %	Off-Peak %	P.M. Peak %	Annual Benefit £1000's ***
Bath A4/A46	- 7	30**	11	120
Reading A329	20**	9**	12**	85
Bournemouth A347	8*	11**	5	48
Slough A4	11*	10**	16**	29

* *90 percent level, other percentages nonsignificant*
** *99 percent level of statistical significance*
*** *Benefits are based on £5.70 per vehicle-hour of delay, derived from the Department of Transport standard values of time and operating costs (revised mid-1987)*

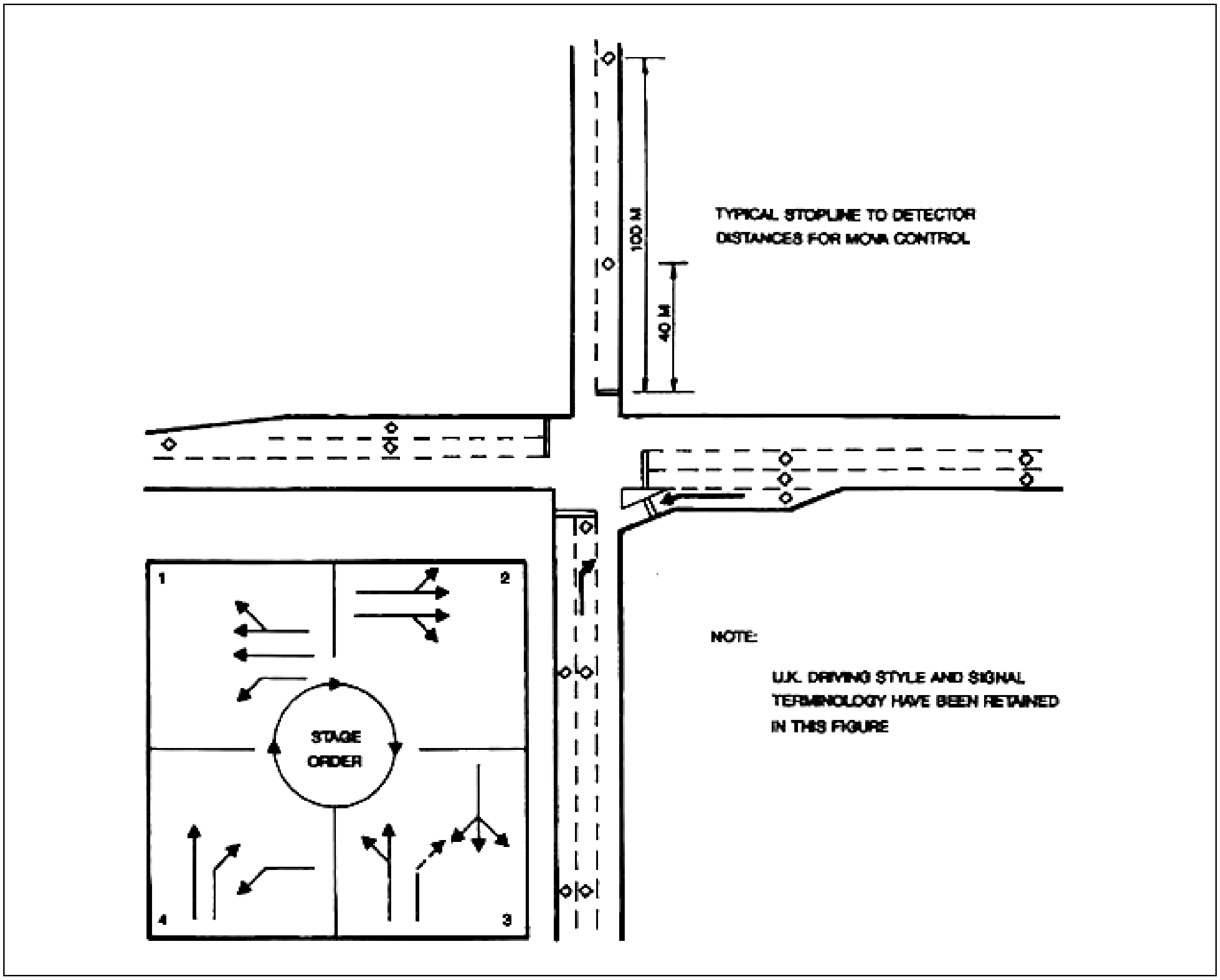


Figure 3-40. Detector locations at a MOVA-controlled junction.

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CHAPTER 4
CONTROL AND MANAGEMENT CONCEPTS - FREEWAYS

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CONTROL AND MANAGEMENT CONCEPTS – FREEWAYS

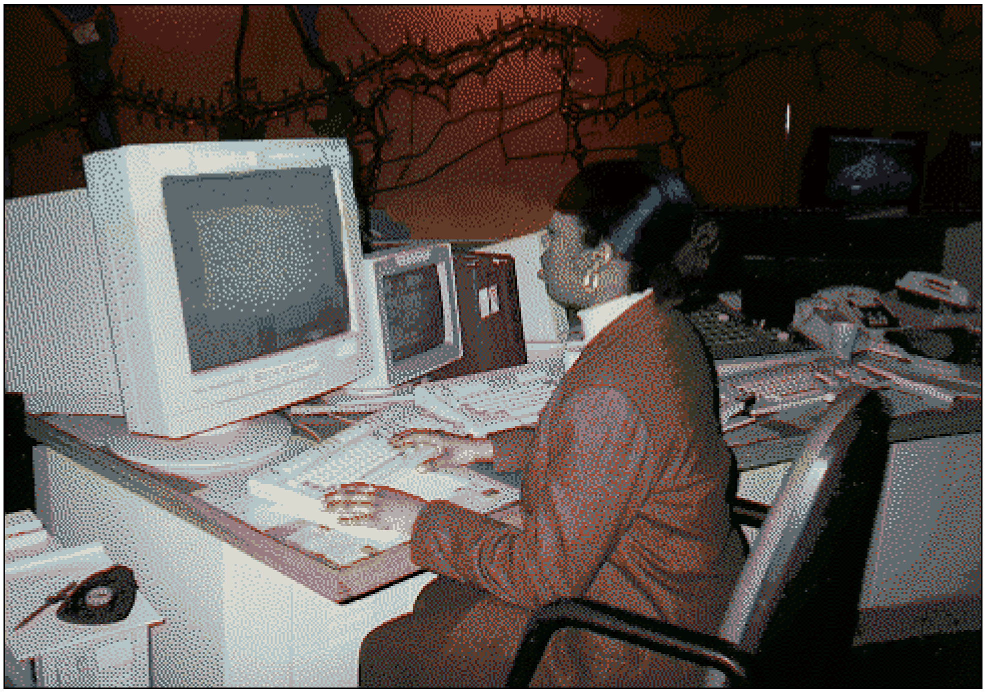

Figure 4-1. Incident management operations at INFORM.

4.1 Introduction

Freeway traffic management represents an expanded concept of traffic control. It includes:

- Freeway traffic control,
- Incident management,
- Aid to stranded motorists,
- Coordination with other facilities, and
- Driver information systems.

These activities provide for:

- Improved operation and safety during off -peak and peak periods, and
- Control during:
  - Maintenance activities,
  - Special events, and
  - Weather emergencies.

The material presented in this chapter reflects the expanded view of freeway traffic management. Table 4-1 shows the organization of this chapter.

Purpose and Scope

Designers originally conceived freeways as free-flowing, limited -access facilities and gave little consideration to traffic control systems. However, continued growth in traffic demand and its resulting congestion has forced a search for solutions. Research and practical experimentation have proven that freeway monitoring and control systems, together with freeway management concepts, have become cost-effective tools for improving freeway traffic operations

Freeway traffic control addresses the problems Of congestion and safety. This chapter first describes the measurement and causes of congestion and related safety problems, and then addresses specific control concepts with proven operational experience. These include:

- Ramp metering,
- Mainline control, and
- Corridor control.

These control concepts further subdivide into the following types:

Table 4-1. Chapter 4 organization.

Section Title	Purpose	Topics
Introduction	Describes characteristics of freeway congestion	• Extent of congestion • Measurement of congestion • Causes of congestion
Ramp Metering	Describes applications and benefits	• Metering rates • Ramp metering strategies • Types of operation • Ramp design requirements • Closure • Exit ramp control • Benefits • Freeway-to-freeway ramp metering • Public acceptance
Mainline Control	Describes use and methods of mainline control	• Driver information systems • Variable speed limit signs • Lane closure and control • Mainline metering • Reversible lane control
Diversion to Surface Streets	Describes methods to divert traffic to control freeway congestion	• Diversion strategies • Diversion models
Incident Management	Describes the problems, solutions, and responses	• Roadway capacity reduction • Incident frequencies • Quantification • Detection/Verification • Electronic monitoring • Response plan • Response services
High Occupancy Vehicle (HOV) Priority Control	Describes benefits and methods	• Separated facilities • Reserved freeway lanes • Metered ramp bypass • Exclusive HOV ramps • Criteria for freeway HOV priority lanes
Simulation	Describes tools used for analysis and design	• FREQ • INTRAS • FRESIM • INTEGRATION • MACK • FREFLO • CORFLO • FRECON
A Look to the Future	Describes concepts being introduced at the current time or in the future	• Advanced ramp metering concepts • Advanced incident detection and management concepts

- Metering or closure,
- Advisory information (speed, travel time, route guidance, diversion),
- Priority treatment (HOV operation),
- Traffic monitoring, and
- Incident management (detection and response).

The discussion of each concept includes a description of:

- Control principles and parameters,
- Functional components, and
- Experience.

Congestion-A Daily Occurrence

Congestion occurs on a freeway when demand exceeds capacity. When this occurs on a freeway section, a bottleneck exists. A bottleneck occurs when:

- Demand increases to a level greater than capacity, or
- Capacity decreases to a level less than demand.

Congestion has become a daily occurrence on many portions of urban freeway networks. Even casual observers can locate points of expected congestion. Congestion commonly expected at predictable locations during approximately predictable periods of time is termed *recurrent* congestion. Maintenance and construction activities, if not properly planned, may result in recurrent congestion.

In contrast, other forms of congestion result from random or less predictable events. Such *nonrecurrent* congestion results most frequently from accidents and incidents. Congestion from *special events* (e.g., sporting events, weekend recreational travel, maintenance and construction activities) may be considered nonrecurrent congestion.

Defining strategies to deal with the problems of congestion requires some perspective on the relative magnitude of each type.

To measure congestion, researchers at Texas Transportation Institute developed a Roadway Congestion Index (RCI), depicted as follows (1):

$$RCI = \left[\frac{\frac{\text{Freeway}}{\text{VMT/Lane - Mile}} \times \frac{\text{Freeway}}{\text{VMT}} + \frac{\text{Principal Arterial Street}}{\text{VMT/Lane - Mile}} \times \frac{\text{Principal Arterial Street}}{\text{VMT}}}{13{,}000 \times \frac{\text{Freeway}}{\text{VMT}} + 5{,}000 \times \frac{\text{Principal Arterial Street}}{\text{VMT}}} \right]$$

As stated in the reference, "An RCI value of 1 .0 or greater indicates that congested conditions exist areawide. It should be noted that urban areas with areawide values less than 1.0 may have sections of roadway that experience periods of heavy congestion, but the average mobility level within the urban area could be defined as uncongested. The RCI analyses are intended to evaluate entire urban areas and not specific locations. The nature of the RCI equation is to underestimate point or specific facility congestion if the overall system has good operational characteristics. "

Table 4-2 shows examples of congestion indices (1). Table 4-3 shows examples of recurring delay and incident delay for freeways, while Table 4 -4 shows examples for arterials (1).

Reference 1 analyzes a number of U.S. urban areas by population density. Five groups were developed, including 4 quartiles of various population density ranges and a fifth group consisting of 3 urban areas with the highest population density. Figure 4 -2 shows congestion trends for these groups (1).

Congestion, both recurrent or nonrecurrent, is characterized by:

- Slow travel speeds,
- Erratic speeds (stop-and-go movement),
- Increased and inconsistent travel times,
- Increased accident potential,
- inefficient operation, and
- Other undesirable conditions that cause user dissatisfaction.

If users expect a certain level of congestion during peak periods, they can plan trips accordingly. However, nonrecurrent congestion can severely impact an otherwise satisfactory trip during peak or off-peak periods. The inability to provide a reliable, although sometimes lower level of service, may prove to be a more serious problem.

Congestion- Its Measurement

A motorist usually thinks of congestion as:

- Overcrowded freeways,

Table 4-2. 1990 roadway congestion levels.

Urban Area	Freeway/Expressway		Principal Arterial Street		Roadway Congestion Index	Rank
	DVMT[1] (1000)	DVMT[2]	DVMT[1] (1000)	DVMT[2]		
Los Angeles, CA	110,350 (177,663)	21,100	80,370 (129,396)	6,480	1.55	1
Washington, DC	25,340 (40,797)	16,610	19,560 (31,492)	8,500	1.37	2
San Francisco-Oakland, CA	42,590 (68,570)	17,820	14,000 (22,540)	6,110	1.35	3
Miami, FL	8,570 (13,798)	14,170	15,810 (25,454)	7,620	1.26	4
Chicago, IL.	38,030 (61,228)	15,680	29,050 (46,771)	6,980	1.25	5
San Diego, CA	27,690 (44,581)	16,050	9,340 (15,037)	5,460	1.22	6
Seattle-Everett, WA	18,920 (30,461)	15,640	9,130 (14,699)	5,800	1.20	7
San Bernardino-Riverside, CA	14,580 (23,474)	16,290	10,150 (16,341)	4,740	1.19	8
New York, NY	82,920 (133,501)	14,050	52,060 (83,817)	6,890	1.14	9
Houston, TX	28,230 (45,450)	14,700	10,830 (17,436)	5,080	1.12	10
New Orleans, LA	4,970 (8,002)	13,810	4,100 (6,601)	6,560	1.12	10

Table 4-3. Freeway and expressway recurring and incident hours of daily delay for 1990.

Urban Area	Recurring Hours of Delay				Incident Hours of Delay			
	Moderate	Heavy	Severe	Total	Moderate	Heavy	Severe	Total
Northeastern Cities								
Baltimore, MD	3,880	7,320	13,970	25,170	8,930	16,830	32,140	57,900
Boston, MA	9,650	20,460	31,260	61,370	33,780	71,620	109,410	214,810
Hartford, CT	3,040	1,070	440	4,550	8,210	2,900	1,180	12,290
New York, NY	101,900	51,840	133,770	287,510	254,750	129,600	334,430	718,780
Philadelphia, PA	9,760	6,360	9,720	25,840	20,490	13,370	20,420	54,280
Pittsburgh, PA	1,420	3,020	6,150	10,590	4,130	8,750	17,820	30,700
Washington, DC	12,730	30,460	64,290	107,480	28,020	67,010	141,430	236,460
Midwestern Cities								
Chicago, IL	11,040	26,020	106,000	143,060	13,250	31,220	127,200	171,670
Cincinnati, OH	8,890	5,590	3,410	17,890	7,120	4,470	2,720	14,310
Cleveland, OH	8,920	6,730	2,060	17,710	6,250	4,710	1,440	12,400
Columbus, OH	730	5,120	8,140	13,990	510	3,590	5,700	9,800
Detroit, MI	9,830	6,490	43,020	59,340	21,630	14,270	94,650	130,550
Indianapolis, IN	2,690	0	1,390	4,080	4,030	0	2,090	6,120
Kansas City, MO	1,510	1,710	0	3,220	4,690	5,310	0	10,000
Louisville, KY	760	50	940	1,750	840	60	1,040	1,940
Milwaukee, WI	2,780	4,720	6,730	14,230	2,780	4,720	6,730	14,230
Minn-St. Paul, MN	5,590	6,780	22,080	34,450	5,030	6,100	19,870	31,000
Oklahoma City, OK	1,970	1,470	0	3,440	2,170	1,620	0	3,790
St. Louis, MO	8,300	2,350	11,470	22,120	9,960	2,820	13,770	26,550
Southern Cities								
Atlanta, GA	4,310	22,330	47,150	73,790	4,740	24,560	51,860	81,160
Charlotte, NC	3,790	990	0	4,780	3,030	790	0	3,820
Ft. Lauderdale, FL	4,630	3,490	1,070	9,190	6,940	5,230	1,600	13,770
Jacksonville, FL	6,330	2,610	0	8,940	9,500	3,910	0	13,410
Memphis, TN	1,640	350	0	1,990	1,800	380	0	2,180
Miami, FL	6,870	4,450	21,260	32,580	10,310	6,670	31,890	48,870
Nashville, TN	3,800	1,530	940	6,270	4,180	1,690	1,030	6,900
New Orleans, LA	840	9,050	6,110	16,000	1,520	16,300	11,010	28,830
Norfolk, VA	820	5,500	10,260	16,580	2,050	13,750	25,650	41,450
Orlando, FL	6,690	2,360	3,410	12,460	10,030	3,540	5,120	18,690
Tampa, FL	700	1,860	3,330	5,890	1,050	2,780	5,000	8,830

Table 4-3. Freeway and expressway recurring and incident hours of daily delay for 1990 (continued).

Urban Area	Recurring Hours of Delay				Incident Hours of Delay			
	Moderate	Heavy	Severe	Total	Moderate	Heavy	Severe	Total
Southwestern Cities								
Albuquerque, NM	580	1,380	920	2,880	630	1,520	1,010	3,160
Austin, TX	4,240	6,680	6,930	17,850	4,660	7,350	7,630	19,640
Corpus Christi, TX	680	0	0	680	750	0	0	750
Dallas, TX	12,670	23,420	47,160	83,250	22,810	42,160	84,890	149,860
Denver, CO	5,480	9,290	21,450	36,220	5,480	9,290	21,450	36,220
El Paso, TX	1,450	1,770	330	3,550	1,590	1,950	370	3,910
Fort Worth, TX	4,610	8,520	17,150	30,280	8,300	15,330	30,870	54,500
Houston, TX	7,350	36,380	91,040	134,770	10,290	50,930	127,460	188,680
Phoenix, AZ	2,420	14,980	12,030	29,430	970	5,990	4,810	11,770
Salt Lake City, UT	1,560	2,090	750	4,400	940	1,250	450	2,640
San Antonio, TX	2,360	10,000	11,540	23,900	2,590	11,000	12,700	26,290
Western Cities								
Honolulu, HI	2,270	3,750	8,830	14,850	4,090	6,740	15,890	26,720
Los Angeles, CA	19,330	21,840	560,610	601,780	23,200	26,200	672,730	722,130
Portland, OR	5,970	4,100	7,080	17,150	11,950	8,200	14,150	34,300
Sacramento, CA	9,190	9,340	3,970	22,500	5,510	5,600	2,380	13,490
San Bernardino-Riverside, CA	9,500	8,950	60,140	78,590	11,400	10,740	72,170	94,310
San Diego, CA	15,570	18,860	43,530	77,960	9,340	11,310	26,120	46,770
San Francisco-Oakland, CA	25,220	21,390	185,850	232,460	32,790	27,810	241,610	302,210
San Jose, CA	9,320	12,240	51,780	73,340	11,190	14,690	62,130	88,010
Seattle-Everett, WA	9,010	44,060	29,920	82,990	12,610	61,690	41,890	116,190
Northeastern Average	20,340	17,220	37,090	74,650	51,190	44,300	93,830	189,320
Midwestern Average	5,250	5,590	17,100	27,940	6,520	6,570	22,930	36,020
Southern Average	3,670	4,960	8,500	17,130	5,010	7,240	12,100	24,350
Southwestern Average	3,940	10,410	19,030	33,380	5,360	13,340	26,510	45,210
Western Average	11,710	16,060	105,740	133,510	13,560	19,220	127,670	160,450
Texas Average	4,760	12,400	24,880	42,040	7,280	18,390	37,700	63,370
Total Average	7,890	10,020	34,390	52,300	13,460	15,770	50,120	79,350
Maximum Value	101,900	51,840	560,610	714,350	254,750	129,600	672,730	1,057,080
Minimum Value	580	0	0	580	510	0	0	510

Table 4-4. Principal arterial street recurring and incident hours of daily delay for 1990.

Urban Area	Recurring Hours of Delay				Incident Hours of Delay			
	Moderate	Heavy	Severe	Total	Moderate	Heavy	Severe	Total
Northeastern Cities								
Baltimore, MD	1,400	2,240	17,280	20,920	1,540	2,470	19,010	23,020
Boston, MA	3,090	4,240	21,660	28,990	3,400	4,670	23,830	31,900
Hartford, CT	1,470	2,360	2,660	6,490	1,620	2,590	2,920	7,130
New York, NY	24,070	45,730	169,480	239,280	26,470	50,300	186,430	263,200
Philadelphia, PA	8,940	15,400	68,870	93,210	9,830	16,940	75,760	102,530
Pittsburgh, PA	4,950	4,950	27,120	37,020	5,450	5,450	29,830	40,730
Washington, DC	3,790	26,160	69,590	99,540	4,170	28,780	76,550	109,500
Midwestern Cities								
Chicago, IL	14,980	27,740	59,210	101,930	16,470	30,510	65,130	112,110
Cincinnati, OH	1,180	590	2,920	4,690	1,300	650	3,220	5,170
Cleveland, OH	1,950	2,980	3,710	8,640	2,140	3,280	4,080	9,500
Columbus, OH	850	2,450	4,620	7,920	940	2,700	5,080	8,720
Detroit, MI	6,080	13,790	61,380	81,250	6,690	15,170	67,520	89,380
Indianapolis, IN	1,680	210	1,540	3,430	1,850	240	1,700	3,790
Kansas City, MO	650	820	5,640	7,110	720	900	6,200	7,820
Louisville, KY	1,340	4,430	2,280	8,050	1,480	4,880	2,510	8,870
Milwaukee, WI	1,830	2,270	4,450	8,550	2,010	2,500	4,890	9,400
Minn-St. Paul, MN	2,520	1,210	13,960	17,690	2,780	1,330	15,360	19,470
Oklahoma City, OK	1,010	2,020	3,680	6,710	1,110	2,220	4,050	7,380
St. Louis, MO	5,260	19,640	15,550	40,450	5,790	21,610	17,110	44,510
Southern Cities								
Atlanta, GA	2,650	7,220	27,690	37,560	2,920	7,940	30,460	41,320
Charlotte, NC	280	3,440	8,380	12,100	310	3,780	9,220	13,310
Ft. Lauderdale, FL	1,870	8,060	12,830	22,760	2,050	8,870	14,110	25,030
Jacksonville, FL	2,020	4,440	9,470	15,930	2,220	4,880	10,420	17,520
Memphis, TN	1,030	3,300	3,480	7,810	1,140	3,630	3,830	8,600
Miami, FL	1,160	6,180	63,730	71,070	1,280	6,800	70,100	78,180
Nashville, TN	700	2,490	9,890	13,080	770	2,740	10,880	14,390
New Orleans, LA	1,530	2,140	7,770	11,440	1,680	2,350	8,550	12,580
Norfolk, VA	1,370	1,880	4,690	7,940	1,500	2,060	5,160	8,720
Orlando, FL	520	2,480	16,360	19,360	570	2,720	17,990	21,280
Tampa, FL	2,560	1,960	11,110	15,630	2,810	2,160	12,220	17,190

Table 4-4. Principal arterial street recurring and incident hours of daily delay for 1990 (continued).

Urban Area	Recurring Hours of Delay				Incident Hours of Delay			
	Moderate	Heavy	Severe	Total	Moderate	Heavy	Severe	Total
Southwestern Cities								
Albuquerque, NM	1,850	3,900	1,230	6,980	2,030	4,290	1,350	7,670
Austin, TX	990	1,660	2,070	4,720	1,090	1,830	2,280	5,200
Corpus Christi, TX	320	170	110	600	360	180	120	660
Dallas, TX	3,710	3,440	4,490	11,640	4,080	3,780	4,940	12,800
Denver, CO	3,850	7,850	18,280	29,980	4,240	8,630	20,110	32,980
El Paso, TX	130	150	600	880	140	170	660	970
Fort Worth, TX	1,890	1,760	2,290	5,940	2,080	1,930	2,520	6,530
Houston, TX	3,750	12,430	12,300	28,480	4,120	13,670	13,530	31,320
Phoenix, AZ	15,610	21,970	27,360	64,940	17,170	24,170	30,090	71,430
Salt Lake City, UT	1,180	1,150	1,500	3,830	1,300	1,260	1,650	4,210
San Antonio, TX	840	560	2,790	4,190	930	610	3,070	4,610
Western Cities							3,480	6,090
Honolulu, HI	1,430	940	3,160	5,530	1,570	1,040	130,170	238,990
Los Angeles, CA	28,350	70,580	118,340	217,270	31,190	77,630	7,360	13,750
Portland, OR	850	4,950	6,690	12,490	940	5,450	18,190	23,790
Sacramento, CA	370	4,720	16,540	21,630	410	5,190	11,250	33,530
San Bernardino-Riverside, CA	9,800	10,450	10,220	30,470	10,780	11,500	1,390	14,610
San Diego, CA	2,400	9,610	1,260	13,270	2,650	10,570	48,190	57,560
San Francisco-Oakland, CA	1,800	6,720	43,810	52,330	1,980	7,390	25,830	32,380
San Jose, CA	3,630	2,320	23,480	29,430	3,990	2,560	24,700	32,230
Seattle-Everett, WA	2,930	3,910	22,460	29,300	3,230	4,300	59,190	82,570
							16,400	27,180
Northeastern Average	6,820	14,440	53,810	75,070	7,500	15,880	17,540	23,470
Midwestern Average	3,280	6,510	14,910	24,700	3,610	7,170	7,300	16,210
Southern Average	1,430	3,960	15,950	21,340	1,570	4,360	30,060	50,320
Southwestern Average	3,100	5,000	6,640	14,740	3,410	5,500	3,870	8,870
Western Average	5,730	12,690	27,330	45,750	6,300	13,960	23,100	35,880
Texas Average	1,660	2,880	3,520	8,060	1,830	3,170	186,430	295,250
Total Average	3,770	7,840	21,000	32,610	4,150	8,630	120	430
Maximum Value	28,350	70,580	169,480	268,410	31,190	77,630	---	---
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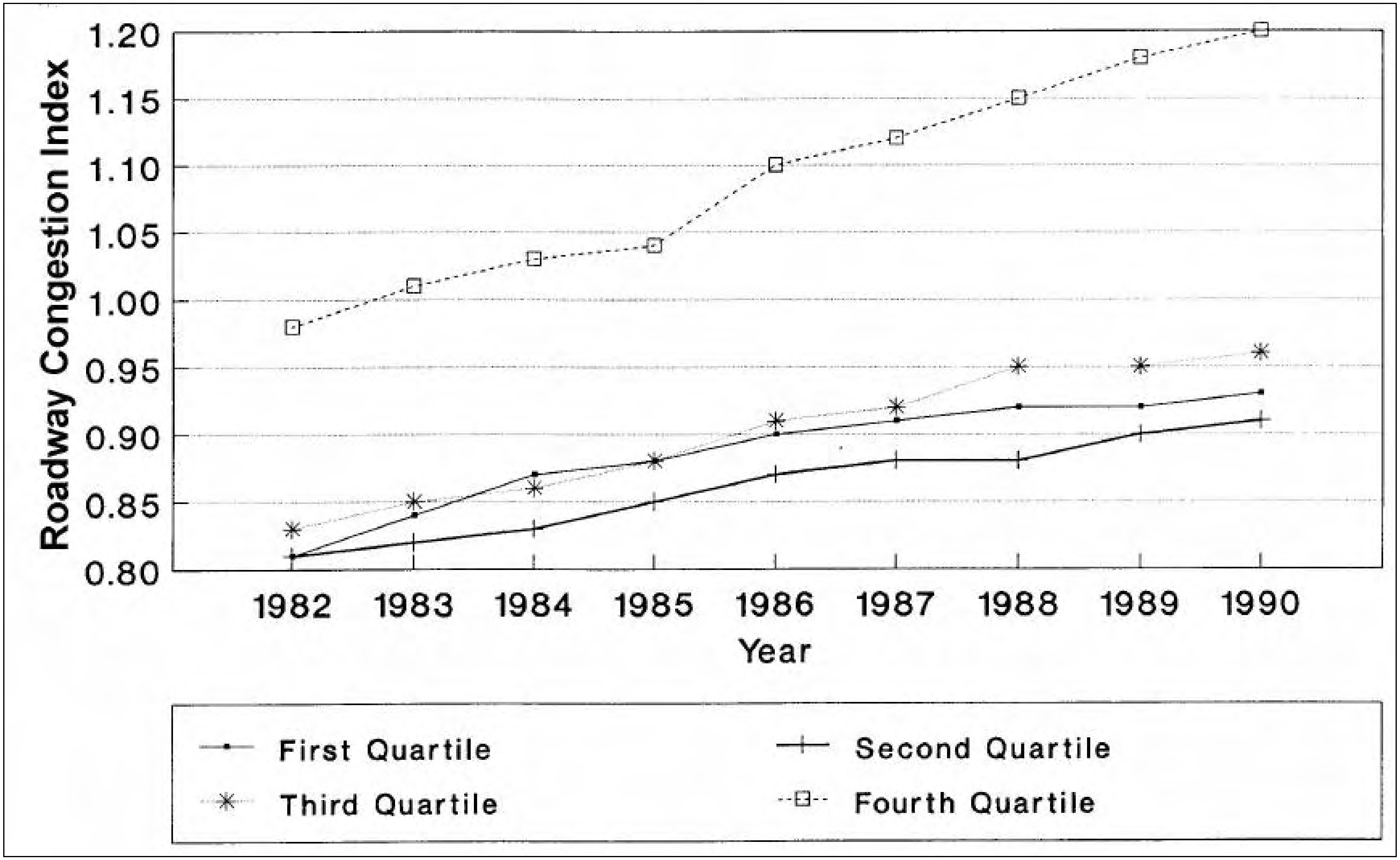


Figure 4-2. Roadway congestion index values grouped by population density, 1982 to 1990.

- Stop-and-go driving conditions, and
- The frustration and discomfort of restricted maneuverability.

The traffic engineer, on the other hand, often expresses congestion in terms of the fundamental relationships among traffic variables such as:

- Flow rate,
- Density (or occupancy), and
- Space mean speed.

Figure 4-3 conceptually illustrates the fundamental relationship between flow rate and density and table 4-5 describes flow characteristics for 3 density ranges. The latest version of the Highway Capacity Manual does not characterize flow in the congested region (2).

The specific value of density defining congestion depends on:

- Geometrics of the freeway section,
- Traffic composition, and
- Weather conditions.

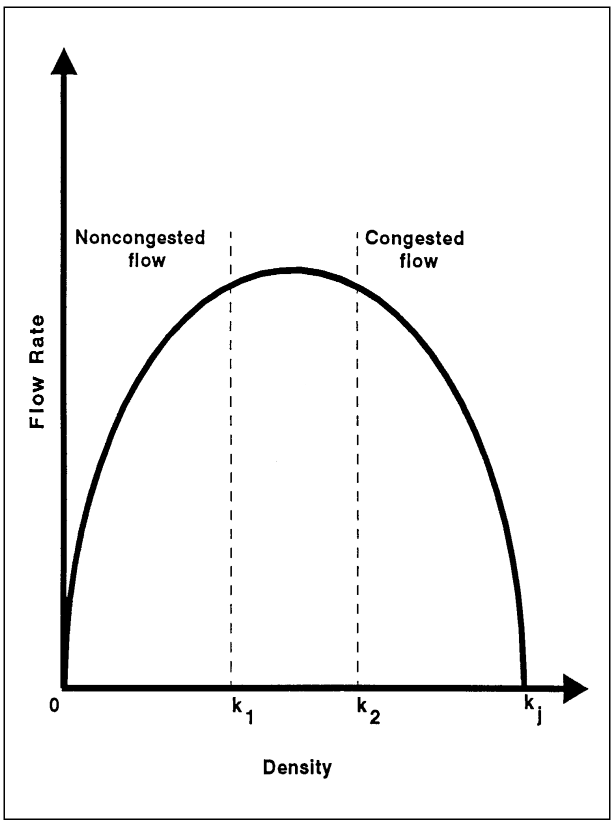


Figure 4-3. Congestion and the fundamental relationship between flow rate and density.

Table 4-5. Traffic flow characteristics relative to density.

Density Range in Figure 4-3 (Vehicles / Lane-Mile)	Flow Characteristics
0 - k_1	• Non-congested • Flow rate increases
k_1 - k_2	• Unstable • Flow rate increases modestly or remains constant • Probability of flow breakdown increases
k_2 - k_j	• Congested • Flow rate decreases (reaches zero at jam density, kj)

The Highway Capacity Manual provides values for the density at the capacity of the freeway as a function of free flow freeway speed. Flow becomes unstable prior to or at this density.

McDermott has reported flow characteristics corresponding to lane occupancies as shown in table 4-6 (3). Figure 4-4 shows generalized freeway traffic operation curves that relate lane occupancy to flow rate and space mean speed (3). As lane occupancy exceeds 20 percent, speeds decrease because of:

- Fewer and shorter gaps between vehicles,
- Increased difficulty of lane changing, and
- Generally more restrictive flow conditions.

Congestion - Its Causes

There is ample literature that describes the numerous factors contributing to congestion and its many manifestations. The works of Moskowitz and Keese, Pinell, and McCasland typify studies that have investigated ways to improve freeway operations (4, 5). These studies identified the following factors contributing to congestion:

- Geometric design,
- Traffic operations,
- Incidents,
- Maintenance and construction, and
- Weather.

Table 4-6. Traffic flow characteristics relative to occupancy.

Occupancy Range (%)	Flow Characteristics
0 - 20	• Non-congested
20 - 30	• Unstable (impending congestion)
30 - 100	• Congested

Geometric Design

The capacity of a freeway usually does not remain constant along its entire length. Certain physical features result in capacity restrictions. Upstream and downstream from the location of these features, capacity usually proves slightly higher, resulting in bottleneck conditions. Table 4 -7 shows examples of physical features that contribute to capacity reductions and resulting congestion.

Traffic Operations

Table 4-8 shows traffic operation factors that contribute to congestion.

Incidents

Traffic incidents prove to be a major cause of nonrecurring congestion. Figure 4 -7 shows the effect of an incident on motorist delay (10).

The number of lane blocking incidents per week on major urban freeways typically ranges from 2.2 to 3.4 incidents per mile (10).

During an incident, roadway capacity reduces disproportionately to the physical reduction in available roadway width as shown in table 4 -9 (10).

Maintenance and Construction

Maintenance and construction cause congestion with significant accompanying delays. Where possible, schedule such activities when low volumes are anticipated; i.e., during nights or weekends. Also plan and schedule all required maintenance in a given section and lane at one time. This will:

Figure 4-4. Generalized traffic flow relationships.

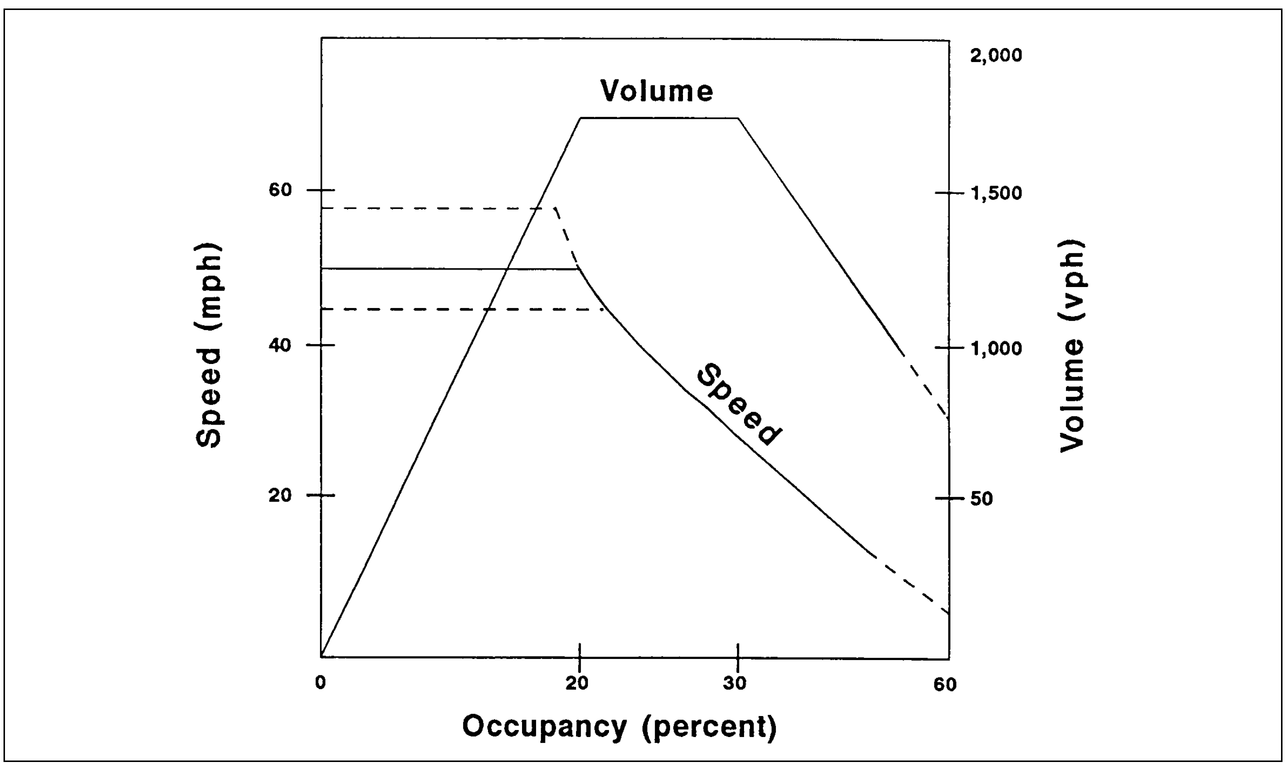


Table 4-7. Geometric design factors causing capacity reduction.

Design Factor	Result
Reduction in lanes	• May cause congestion where number of lanes is reduced • Even though lane drop occurs at exit ramp, thru volume may exceed remaining capacity • Weaving out of dropped lanes may create turbulence, cause speed to decrease, and decrease capacity. (May cause problem where multiple freeways merge without maintaining the same number of thru lanes.)
Horizontal curvature	• Moderately sharp horizontal curve may reduce capacity • In heavy flow, vehicle may cross into next lane, causing hesitation and speed decreases in adjacent lanes. Even momentary speed decreases during periods of unstable flow can result in congestion.
Vertical alignment	• Grades reduce capacity, particularly with trucks present (2) • Although design standards impose limitations on acceptable grades, vertical alignment may cause small, but imperceptible, speed changes that affect following traffic and can result in congestion • Upgrades in tunnels limit capacity
Other physical features: • Lane widths • Lateral clearance • Ramp design • Surface conditions (2)	• Older freeways may have lanes narrower than 12 ft standard, resulting in capacity reduction • Lateral obstructions may reduce capacity if located closer than 6 ft to a traveled lane. Examples include: - bridge abutments - retaining walls - illumination poles - sign supports • Lack of full-shoulder-width bridges reported to result in a point reduction of capacity

- Benefit the motorist, and
- Reduce costs, since maintenance and protection of traffic often represents a significant expense in freeway maintenance operations.

Also provide adequate on -site traffic control and advance information to motorists.

Use of the media and on-highway traveler information systems (chapter 10) to report expected and current construction delays can:

- Assist motorists in planning for and avoiding the delay, and
- Reduce demand during reduced capacity periods.

Weather

Rain and snow significantly reduce freeway capacity. Table 4-10 summarizes the limited research on this subject as reported by the Highway Capacity Manual (2).

4.2 Ramp Metering

Ramp metering has proven to be the most widely-used form of freeway traffic control. It has seen application in at least 20 urban areas in the United States arid other countries. Ramp metering aims to eliminate, or at least reduce, operational problems resulting from freeway congestion.

Table 4-8. Traffic operations factors causing congestion.

Traffic Operation Factors	Result
Volume/Capacity relationship	• Traffic demand in excess of the facility's capacity will cause congestion • Number of vehicles actually using freeway during congested periods does not measure demand (number of vehicles seeking to use facility) because of diversion to other: - routes - time periods - modes Actual demand best measured by origin-destination surveys where times of desired trips can be obtained. Volumes measured on freeway sometimes termed *manifest* demand. • Relationship of capacity and manifest demand at a specific bottleneck shown in top portion of figure 4-5 (6). Demand exceeds capacity for a 30-minute period. In lower portion of figure, congestion begins at time when capacity is first exceeded, then extends for a time long enough to allow capacity to dissipate demand backlog. Thus, congestion period is longer than time period for which demand exceeds capacity. • Capacity is a constant property of a roadway section, while its ability to service traffic (service rate) varies with density (figure 4-3). Queuing and congestion result upstream of the point where manifest demand exceeds capacity.
Hysteresis effects	Evidence indicates that the volume-density relationship depends on whether prior flow conditions were congested or non-congested as illustrated by figure 4-6 (7). Some researchers explain this effect in terms of catastrophe theory (8, 9). As volume increases for example, during a peak period, the non-congested flow curve of figure 4-6 represents operation. At some point in the overlap region, operation changes to the lower (congested flow) curve. This results in a lower capacity for the freeway section with accompanying increases in density in this and upstream sections. This congested condition will likely remain until upstream demand volumes fall below the capacity of the congested flow curve, at which point operation resumes on the non-congested flow curve.
Unrestrained ramp access	• Frequently results in bottlenecks and attendant congestion • When the sum of mainline volume and entry ramp volume exceeds mainline capacity, congestion and queuing result
Exit ramp queues	• Occasionally results in freeway mainline congestion • Can result in queue of vehicles extending back onto the freeway when: - exit ramp demand exceeds capacity of a merging area or downstream intersection - lack of storage on the ramp Such conditions can develop because of: • Congestion on the surface street system • Heavy exit ramp demand due to special events such as ballgames, fairs, tournaments, etc.
Weaving maneuvers	• Presence of heavy weaving movements frequently cause freeway mainline congestion • Heavy weaving may result from: - ramp locations determined during design - heavy traffic flows to or from specific generators Reference 2 describes the effects of weaving

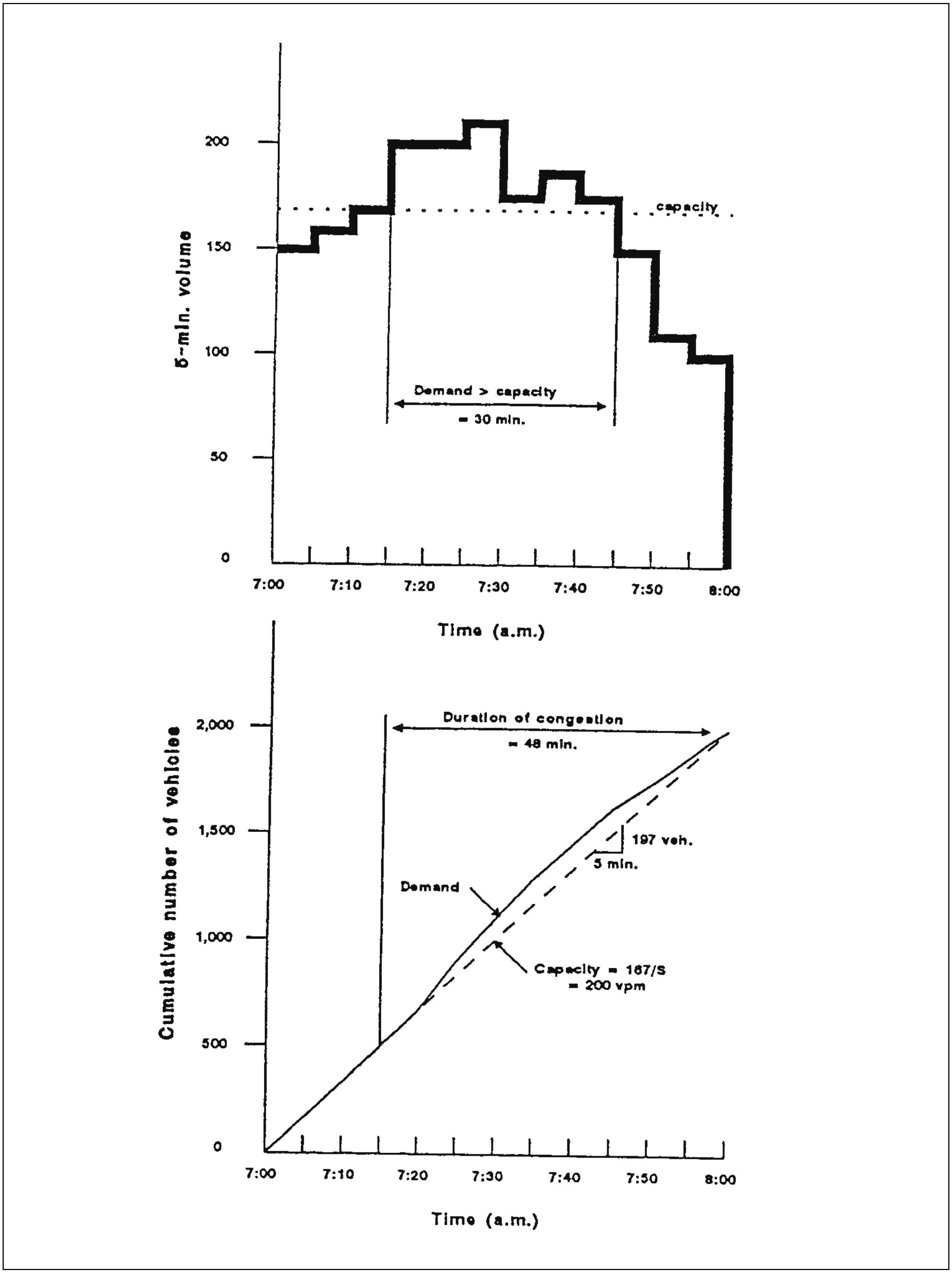


Figure 4-5. Relationship among demand, capacity, and congestion.

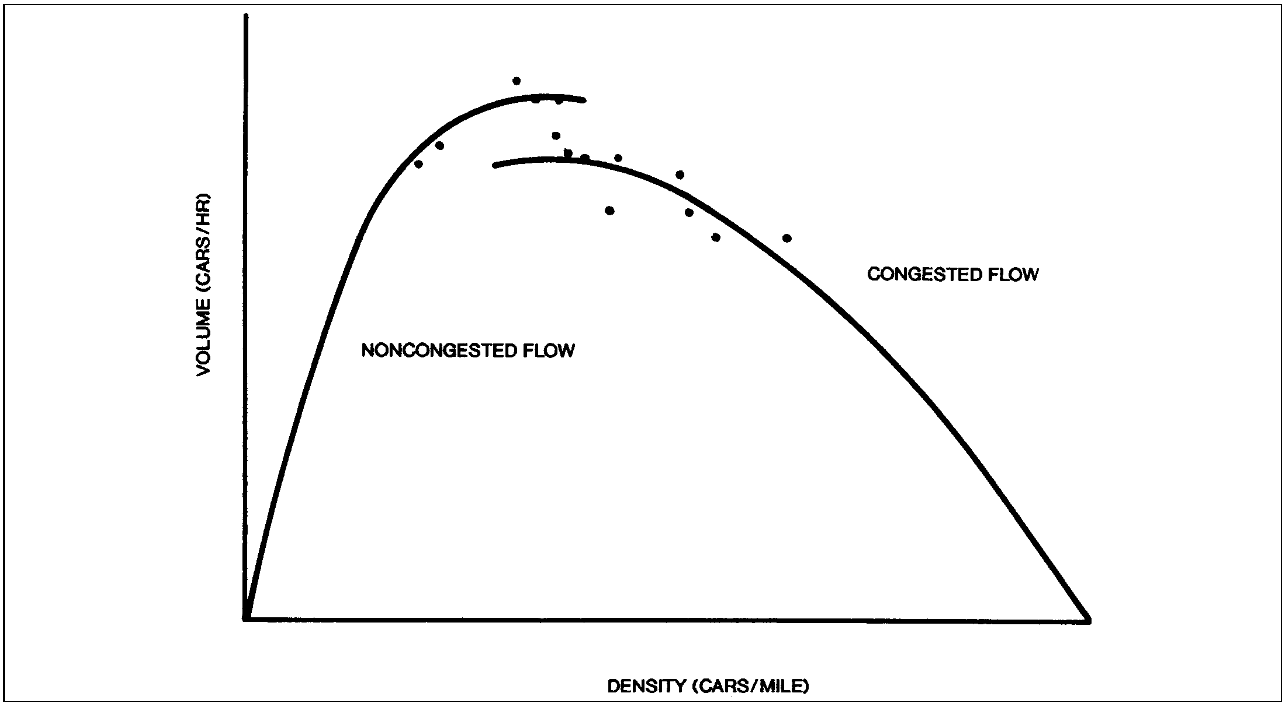


Figure 4-6. Discontinuous flow-concentration curve.

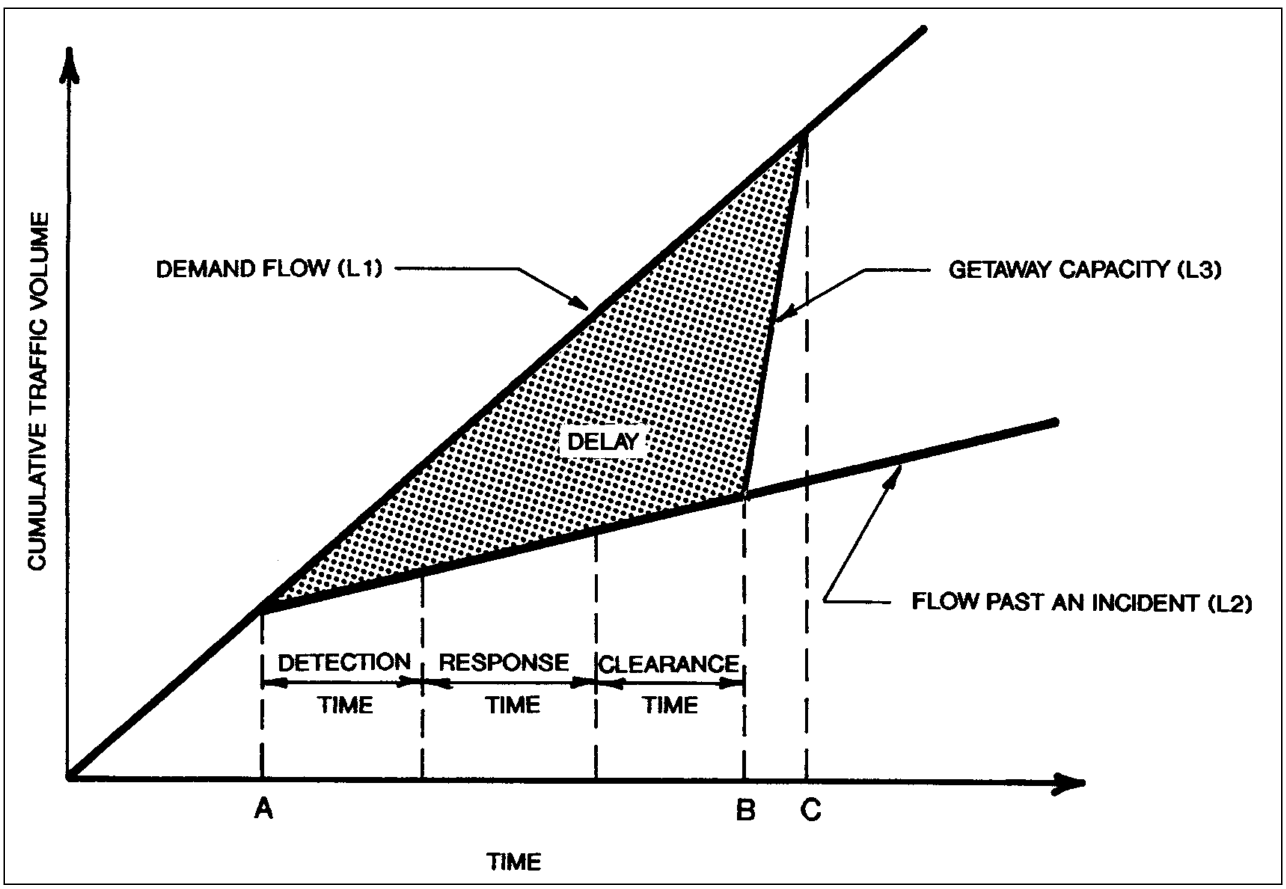


Figure 4-7. Effect of an incident on motorist delay.

Table 4-9. Percentage of freeway section capacity available under incident conditions.

Number of Freeway Lanes in Each Direction	Shoulder Disablement	Shoulder Accident	Lanes Blocked		
			One	Two	Three
2	0.95	0.81	0.35	0	N/A
3	0.99	0.83	0.49	0.17	0
4	0.99	0.85	0.58	0.25	0.13
5	0.99	0.87	0.65	0.40	0.20
6	0.99	0.89	0.71	0.50	0.25
7	0.99	0.91	0.75	0.57	0.36
8	0.99	0.93	0.78	0.63	0.41

Robinson and Doctor describe ramp metering case experiences and benefits, factors to be considered, and guidelines for implementation (11). The paper also contains an extensive bibliography and set of references.

Ramp metering regulates the number of vehicles entering the freeway, so that demand does not exceed capacity. Some traffic desiring access to the freeway mainline will wait on the ramps before receiving a signal to enter. Instead of waiting, some vehicles may choose to:

- Not use the freeway at all,
- Enter it from another location, or
- Enter at another time of day.

Some drivers may elect to use public transit. For at least a portion of its trip, *diverted* traffic takes another:

- Route,
- Time, or
- Mode of transportation.

Thus, ramp metering tends to maintain uninterrupted, non-congested flow on the freeway i.e., traffic operates on the non-congested flow curve of figure 4-6 for as long as possible.

Table 4-11 summarizes two metering approaches, *restrictive* and *non-restrictive*. Partially restrictive metering provides a lower level of manifest demand control than fully restrictive metering.

Table 4-10. Effect of weather conditions on freeway capacity.

Location	Effect
Gulf Freeway (Houston)	Rain: Reduction in capacity of 14-19%.
I-35 (Minneapolis)	Rain: "Trace" reduces capacity by 8 percent. Each 0.01 in/hr increase reduces capacity by an additional 0.6 percent. Snow: "Trace" reduces capacity by 8 percent. Each 0.01 in/hr (water equivalent) reduces capacity by an additional 0.6 percent.

Metering Rates

The calculation of metering rates depends on the metering purpose: *congestion reduction* or *merging operation safety* improvement.

- Congestion reduction - If the metering system is intended to eliminate or reduce congestion, demand must be kept below capacity. Therefore, the metering rate depends on the relationship among:
  - Upstream demand,
  - Downstream capacity, and
  - Volume of traffic desiring to enter the freeway.

Table 4-11. Characteristics of types of control.

Types of Control	Diversion Intent	Improvement Achieved
Restrictive	Sufficient queues and diversions to maintain non-congested freeway flow or to limit extent and duration of congestion during the peak traffic period	Reduction of manifest demand on freeway results in improved service levels Smoothing of ramp platoons improves safety and traffic operations at merge areas
Non-restrictive	Minimal diversion	Smoothing of ramp platoons improves safety and traffic operations at merge areas

In many cases, operational and geometric constraints are include reduction in demand below capacity; however, at feasible locations, ramp metering at rates satisfying the constraints often reduces the level and duration of congestion.

The merging capacity at the ramp or the capacity of a downstream bottleneck determines downstream capacity.

- If the sum of upstream demand and ramp demand proves less than or equal to the capacity at some point downstream of the merge (the critical location may or may not be before the next entry ramp), metering is not needed to prevent congestion, and
- If the upstream demand exceeds downstream capacity, metering does not eliminate congestion but reduces it.

Subsequent paragraphs provide several examples that illustrate procedures for setting metering rates.

- Safety - In many cases, ramp metering provides a smoother ramp merging operation.

  The primary merging safety problem involves rear-end and lane-change collisions caused by platoons of vehicles on the ramp competing for gaps in the freeway traffic stream. Metering breaks up these platoons and facilitates single-vehicle entry.

  Metering rates for this purpose are as follows:

  - Lower bound equals the peak hour volume, and
  - Upper bound equals the maximum meteri ng rate for the facility (e.g., 900 v/hr for a single lane meter).

CALTRANS recommends that a minimum of 240 v/hr and a maximum of 900 v/hr be metered in a single lane (12). CALTRANS also recommends that a 2 lane meter provide a minimum metering rate of 500 v/hr.

Specific computational procedures for establishing metering rates are given later in this chapter.

Ramp Metering Strategies

Ramp metering strategies based on current or predicted demand -capacity conditions and real -time traffic measurements require a description or model of traffic flow. Frequently-used indicators of operating conditions for traffic -responsive metering include the relationships among (13):

- Flow rate, q;
- Space-mean speed, u; and
- Density, k.

Figure 4-8 illustrates these relation ships, while table 4-12 shows their major features.

The values of q_m, u_f, u_m, k_m and k_j, and the shapes of the curves, depend on several factors, including:

- Geometrics of the roadway,
- Composition of traffic, and
- Weather conditions.

Therefore, these values may differ for each roadway section, and each section may have more than one set of values.

Basic Strategy

Since congestion occurs whenever demand exceeds capacity, the values of q_m, u_m and k_m define

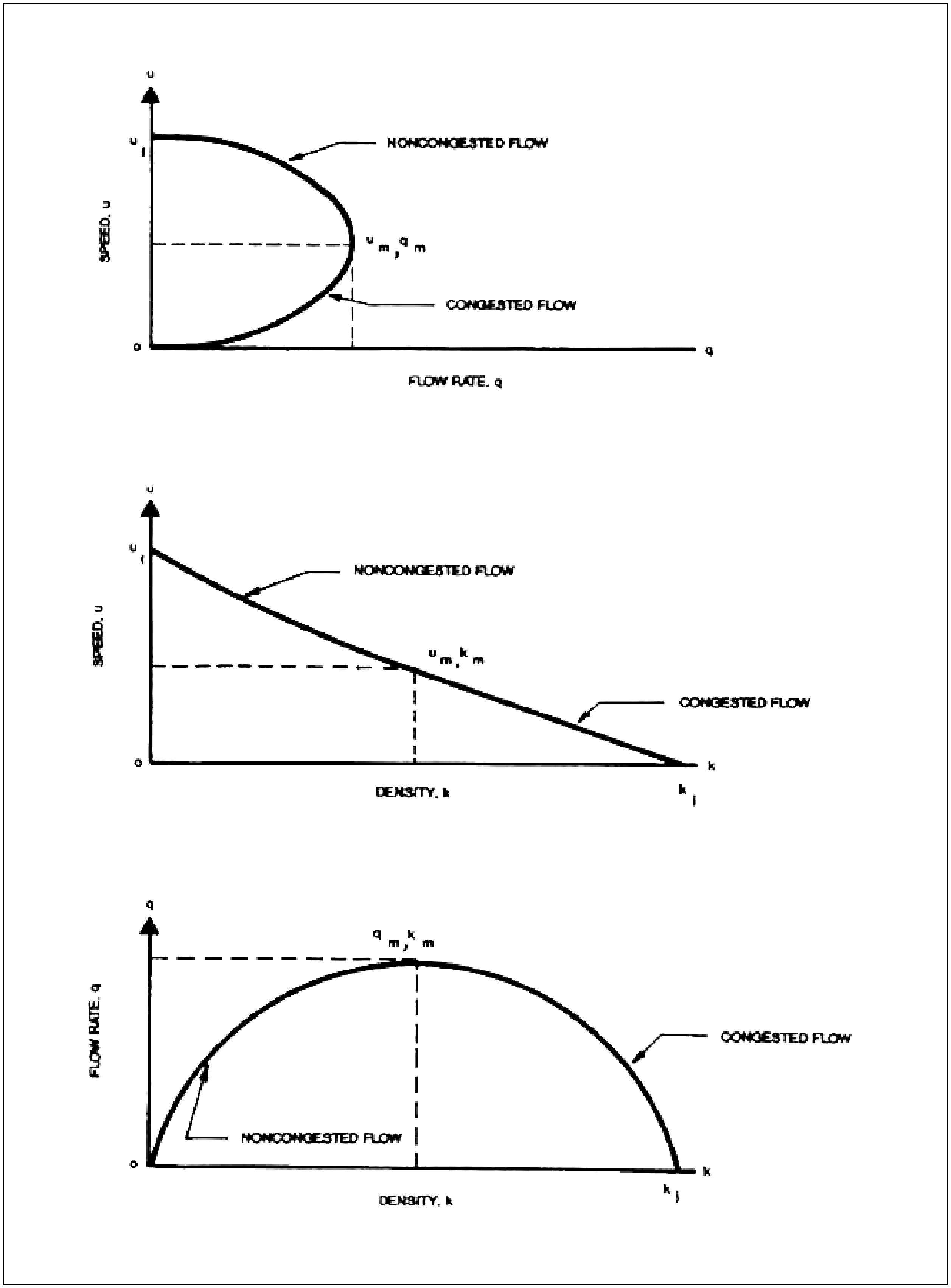


Figure 4-8. Flow rate-speed-density relationships.

Table 4-12. Characteristics of flow-density relationship.

Density	Flow
$k = 0$	No vehicles on roadway; zero flow rate; traffic travels at free flow speed, u_f
$k = k_m$	Flow rate at maximum value, q_m, capacity of roadway; speed decreases to u_m
$k = k_j$ (jam density)	Flow rate decreases to zero

boundaries between non-congested and congested flow. Metering aims to prevent or reduce congestion; i.e., to keep traffic flow variables at levels on the uncongested-flow portions of the traffic flow relationship. The basic strategy of traffic-responsive metering follows:

- Obtain real-time measurements of traffic variables on the freeway and entry ramps,
- Based on these measurements, determine where the freeway section is operating on the traffic flow curves, and
- Determine the maximum ramp metering rate at which vehicles can enter the freeway to maintain uncongested operations.

Lane occupancy (a surrogate measure for density) and *flow rate* (volume) generally describe freeway traffic conditions for traffic-responsive metering, since conventional vehicle detectors can measure these control parameters in real -time.

Several variations of traffic-responsive metering use different combinations of traffic variables. Although most report positive effects on freeway operations, none has generally proven superior. In fact, new strategies are still being formulated to find better modes of control. However, the principal traffic-responsive strategies remain:

- Demand-capacity control, and
- Upstream occupancy control.

Demand-Capacity Strategy

Demand-capacity control features the selection of metering rates by performing a real -time comparison of upstream volume and downstream capacity. Measured upstream volume is compared with either:

- A preset value of downstream capacity determined from historical data, or
- A real-time value computed from downstream volume measurements.

The difference between the upstream volume and the downstream capacity then becomes the allowable entrance ramp volume. This ramp volume is expressed as a metering rate and is used during the next control interval (usually 1 minute). If the upstream volume exceeds downstream capacity, a minimum metering rate is used (table 4 -13).

The control algorithm may use a fixed value for downstream capacity. The disadvantage of a fixed value is that the correct value may prove difficult to estimate for the site. The value may also vary with weather conditions, traffic composition, and incidents.

As an alternative to a fixed value for capacity, a detector can measure the actual downstream capacity.

A variation on this approach controls the metering rate entirely on the basis of downstream occupancy. Hadj - Salem et al. and Papageorgiou et al. propose the following control law (15, 16):

$$r(i) = r(i-1) + K_R\,(\hat{o} - o_{out}(i)) \qquad (4.1)$$

Where:

i	=	Computation iteration
$r(i)$	=	Metering rate
$\hat{o}$	=	Preset desired value of downstream occupancy
o_{out}	=	Measured occupancy
K_R	=	Coefficient

Upstream Occupancy Strategy

Occupancy control uses real-time occupancy measurements generally taken upstream of the entrance ramp. One of a number of predetermined metering rates is selected for the next control interval (usually 1 minute) on the basis of occupancy measurements taken during the current control interval. For a given entrance ramp, the metering rate for a particular value of occupancy is based on a plot of historical volume/occupancy data collected at each measurement location. Figure 4 -9 shows an example of a typical plot (15). Such a plot determines an approximate relationship between volume and occupancy at capacity. Thus, for each level of occupancy measured, a metering rate can be computed that corresponds to the difference between the predetermined estimate of capacity and the real-time estimate of volume. If the measured occupancy exceeds or equals the preset capacity occupancy, a minimum metering rate is selected. Table 4-14 shows another example (14).

Table 4-13. Types of metering arrangements.

Type of Metering	Number of Metered Lanes	Approximate Range of Metering Rates (v/hr)	Comments
Single vehicle entry per green interval	1	240 - 900	N/A
Single vehicle entry per green interval per lane	2	400 - 1500	• Applies when required metering rate exceeds 900 v/hr • Requires two lanes for vehicle storage • Vehicles may be released from each lane simultaneously or sequentially
Single lane multiple vehicle entry per green interval (platoon metering)	1	200 - 1100 (14)	• Platoon lengths permit passage of 1 to 3 vehicles per green interval • Principally used to increase metered volumes when geometrics do not permit use of more than one metered lane • Requires changeable sign indicating permitted number of vehicles in green interval • MUTCD requires yellow interval after green

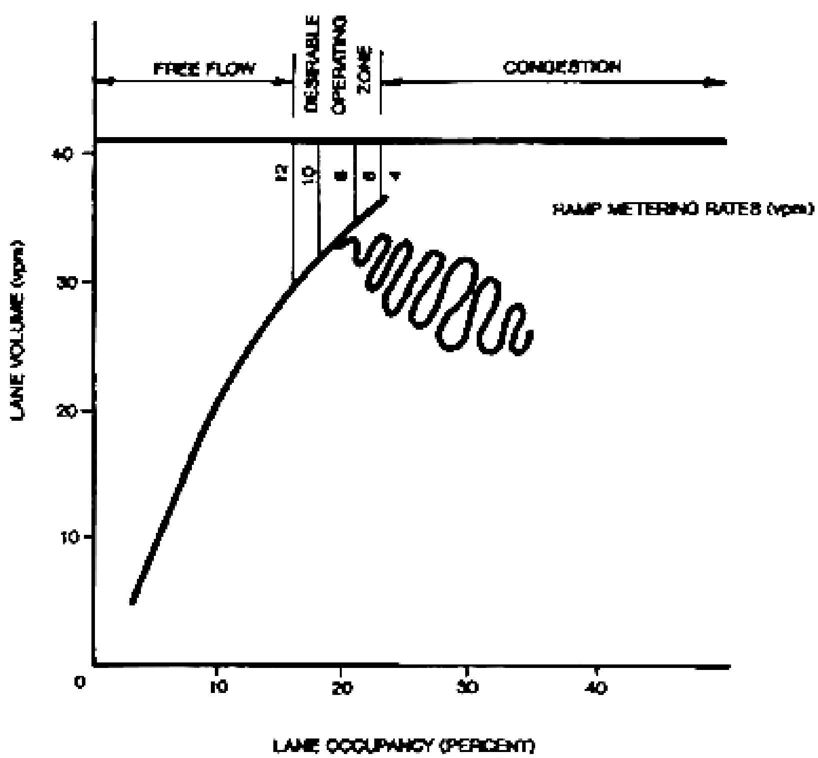


Figure 4-9. Typical volume-occupancy plot used in the calculation of entrance ramp metering rates Chicago, IL.

Table 4-14. Local actuated metering rates as a function of mainline occupancy.

Occupancy (%)	Metering Rate (Vehicles/Minute)
≤ 10	12
11 - 16	10
17 - 22	8
23 - 28	6
29 - 34	4
> 34	3

A mode is sometimes enabled that allows ramp meters to use the more restrictive of the *metering rates:*

- Calculated on a traffic-responsive basis, or
- Programmed on a time-of-day basis.

While ramp metering is usually initiated and terminated on a time-of-day basis, this can also be done traffic-responsively, thus enabling off-peak control in response to incidents or construction. To perform this control effectively, provide adequate filtering in the algorithm to prevent short-period data fluctuations from initiating or terminating metering operation.

Types of Operation

Table 4-15 shows the possible types of ramp metering operation. Use local ramp metering:

- For safety improvements,
- To control one or a few ramps where downstream freeway sections experience recurrent congestion, or
- Where *systemwide* metering proves difficult because metering is not feasible at certain ramps.

Systemwide metering usually controls major freeway sections, and often becomes one element of an integrated traffic management plan. The types of ramp metering in table 4-15 are often considered *modes* in many contemporary monitoring and control systems. The system may select different modes of operation for different time periods or locations. The following paragraphs describe types of metering.

Local Ramp Metering

Table 4-16 describes local ramp metering strategies.

Systemwide Ramp Metering

Systemwide Pretimed Metering

Systemwide pretimed metering refers to the application of pretimed metering to a series of entrance ramps. The metering rate for each ramp is determined in accordance with:

- Its local demand-capacity constraint, and
- Demand-capacity constraints at the other ramps.

Figure 4-10 portrays a case where the volume at a single ramp can be reduced sufficiently to bring mainline volume below capacity. However, in many major urban areas, a sufficient volume reduction at a single ramp may not be possible because of:

- Minimum metering volume constraints,
- Lack of vehicle storage space, or
- Too large a capacity deficiency.

Systemwide ramp metering strategies provide increased levels of control by distributing the metering task over a number of upstream ramps.

A number of approaches have been developed to establish metering rates for pretimed networks (17). The procedure described in table 4-17 requires peak

	Local Ramp (Standalone) Metering	Systemwide Metering
Pretimed	✓	✓
Traffic-Responsive	✓	✓ •
Operator Controlled	✓ •	✓ •

Table 4-15. Types of ramp metering operations.

period volume data, but not ramp-to-ramp origin-destination (O-D) data. Table 4-17 shows the procedure, while. figure 4-11 and table 4-18 apply the procedure to a specific scenario. The procedure represents one way of assigning metering rates; other techniques are possible. The procedure proves most useful for a relatively small number of entry ramps (e.g., 5 or fewer). Therefore, it may prove useful to divide a long freeway into smaller sections. Applicable sections for the procedure often lie between freeway-to- freeway or other major interchanges.

The example represents a congested section of freeway with a viable surface street alternate.

Systemwide Traffic-Responsive Metering

Systemwide traffic-responsive metering selects rates at each ramp in accordance with the system, as well as local demand-capacity constraints.

Table 4-16. Local ramp metering strategies.

Strategy	Description
Pretimed	Reduce ramp flow so mainline flow becomes less than capacity of section downstream of ramp. Figure 4-10 illustrates requirements for metering rates, storage, and diversion.
Traffic-Responsive	Select metering rates on basis of real-time measurements of traffic variables. Usually occupancy based.

Jacobson et al. (18) describes a systemwide traffic-responsive ramp metering algorithm that also computes a local rate based on a schedule of metering rate versus occupancy (similar to figure 4-9). A system metering rate based on bottleneck conditions is also computed and the more restrictive rate is used.

A bottleneck is identified when:

- A threshold occupancy is exceeded, and
- Vehicle queues are present.

Figure 4-12 shows the conditions for bottleneck detection.

Equation 4.18 represents the rate at which vehicles are being stored:

$$U_{i(t+l)} = (qIN_{it} + qON_{it}) - (qOUT_{it} - qOFF_{it}) \qquad (4.18)$$

Where:

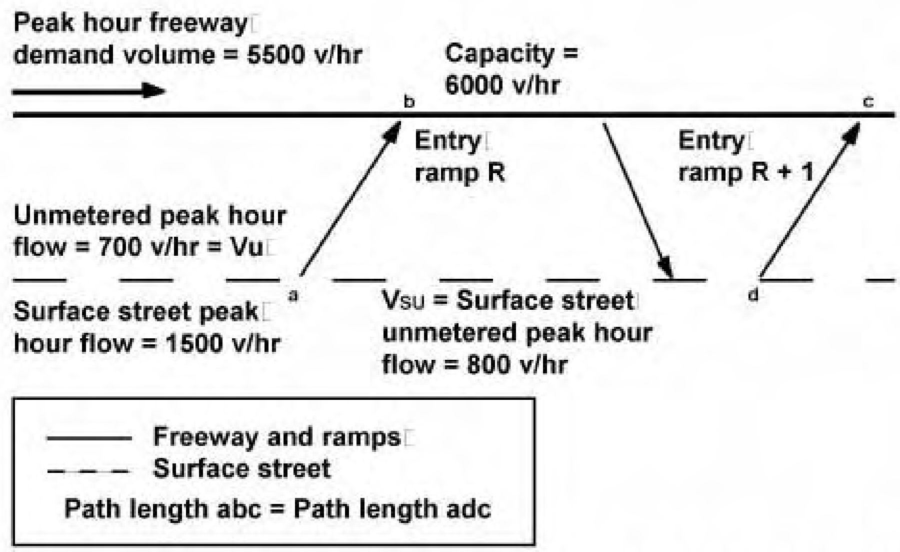
$U_{i(t+l)}$ = Upstream ramp volume reduction for section i required in next metering interval (t+1), and

qIN_{it}, qON_{it}, $qOUT_{it}$, and $qOFF_{it}$ are shown in figure 4-12.

An area of influence (a group of ramps upstream of the bottleneck section) is defined. Ramps within this area are collectively metered to reduce the entering volume by $U_{i(t+l)}$. Assignable weighting factors determine how this volume reduction is apportioned among the upstream ramps in the area of influence.

One key algorithm feature is that the bottleneck identification and upstream volume reduction computations do not require direct knowledge of the bottleneck capacity. A number of adjustments may be made to the calculated metering rates (18).

1. Scenario



Unmetered operation results in total demand at Ramp R of 5500 + 700 = 6200 v/hr which exceeds capacity of 6000 v/hr. Freeway congests upstream of entry ramp R.

2. Metering Requirement to Avoid Congestion

To avoid congestion, entry ramp R must be metered to regulate flow. The metered volume, Vm, must be held to 500 v/hr or less. This would divert 200 v/hr to the surface street alternate.

3. Estimation of Ramp Metering Delay to Produce Required Diversion

Motorists at entry ramp R will be encouraged to divert to entry ramp R+1, other downstream entry ramps, other routes or other modes in sufficient numbers if they experience a sufficiently long entry ramp delay. This delay may be estimated by the use of a traffic assignment model. Various computer-based assignment models and simulations and other analytical models are available for this purpose. For the simple case described by this example, the assignment model represented by equation 4.2 is used. This model and it's symbol definitions are discussed in section 4.4. Other diversion models are also discussed in section 4.4.

$$p = 50 + \frac{50\,(d + \frac{1}{2}t)}{\sqrt{(d - \frac{1}{2}t)^2 + 4.5}} \qquad (4.2)$$

Figure 4-10. Example demonstrating the interaction of ramp metering requirements, diversion impacts, and ramp storage requirements.

3. ***(continued)***

Where:

p is the percentage of vehicles actually entering the freeway using, as a reference, the total number of vehicles on the surface street upstream of the ramp that could use the freeway route

t is the surface street route travel time less the freeway travel time (in minutes)

d is the surface street travel distance less the freeway travel distance (in miles)

Vehicles in link a-d include:

- Vehicles that are freeway candidates but have chosen to use the surface street alternate (V_{cu})
- Vehicles that constitute local traffic or traffic destined for locations not served by the freeway (V_L)

Travel time difference for the unmetered case is t_u

Travel time studies show that:

t_u = surface street (path a-d-c) travel time - freeway (path a-b-c) travel time = 111 seconds prior to metering

Capacity and signal timing studies show that the addition of 200 v/hr will increase the travel time on link a-d by 32 seconds

$$t_{sd} = 32 \text{ seconds} \quad (4.3)$$

From the scenario:

$$V_{su} = V_{cu} + V_L = 800 \text{ v/hr} \quad (4.4)$$

Equation 4.2 is solved as follows:

$$d = 0 \quad (4.5)$$

$$t_u = 111 \text{ seconds} = 1.85 \text{ minutes} \quad (4.6)$$

Using p_u to represent the fraction using the unmetered freeway ramp,

$$p_u = 50 + \frac{50\,(0 + 0.5\,(1.85))}{\sqrt{\left(0 - \frac{1.85}{2}\right)^2 + 4.5}} = 70\% \quad (4.7)$$

The assignment model infers from the measurements that 70 percent of the ramp candidates use the ramp in the unmetered scenario.

The total volume of ramp candidates may be inferred from the following:

Vc = Ramp Candidate Volume

$$Vc = \frac{\textit{Volume selecting ramp}}{(0.01)\ \textit{Percentage selecting ramp}} \quad (4.8)$$

$$Vc = \frac{700}{(0.01)\,(70)} = 1000 \text{ v/hr} \quad (4.9)$$

Figure 4-10. Example demonstrating the interaction of ramp metering requirements, diversion impacts, and ramp storage requirements (continued).

3. ***(continued)***

The ramp candidate volume using the surface streets (V_{cu}) and the local surface street traffic (V_L) is obtained as follows:

$$V_{cu} = (1-p_u)\,(1000) = 300 \text{ v/hr} \tag{4.10}$$

$$V_L = V_{su} - V_{cu} \tag{4.11}$$

$$V_L = 800 - 300 = 500 \text{ v/hr} \tag{4.12}$$

The diversion fraction p_m under metering conditions is computed as follows:

$$p_m = \frac{V_m}{V_{cu} + V_u} \tag{4.13}$$

$$p_m = \frac{500}{300 + 700} = 0.5 \tag{4.14}$$

To obtain an appropriate value for p in equation 4.2, multiply p_m by 100.

Using p_m = 50 percent, equation 4.2 is used to obtain t_M, the time difference between the paths under metering conditions. Solution of this equation leads to:

$$t_M = 0 \tag{4.15}$$

Now compute the ramp delay time, t_{RD}, required under metering conditions to achieve the 50 percent diversion required under metering conditions. This is given by:

$$t_{RD} = t_u - t_M + t_{sd}$$
$$t_{RD} = 111 - 0 + 32 = 143 \textit{ seconds} \tag{4.16}$$

4. <u>**Compute the Storage Requirement**</u>

$$N_S = V_m\, t_{RD} \tag{4.17}$$

Consistent units must, of course, be used for V_m and t_{RD}. Using the hours-to-seconds conversion factor of 3600:

$$N_S = \left(\frac{500}{3600}\right)(143) = 19.86 \text{ or } 20 \text{ vehicles}$$

It is prudent to incorporate a safety factor (say 30 percent) to allow for peak hour, day-to-day variations, and to allow for errors in the traffic data and traffic assignment model.

Thus, storage for 26 vehicles (20 x 1.3) is required.

An allowance of 26 feet per stored vehicle is commonly used. The storage space requirement is:

26 (26) = 676 feet

This may be accomplished using either single- or dual-lane meters. Additional space may be required between the tail of the queue and the upstream non-ramp traffic stream. This is discussed later in the section.

Figure 4-10. Example demonstrating the interaction of ramp metering requirements, diversion impacts, and ramp storage requirements (continued).

Table 4-17. Procedure for establishing pretimed metering rates for systemwide ramp metering -pretimed.

Step 1
Using peak period count data, develop a balanced flow diagram of the freeway network as illustrated in figure 4-11.

Step 2
Identify the capacity of freeway sections downstream of entry ramps.

Step 3
Identify the capacity deficiencies of the network sections in Step 2.

Step 4
Identify the entry ramp with the largest downstream capacity. This ramp is termed Ramp A for purposes of illustration.

Step 5
Compute the metering rate for Ramp A required to eliminate the capacity deficiency of the downstream mainline section. If this deficiency cannot be eliminated, use the minimum feasible metering rate. Identify the level of diversion and check storage and equilibration.

Assign the diverted traffic to the next downstream ramp, if appropriate.

Step 6
Assign the diverted traffic to the next downstream ramp (or to other ramps) as appropriate. Recompute the new mainline and ramp volumes for ramps downstream of A. Compute capacity deficiencies.

Step 7
If the largest remaining deficiency has moved from Ramp A to another mainline section, repeat Steps 4 through 6 for that section. Continue this process until no deficiencies remain or until metering rates cannot be further reduced.

Step 8
If the largest remaining deficiency is still at Ramp A, then perform Step 5 for the ramp upstream of Ramp A. Perform Step 6 if the metering rate for that ramp cannot be reduced, then reduce the metering rate for the next upstream ramp and perform Step 6. Select the metering rate (subject to constraints) to correct the largest ramp deficiency between the metered ramp and Ramp A. Continue this process until one metering rate has been changed or until the test at all upstream ramps has been performed.

Applications of Ramp Metering Types

As each ramp metering type may suit certain applications, identify the objectives in each case. Table 4-19 provides general guidelines for the selection of metering types. As an urban area becomes more complex and congested, the number of objectives at each ramp generally increases.

Ramp Design Requirements

Ramp Storage

Adequate storage space must exist at metered ramps to assure that queues of waiting vehicles win not seriously impact non-freeway traffic. Queued ramp traffic should not block frontage roads or surface streets. Often, *queue detectors* are installed on the ramp just downstream of the frontage mad, surface street, or other critical point. When queues build up across these detectors, vehicles are metered at a higher rate to avoid spillback of congestion into the critical area.

In many cases, adequate ramp storage can only be obtained by using 2 lanes. Storage requirements depend on:

- Ramp demand volumes and metering rates,
- Ramp entry flow patterns (e.g., platoons caused by nearby signals upstream of the ramp may increase storage requirements),
- Availability of surface street storage, and
- Precision of queue control. Accurate queue control by rapid metering rate adjustments may reduce storage requirements.

CALTRANS has developed ramp meter design guidelines that include the storage requirements shown in figure 4-13 (12). Others have

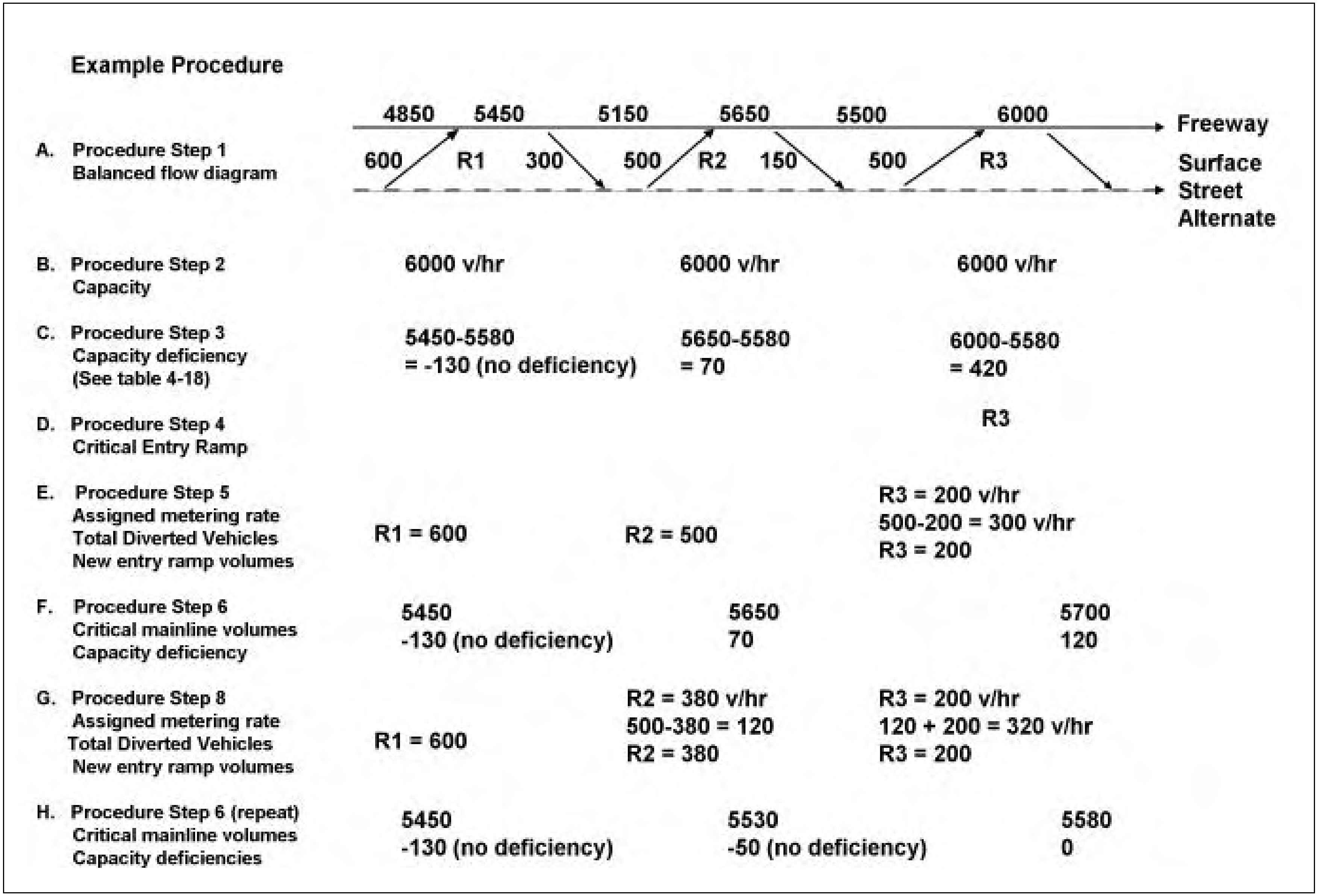


Figure 4-11. Example for use of procedure for pretimed metering rates for systemwide ramp metering.

Table 4-18. Example of use of procedure for pretimed systemwide ramp metering.

Example Procedure A
(Table 4-17, Step 1)
Balanced flow diagram developed from count data.

Example Procedure B
(Table 4-17, Step 2)
Capacity calculated for potentially critical mainline sections.

Example Procedure C
(Table 4-17, Step 3)
The maximum desired volume on the potentially critical freeway sections is established as:

V/C = 0.93
0.93 x 6000 = 5580

Example Procedure D
(Table 4-17, Step 4)
Comparison of deficiencies identifies ramp R4 as the critical entry ramp.

Example Procedure E
(Table 4-17, Step 5)
Complete correction of the deficiency at R3 requires a metering rate of:

500 - 420 = 80 v/hr

This is below the value of 200 v/hr, considered a minimum for single lane meters. Therefore, establish the metering rate of R3 at 200 v/hr. The storage requirements and equilibration procedures illustrated in figure 4-11 should be applied to check for feasibility. This example assumes that these requirements are met. If they are not satisfied, increase the assigned metering rate and repeat the procedure.

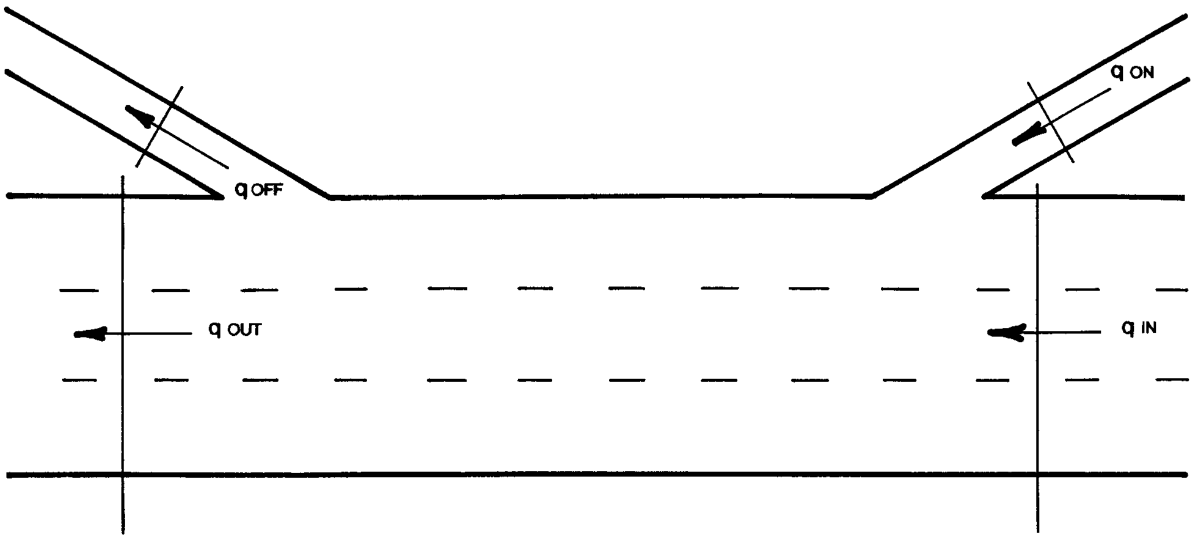
Example Procedure F
(Table 4-17, Step 6)
Substituting the assigned metering rate of R3, adjust the volumes of the potentially critical mainline sections downstream of R3. Recompute the capacity deficiency for this section.

Example Procedure G
(Table 4-17, Step 8)
Since the largest deficiency remains at the section downstream of Ramp R3, use Step 8 of the procedure. This step calls for metering to be used at Ramp R2. Deficiency correction requires a metering rate of:

500 - 120 = 380 v/hr

Metering at R2 results in 120 vehicles diverted fro m Ramp 2 to Ramp 3 and a total of 320 vehicles at R3. Storage and arterial equilibration must be checked at R2 and equilibration must be rechecked at R3.

Example Procedure H
(Table 4-17, Stop 6 repeated)
In this example, the mainline volumes are comput ed and the remaining capacity deficiencies are satisfied.



1. CAPACITY CONDITION

$P_{it} \geq P_{THRESH_i}$

WHERE

P_{it} = AVERAGE OCCUPANCY ACROSS THE DOWNSTREAM DETECTOR OVER THE PREVIOUS 1-MINUTE PERIOD, AND

P_{THRESH_i} = THE OCCUPANCY THRESHOLD FOR THE DOWNSTREAM DETECTOR STATION THAT DEFINES WHEN SECTION i IS OPERATING NEAR CAPACITY. (THESE THRESHOLDS ARE PARAMETERS THAT CAN BE TUNED FROM THE OPERATOR'S CONSOLE FOR EACH FREEWAY SECTION)

2. VEHICLE STORAGE CONDITION

$q_{IN_{it}} + q_{ON_{it}} \geq q_{OUT_{it}} + q_{OFF_{it}}$

WHERE

$q_{IN_{it}}$ = VOLUME ENTERING SECTION i ACROSS THE UPSTREAM DETECTOR STATION DURING THE PAST MINUTE,

$q_{ON_{it}}$ = VOLUME ENTERING SECTION i DURING THE PAST MINUTE FROM THE EXIT RAMP,

$q_{OUT_{it}}$ = VOLUME EXITING SECTION i ACROSS THE DOWNSTREAM DETECTOR STATION DURING THE PAST MINUTE, AND

$q_{OFF_{it}}$ = VOLUME EXITING SECTION i DURING THE PAST MINUTE ON THE EXIT RAMP.

Figure 4-12. Conditions for bottleneck identification.

Table 4-19. General guidelines for types of ramp metering.

Application	Pretimed Local	Traffic-Responsive Local	Pretimed Systemwide	Traffic-Responsive Systemwide (Note 1)
1. Achieve smoother flow at merge (safety improvement - preserve merge capacity)	Applicable	Applicable	Applicable	Applicable
2. Spot congestion problems - sufficient control for one meter to satisfy	Applicable if congestion time period stable	Applicable	Applicable	Applicable
3. Congestion requiring control distributed over several meters	Not Applicable	Not Applicable	Applicable if congestion time period stable	Applicable
4. Scheduled special events	Applicable if one meter can satisfy and congestion time period stable	Applicable if one meter can satisfy	Applicable if congestion time period stable (Note 2)	Applicable
5. Highly variable mainline demand	Not Applicable	Applicable if one meter can satisfy	Not Applicable	Applicable
6. Congestion due to spillback from exit ramp onto mainline	Applicable if one meter can satisfy and congestion time period stable	Applicable if one meter can satisfy	Applicable if congestion time period stable	Applicable
7. Congestion due to incidents	Not Applicable	Applicable, but systemwide preferred	Not Applicable	Applicable
8. Congestion due to construction	Not Applicable	Applicable, but systemwide preferred	Applicable (Note 2)	Applicable
9. Use in combination with other controls:				
• Closure	Unlikely to be Applicable	Unlikely to be Applicable	Applicable	Applicable
• CMS	Not Applicable	Limited Applicability	Not Applicable	Applicable
• Route Guidance	Not Applicable	Not Applicable	Not Applicable	Applicable
10. Backup mode	Backup to Traffic - Responsive - Local	Backup to Traffic - Responsive - Systemwide	Backup to Traffic - Responsive - Systemwide	Not Applicable

Note 1: Assume that pretimed systemwide and local traffic-responsive modes are available.
Note 2: Applicable only if rates and times are alterable through communications.

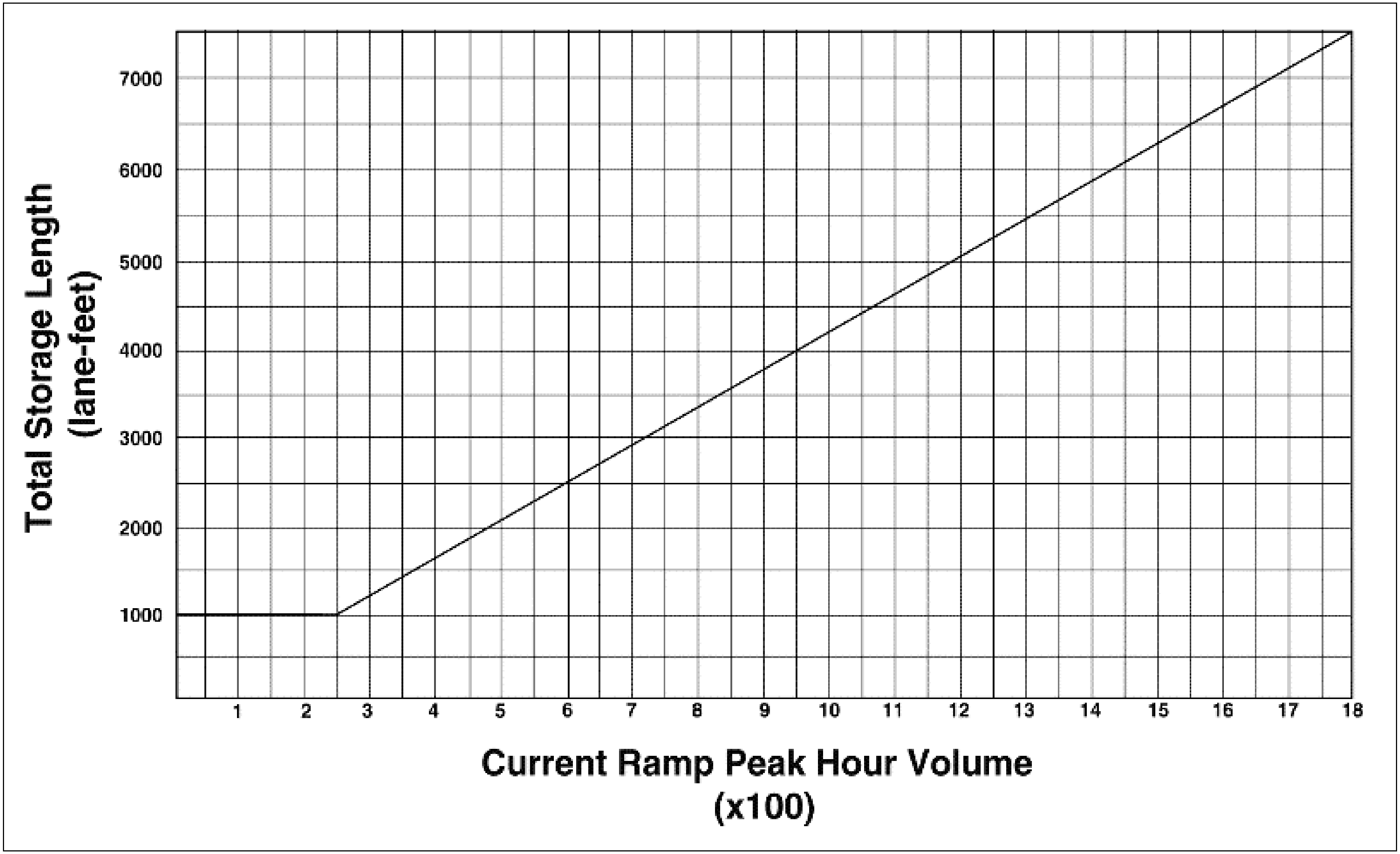


Figure 4-13. Recommended ramp meter storage.

recommended less restrictive conditions. Reference 19, for example, describes the following criteria:

> "... metering is *considered feasible if the available* ramp storage *exceeded 10* percent of *the* premetered peak hour volume. If *there is* storage for 5 *percent to* 10 *percent of the* peak volume, *metering may still be feasible; but additional analysis is* required *and possibly* mitigating measures (e.g., *additional ramp lane, queue detection, etc*.). Ramp metering is not *considered feasible if* the storage is *less than* 5 *percent of the premetered peak* hour *volume.* "

Acceleration Lane Characteristics

The location of the meter relative to die merge area must provide sufficient distance for vehicle acceleration. Reference 12 gives examples of representative designs. A merge detector may optionally be used to inhibit metering when a vehicle occupies the merge detector.

Ramp Metering in Conjunction with Transit and Paratransit

A priority system of ramp metering may encourage single occupant vehicles (SOV) to use public transit or carpools. This concept provides preferential treatment to buses and/or carpools so that they enter the freeway with little or no delay, while other vehicles must wait. Subsequent sections of this chapter describe a number of bus/carpool priority controls.

Implementation of Ramp Meters

Table 4-15 shows the types of metering arrangement s that have been implemented. Each of these arrangements can incorporate HOV bypass lanes (section 4.6).

Table 4-20 shows the required, or in some cases optional, components for implementing ramp meters. Figure 4-14 shows a typical ramp metering equipment layout, while figure 4 -15 shows a typical installation.

Most current metering systems use:

- The demand detector to initiate green, and
- The passage detector to return the signal to red.

An alternate approach, often used in earlier systems, employs a fixed green (or green -plus-yellow) interval of approximately 3 seconds, followed by red for the remainder of the ramp meter cycle.

Metering Operation Overrides

The operations initiated by the check -in detector, check-out detector, merge detector, and queue d etector may become disturbed in the event of equipment failure or a change from the expected ramp flow pattern. For example, a vehicle may stop prior to detection by the check-in detector *(short stop*). The way to handle these irregularities depends on the specific layout of the ramp detectors. Reference 22 provides examples of override techniques.

The ramp metering queue detector override approach becomes particularly important and often determines potential ramp metering benefits. Ramps with insufficient storage space may frequently initiate the override option. When this happens, the ramp meter may operate intermittently, leading to a reduction of metering benefits. It may also lead to flow irregularities near the ramp entrance. In some cases, TV monitoring and manual metering rate adjustment is used in lieu of queue detectors.

Closure

Closure of an entrance ramp represents the most restrictive form of metering i.e., the metering rate is zero. Therefore, it is usually the least popular and is subject to considerable public opposition. Nonetheless, the procedure has been successfully implemented in Houston. Closure has seen effective use as a single -spot improvement on freeways in Beaumont and Corpus Christi, Fort Worth and San Antonio. Closure may mitigate serious weaving problems. Railroad crossing gates are often used for control, and trail blazers may be used to delineate an alternate route.

Although this form of control can provide operational benefits, it lacks flexibility. If applied inappropriately, it can result in underuse of freeway capacity, and overloading of alternate routes.

Application

Because of its limitations, use ramp closure only on a limited basis when metering proves inadequate. Table 4-21 provides examples of entry ramp closure applications.

Methods

Methods of entrance ramp closure include:

- Manually placed barriers,
- Automated barriers,
- Fixed signing, changeable message signing, and signals.

Experience in Detroit and Los Angeles indicates that signs alone cannot effect a positive entrance ramp closure (23, 24). Automated barriers allow automatic closure and opening, which increases the flexibility of this control. It is also recommended that devices warning of impending closure with automatic

Table 4-20. Ramp metering components.

Component	Description
Ramp metering signals	Two standard signal displays: • 3-section (red-yellow-green) • 2-section (red-green) The MUTCD advises a yellow change interval only when vehicles are released in groups (*platoon metering*) (20).
Local controller	Current designs often use a type 170 controller (21). Several cabinet arrangements (Model 336C, 334) support ramp metering functions. Special ramp meter control software programs are used in the type 170 controller.
Warning sign	MUTCD requires one or 2 advance ramp control warning signs with flashing beacon. Beacon flashes when ramp metering is active (20).
Check-in (demand) detector	A check-in (or demand) detector is placed on the approach to the ramp metering signal, so that the signal remains red until a vehicle is detected at the stopline, as shown in figure 4-14. When a vehicle is detected by the check-in detector, the ramp metering signal changes to green, provided that minimum red time has elapsed. To minimize the sensitivity of ramp meter operation to the stopping or queuing position of approaching vehicles, 2 or more demand detectors in one lane are sometimes used (12).
Check-out (passage) detector	Many systems use a check-out (or passage) detector to assure single-vehicle entry. After passing the ramp metering signal, a vehicle is detected by the passage detector, installed just beyond (about 8 ft (2.4 m) past) the stopline. When the passage detector senses a vehicle, the green interval terminates. In this way, the green interval allows the passage of only one vehicle.
Queue detector	Many ramp metering systems use one or more queue detectors to prevent ramp traffic from blocking frontage roads or surface streets. Place the queue detector in advance of the ramp metering signal: • At a strategic point on the ramp • On the frontage road When the filtered occupancy of the queue detector exceeds a prestored threshold (thus indicating the presence of the queue on this detector), the ramp meter responds by: • Increasing the metering rate • Terminating metering
Merge detector	A detector is sometimes used to sense the presence of vehicles in the primary merging area of the ramp and freeway mainlines.

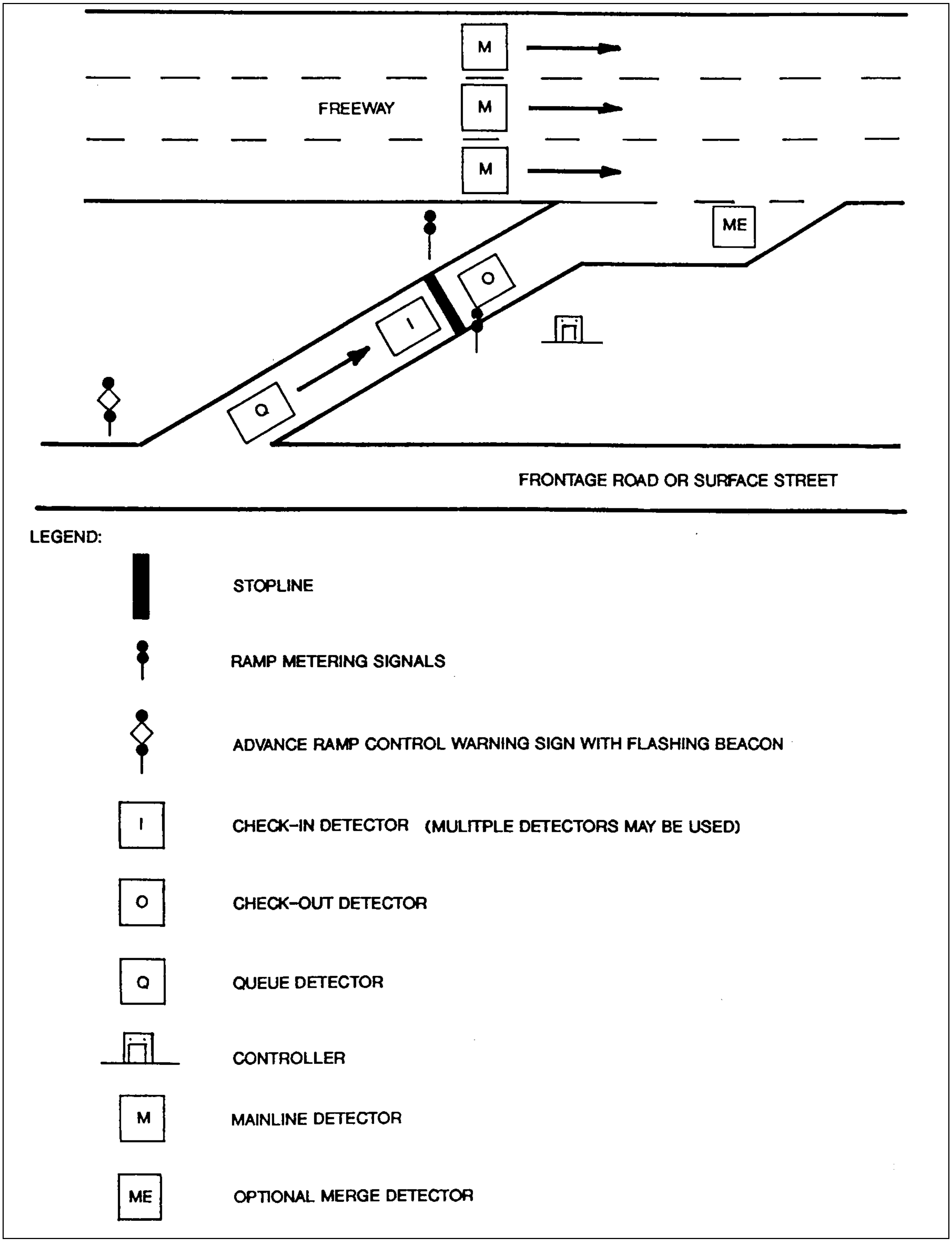


Figure 4-14. Typical entrance ramp metering system layout.

Figure 4-15. Ramp metering signals.

barriers be provided. Manual placement of barriers usually suits short-term or trial control projects.

Exit Ramp Control

Because of limited opportunities for effective application, exit ramp control seldom sees use for freeway traffic control. In many situations, exit ramp control may counter the objective of safe and efficient freeway operations. If used, it only applies in circumstances where motorists can reach destinations with alternate exits.

Exit ramp control consists of:

- Exit ramp metering, and
- Exit ramp closure.

As with entrance ramp closure, to avoid motorist confusion, exit ramp closure should normally be implemented on a scheduled basis. Exit ramp metering may increase safety hazards and congestion on freeways, while possibly reducing congestion on adjoining surface streets. Since the total effect often proves negative, its use may be inconsistent with the primary purpose of freeway traffic control.

Exit ramp closure can effectively reduce safety hazards and congestion caused by excessive weaving between closely spaced ramps and long queues on exit ramps. Also, exit ramp closure downstream of a lane drop can encourage traffic to leave the freeway at exit ramps upstream of the lane drop. This decreases demand downstream of the lane drop. However, as with entrance ramp closure, exit ramp closure may prove unacceptable because of the increased travel created for some motorists.

Benefits

Ramp metering offers several direct benefits. It generally provides a higher and more predictable level of service on the freeway. Ramp metering also improves the efficiency of freeway operation by:

- Maintaining non -congested freeway flow, or
- Reducing freeway congestion.

It can also improve merging safety, particularly at entrance ramps with inadequate sight distances. Ramp metering smoothes the input of traffic over short periods of time

Table 4-21. Ramp closure applications.

Application	Mitigation
Adequate storage not available for metering	Closure of entrance ramp eliminates storage problem.
Traffic demand on freeway immediately upstream of entrance ramp at capacity, and alternate route with adequate capacity available	Closure of entrance ramp prevents demand from exceeding capacity on immediately downstream freeway section. Diverts traffic demand to alternate route. Applicable when required metering rate is impractically low. May prove more practical to close ramp.
As a response element in an incident response plan or to prevent build-up of unacceptable conditions	Can limit vehicle exhaust emissions in covered roadway sections under various conditions. For example, Boston Central Artery/Tunnel project plans to use entry ramp closure as part of its incident response plans.

Table 4-22 describes the benefits of traffic-responsive metering in a number of metropolitan areas (25).

The benefits offered by pretimed metering versus no control include:

- Increased mainline speeds (reduced travel time)
- Higher service volumes,
- Less delay,
- Safer merging operations, and
- Reduced user costs.

The *controllability index* measures how much traffic-responsive control can vary the metering rates and is defined as follows (14):

$$\text{Controllability Index} = \frac{I_{pc} - I_{min}}{I_{min}}$$

Where:

I_{PC} Total metered input with pretimed control
I_{min}, Total metered input when minimum metering rates are used

Beyond pretimed metering, the incremental benefits gained from traffic-responsive metering (local or systemwide) depend on the following factors (14):

- *Var1iations in overall traffic demand pattern* - Traffic demand on the freeway and entrance ramps exhibits 2 types of variations:
  - Shift in demand level, and
  - Short-term fluctuations.

  The larger these variations, the greater the potential exists for benefits from traffic-responsive metering.
- *Mainline capacity reductions* - Reductions in mainline freeway capacity result from accidents, traffic incidents, and adverse weather conditions. As the frequency and impact of these capacity-reducing factors increase, the need for traffic-responsive metering (to cope with variations in available capacity) grows.

Systemwide traffic-responsive metering is often implemented in conjunction with the installation of a multipurpose surveillance and control system based on traffic detectors. When implemented in this way, the incremental cost for systemwide traffic-responsive metering (as compared with pretimed metering) is nominal.

As mainline volume increases in the peak period, and as demand approaches capacity for an increasing number of mainline sections, demand -responsive control becomes increasingly important in the time period before peak demand. Demand -responsive control during this period can prolong the period of uncongested flow. Figure 4 -16 shows an example of the benefits of traffic-responsive local and systemwide metering over pretinied metering (14).

Freeway -to-Freeway Ramp Metering

This control aims to improve traffic conditions downstream of major merges. The technique has been applied in Minnesota, California, Texas and Washington. Freeway- to-freeway metering has

Table 4-22. Summary of ramp metering benefits.

Location	"Before" Speed		"After" Speed		Change in Travel Time (%)	Change in Accident Rate (%)	Change in Volumes (%)
	mi/hr	km/hr	mi/hr	km/hr			
Portland, OR	16	28	41	66	- 61	- 43	N/A
Minneapolis/St. Paul, MN	34	55	46	74	N/A	- 27	+ 32
Seattle, WA	N/A	N/A	N/A	N/A	- 48	- 39	+ 62
Denver, CO	43	70	50	81	- 37	- 5	+ 19
Long Island, NY	29	47	35	56	- 20	N/A	0

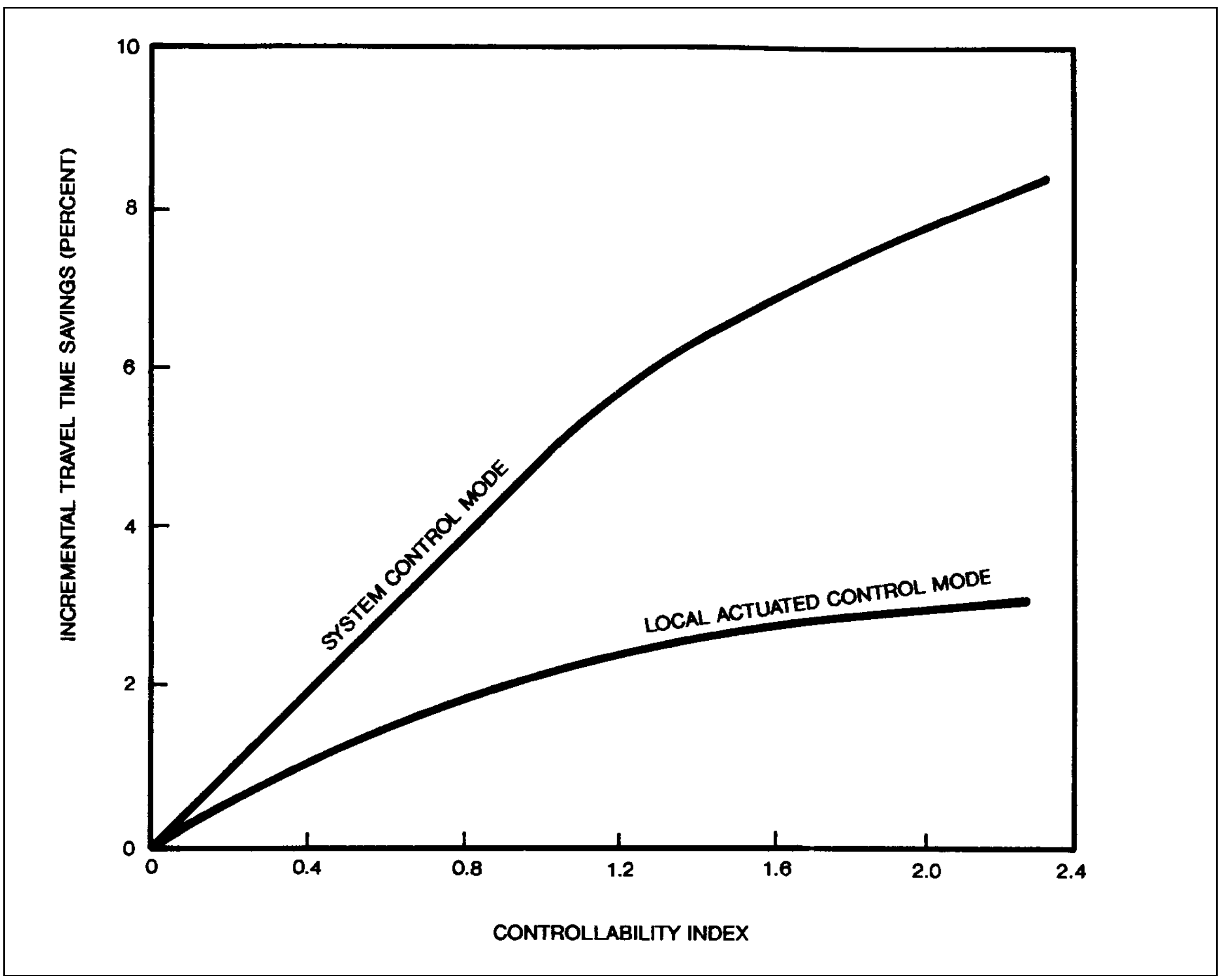


Figure 4-16. Relationship between the controllability index and incremental travel-time savings.

generally improved flows downstream of the merge. Jacobson and Landsman offer guidelines for the selection of appropriate sites (26). These are summarized in table 4 -23.

Gordon quantifies reduction in overall delay from diversion and describes how to estimate ramp waiting time and storage space requirements (27).

Public Acceptance

The success of ramp metering depends on public acceptance to overcome the effects of additional:

- Ramp delay, and
- Surface street volumes and delays resulting from diversion.

To initiate a ramp metering system, inform the public as to:

- The basic reasons for the system
  - Severe congestion,
  - Inefficient freeway operation, and
  - A realistic expectation of the system's benefits (reduced delays and accidents) and costs.
- The alternative choices available.

Stress the system's equitable allocation of available capacity. Closely monitor and fine -tune the operation to achieve these objectives, and keep the public informed.

4.3 Mainline Control

Mainline control concerns the regulation, warning, and guidance of traffic on the main freeway lanes to achieve:

- Improved uniformity and stability of traffic flow and forestall congestion,
- Reduced potential for rear -end collisions if congestion does develop,
- Incident management and recovery from congestion,
- Diversion of freeway traffic to alternate routes to better use corridor capacity, and
- Increased directional capacity using reversible lanes.

Mainline control typically employs one or more of the following means:

Table 4-23. Guidelines for freeway-to-freeway ramp metering.

- Consider locations where recurrent congestion is a problem or where route diversion should be encouraged
- Consider route diversion only where suitable alternative routes exist
- Avoid metering twice within a short distance
- Avoid metering single lane freeway-to-freeway ramps that feed traffic into an add-lane
- Do not install meters on any freeway-to-freeway ramp unless analysis ensures that mainline flow will be improved so that freeway-to-freeway ramp users are rewarded
- Install meters on freeway-to-freeway ramps where more than one ramp merges together before feeding onto the mainline, and congestion on the ramp occurs regularly (4 or more times a week during the peak period)
- If traffic queues that impede mainline traffic develop on the upstream mainline because of a freeway-to-freeway ramp meter, then the metering rate should be increased to minimize the queues on the. Upstream mainline, or additional storage capacity should be provided
- Freeway-to-freeway ramp meters should be monitored and be controllable by the appropriate traffic management center
- Whenever possible, install meters at locations on roadways that are level or gave a slight downgrade, so that heavy vehicles can easily accelerate. Also, install meters where the sight distance is adequate for drivers approaching the meter to see the queue in time to safely stop.

- Driver information systems,
- Variable speed limit signs,
- Lane closure and lane control,
- Coordinated controls for incident management
- Mainline metering,
- Freeway-to-freeway ramp metering, and
- Reversible lane control.

Driver Information Systems

As a form of mainline control, driver information systems primarily advise motorists of freeway conditions ahead. They provide real -time information to enable motorists to drive more safely and divert to alternate routes, if necessary. Chapter 10 describes these technologies.

Variable Speed Limit Signs

The variable speed limit signs used by some operating agencies (often toll facilities) warn motorists to reduce speed due to weather conditions or construction. These signs can assist in incident management.

Lane Closure and Lane Control

Lane closure prohibits entry to one or more freeway mainlines, and can increase efficiency and safety during periods of reduced capacity. Closure usually applies to:

- Advance warning of lane blockage,
- Improved entrance ramp merging operations, and
- Tunnel control.

In addition, lane control signals (see chapter 10) can assist in reversible lane control. HOV facilities using reversible lanes exemplify this application.

Mainline Metering

Mainline metering can accomplish the following objectives:

- Deter traffic from using the freeway, Particularly in bottleneck areas,
- Smooth traffic flow through a bottleneck,
- Provide more equitable distribution of delay penalties with respect to motorists entering at metered ramps, and (26)
- Minimize congestion -induced emissions in environmentally sensitive areas (such as tunnels).

Mainline metering can cause queues on the mainline, which may be met by significant community opposition.

Toll facilities often function as mainline meters. The principal example of mainline metering in the U.S. is westbound I-80 at the San Francisco-Oakland Bay Bridge (26). Shown in figure 4 -17, this installation places the mainline meters just downstream of a 22-bay toll plaza (26). Westbound traffic approaching the San Francisco-Oakland Bay Bridge passes through the toll plaza and is then metered to narrow the 22 lanes of traffic into 4 lanes as efficiently as possible. HOV lanes allow HOVs to bypass the traffic queues.

Meters have smoothed traffic flow at the merge and helped heavy vehicles attain normal speed before reaching the uphill bridge approach. Prior to metering, downsteam throughput on the bridge averaged 8200 to 8300 v/hr. Throughput after metering averaged 9500 v/hr (28). Public acceptance of the long queue delays has been good (26).

Reversible Lane Control

Reversible lanes change the directional capacity of a freeway to accommodate peak directional traffic demands. To warrant reversible lanes, peak -period traffic volumes must exhibit and/or be predicted to exhibit significant directional imbalance (e.g., 70/30 percent). If warranted, reversible lanes can use right-of-way more efficiently and economically.

Reversible lanes have been designed and implemented on some freeways (e.g., Kennedy Expressway in Chicago and Interstate 5 in Seattle.

The Kennedy Expressway has a 7 -mile, 2-lane reversible roadway in the median strip. The reversible lanes serve as express lanes and have only one access between their terminals for outbound-only flow. The outer roadways have 3 to 4 lanes and operate in only one direction.

Interstate 5 on the northern approach to Seattle has a 7.5-mile reversible -lane section in the median. However, the reversible lanes are not express and have several interchange points. The major features of this system include (29):

- The only transfer points between the reversible-lane section and the outer roadways are at the 2-ends of the section. The other 7 interchanges are direct transfers between the reversible lanes and the arterial street system.
- The ramp connections to the reversible roadway are controlled by devices that include:
  - Horizontal shear gates,

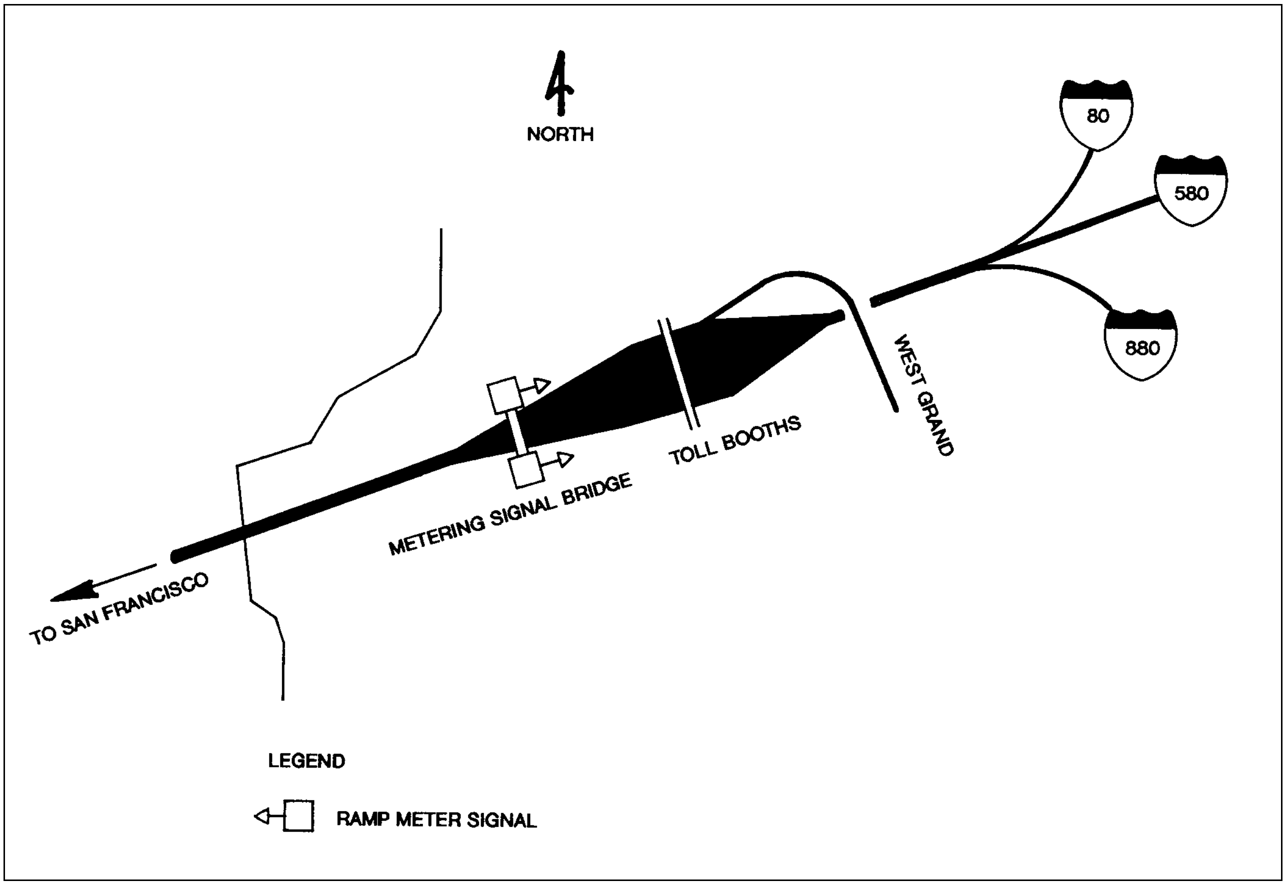


Figure 4-17. Mainline meter on 1-80, Oakland, CA (westbound direction).

- Vertical-lift gates, and
- Changeable message signs to inform the motorist of the direction in which the roadway is operating.

These devices can be activated either locally at each ramp site, or remotely from a central control office adjacent to the freeway.

- Lane reversal is usually performed at the same time 7 days a week, so that motorists can become familiar with the system.

4.4 Diversion to Surface Streets

Restrictive metering strategies attempt to reduce entrance ramp demand and generally cause some diversion of trips to other parallel routes, This maximizes use of total *corridor* capacity. For some trips, ramp metering makes the freeway less attractive than:

- Available alternate routes,
- Using the freeway at another time, or
- Transferring to another mode of transportation.

In this way, ramp metering helps distribute the total traffic load among all corridor routes and modes and steadies demand in peak periods.

Diversion may also be initiated by changeable message signs on the freeway or near freeway entries which advise motorists of delays on the freeway.

To be successful, alternate route capacities must accommodate diverted traffic. Corridor capacity on the surface streets may increase by:

- Retiming traffic signals,
- Providing a traffic-responsive signal system,

- Use of parking lanes for left-turn lanes,
- Reversible lane operation, and
- Geometric improvements.

Diversion strategies tend to cause motorist delays at ramp queues or on the freeway mainline. The motorist's choice to divert or accept ramp delays depends on:

- Destination,
- Driving preference, and
- Perceived difference in travel times between routes.

The analyst can use a number of models to estimate the extent of diversion. Many of them require origin/destination data, which is often difficult to collect.

Equation 4.2 formulates a simple traffic assignment model discussed by Moskowitz (30).

$$p = 50 + \frac{50\,(d + \frac{1}{2}t)}{\sqrt{(d - \frac{1}{2}t)^2 + 4.5}} \qquad (4.2)$$

Where:

p = Percentage using the freeway

d = Distance saved by the freeway (mi)

t = Time saved by the freeway (minutes)

Figure 4-18 plots equation 4.2 for the case where freeway travel distances equal surface street routes.

Huchingson and Dudek provide data that generally corroborates the Moskowitz data (31). A later study, however, indicates that higher levels of time saved on the alternate route are required to achieve a given percentage diversion (32).

Other studies also describe assignment of traffic between a freeway and its frontage road (33-35).

Diversion models such as equation 4.2 imply that an equilibration process occurs. The freeway corridor demand divides between die freeway and surface street alternates at the appropriate ratio to satisfy the model. For example, entrance ramp metering decreases the value of t in equation 4.2. The decrease represents the difference between the time in the ramp queue and the increase in travel time on the surface streets resulting from additional diversion.

4.5 Incident Management

The *FHWA Freeway Incident Management Handbook* represents an important incident management source (10). Much of the material in this chapter is drawn from this reference.

Incident management is the coordinated, preplanned use of human and technological resources to restore full capacity after an incident occurs, and to provide motorists with information and direction until the incident is cleared. Incident management programs vary widely in cost and sophistication, but all share the common elements discussed in this section.

This section uses the following definitions:

- Incident - Any non-recurrent event that causes a reduction in roadway capacity or abnormal increase in demand.
- Incident management - The spectrum of activities involved in detecting, responding to, and clearing roadway incidents.

The Problem

Roadway Capacity Reduction

The most common types of incidents cause capacity reductions as shown in table 4-9. The table illustrates the dramatic effects on roadway capacity caused by incidents that do not actually block traveled lanes.

Incident Frequencies

Table 4-24 shows typical incident frequencies in some major metropolitan areas (36, 37). Table 4-25 shows a summary of all types of incidents occurring on a 5-mile (8-kilometer), 12-lane section of Highway 401 in Toronto, carrying an Average Daily Traffic (ADT) of 270,000. The Toronto data indicates a rate of approximately 19 incidents per million vehicle miles. Other data shows from 40 to 200 incidents per million vehicle miles (per 1.6 million vehicle kilometers) (38).

Quantification

Studies have shown that delays to motorists increase geometrically with the time it takes to clear an incident. Based on data in Schrank et al., the estimated cost resulting from incidents amounts to over sixty million dollars each day (1). Incident congestion can lead to secondary accidents by causing unexpected stops or slowdowns. Another problem is increased danger to motorists, police officers, and other response personnel who are out of their vehicles as a result of an accident.

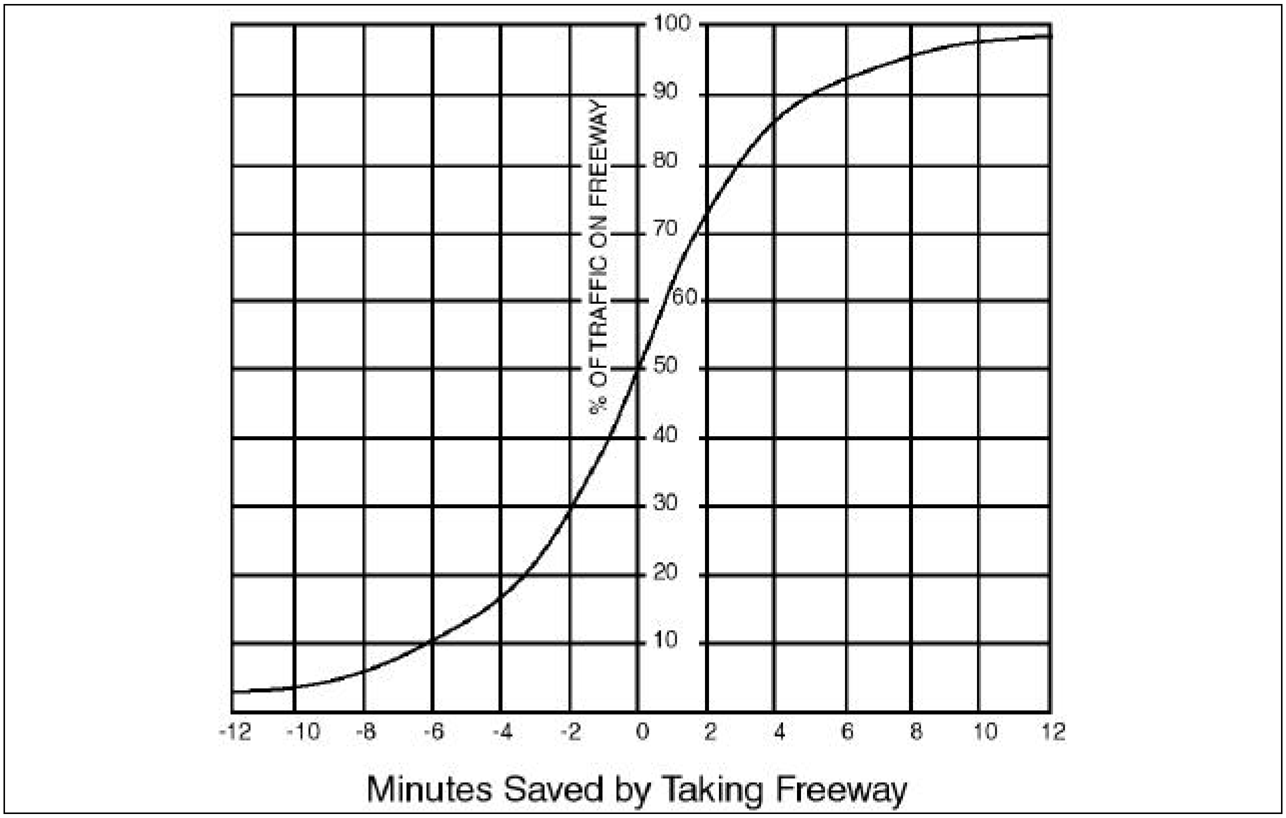


Figure 4-18. Equation 4.2 for the case of equal freeway and surface travel distances.

The magnitude of delay caused by any incident can be computed identifying demand volumes and remaining capacity during the incident and its duration. To quantify a given delay, traffic volumes and incident durations can be graphically represented as shown in figure 4 -7. The horizontal axis is a time-line indicating the occurrence of incident -related events and the overall duration of their impact on traffic flow. The vertical axis represents cumulative traffic volume (the sum of the vehicles passing any given point on the freeway in a defined period). The demand flow or volume is represented by the slope of Ll. When an incident occurs (Time A), the reduced roadway capacity (L2) is less than the demand flow because of a lane blockage. This reduced capacity remains in effect until the incident is cleared from the freeway (Time B). At that time, the queued traffic can begin to flow at getaway capacity (1-3) approaching the freeway's capacity. When the last vehicle in the queue reaches the normal flow speed and traffic resumes flowing at the demand volume (Time Q, the effects of the incident are over (39).

A number of factors determining the magnitude of incident-caused delay, which is represented by the shaded area in figure 4 -7. Only some of these factors can be influenced by freeway incident management techniques. Other factors, such as the freeway's capacity and demand flow, are fixed. Unless an incident occurs just before or at the end of a peak period or traffic is diverted during an incident, the demand flow rate is assumed to remain constant for the duration of the incident.

Two factors that can be influenced by incident management techniques are the reduced capacity past the incident and the incident's total duration. Effective onsite traffic management techniques optimize use of whatever freeway capacity remains after the incident. Graphically, this is represented in figure 4-19 by an increase in the slope of the reduced roadway capacity (L2) to create an improved flow rate L2'(10).

Another factor influencing total delay is the time from the moment the incident occurs to the time it is cleared from the freeway. This time interval (AB) can be expressed as the sum of the detection, response, and clearance times shown in figure 4 -7. Minimizing these times through efficient incident management (figure 4 -19) results in less total delay.

The Solutions

To be effective, incident management programs need to focus on ways to reduce:

Table 4-24. Incident frequencies.

City	Distance		Period	Lane Blocking Incidents Per Week	
	mi	km		Total	Per mi (km)
Houston	6	10	6:00 a.m. to 7:00 p.m.	13	2.2
Chicago	135	217	24 hours	360	2.7
Toronto	5	8	6:00 a.m. to 7:00 p.m.	17	3.4

Table 4-25. Incidents on section of highway 401, Toronto, June 8 - September 4, 1987.

Incident Severity	Incident Type						Total		Number Per Week
	Reportable Accidents		Non-Reportable Accidents		Non-Collision Incidents				
	Number	%	Number	#	Number	#	Number	%	
Shoulder Blocking	93	47	50	67	1332	93	1475	87	113
1 Lane Blocking	85	43	22	30	83	6	190	11	15
2 Lane Blocking	16	8	2	3	3	<1	21	1	2
>2 Lane Blocking	3	2	0	0	2	<1	5	<1	<1
Total	197	100	74	100	1420	100	1691	100	N/A

- The time to detect an incident,
- The time to identify the nature of an incident,
- The time to respond with appropriate personnel and equipment to deal with a particular incident,
- The time to clear an incident and restore roadway capacity, and
- Traffic demand during the incident through institution of a variety of traffic management measures.

The measures needed to achieve these reductions are discussed below.

Detection/Verification

Definitions include:

- *Detection* - Determining that an incident has occurred, and
- *Verification* - Determining the precise location and nature of an incident, as well as the display, recording, and communication of this information to the appropriate agencies.

Rapid detection is necessary to minimize the period of time during which roadway capacity is reduced by an incident. Proper verification is required to reduce the time required to deploy an appropriate response to the scene of an incident.

Table 4-26 lists the detection/verification techniques currently available, along with their respective advantages and disadvantages (10). The

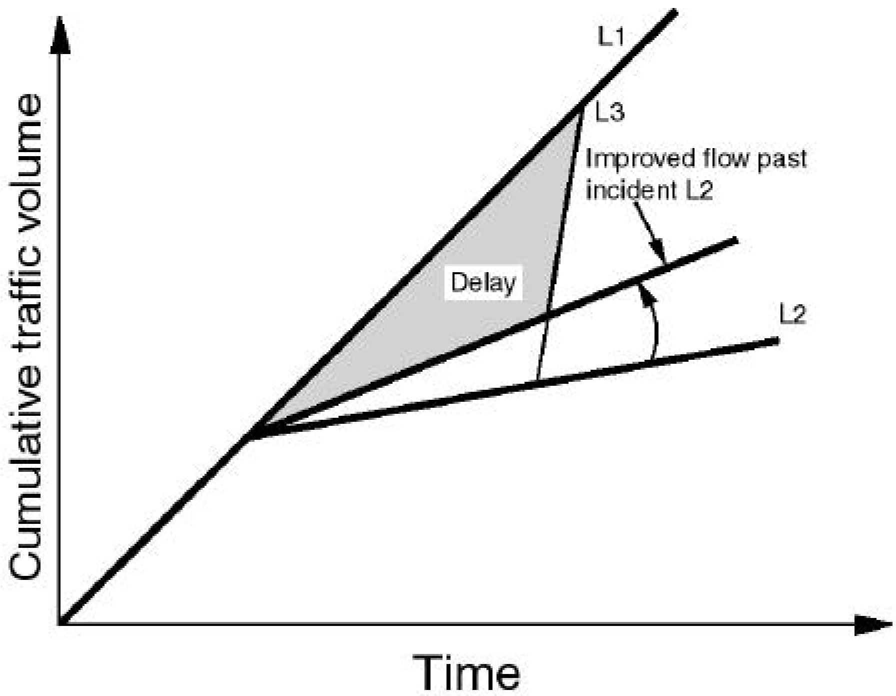


Figure 4-19. Delay reduction caused by increasing flow.

responsible incident management agencies must select techniques from this list that are most appropriate for their region and budget.

Electronic Monitoring

Since the early 1970s, various algorithms have been developed that attempt to identify incidents through analysis of mainline detector data. Two recent research reviews have been performed on this subject (40, 41). Algorithms developed to date require performance trade- offs among:

- Detection rate,
- False alarm rate, and
- Mean time to detect.

Chen and Chang categorize incident detection algorithms into classes A, B, C, and D, as shown in table 4-27 (40). The additional classes are identified by Gang -Len et al. (52).

Three algorithms currently used and specified for North American traffic systems are the California, APID, and McMaster Algorithms. Performance results among the algorithms generally prove difficult to compare. These algorithms generally identify the discontinuity in occupancy and/or speed between detector stations upstream and downstream of an incident. Congestion buildup upstream of the incident and the absence of congestion downstream of the incident causes the discontinuity.

A number of traffic operations centers believe that other methods, such as motorist cellular call -in and TV monitoring, provide incident detection:

- More rapidly,
- With a higher detection probability, and
- With a lower false alarm rate.

Table 4-26 shows some typical methods in this category.

Problems with the current algorithms are due in part to the need for calibration to the particular site, which in turn requires extensive data collection and analysis. Analysis procedures are frequently unclear and poorly documented. Thus, it often proves impractical for operations personnel to effectively use these algorithms.

In addition, the algorithms are limited by their inability to detect incidents when traffic flow is not sufficiently disturbed. This can often occur under light traffic conditions and for incidents on the shoulder.

Table 4-26. Detection/verification techniques.

Technique	Definition	Advantages	Disadvantages
Motorist Cooperative Media	Use of Emergency Telephones, Call Boxes, CB radio, Cellular Telephone (911)	Uses commercial information services	Is dependent on motorist input. Quality of information varies significantly.
Commercial Traffic Information	Use of organizations such as Shadow Network (commercial traffic reporting service)	Requires no cost to agency	May not be all inclusive. Is limited to resources of commercial organization.
Fleet Operators	Use of transit, taxi, and truck drivers to report and verify incidents	Requires no cost to agency. Provides large number of observers.	Relies on conscientious drivers
Patrol Vehicles	Use of vehicles patrolling for enforcement or maintenance purposes to report incidents to operations center	Serves both detection and verification functions. Uses ongoing patrol operations.	May require additional personnel/vehicles to maintain patrolling frequency during congested conditions. May delay detection due to non-uniform headway between patrols. May impede verification when congestion slows patrols.
Service or Courtesy Vehicles	Use of special vehicles that provide assistance for common breakdowns (fuel, flat tire, jump-start, push off roadways)	Can detect and verify incidents on its beat, although primarily a response technique	May provide sporadic reports. Depends on location of fleet vehicles.
Fixed Observers	Use of observers positioned in towers or buildings along the highway to report incidents	May be a useful interim measure. May be useful for detection and some verification.	Is labor-intensive. Provides limited area of coverage. Requires construction of towers or access to available observation sites. Is limited to mild weather conditions.
Aerial Surveillance	Use of helicopters and small planes to report incidents	May be useful for detection and verification	Requires large capital investment. Has high operations cost. Occasions delays in detection until plane passes over incident.

Table 4-26. Detection/verification techniques (continued).

Technique	Definition	Advantages	Disadvantages
Electronic Surveillance	Use of sensors placed along the roadway to detect the presence of vehicles and automatic processing of this data to determine congestion. Includes induction loops, magnetometers, sonic and wide-area detection systems.	Can continuously monitor entire roadway section. Provides rapid detection, especially in high-volume conditions.	Requires large capital investment. Has long lead time in designing and implementing system, and high maintenance costs. Cannot detect non-congestion-causing incidents.
Closed-circuit television (CCTV)	Use of television cameras placed along the roadway	Serves as effective verification technique, allowing rapid determination of nature of incident. Serves effectively in bridge/tunnel applications where length of required coverage is limited.	Requires large capital investment. Has high maintenance cost. Requires coaxial cable, fiber optic interconnect, or wireless communication.
Automatic Vehicle Identification (AVI)	Potential use of AVI-equipped vehicles to measure travel time between monitoring stations (Potential application)	Does not require sensors in roadway	Requires reasonably large sample of AVI-equipped vehicles (long travel times may be indicative of either incident or heavy volume)

Tables 4-28 and 4-29 describe 2 major classes of incident detection algorithms currently used in North America.

The FHWA and other agencies are currently performing research on incident detection algorithms.

CCTV Monitoring usually represents the fastest and most assured technique for detecting and confirming incidents. Full TV coverage usually requires camera placements at nominal spacing of 0.75 mi (1.2 km), depending on horizontal and vertical alignment. Complex interchanges may require additional cameras for coverage, as will nearby critical surface street intersections.

Table 4-31 describes camera characteristics in contemporary systems.

Medium- or large-scale freeway systems often require many cameras. Often, a separate monitor for each camera does not prove feasible due to space limitations at the Traffic Operations Center. Yet operators must be able to monitor each camera quickly and accurately. Thus, the number of monitors required will depend on the number of cameras in the system. Table 4 -32 shows techniques used singly or in combination that allow for this capability. Designers often specify videotape storage capability.

Chapter 9 describes techniques for communicating video information, including coded video transmission.

Response

Response is the activation, coordination, and management of the appropriate personnel, equipment, and communication links and motorist information media as soon as there is reasonable certainty that an incident has occurred.

Early and effective response is of critical importance to the incident management process. Timely response reduces the incident's duration, and

Table 4-27. Incident detection classes.

Class	Name	Description
A	Pattern Recognition Approach	California Algorithm is currently the most commonly-used algorithm in this class (42, 43). All Purpose Incident Detection (APID) Algorithm is receiving increased emphasis (44). These algorithms perform several tests on the traffic states for detector stations upstream and downstream of the incident.
B	Statistical Approach	A number of algorithms developed in this class; none used significantly in North America. Use statistical tests, time series analysis, or classical filter theory to model traffic flow. Incident detected when the processed traffic variable lies outside the normal range. Stephanedes and Chassiakos describe one such approach (45).
C	Catastrophe Theory Approach	This concept led to development of the McMaster University Algorithm, tested and currently undergoing refinement on Province of Ontario freeways (46, 47). This algorithm is based on classification of volume versus occupancy data into a number of regions defined by boundaries in the volume-occupancy plane (48-50).
D	Neural Network Approach	An emerging approach that uses concepts of neural networks to identify patterns in volume and occupancy data which identify traffic states associated with incidents (51).
E	Image Processing Coupled with Artificial Intelligence Approach	To overcome the limitations of loop detectors, research has been directed toward development of video-based, wide-scope sensors that can monitor traffic stream behavior (52). The approach entails tracking vehicle behavior within the camera's field of view to detect incidents or traffic flow that indicates incidents outside the camera's field of view. Varying levels of incident detection using image processing are being investigated using the INVAID system (UK), AUTOSCOPE (USA), and VIEWS (Europe). In Japan, an image processing incident detection method is also being investigated.
F	Dynamic System Model Approach	This approach uses algorithms that generally divide the freeway section under surveillance into discrete segments with traffic behavior being depicted through a dynamic traffic flow model (52). Incidents are identified through either abrupt changes or disturbances in the model parameters.

Table 4-28. All-purpose incident detection (APID) algorithm.

DEFINITIONS

OCC (i,t)	=	Average lane occupancy at detector station i for polling cycle t
OCCDF	=	Occupancy averaged across all lanes of the upstream detector station less the occupancy averaged across all lanes of the downstream detector station
OCCDF (i,t)	=	**OCC (i,t) - OCC (i+1, t)**
OCCRDF	=	Relative spatial difference in occupancies or the difference in occupancies between upstream and downstream detector stations divided by the occupancy of the upstream detector station
OCCRDF (i,t)	=	**OCCDF (i,t) / OCC (i,t)**
DOCC	=	Occupancy of the downstream detector station
DOCC (i,t)	=	**OCC (i+1,t)**
DOCCTD	=	Relative temporal difference in downstream occupancy that analyzes the data for more than one polling cycle
DOCCTD(i,t)	=	**OCC [(i+1, t-2) - OCC (i+1,t)] / OCC (i+1, t-2)**
SPD (i,t)	=	Average lane speed at detector station i for polling time t
SPDTDF	=	Relative temporal difference in speed
SPDTDF	=	(SPD (i,t-2) - SPD (i,t)) / SPD (i,t-2)

TEST GROUPS

The APID algorithm consists of a series of test groups. Of the enabled test groups, all tests must pass to declare an incident.

- High Volume Incident Detection Group

This series of tests establishes thresholds for the difference in occupancy between the detector stations, the ratio of the difference to the occupancy of the upstream station, and a minimum value of occupancy for the downstream station. The tests are:

OCCDF > th_id1
OCCRDF > th_id2
DOCC > th_id3

- Medium Volume Incident Detection Group

Under lower demand volume conditions, the following tests may be used. Speed is introduced as a test variable. The tests are:

OCCRDF > th_me_id1
SPDTDF > th_me_id2

- Persistence Test Group

This test requires the relative occupancy difference to be present for a minimum time.

OCCRDF > th_pt for a minimum of pst_test_period

- Compression Wave Test Group

The following conditions define the presence of a compression wave because the temporal occupancy difference at the downstream station is too short. The presence of a compression wave inhibits the incident detection algorithm. The use of this test reduces the false alarm rate.

DOCC > th_cw1
DOCCTD ≤ th_cw2 for cw_test_period

- Incident Clearance

The incident is declared cleared when

OCCRDF < tj_inc_clr

Table 4-29. McMaster algorithm.

Based on dividing volume versus occupancy phase plane into a number of regions or states as shown in figure 4 -20. Boundaries Vcrit, OCMAX, and G(OCC) divide the diagrams into fundamentally different flow conditions. OCMAX and G(OCC) are maximum values of uncongested occupancy. Vcrit distinguishes State 3 from State 4. If a detector is in State 2 or State 3 (congested), a test is performed on the	downstream detector. The situation is classified as shown in table 4 -30. Since publication of Gall and Hall, the volume occupancy phase plane divisions have been further refined (48). Hall at al. (1993) describes additional regions and also provides a different set of divisions (or templates) for detector stations subject to recurrent congestion (53)

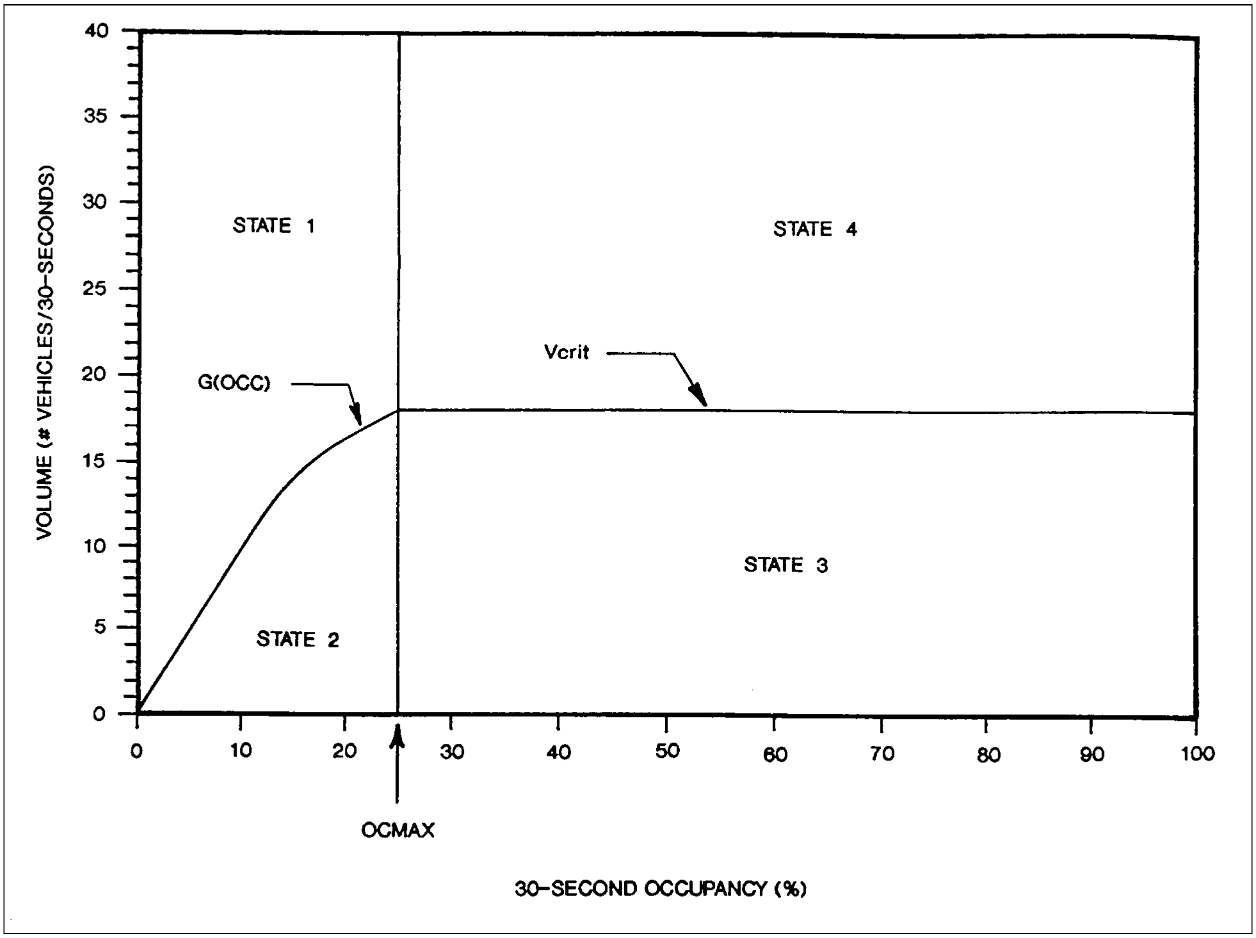


Figure 4-20. An illustration of the volume-occupancy template for traffic state classification.

Table 4-30. Identification of incident by McMaster algorithm.

Downstream Detector State	Upstream Detector State	
	2	3
1	Incident	Incident
2	Incident	Incident
3	Congestion cause located further downstream	Congestion cause located further downstream
4	Recurrent congestion	Recurrent congestion

Table 4-31. Commonly specified camera characteristics.

- **Image Sensor**
  Solid-state, color-sensing, charge-coupled device
- **Scene Illumination**
  Full resolution 0.5 foot candies
  Usable picture 0.1 foot candies
- **Active picture elements.**
  Minimum of 510 vertical and 492 horizontal
- **Camera lens**
  Zoom capability, variable focus, automatic iris
- **Pan and tilt drive capability**
- **All weather enclosure with controlled heater and blower, defroster and defogger**

therefore, the time of roadway operation at reduced capacity. An effective response plan provides an appropriate response to a given incident.

Response Plan

An effective response plan requires inter -agency coordination from its inception. Once the plan is established and activated, it should continue to evolve as lessons are learned are incorporated. During this evolutionary process, the working relationships among agencies must continue to be nurtured for the plan to be successful. Table 4 -33 lists the minimum requirements for an effective response plan (10).

Coordinated Controls for Traffic Management Under Incident Conditions

A coordinated set of CMS messages, lane control signals, and variable speed limit signs can be used to implement incident management plans. These controls function at 2 levels:

- Storage of traffic control device (e.g., lane control signals changeable message signs, etc.) states and motorist advisory messages for each traffic incident (including construction and special events). Upon selection or modification of the appropriate incident response plan by the operator, all devices in the plan are automatically set to the appropriate state. Figure 4-21 shows an example of a simple incident response plan for a two lane tunnel tube. Tunnels in Norfolk (164, 1264, 1664) and Baltimore (Fort McHenry Tunnel), as well as certain freeways, currently employ this approach.

Table 4-32. Techniques for displaying CCTV when using fewer monitors than cameras.

- Display cameras on a TV screen divided into several quadrants (e.g., 4 quadrants)
- Use a video switcher and control to display video from a particular camera. The switcher may be programmed to make a tour of all cameras in succession.
- Use incident detection algorithms to identify camera images that should be observed for purposes of incident confirmation
- Present digitized video camera image on traffic control system video display terminal

Table 4-33. Incident response plan.

Section	Function
Participating Agencies	• Lists all participating agencies and the telephone number of incident management coordinator • Lists other participating agencies
Summary	• Describes major plan elements
Levels of Implementation	• Describes series of levels of incident management intensity and conditions under which each level is to be invoked
Traffic Management	• Describes communication procedures for each roadway section, agencies to be informed, diversionary routes, traffic control locations, local and regional signing
Resources and Responsibilities	• Lists each agency, key personnel, contact numbers, responsibilities, and other pertinent information
Media Contacts	• Lists each media contact, key personnel, contact numbers, responsibilities, and other pertinent information
Team Coordinators	• Lists all involved agency coordinators, and telephone numbers

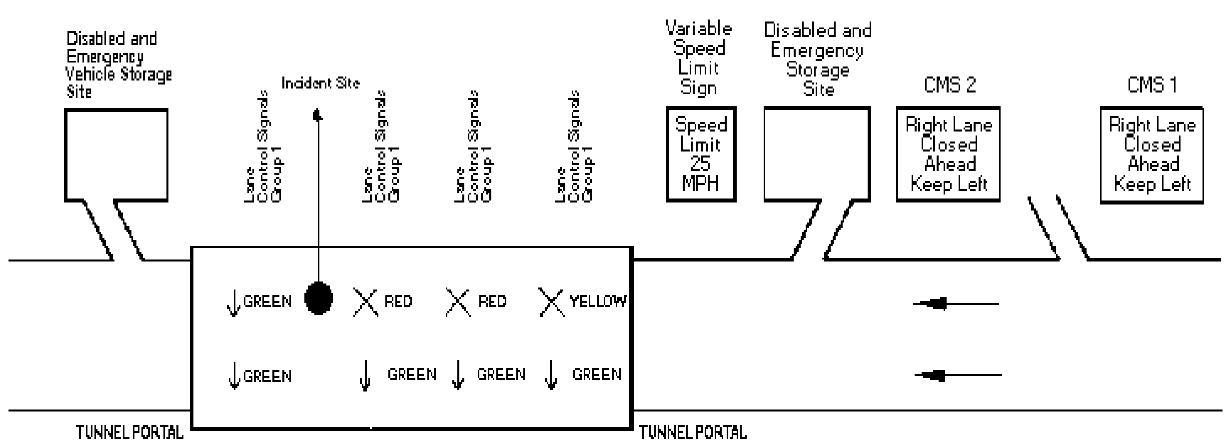


Figure 4-21. Example of integrated incident management plan for traffic control devices.

- In addition to the features included above, this level includes video display terminal (VDT) screens that enable the operator to classify incidents by location. Classification may include station number and lane, and type of incident (e.g., minor, multiple vehicle with fire, spill, etc.). The system screens request more information (if required) and recommend a response plan. The plan not only includes setting the device states as described above, but also identifies emergency services required and appropriate agency contacts. The plan takes effect on modification or confirmation by the system operator. Implementation can include automatic communication and display of requirements to emergency vehicles and other affected agencies.

This latter level of control provides incident VDT screens that enable the operator to track the time when:

- Incidents occur,
- Emergency services are notified and provided, and
- The incident was cleared.

The system can retain data files to analyze performance.

Ritchie and Prosser discuss die development of this approach (54). Many of these elements have been incorporated into the design for Boston's Central Artery and Tunnel project (55).

Khattak et al. discuss a technique that uses classified incident data to predict incident duration (56). This quantity may assist in developing response strategies and messages to motorists,

Response Services

Several types of response services may be considered. Their characteristics are summarized in table 4-34 (10).

Removal

Removal of wreckage, debris, spilled materials, etc. from the roadway and restoring the roadway capacity to its pre-incident condition is a key element of incident management. The roadway and adjoining areas must be cleared to minimize disruption to the traffic stream. Effective removal requires the availability of necessary equipment and personnel and the means to achieve rapid dispatch in handling all types of incidents. It requires expertise and judgement to assess when and how the removal operation is to be carried out. Incident response plans must include removal procedures for each incident scenario. Liability in connection with rapid removal policies is viewed as a major issue by many public agencies (38).

Table 4-35 lists the resources required for some typical incidents (10).

Accident investigations should be conducted by the police in a way that minimizes disruptions to freeway traffic. Where possible, investigations should be conducted off the freeway shoulder at safe locations not visible to mainline motorists such as nearby off-ramps, low-volume streets, parking lots, or designated accident investigation sites.

Accident Investigation Sites (AISs) are specially designated and signed areas off the freeway where drivers of damaged vehicles can exchange information and police and motorists can complete necessary accident forms out of the view of mainline drivers. This reduces rubbernecking, which is a major cause of both congestion at incident scenes and secondary vehicle and pedestrian accidents associated with accident scene activities.

Traffic Management

Traffic management includes application of traffic control measures in the incident area including: lane closures and openings; establishing and operating alternate routes; diversions; parking of emergency vehicles; and ensuring safety of incident victims, motorists, and emergency personnel.

The *Freeway Incident Management Handbook* discusses the following elements of traffic management for incidents (10):

- Scene Management,
- Alternate Route Planning, and
- Traffic Control Guidelines
  - Use of freeway shoulders
  - Merging techniques
  - Contraflow operations
  - Ramp diversion
  - Timing of removal
  - Special event planning

Information to Motorists

Information to motorists is the activation of various means of communicating incident site traffic conditions to motorists.

Motorists need to receive information on traffic conditions and suggested adjustments to normal travel patterns in order to fully realize the effectiveness of an incident management plan. Information to motorists must be accurate and timely. Methods being used to provide information to motorists are listed in table 4 -36, along with advantages and disadvantages of each (10).

Table 4-34. Response service characteristics.

	Service Patrol	Courtesy Patrol	Police Patrol
Capabilities/ Function	• Uses patrol vehicles with gasoline, water, pressurized air, jumper cables, fire extinguisher, first aid, tools, jacks, broom, push bumpers	• Is usually less extensive than service patrol • Can provide up to 15 assists per day per vehicle • Usually operates weekdays, morning and evening peak periods	• Serves as incident response coordinator • Requests other response vehicles • Performs accident investigation • Pushes disabled vehicles onto shoulder
Advantages	• Solves minor problems/ breakdowns • Provides quick removal from travel lane • Provides regular, frequent assistance • Provides incident verification; occasional detection	• May be operated by public agency • Can be funded by private enterprise, such as major gasoline company, bank, store, radio station or auto dealer (example, Samaritan program)	• Can be based on existing patrol presence or dedicated freeway patrol • Has law enforcement presence • Provides accurate verification • Uses police communications • Uses police car push bumper
Disadvantages	• Incurs cost to agency for equipment and personnel if agency operated or contracted	• If privately operated, is not under control of agency • Assists individual motorist, but does not focus on restoration of capacity	• If not a dedicated freeway patrol, places law enforcement as first priority, above incident management • Is costly if adequate number of patrols provided

Table 4-35. Required resources for incident removal.

Incident Type	Equipment	Personnel	Contacted Via
Stall (Car)	Service Patrol	• Service Patrol Driver(s)	• Radio (frequency)
Stall (Truck)	Tow Truck(s)	• Tow Truck Driver(s) • Police	• Telephone • Radio (frequency)
Overturned Tractor-Trailer	Heavy-Duty Wrecker	• Wrecker Driver(s) • DOT • Police	• Telephone call by DOT Maintenance • Telephone • Radio (frequency)
Hazardous Material Spill	Various, depends on material	• Hazardous material cleanup company (HAZMAT) • Office of Emergency Services • Fire Department • Police • DOT	• Telephone • Telephone • Radio (frequency) • Radio (frequency) • Telephone

Table 4-36. Traveler information techniques.

Motorist Info Media	Advantages	Disadvantages
Changeable Message Signs	• Reaches all motorists at sign location • Requires no in-vehicle equipment • Can be updated remotely and automatically • Provides timely information with frequent updates • Can be at fixed locations or portable (truck or trailer mounted)	• Has limited content due to human limitations in absorbing visual messages • Requires supporting structure • Visibility can be affected by ambient conditions • Limits communication to those points where (fixed) signs are located
Highway Advisory Radio (audio signing)	• Can provide more detailed message than changeable message sign (CMS) • Has larger area of coverage than CMS • Can be updated remotely and automatically • Can broadcast message to specific area where information is needed • Can be at fixed location or portable (truck or trailer mounted) • Is usually less costly than CMS and supporting structure	• Requires motorists to have working radio and requires tuning to broadcast frequency
Commercial Radio	• Reaches large segment of motorists • Permits cost to be borne primarily by private sector • Permits information from traffic operations center to be automatically transmitted to commercial stations	• May delay reports to fit into station's programming • Requires reports to be areawide • Does not target information to specific locations • Requires motorists be tuned to station broadcasting traffic information
Print Media	• Is effective for conveying info on construction and maintenance activities, special events, and long-term incidents • Can be in the form of newspapers or brochures/pamphlets distributed to freeway users	• Provides no real-time information
Citizens Band Radio	• Large number of vehicles (especially commercial) are equipped with CB	• Requires CB-equipped vehicle • Requires means of transmission
Commercial Cable TV	• Can display traffic conditions graphically • Is effective for pre-trip planning	• Reaches small segment of motorists

Table 4-36. Traveler information techniques (continued).

Motorist Info Media	Advantages	Disadvantages
Cellular Telephone Conventional Telephone	• Permits motorist to dial in for info when it is needed, either at home using conventional telephone or in the vehicle by cellular phone • Can target information to specific areas using voice-response systems • Recognizes that number of cellular telephones are expanding rapidly	• Requires cellular telephone-equipped vehicle • Entails cost to motorist for call (in some cases, cost-free service is provided)
Alpha/Numeric Pagers	• Provides automatic motorist alert	• Is limited to subscribers
In-Vehicle Route Guidance (Future)	• Can provide detailed traffic and diversion information in graphic or text format	• Requires sophisticated in-vehicle equipment

4.6 High-Occupancy Vehicle Priority Control

Priority control for high-occupancy vehicles (HOVs) on freeways provides preferential treatment for buses, vanpools, and carpools in the form of travel time advantage and reliability over lower Occupancy vehicles. Preferential treatment relieves traffic congestion by encouraging more efficient use of vehicles. Objectives include:

- Serving person demand for a freeway corridor, and
- Reducing vehicle demand by inducing more people to use high-occupancy vehicles.

Benefits include:

- Travel time and reliability improvements for people in the HOVs,
- More efficient use of the facility because of modal shift to higher occupancy vehicles, and
- Reductions in air-pollutant emissions and total fuel consumption.

Priority control methods include:

- Separated facilities,
- Reserved lanes (concurrent flow and contraflow), and is limited to subscribers
- Priority access control (57).

Separated Facilities

Positive separation of HOV and conventional traffic usually proves to be the most expensive treatment, it requires major construction. Separate HOV Since facilities experience few of the enforcement and safety problems encountered by nonseparated treatments. Separation techniques range from buffer lanes without physical barriers to parallel physical barriers. An example, shown in figure 4-22, includes portions of the Shirley Highway (1-395) in the Washington, DC area (58). 1-66 in Northern Virginia provides freeway priority by reserving all peak direction lanes for HOV use. Controlled use by authorized vehicles (buses, carpools, and vanpools) has been implemented in Houston on single-lane reversible facilities. CCTV and changeable message signs may be needed in such operations to monitor and control terminal and intermediate access points.

Reserved Freeway Lanes

Table 4-37 shows examples of operating HOV facilities (59). Figure 4-23 and figure 4-24 shows HOV lane person movement and figure 4-25 shows HOV travel time savings (59).

Freeway lanes reserved for HOV use have 2 basic configurations:

Figure 4-22. Shirley Highway 1-395.

- *Concurrent flow* **-**Reserved lanes in the same direction as peak flow and on the same side of the median (figure 4 -26).
- *Contraflow* **-** Reserved lanes on the opposite side of the median where HOVs move against the flow of traffic.

Concurrent flow reserved lanes designate a normal lane in the peak direction for HOV use. This preferential lane may be provided by:

- Adding a lane through construction or restriping *(add-a-lane),* or
- Preempting an existing normal -use lane *(take-a-lane).*

Experience with take -a-lane projects has revealed significant public opposition, as borne out by reaction to the diamond lane on the Santa Monica Freeway. By contrast, public acceptance of add-a-lane projects has been high, even with compromises in lane width standards. Enforcement is the primary problem in concurrent-flow lanes (60). Violating vehicles have virtually unrestricted access to the lane and positioning enforcement officers at proper locations proves difficult. Thus, the need has arisen for a special enforcement plan.

Application of contraflow lanes has been limited to areas of extreme congestion where directional flow imbalance permits their use. This approach is sometimes used as an interim measure during the definition and development of long -range solutions. Table 4-38 describes 2 contraflow projects in New York on severely congested approaches to tunnels.

Disadvantages of freeway contraflow lanes include:

- Labor-intensive da ily operations to set out and retrieve traffic cones used as lane delineation markers, and
- Potential for serious accidents introduced by this operation.

Metered Ramp Bypass

At ramp metering locations, bypass lanes can be provided so that buses, vanpools, and carpools avoid delays associated with ramp queues.

This treatment may be used in conjunction with HOV lanes accessed from the general freeway lanes. Figure 4-27 depicts the AASHTO plan for an HOV bypass lane, while figure 4 -28 shows a separate HOV bypass lane (61, 62). Lomax and Pubs describe bypass lane requirements and designs (63).

Exclusive HOV Ramps

Ramps may be provided for the exclusive use of HOVs and/or buses. Applications include provision of access between:

Table 4-37. Description of operating HOV facilities.

Facilities	No. of HOV Lanes	Frwy. Lanes	Length (mi/km)	Eligible Vehicle	Hrs. of Service	Peak Period Length	Separation From Non-HOV	Signing & Marking **	Comments
EXCLUSIVE									
I-10 Houston	1 (reverse)	3	6.2 (10.0)	2 +	AM/PM	3/3	Barrier	a,b,c,d,e	
I-45 Houston	1 (reverse)	3	9.6 * (15.5)	Bus/Van	AM/PM	3/3	Barrier	a,b,c,d,e	Elig by permit
I-10 El Monte	1/direction	4	11.0 (17.7)	3 +	24	4/4	Barrier (4 mi (6.4 km)); 13 ft (4 m) shldr, (7 mi (11.3 km))	a, d	
I-395 Wash, DC	2 (reverse)	4	11.0 (17.7)	4 +	AM/PM	2.5/3	Barrier	a,b,d,e	
I-66 Wash, DC	2/direction	NA	9.6 (15.5)	3 +	AM/PM	2/2	NA	a,b,d,e	High violation
CONCURRENT FLOW									
Moanalua Fwy., HI	1/direction	3	2.3 (7.7)	3 +	AM/PM	—	Paint Stripe	a, d	High violation
SR-91 LA	1 (EB only)	4	8.0 (12.9)	2 +	PM	NA/4	1 to 2 ft (0.3 to 0.6 m) Paint Stripe	a, b, c	
I-95 Miami	1/direction	3	7.5 (12.1)	2 +	AM/PM	2/2	Paint Stripe	a, d	High violation
SR-55 Orange, LA	1/direction	3	11.0 (17.7)	2 +	24	3/3	1 ft (0.3 m) Paint Stripe	a, e	
I-4 Orlando	1/direction	2	6.2N, (10.0N) 14.5S (23.3S)	2 +	AM/PM	2/2	Paint Stripe	a, d	Not enforced
Bay Bridge, SF	3 (WB only)	16	0.9 (1.5)	3 +	AM/PM	3/3	Pylons/Striping	a, b, d	Br Toll Bypass
SR 101, SF	1/direction	3	3.7 (6.0)	3 +	AM/PM	3/3	Paint Stripe	a, d	Looks unused
I-5 Seattle	1/direction	4	4.0N, (6.4N) 5.6S (9.05)	3 +	24	—	Skip Stripe/Ln Markers	a, d	Looks unused
SR-520 Seattle	1 (WB only)	2	3.0 (4.8)	3 +	VARY	NA/2	8 in (203 mm) White Stripe	a, b	Outer Frwy Ln
I-15 San Diego	2(reverse)	2	9.5 (15.3)	2 +	AM/PM	3/3	Barrier	a, c, d	Opens 10/18/88
I-10 Phoenix	1/direction	3	3.0 (4.8)	3 +	24	—	4 in (101 mm) Paint Stripe	a, d	Partial open

* In a.m., 3.2 mi (5.1 km) concurrent flow + 9.6 mi (15.5 km) = 12.8 mi (20.6 km)

** a = static, b = variable message, c = lane assign arrow, d = pavement markings, e = bus or HOV only, f = portable signs

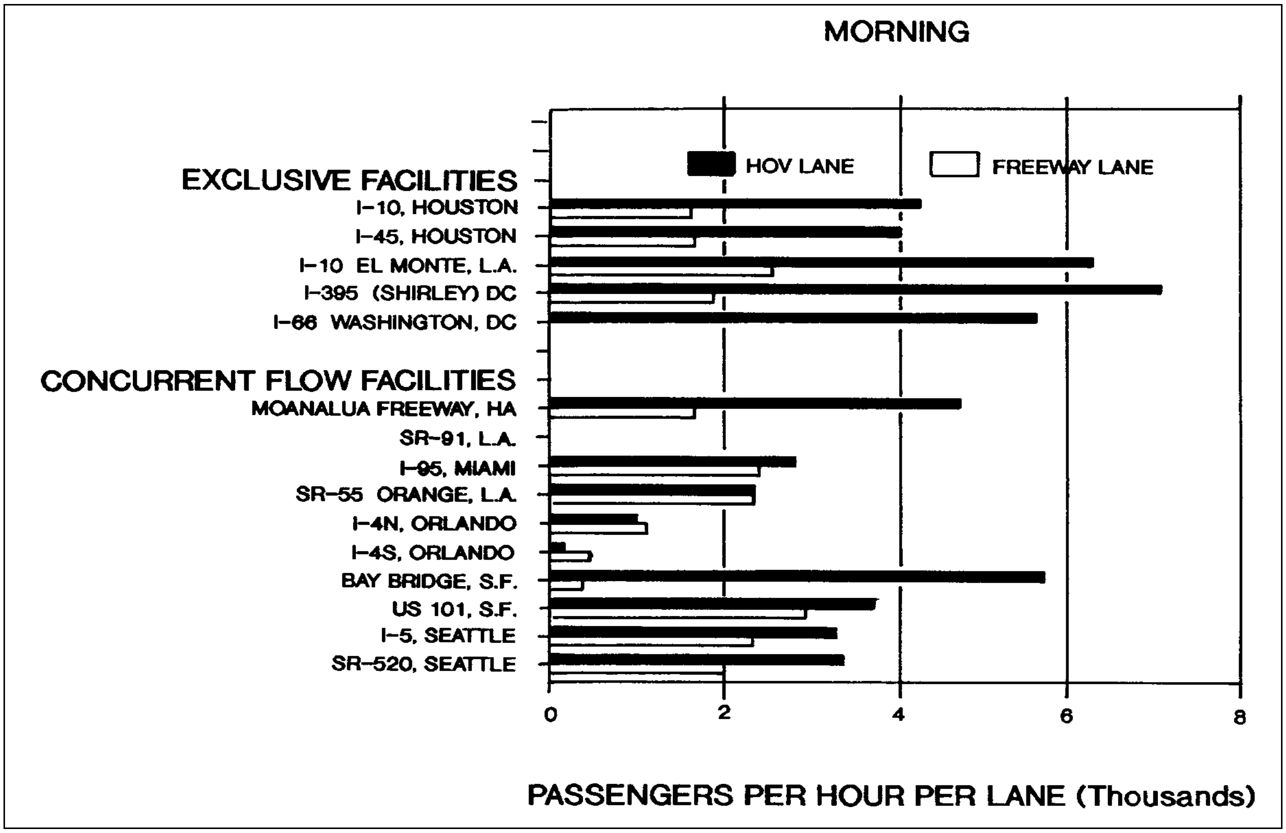


Figure 4-23. Comparison of freeway and HOV lane person movement during peak hour (a.m.).

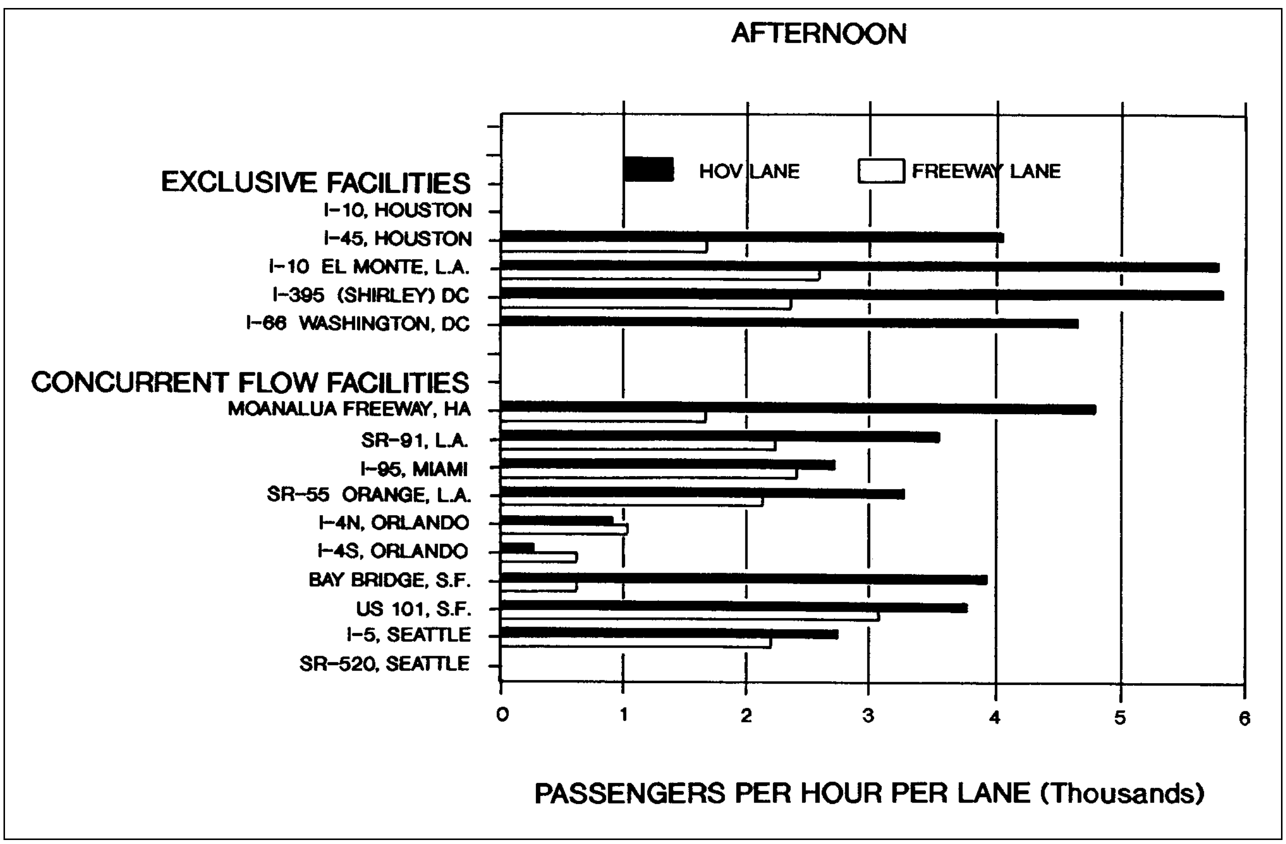


Figure 4-24. Comparison of freeway and HOV lane person movement during peak hour (p.m.).

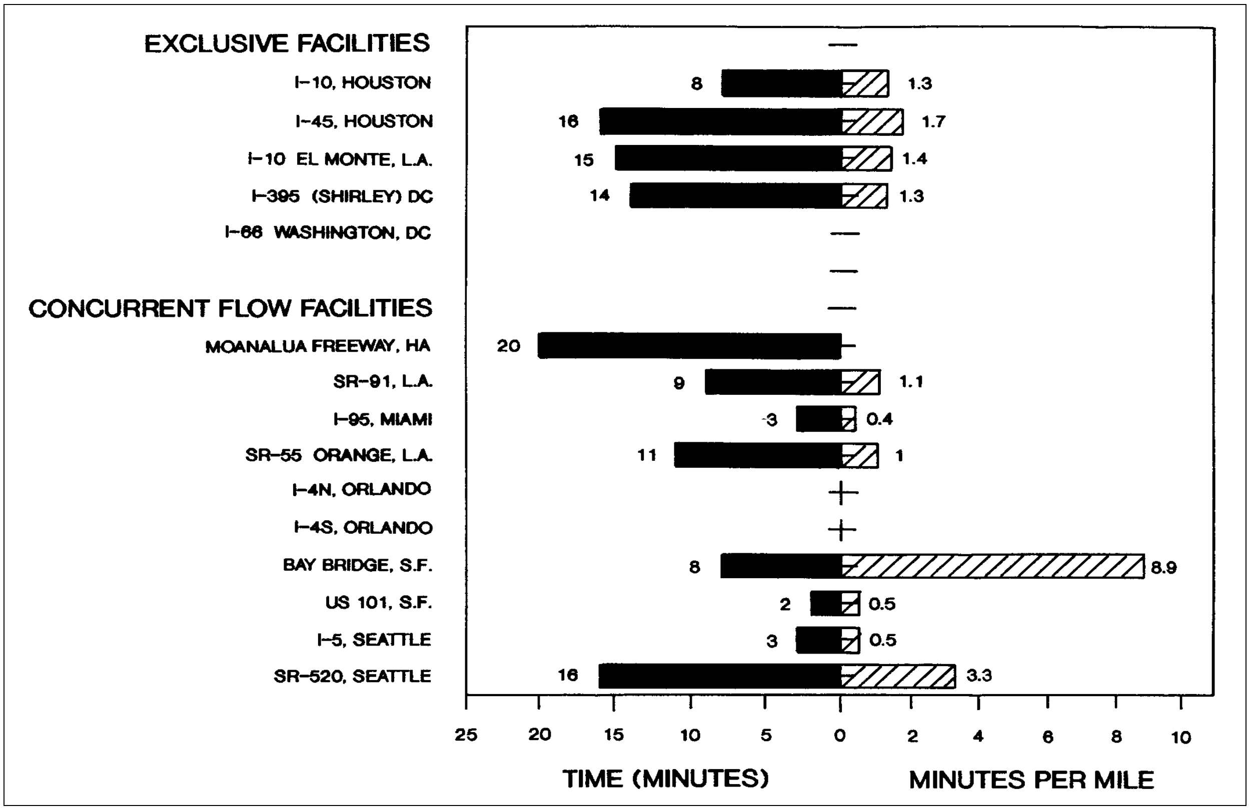


Figure 4-25. Average peak hour travel time savings for HOV lanes.

Figure 4-26. Long Island Expressway HOV express lanes.

Table 4-38. Characteristics of contraflow HOV lanes on grade-separated facilities in the New York metropolitan area.

Lane Characteristics	New Jersey	New York
Route	1-495 approach to Lincoln Tunnel	1-495 approach to Queens Midtown Tunnel
Length in miles	2.5	2
Year started	1971	1972
AM / PM	AM	AM
Remaining traffic lanes	2	2
Buffer lane	No	No
Typical bus volumes	500/peak hour 900/peak period	120/peak hour 200/peak period
Typical passenger volumes	21,000/peak hour 35,000/peak period	6,000/peak hour 10,000/peak period

- Bus terminals and HOV lanes or general lanes,
- Surface streets and HOV lanes, and
- HOV lanes and park-and-ride facilities.

Criteria for Freeway HOV Priority Lanes

Cechini indicates that HOV lanes effectively increase people throughput when (59):

- Non-HOV lanes operate in a congested mode at least during the peak hour,
- Facility expedites the flow of 14OVs without adversely affecting mixed-flow traffic,
- Facility appears adequately utilized - The HOV lane carries at least 800 to 1,000 vehicles in the peak hour,
- Time savings to HOVs exceeds 1 min per mile (per 1.6 kilometer) with a total time savings of at least 5 to 10 min per trip,
- Development policy and operations management are closely coordinated from a regional and multiagency perspective,
- HOV lane is separated from mixed-flow lanes by either an actual barrier or a buffer area,
- Enforcement is integrated into the design of the project, and
- HOV lane is implemented in conjunction with (and enhanced by) other strategies to increase vehicle occupancy, such as:
  - Park-and-ride lots,
  - Transit/carpool transfer centers,
  - New bus services *(Freeway Flyer)*
  - Ramp treatments,
  - Carpool matching services, and
  - Vanpool programs.

4.7 Simulation

As with signalized networks, simulation often proves to be a valuable tool in the analysis and design of freeway control systems. This section discusses some available freeway simulation models.

FREQ Family

Work on the first of the FREQ family of models began in 1968 at the University of California at Berkeley. From this first model, FREQ, extensions and refinements produced FREQ2 and FREQ3, with particular attention directed to shock wave analysis, computer efficiency, and output format (64-66), Current versions are FREQ10 and FREQ11.

Input to the model includes time slice traffic counts and facility design features. A synthetic O-D procedure is incorporated that converts the traffic

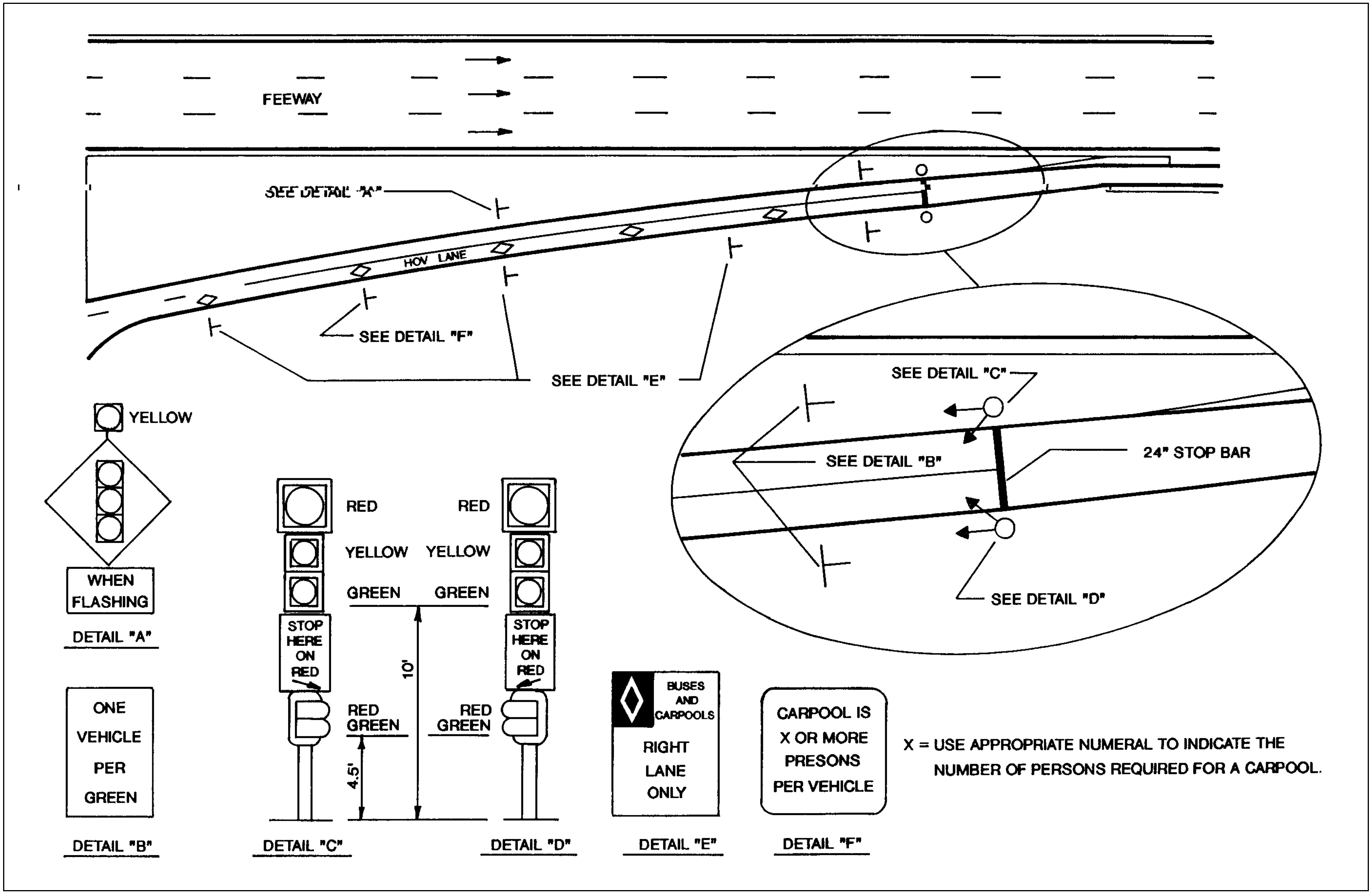


Figure 4-27. Typical ramp meter and HOV bypass lane installation.

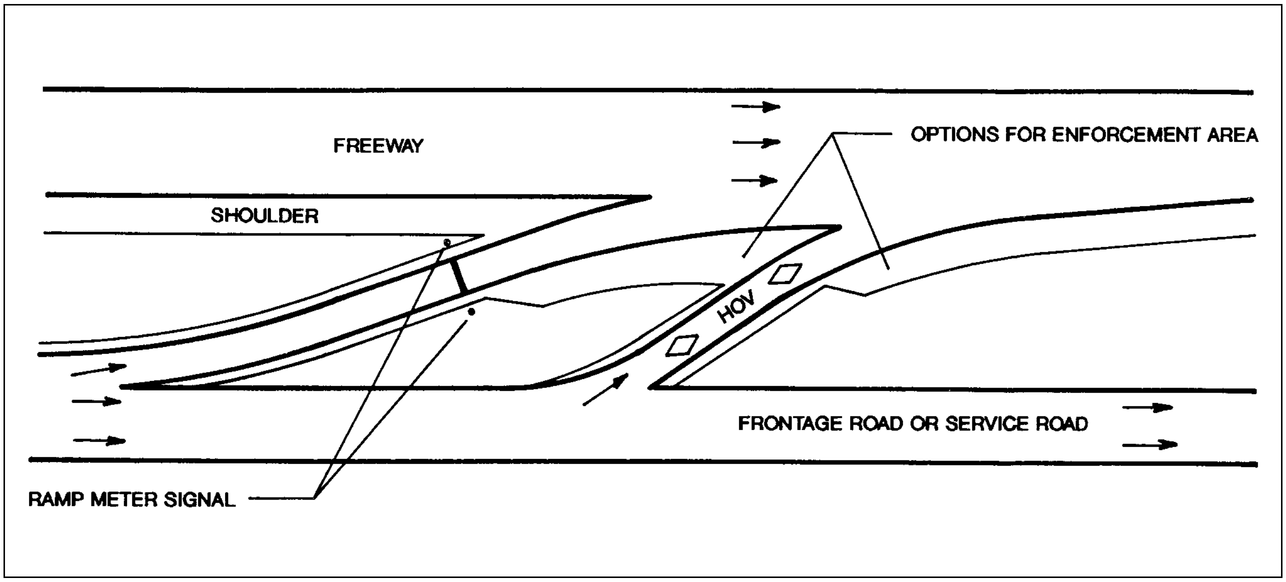


Figure 4-28. Separate HOV bypass lane at metered entrance ramp.

counts into time slice origin -destination demand tables. The user provides subsection capacities based on facility design features. The simulation model predicts traffic performance in the freeway corridor for the period of time prior to implementing a traffic management strategy. Design improvements such as added HOV lanes and/or mixed flow lanes can be incorporated and the simulation model will predict the effect of these improvements without traveler responses. Optimized entry control strategies can be generated either with or without the design improvements, and the model will predict the effect of these improvements without traveler responses (67).

The FREQ model also includes spatial and modal response sub-models which predict and reassign users to alternate routes and/or multi -occupancy vehicles. The simulation model can predict the short-term and longer -term traffic performance of implementing the design/control improvement with spatial and/or modal responses.

As with other models, data requirements to operate the FREQ family are extensive. The freeway is broken into homogeneous subsections that are usually stretches of freeway between on-ramps and off-ramps changes in freeway width, etc, The physical characteristics of each freeway subsection necessary for input follow:

- Length,
- Number of lanes,
- Lane width,
- Capacity,
- Truck factor,
- Grading,
- Length of grade, and
- Design speed.

In addition to the physical characteristics of freeway subsections, the model considers ramp characteristics:

- Location of on-ramps and off-ramps,
- Characteristics of special ramps (multilane ramps, left-hand side ramps), and
- Ramp metering limit and/or capacities.

The FREQ models also require demand data, which consists of

- *An origin/destination table for each time slice* -This may be in the form of traffic counts of hourly rates and may be either measured or simulated.
- *Passenger volume data* - In some cases, it is desirable to measure passenger throughput (as in priority entry control simulation). The user may vary the average vehicular occupancy during each time slice.

For the FREQ7PE model, data is also required on the arterial capacity and flow rates, as well as a measure of die progression together with arterial capacity. FREQ models are supported by the University of California, Berkeley.

Integrated Traffic Simulation Model (INTRAS)

INTRAS was developed for use in studying freeway incident detection and control strategies (68). It is based on knowledge of freeway operations and surveillance systems, and incorporates detailed traffic simulation logic that has been developed and validated for use in this model. INTRAS is a microscopic model that uses car-following and lane-changing algorithms to simulate the movement of individual vehicles. For this reason, it has the ability to examine both traffic control and geometric alternatives, even in complex freeway design situations such as interchanges.

To allow simulation of freeway control policies, including ramp metering and diversion, INTRAS has the capacity to model the off-freeway environment.

To facilitate simulation of closed-loop incident detection and control (as well as offline traffic analysis), the INTRAS model contains a realistic surveillance system simulation capability. INTRAS includes the ability to visualize vehicle trajectories and contours of measures of effectiveness (MOEs) in the time-space plane. The model also contains a statistical analysis module that permits comparison of MOEs from different simulation runs or field data using standard parametric and nonparametric tests.

Finally, a fuel-consumption and vehicle-emission evaluation model is built into INTRAS, and is patterned after a similar module developed for NET-SIM.

INTRAS can simulate an incident at any location on a freeway link for any length of time. The incident may block one or more lanes or be confined to the shoulder.

Data required includes:

- Geometric data
  - Link length,
  - Number of lanes,
  - Lane channelization,
  - Type of link,
  - Grade,
  - Radius of curvature,
  - Percent superelevation, and
  - Pavement type.

- Operational data
  - Entry-link flow rates,
  - Percentage of inter-city buses,
  - Heavy single-unit trucks,
  - Trailer trucks,
  - High performance passenger cars,
  - Low performance passenger cars,
  - Turning percentages at intersections,
  - Discharge headways,
  - Lost time, and
  - Free flow speeds.

- Control data
  - Stop sign,
  - Pretimed or actuated signal,
  - Signal timing,
  - Ramp control operation,
  - Location and type of detectors, and
  - Location, type, and time of incident.

The INTRAS model was reprogrammed in accordance with structured design techniques and enhanced to make it more user friendly and more widely applicable. The revised model is called FRESIM and has been incorporated into the TRAF family of programs developed by FHWA.

TRAF is an integrated simulation system developed by the FHWA. It contains component models capable of simulating a full range of roadway facilities at varying analysis levels.

Freeway Simulation Model (FRESIM)

FRESIM is a microscopic, stochastic, time-scanning simulator capable of simulating freeway traffic operations (69, 70). it is capable of analyzing complex and unusual geometric configurations and detailed interactions among different designs, controls, and traffic variables. Individual vehicle movements and driver decisions can be explicitly modeled. A wide range of prevailing freeway geometries can be simulated including:

- Ramp junctions,
- Variations in grade;
  - Curvature, and
  - Superelevation,.
- Lane additions/drops,
- Blockage incidents, and
- Auxiliary lanes.

Operational features modeled by FRFSIM include:

- Stochastic driver types and vehicle types,
- Mandatory and discretionary lane change logic,

- Car-following logic,
- Weaving operations,
- Ramp metering,
- Merge and diverge maneuvering,
- Surveillance systems and incident detection,
- Advanced warning signs, and
- Biased lane assignment for trucks.

The statistical output provided covers a wide range of measures of effectiveness (MOEs) including:

- Vehicle trips,
- Lane changes,
- Vehicle miles,
- Vehicle minutes,
- Total travel time,
- Delay time,
- Average volumes and speeds,
- Moving time,
- Density,
- Optional output of fuel consumption, and
- Emission rates of hydrocarbons:
  - Carbon monoxide, and
  - Nitrogen oxides.

The FRESIM model is a considerably enhanced and reprogrammed version of its predecessor, INTRAS. The enhancements include improvements to the geometric representation and the operational capabilities of the INTRAS model. Thus, FRESIM can:

- Simulate more complex freeway geometries,
- Provide a more realistic representation of traffic behavior, and
- Perform as a more flexible, user-friendly model than the INTRAS model.

FRESIM is the most powerful and detailed freeway simulation model developed to date by Federal Highway Administration (FHWA) and is a component model in TRAF.

Finally, through the use of interface links, FRESIM can be linked to the urban network simulation (TRAF-NETSIM) model, which in rum allow s for modeling of adjacent surface street networks. TRAF-NETSIM is discussed in more detail in chapter 5. The model resulting from the interface of FRESIM with TRAF-NETSIM is called the Corridor Simulation (CORSIM) model. To date, this model is still in its developmental stages, but should be released in the near future.

INTEGRATION Model

Dr. M. Van Aerde and his team at Queen's University in Kingston, Canada have developed INTEGRATION for modeling dynamic traffic networks and controls.

The INTEGRATION simulation model analyzes a number of specialized problems relating to:

- Operation and optimization of integrated freeway /arterial traffic networks,
- Real-time traffic control, and
- Route guidance systems.

The model is a deterministic macroscopic model explicitly developed for ITS applications in freeway corridors. The INTEGRATION model features the following capabilities (67, 71, 72):

- Simultaneously models freeways and arterials,
- Models individual vehicles with self -assignment capability,
- Has 5 vehicle types with varying levels of information available to the driver,
- Can optimize traffic signals, and
- Simulates multiple incident and construction scenarios.

An auxiliary program is available called QUEENSOD which generates time slice traffic demand origin-destination (O-D) tables based on traffic counts. The O-D tables, physical network, and the intersection and ramp signal control serve as input to the model. The traffic assignment routines and traffic performance predicted by the model operate concurrently to load the traffic onto the network and thus predict traffic performance in the freeway corridor.

ATMS strategies such as on-freeway HOV lanes, incident management, entry control, and intersection signal control can be investigated. ATIS strategies such as highway advisory radio (HAR), changeable message signs (CMS), and in-vehicle information systems can be simulated. Various vehicle types can obtain current travel time information either precisely or with noise at every node in the corridor, at HAR/CMS locations, or not at all.

The output of the model is very comprehensive and includes offline geographic maps of the entire corridor or sub-parts with superimposed input/output data and with the option of online vehicle animation for any portion of the corridor. Vehicles can be color-coded to represent vehicles in free-flowing conditions, vehicles in congested-flow conditions, and/or special vehicles such as HOV vehicles or vehicles receiving updated traffic travel time information.

The demonstration version of INTEGRATION runs on virtually any 386 or 486 microcomputer with at least 2MB of memory. Versions that simulate larger networks require more powerful computers; with 16 to 64MB of RAM (72).

All versions require the same input data and generate the same output. Input data files are entered as ASCII characters in a tabular format. The network input, control, traffic input, and incident data follow:

- Node coordinates, 8 node type designations (x and y values),
- Link length, location, type and lanes,
- Signal cycle length, green band type, and offsets,
- Vehicle departure times and O-D demand,
- Incident start, end, location, and severity,
- Average link flows/travel times on link (optional),
- Time series of anticipated link flows/travel times for 2 vehicle types (optional),
- Externally-specified, constant, all-or-nothing routing for HOV vehicles, and
- Time series of multipath routines for one vehicle type.

While running the simulation, several outputs are displayed:

- Vehicle moving situation and traffic signal displays,
- Time/departure statistics,
- The minimum path trees in offset at a given time, and
- Labels of all links and nodes.

The model also creates the following files:

- O-D travel time statistics,
- System-oriented link statistics,
- Signal timing plan summary,
- Summary statistics of completed trips,
- Incident summary,
- Unlabelled output statistics,
- Labeled output statistics, and
- Run error file.

Both the demo version of the model and commercial versions have been implemented in LAHEY FORTRAN, and distributed as compiled, executable models.

MACK

MACK and its later versions are deterministic, macroscopic simulations that model vehicle conservation and corresponding set of speed-density equations.

In MACK I, traffic dynamics are described by the numerical solution of fluid-flow differential equations, appropriately modified to represent traffic. This model exhibits global dynamic responses to freeway traffic flow with a minimum of computation. Though it can simulate system response to incidents that block one or more lanes on a roadway section, the model does not distinguish flow by lanes.

MACK II introduced a new equilibrium speed-density relationship and a structural change in the dynamic speed relationship. The MACK II and INTRAS models were applied to a segment of the Shirley Highway outside of Washington, DC, with both incident-free and incident scenarios. The authors recommended adoption of MACK II for making preliminary evaluations of control strategies for responding to incidents. This was based on:

- Qualitative agreement between MACK II and INTRAS results, and
- Significant cost difference between execution of the macroscopic MACK model and the microscopic INTRAS model.

FREFLO Model

FREFLO is a macroscopic freeway simulation model based on the principle of flow conservation and speed-density relationships (73). The speed-density relationship is incorporated into a dynamic speed relationship. The Freeway Flow Model (FREFLO) involves 2 significant extensions beyond its predecessor, the MACK model:

- The restriction to a single linear segment has been removed: a fairly general network, including disjoint segments, is now accommodated, and
- Buses/carpools, autos, and trucks are distinguished as three distinct vehicle types.

FREFLO can simulate:

- Geometric improvements,
- HOV lanes,
- Bus operation,
- Lane closures, and
- Incidents on a freeway.

Freeway-to-freeway connectors, involving merge and diverge, can also be accommodated. Typical inputs to FREFLO include:

- Roadway geometry,
- Operational characteristics,
- Volumes, and
- Turning movement percentages.

Output from FREFLO covers a wide range of MOEs including:

- Vehicle trips,
- Vehicle miles,
- Total travel times,
- Delay times,
- Average volumes and speeds,
- Person trips, and
- Person miles.

The connections between freeways and surface streets are not modeled by FREFLO. However, FREFLO is a component model of the TRAF integrated simulation system, so that establishing interface links to the appropriate TRAF model, surrounding surface street systems can be simulated concurrent with freeway modeling. To accomplish this, FREFLO can be combined with the TRAF models NETFLO Level 1 and/or NETFLO Level 2 to produce the CORFLO model, which can simulate networks of surface streets and freeways.

CORFLO Model

CORFLO is a multiple model network that combines the Freeway Flow model (FREFLO) with the Network Flow models NETFLO Level 1 and/or NETFLO Level 2 (73). FREFLO is a macroscopic freeway simulation model and NETFLO Levels 1 and 2 are macroscopic urban network simulation models. NETFLO Levels 1 and 2 are discussed in more detail in chapter 3. To utilize CORFLO, the network is divided into adjoining subnetworks to be simulated by the individual models. The adjoining subnetworks are combined using interface nodes. Interface nodes are points at which vehicles enter or leave one subnetwork to enter or leave another. The links that enter into the interface node are called entry interface links and the links that exit the interface node are called exit interface links. A vehicle leaving a subnetwork is stored in a Vehicle Holding Area (VHA) until it can be moved by the relevant simulation model for the adjoining network.

The traffic stream entering an interface node is always disaggregated into individual vehicles to represent the traffic stream in a common format. This is necessary, since the logic that represents traffic stream flow varies for different subnetwork models. The disaggregate traffic representation is transformed, to suit the relevant subnetwork model, on the interface entry link. A time interval is also set by the user to define the time a subnetwork model simulates before it is brought into central computer memory. The next subnetwork is then brought in and simulated over the same time interval. This process is continued until the simulation is over.

FRECON Model

FRECON and its update, FRECON II, are dynamic, macroscopic freeway simulation models that have been developed from FREFLO. The original version simulates freeway performance and generates point detector information for calibration and validation.

The model can interact with control programs to evaluate pretimed, local-traffic-responsive, and segment-wide control strategies. Traffic data includes on- and off-ramp and mainline volumes. Detector locations and incident descriptions are optional inputs. Outputs include contour maps of traffic performance measures and time profiles.

FRECON if contains enhancements that simulate alternative routes (surface streets), as in a corridor. It can simulate a freeway with mixed modes of ramp metering, as well as the driver's spatial diversion due to ramp metering. Additional outputs include surface street performance, corridor performance, and the effects of occupancy and diversion (74, 75).

4.8 A Look to the Future

Future improvements will likely take place in the following areas:

Advanced Ramp Metering Concepts

- Serious limitations in metering efficiency often result from the inability to properly manage the ramp queue under heavy-ramp-demand conditions. Proper management requires maintenance of the queue, and at the same time, prevents spill-back upstream of the ramp. Improved queue control algorithms are being developed to address this issue. The use of multipoint detectors for queue control will also ameliorate this problem.
- Traffic-responsive initiation of ramp metering m facilitate traffic management, particularly under off-peak-period incident conditions and under conditions such as weekends and holidays.
- With the increasing realization that much of the current freeway traffic congestion results from the merging of freeway flows, it is likely that the emphasis on freeway-to-freeway ramp metering will increase.

Greater provision of congestion information to the motorist will improve the results afforded by this technique.

Advanced Incident Detection and Management Concepts

Together with individual researchers, FHWA continues to devote significant resources toward this effort. Current research efforts include:

- Development of incident detection algorithms based on non-traditional techniq ues. Techniques such as fuzzy set theory and artificial neural networks are being introduced to improve the incident detection process (76, 77, 78).
- Use of knowledge-based techniques, preplanned responses, and historic data to assist in incident management.

Methodologies for estimating incident duration, and the use of knowledge-based systems will further refine the process of incident management (56, 79-82). Software is currently being developed that will provide operations personnel with immediately-accessible incident response plans.

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CHAPTER 5
CONTROL AND MANAGEMENT CONCEPTS - INTEGRATED SYSTEMS

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CHAPTER 5
CONTROL AND MANAGEMENT CONCEPTS - INTEGRATED SYSTEMS

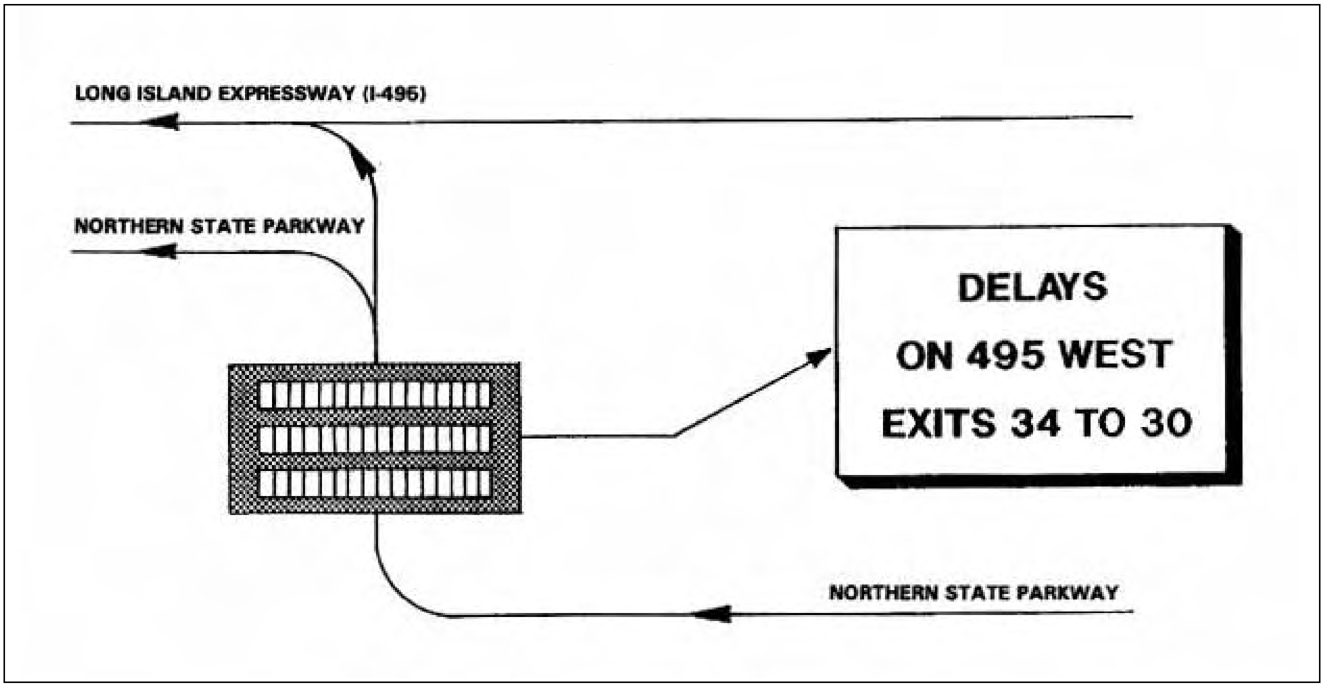

Figure 5-1. Diversion advisory message in the INFORM corridor.

5.1 Introduction

Integrated Traffic Management Systems (ITMS) coordinate traffic control within a corridor or area. ITMS integrate:

- Hardware with software elements,
- Traffic signal systems,
- Freeway management systems, and
- Traveler information systems (1).

This chapter describes corridor traffic control and strategies, and provides examples of currently operating corridor systems. Table 5-1 shows the organization of this chapter.

5.2 Traffic Corridors

A traffic corridor consists of:

- A major route such as a freeway,
- One or more parallel routes, and
- A number of crossing freeways or surface street arterials.

Corridor highways provide the major directional trunk service in a corridor's catchment area, and may feature the following characteristics:

- Modern freeway and arterial monitoring, control, and motorist information systems.
- Complementary service as a transit corridor. Transit services may include:
  - High occupancy vehicle (HOV) lanes and bypass ramps,
  - Park and ride facilities, and
  - Heavy or light rail service.
- Toll facilities.

Table 5-2 shows the relationship of high level traffic control and management strategies to the technologies which may apply.

The following paragraphs describe traffic control measures in 3 representative corridors.

Table 5-1. Chapter 5 organization.

Section Title	Purpose	Topics
Traffic Corridors	Describes corridor control and techniques	• Examples of corridor control • Transportation corridors
Strategies for Control of Traffic Corridors	Describes operating strategies and control tactics	• Local coordinated strategy • Areawide integrated strategy • Diversion strategy • Congestion strategy
A Look to the Future	Describes future trends	• Adaptive signal systems • Wide-area control strategies

Examples of Corridor Control

Table 5-3 summarizes the devices and techniques currently being used in three operating corridors.

- **Smart Corridor (2, 3)**

  This corridor approximates 14 mi (22.5 km) and contains the Santa Monica Freeway and 5 parallel arterial streets in Los Angeles. Equipment on the freeways will undergo upgrading, and the Los Angeles Automated Traffic Surveillance and Control (ATSAC) surface street control system will be expanded. A central corridor database will be provided. The corridor will interface with the Harbor and Ventura Freeway traffic control systems. The project is currently in design/construction.

  An expert system will be developed and implemented at the City and CALTRANS TOCs. This system will automate incident identification and verification, and provide decision support through the integration of the expert system with the prestored operation plans. For inexperienced operators in the control centers, the expert system can serve as a training tool. It will recommend the necessary steps to solve a congestion problem, based on similar past incidents.

Gardiner-Lake Shore Corridor (4, 5)

The Gardiner-Lake Shore Corridor consists of an urban freeway (the F.G. Gardiner Expressway) and a parallel signalized arterial (Lake Shore Boulevard), which together form a 13.5 km (8.4 mi) major access corridor into downtown Toronto. Portions of the corridor system are currently being implemented and other portions became operational in 1994. Novel features include:

- **SCOOT** - The SCOOT (see section 3.9) traffic signal control system controls Lake Shore Boulevard signals to rapidly respond to traffic diverted from the freeway. Certain control parameters in SCOOT which increase system responsiveness may be changed under freeway incident conditions.

- **Intensive Corridor Management** - Response plans will be used for incidents and special events. The system operator may select from among these plans, previously prepared and stored in the traffic monitoring computer. These plans use not only conventional motorist communication and control devices, but lane control signals (LCS) as well. Together with changeable message signs (CMS), the LCS will assist in managing traffic flow under queuing conditions. It is expected that these procedures will reduce the number of secondary accidents.

- **INFORM Corridor (6)**

  The Information for Motorists (INFORM) corridor contains 2 major freeway facilities, the Long Island Expressway (LIE-Interstate 495), the Northern State Parkway/Grand Central Parkway (NSP/GCP), and a number of parallel and crossing arterial streets and freeways, for a total of 136 mi (219 km) of controlled roadways. The corridor extends east from the Borough of Queens in New York City, through Nassau County and into Suffolk County. The system consists of electronic monitoring, communications, signing, and control components, providing motorist information for warning and route diversion, ramp control, and signal control. The system, which became operational in the mid-1980s, controls a corridor approximately 40 mi (64.4 km) in length.

Table 5-2. Relationship of high level corridor control and management strategies to control techniques and technologies.

High Level Corridor Control and Management Strategies / Techniques and Technologies	Detect Incidents	Manage Incidents	Enhance Safety and Manage Traffic Flow on Incident Impacted Routes	Restrict Traffic Entry on Freeway Routes	Divert Traffic to Less Congested Corridor Facilities	Optimize Traffic Throughput in Corridor	Adapt Corridor Controls to the Real-Time Areawide Traffic Management Requirements
Automatic Electronic Freeway Monitoring	✓			✓	✓	✓	
Incident Detection Algorithms	✓						
CCTV	✓	✓					
Automatic Positioning of Cameras		✓					
Non-Electronic Incident Management Techniques (Patrols, etc.)	✓	✓	✓				
Queue Detection and Management			✓		✓	✓	
CMS		✓	✓	✓	✓	✓	
HAR		✓	✓	✓	✓	✓	
Lane Control Signals		✓	✓				
Ramp Meters		✓		✓	✓	✓	
Arterial Traffic Control Using On-Street Masters		✓			✓	✓	
First Generation Arterial Traffic Control System		✓			✓	✓	
Advanced, Rapid Response (Adaptive) Arterial Traffic Control System		✓			✓	✓	
Additional Interfaces to Arterial Traffic Control System and Arterial Control Strategies to Facilitate Diversion from the Freeway		✓			✓	✓	
Preplanned Incident Management Motorist Information Displays		✓	✓	✓	✓	✓	
Ties to Other Traffic Operations Centers		✓					✓
Commercial Radio/TV Advisory		✓	✓	✓			✓

Table 5-3. Examples of corridor capabilities.

Techniques and Technologies	Smart Corridor Los Angeles	Gardiner-Lake Shore Corridor Toronto	Current INFORM Corridor Long Island, NY
1. Automatic Electronic Freeway Monitoring	✓	✓	✓
2. Incident Detection Algorithms	✓	✓	✓
3. CCTV	✓	✓	Partial
4. Automatic Positioning of Cameras		✓	
5. Non-Electronic Incident Management Techniques (patrols, etc.)	✓	✓	✓
6. Queue Detection and Management		✓	
7. CMS	✓	✓	✓
8. HAR			
9. Lane Control Signals		✓	
10. Ramp Meters	✓	✓	✓
11. Arterial Traffic Control Using On-Street Masters			
12. First Generation Arterial Traffic Control System	✓		✓
13. Advanced, Rapid Response (Adaptive) Arterial Traffic Control System		✓	
14. Additional Interfaces to Arterial Traffic Control System and Arterial Control Strategies to Facilitate Diversion from the Freeway		✓	
15. Prestored, Incident Management Motorist Information Displays		✓	
16. Ties to Other Traffic Operations Centers	✓	✓	✓
17. Commercial Radio/TV Advisory	✓	✓	✓

Although TV monitoring was not incorporated into the initial design, partial coverage has been added in recent years. Unique features of INFORM include:

- Two parallel limited access highways
- Operation and technical su pport of the system performed by private traffic consulting firms under contract to the New York State Department of Transportation (NYSDOT)
- An interface that provides speed information for freeway zones in a digital format. This information is compatible with graphical display software developed by NYSDOT for use at remote locations.

NYSDOT is in the process of upgrading and expanding INFORM. Table 5-4 describes the current INFORM configuration.

Transportation Corridors

Corridors may also provide functions and services in support of transit. Examples include:

- **CTA Smart Bus (7)**

  This is a Federal-local cooperative project. It will identify Automatic Vehicle Location (AVL) and bus traffic signal preemption technologies and analyze their impact on vehicular traffic and bus operations in a Chicago transportation corridor. The project will examine innovative bus service improvements, including automatic vehicle monitoring (AVL) and computer driven dispatching techniques. Real-time information systems for travelers will be provided at wayside and on-board the vehicle.

- **Houston Smart Commuter IVHS Operational Test Project**

  Through the application of innovative approaches using advanced technologies, this test will examine the potential for gaining more efficient use of major travel corridors through:

  - Greater use of high-occupancy commute modes,
  - Shifts in travel routes, and
  - Changes in travel time.

  The test includes 2 different but compatible components:

  - I-45 North Bus Lane, and
  - I-10 West Carpool Lane.

Table 5-4. INFORM configuration.

Corridor Length mi (km)	40 (64)
Controlled Roadways mi (km)	136 (219)
Loop Detectors	2,400
Changeable Message signs	101
Ramp Meters	75
Intersection Traffic Signals	133
Closed Circuit TV Cameras	44
Citizen Band Radios	22

Both focus on the provision of real-time pre-trip information to individuals in their homes and workplaces. In addition, both center on enhancing the use of the Houston HOV lanes. The I-45 North Bus Component focuses on the traditional suburban-to-downtown travel market in the I-45 North Corridor, whereas the I-10 West Carpool Component focuses on the suburban-to-suburban travel market.

A number of local, State, and national benefits will be realized from this test. These include:

- Gaining more efficient use of the travel corridors by increases in average vehicle occupancy, and

- Enhancing the use of existing investments in the HOV lanes and support facilities by attracting more bus riders and carpoolers.

Realization of these benefits is expected to:

- Help reduce the need for expensive freeway expansion projects,

- Assist in meeting areawide air quality and energy objectives, and

- Enhance the operation of the transit system.

5.3 Strategies For Control Of Traffic Corridors

FHWA has sponsored a study entitled "Coordinated Operation of Ramp Metering and Adjacent Traffic Signal Control Systems" (8). The study developed operating strategies and control tactics to address the problem of congestion in corridors. The impact of these measures was evaluated by simulation.

Four operating strategies were devised:

- Local Coordinated Strategy - Used when freeway demands do not require integrated ramp control.
- Areawide Integrated Strategy - Used when freeway is in traffic-responsive area control mode.
- Diversion Strategy - Used to handle freeway incidents.
- Congestion Strategy - Used when traffic demand exceeds capacity in sub-area of corridor.

In the *Local Coordinated Strategy*, ramp meter rates are selected and adjusted based on local conditions such as traffic signal timings at each interchange. Traffic signal timings at each interchange may also be modified based on the current metering rates, if these are a more critical consideration at the moment.

When freeway traffic demand has increased to the extent that any change in metering rate of any ramp may affect traffic flow at other ramps, then an *Areawide Integrated Strategy* is used to prevent freeway congestion. This strategy sets ramp metering rates according to corridor flow optimization rather than local conditions at interchanges. It also requires frequent adjustments in traffic signal timing plans and ramp metering rates to react to short -term stochastic changes in traffic flow.

The *Diversion Strategy*, on the other hand, deals with incidents. It assigns special timing plans for both arterial signals and ramp meters at locations affected by the selected diversion routes.

If the traffic demands exceed the capacity of a critical sub-area of a corridor, the *Congestion Strategy* is used, since traffic control objectives change to manage the spread of congestion rather than to handle demand.

Table 5-5 shows the relationship between strategies and tactics. A matrix (table 5-6) identifies the permissible transitions between operating strategies. Parameter threshold values define the boundaries between states. Reference 9 provides additional information.

5.4 A Look to the Future

The surface street system often provides the major alternate route in the event of freeway incidents.

Table 5-5. Relationship between strategies and tactics.

Tactics	Strategies			
	Local	Areawide	Diversion	Congestion
Corridor-Related Tactics				
Inhibit Metering			✓	✓
Simultaneous Offsets				✓
Short Cycling			✓	✓
Double Cycling			✓	✓
Reverse Progression				✓
Green Metering				✓
All Red Extension				✓
Interchange Area Tactics				
Off-Ramp Priority		✓	✓	✓
On-Ramp Access Control		✓		✓
Arterial Priority	✓	✓	✓	
Freeway Priority	✓	✓		✓
On-Ramp Priority			✓	✓
Equity Offset				✓
Queue Management				✓
Demand Storage				✓
Inhibit Metering			✓	✓
Ramp Closure			✓	✓

Table 5-6. Strategy decision matrix.

Existing State	New State			
	Local	Areawide	Diversion	Congestion
Local	Not Applicable	Existing Mechanism	Operator Decision	Not Allowed (Switch to Areawide)
Areawide	Existing Mechanism	Not Applicable	Operator Decision	TOD (time-of-day) TRSP (traffic-responsive) Manual
Diversion	Operator Decision	Operator Decision	Not Applicable	Not Allowed (Switch to Areawide)
Congestion	Not Allowed (Switch to Areawide)	TOD TRSP Manual	Operator Decision	Not Applicable

Highly responsive and adaptive traffic signal systems (section 3.12) will provide increased arterial capacity and reduced travel time in the event of freeway incidents or other non-recurrent events in the corridor.

Allgood, et al. suggest that non-deterministic analysis techniques used in conjunction with traffic models and wide-area surveillance techniques will form the basis for wide-area control strategies (10).

In most cases, the traveler principally wants to travel a congested corridor in minimum time. Highway based and vehicle based traveler information systems, supported by corridorwide and areawide dynamic and historic traffic databases, will provide this information. In all likelihood, traffic probes will provide a significant amount of traffic condition data on the major surface streets in a large corridor, since extensive surveillance often does not prove feasible.

References - Chapter 5

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CHAPTER 6
DETECTORS

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DETECTORS

Figure 6-1. Radar detector.

6.1 Introduction

Any traffic-responsive control system depends on its ability to sense traffic. A system accomplishes this by using one or more of the following detector types:

- Conventional
  - Inductive Loop,
  - Magnetometer,
  - Magnetic, and
  - Pressure.
- Non-pavement invasive
  - Radar/Microwave,
  - Sonic,
  - Video Image Processing, and
  - Infrared.
- Special-purpose
  - Bus,
  - AVI/ETTM,
  - Overheight,
  - Environmental,
  - Pedestrian, and
  - Pre-emption.

A system can use traffic detectors singly or in combination to measure variables such as:

- Presence,
- Volume,
- Speed, and
- Occupancy.

Systems use these variables as control parameters:

- At individual signalized intersections,
- In coordinated traffic-responsive signal systems, or
- For freeway operations.

For example, at an actuated intersection, detector outputs influence decisions such as extending green or assigning right-of-way. The local controller will:

- Process these outputs,
- Compare processed detector information with some preset control parameter or parameters, and
- Make a decision on intersection phasing and timing.

This chapter discusses the following aspects of detectors:

- Types,
- Locations and configurations,
- Applications, and
- Future technology.

Table 6-1 shows overall organization of the chapter.

6.2 Detector Types

For conventional detector types (inductive loop, magnetometer, magnetic, and pressure), this section discusses:

- Principles of operation,
- Sensitivity characteristics, and
- Electronics.

The section also describes non-pavement invasive and special-purpose detectors.

Today, the inductive loop detector remains the most widely used type, with radar and image processing finding increasing application.

Inductive Loop Detector (ILD)

Principles of Operation. The inductive loop detector (ILD) illustrated in figure 6-2 remains the most prevalent vehicle detector for:

- Individual signalized intersections,
- Signal systems, and
- Freeway monitoring systems.

The FHWA *Traffic Detector Handbook* extensively discusses the ILD, which consists of (1):

- One or more turns of insulated loop wire wound in a shallow slot sawed in the pavement,
- A lead-in cable from the curbside pullbox to the intersection controller cabinet, and
- A detector electronics unit housed in an intersection controller cabinet.

The detector unit drives energy through the loop at frequencies in the 10 to 200 KHz range. The ILD forms a tuned electrical circuit with the loop wire as the inductive element. When a vehicle passes over or stops within the loop, it decreases the loop inductance.

This decrease actuates the detector output relay or circuit, which sends an impulse to the controller signifying vehicle passage or presence.

Loop Characteristics. In all loop detectors, the wire and lead-in cables have a combined *resistance, inductance, and capacitance*. Inductive loops, lead-in wires, and lead-in cables typically use #12, #14, or #16 AWG wire.

Resistance **—**Wire *resistance* varies inversely with the square of wire diameter. A volt ohm meter (VOM) often measures resistance to direct current. Since wire resistance to alternating current increases with frequency, a VOM cannot measure it, but a *quality factor* measurement can be made (1).

Inductance **—** All wires carrying an electrical current produce magnetic flux that links with (i.e., encircles) the current. *Inductance*, measured in henries (H), characterizes the effect of this flux. Inductance of a wire is called *self-inductance* but if flux from current flowing in a wire couples to other wires, then *mutual* inductance results.

Loop detector units operate within a *range* of inductance. The following factors must result in an inductance within the unit's range:

- Loop size,
- Number of turns of loop wire, and
- Lead-in length.

Outside of this range, the detector will not operate properly. NEMA specifies that a detector unit must operate satisfactorily over a range of 50 to 700 microhenries (at 50 KHz) (2). Several available ILDs operate at much higher inductances using a series combination of loops. When measuring loop inductance at 20 KHz or greater, specify frequency, since inductance depends on frequency.

Determining Inductance. Table 6-2 shows loop inductance as a function of size and number of turns (3). The boundaries show recommended designs, but loops as large as 6- by 35-ft (1.8- by 10.7-m) can have 3 turns. To the loop inductance, add the lead-in inductance at the rate of 0.23 microhenries per foot. Table 6-3 shows the effect of wire size on inductance and the loop quality factor Q (1).

Connecting loops also affects inductance. A *series* connection provides a maximum magnetic field, but proves to be the most sensitive configuration when used with extra-long lead-in cable. A digital-type detector that operates on inductance changes is recommended with series connections. A user may also reduce inductance by connecting loops in *parallel*. Again, exercise care to keep inductance

Table 6-1. Chapter 6 organization.

Section Title	Purpose	Topics
Detector Types	Discusses conventional detection and new detection technology	• Inductive loop detector - principles of operation - loop characteristics - loop shape - preformed loops - detector electronics unit • Magnetometer detectors - principles of operation - probe characteristics • Magnetic detectors - principles of operation - probe characteristics • Pressure detectors • Non-pavement invasive detectors - radar/microwave detectors - sonic detectors - video image processing system - infrared detectors • Special purpose detectors - bus detector - AVI detectors - overheight vehicle detectors - environmental detectors - pedestrian detectors - preemption devices • Comparison of vehicle detectors
Detector Operations Summary	Describes relationship between controller and detector	• Detector-controller relationship - low-speed approaches - high-speed approaches
Vehicle Detector Location and Configuration	Describes alternative designs and applications	• Isolated actuated intersection control - small-area detectors - large-area detectors - left-turn lanes - OPAC detection scheme - MOVA detection scheme - detection of small vehicles • Control of arterial and network intersections - ILD applications for system detectors - arterial street systems - network control systems - freeway monitoring and control
A Look to the Future	Describes issues in applying new techniques to traffic systems	• Operational use of new detectors • Additional capabilities of new detectors

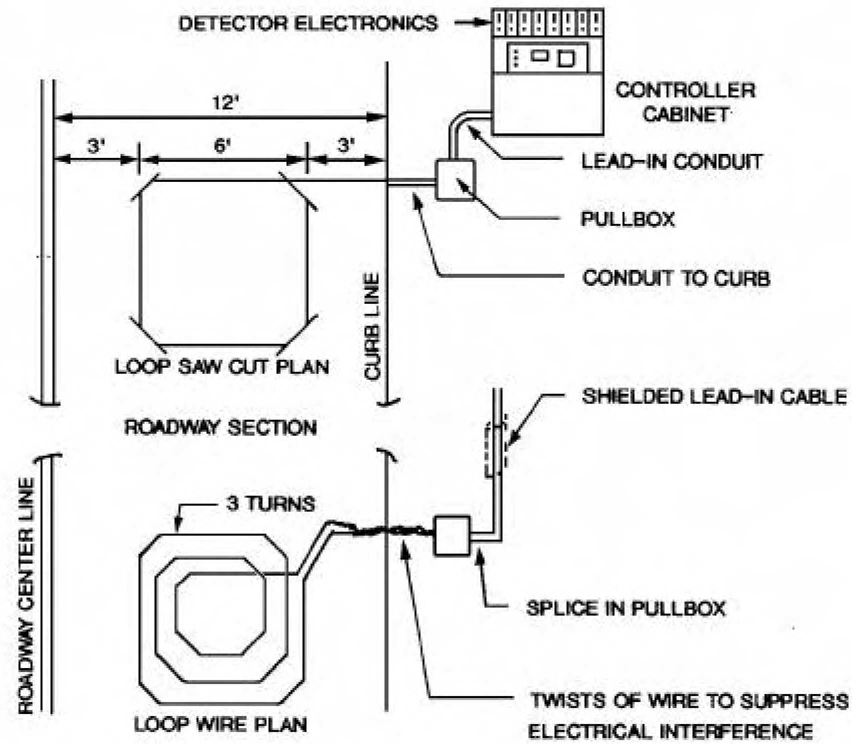


Figure 6-2. Principal components of an inductive loop detector.

above the lower operating range of the detector. A series/parallel connection can also maintain an acceptable inductance level.

Detector sensitivity is the minimum percent change in total loop inductance that causes the detector to actuate (1). Many users specify that detectors respond to a 0.02 percent change in inductance at the detector. This degree of sensitivity provides some safety margin by offsetting the inductance present in the lead-in cable, but usually suffices to detect high-bed trucks and motorcycles.

However, NEMA recognizes differences in detector unit design by calling out both *delta L* and *delta L/L* for its test vehicle definition. Delta L refers to a change in inductance. NEMA specifies 3 sizes of motor vehicles in terms of the delta L produced by each. For example, NEMA TS2 specifies that in order to meet sensitivity requirements, candidate units must detect any of 3 different size vehicles on any of 3 defined loop configurations (2).

Capacitance **—** Occurs between the loop conductors and slot side wall and varies directly with the dielectric constant of the slot sealing material. A capacitance change will occur if water is absorbed by:

- The slot sealing material, or
- Any space in the slot not filled with sealing material.

At frequencies of 10 KHz or greater, capacitance becomes important and a change can result in unstable loop detector operation.

Loop Shape. The shape of loops received a great deal of research during the 1970s and 1980s. The desire to detect all forms of vehicles, from bicycles to motorcycles to high-bed trailer trucks, while avoiding

Table 6-2. Calculated loop inductance in microhenries.

Loop Size (ft (m))	Turns						
	1	2	3	4	5	6	7
5 x 5 (1.5 x 1.5)	9	30	62	104	155		
6 x 6 (1.8 x 1.8)	10	37	76	129	194	269	355
6 x 10 (1.8 x 3)	14	51	107	181			
6 x 15 (1.8 x 4.6)	19	69	147	249			
6 x 20 (1.8 x 6.1)	24	88	187	320			
6 x 22 (1.8 x 6.7)	26	96	204	349			
6 x 25 (1.8 x 7.6)	29	107	229	392			
6 x 30 (1.8 x 9.1)	34	126	272	461			
6 x 35 (1.8 x 10.7)	39	146	315	542			
6 x 40 (1.8 x 12.2)	43	165	359	618			
6 x 45 (1.8 x 13.7)	48	185	402	695			
6 x 50 (1.8 x 15.2)	53	205	447	773			
6 x 55 (1.8 x 16.8)	58	225	492	853			
6 x 60 (1.8 x 18.3)	63	245	537	932			
6 x 65 (1.8 x 19.8)	67	265	583	1012			
6 x 70 (1.8 x 21.3)	72	286	628	1092			

Note: Spacing between loop conductors: 5.9 in (150 mm), center to center. Boundaries (shaded areas) show the designs recommended for normal use.

Source: Reference 3

The general standard to keep inductance within the detector unit's required range follows:

Loop Parameter (ft (m))	Turns (no.)
Under 30 ft (9m)	3
Over 30 ft (9m)	2

detection of vehicles in adjacent lanes, led to several loop designs. Each design purports to have advantages over the others. Figure 6-3 provides examples of various small loop shapes. Some of these are commonly used, while others apply to either (1):

- A site-specific location, or
- A particular range of vehicles.

A number of agencies and universities have conducted tests to determine optimum loop shape (4, 5). Typically, these projects involved installation of several different shapes, followed by testing and comparing their sensitivities in detecting several test vehicles. No one project tested all currently used loop designs. In most instances, sensitivity differences did not prove significant, given the state-of-the-art in detector electronic units. Therefore, one particular design does not dominate. However, as discussed in later sections, some loop designs are better suited to detection of small vehicles or high-bed trucks.

Many states specify the small and long loop shapes that are acceptable within their jurisdictions. For example, figure 6-4 shows California's specified shapes (1). This specification gives each unique shape a letter designation (e.g., Type A represents a typical 6- by 6-ft (1.8- by 1.8-m) loop, etc.).

Preformed Loops (6). Several detector manufacturers offer a preformed loop assembly consisting of a continuous unspliced length of #14 AWG THHN wire completely enclosed in a 1/2-in (13-mm) heavy wall PVC pipe. The assembly comes with twisted lead-in wire of specified length to reach the first pull box. The watertight assembly is sealed at the lead-in Tee fitting. The lead-in portion of the Tee has a short stub of 1/2-in (13-mm) PVC pipe so that the installer

Table 6-3. Response loop parameters. *

Wire Gauge (AWG)	Turns									
	1		2		3		4		5	
	Inductance (uh)	Quality Factor (Q)	Inductance (uh)	Quality Factor (Q)	Inductance (uh)	Quality Factor (Q)	Inductance (uh)	Quality Factor (Q)	Inductance (uh)	Quality Factor (Q)
12	10	20	35	30	73	37	123	43	184	47
14	11	16	36	24	74	30	125	35	186	40
14**	63	12	89	14	128	18	180	21	243	25
16	11	12	37	18	75	23	126	28	188	31
18	11	8	37	13	77	17	127	20	189	23

* *6- by 6-ft (1.8- by 1.8-m)* ** *With lead-in cable*

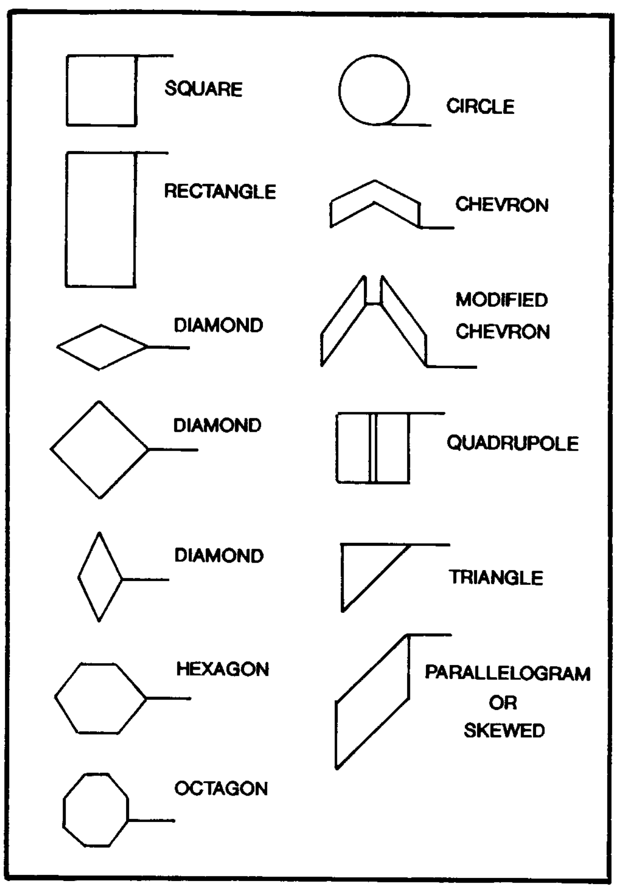


Figure 6-3. Small loop shapes.

can add the necessary additional 1/2 -in (13-mm) PVC and couplings to seal and protect the twisted lead -in to the pull box. Some models come with watertight slip joints at the four corners. This allows folding of the preformed loops for shipment.

The loops should be fabricated with PVC conduit of a size sufficient to contain the required number of turns. The wire within the loop should be installed such that there will be no movement of:

- The bundle of wire within the conduit, and
- Individual conductors with respect to each other.

The loops may be fabricated from multiconductor cable (untwisted) with 40 mil (1 mm) polyethylene insulation on all conductors and a 40 mil (1 mm) polyethylene outer jacket. Lead -in wire to the loop wire splice should be:

- Soldered,
- Covered with heat -shrink tubing, and
- Waterproofed with sealant within a section of PVC pipe.

Table 6-4 summarizes preformed loop applications while table 6-5 describes advantages and disadvantages of preformed loops.

Detector Electronics Unit

Principles of Operation —The electronics that generate the induction field and monitor an ILD have changed considerably since the early 1970s. Modern

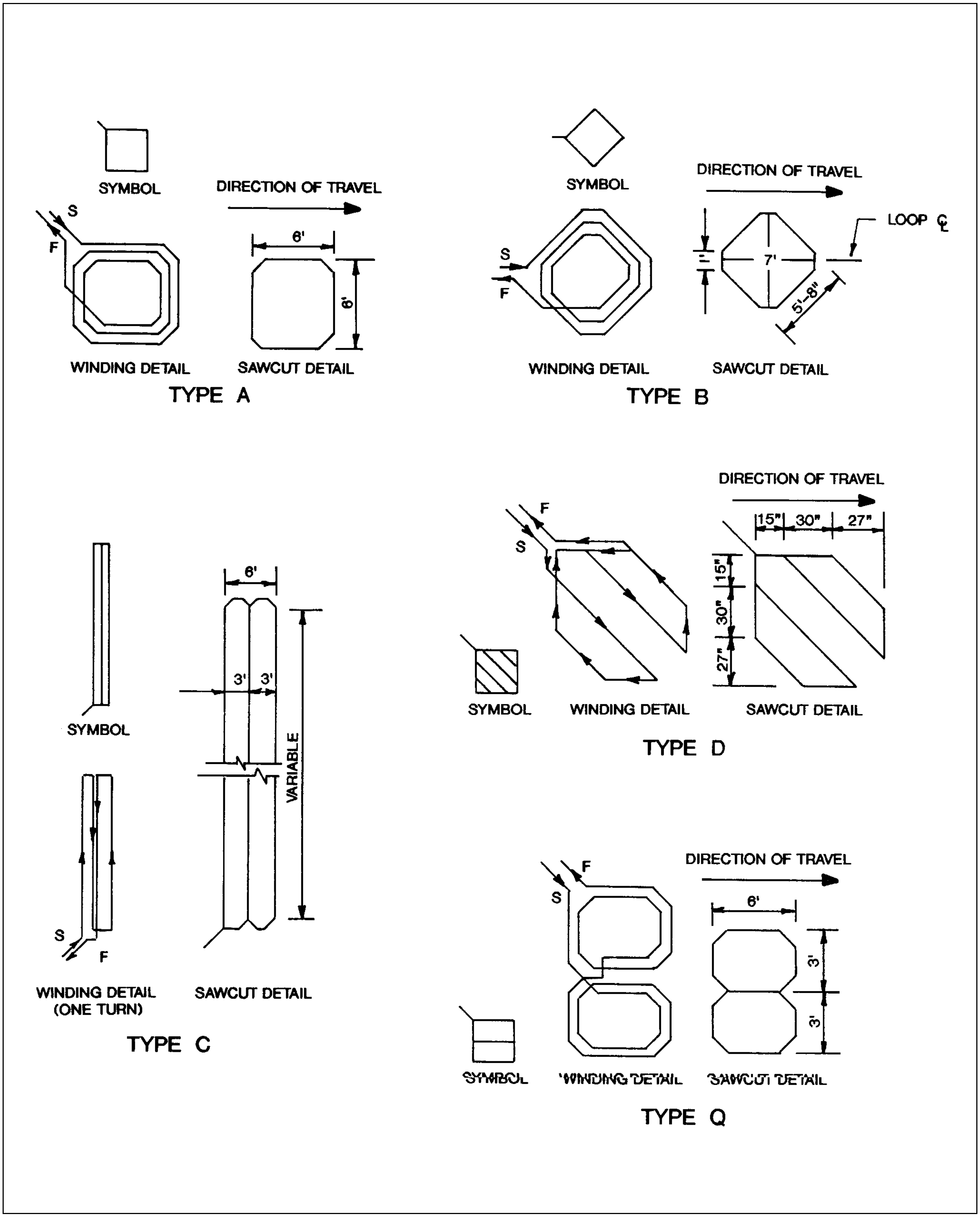


Figure 6-4. Examples of State specified loop shapes (California).

Table 6-4. Performed loop installations.

Possible Applications	Possible Installation Techniques
• Concrete • Asphalt pavement	• Placed in a 1-in (25-mm) or wider slot in existing pavements as conventional loops are installed • Placed on top of the base course before paving with bituminous surface • Installed 2 to 3 in (50 to 75 mm) beneath the untreated base course of a concrete roadway • Anchored to existing pavement and overlaid by at least 2 in (50 mm) of asphalt paving • Included in the pour of a concrete bridge deck

units compensate for or track drift in the resonant frequency caused by changes in moisture and temperature. The types of detector electronics include:

- Analog phase-shift,
- Digital
  - Frequency-shift,
  - Ratioed frequency-shift,
  - Period-shift, and
  - Ratioed period-shift.

Analog detector units, though fast and sensitive enough to detect bicycles, have become obsolete because of circuit complexity and their higher costs. These units also require field tuning and calibration, and set up proves more difficult in comparison to digital units.

Digital frequency shift detector units have 2 disadvantages: First, sensitivity decreases with the square root of the combined loop and lead-in cable inductance. A long lead-in cable will sacrifice some detector sensitivity. Second, sensitivity changes with the loop oscillator frequency. Whenever this oscillator frequency is changed (to avoid crosstalk problems with adjacent loops), the sensitivity setting has to be changed accordingly.

Digital ratioed frequency shift detector units automatically adjust the frame time (time to count the detector oscillator frequency), such that the no-call frequency count remains constant. In this way, the sensitivity remains independent of the loop/lead-in cable inductance.

Digital period shift detector units have sensitivities increasing with the square root of the combined loop and lead-in cable inductance. Changes in the lead-in cable lengths will necessitate some sensitivity adjustments.

Digital ratioed period shift detector units make the threshold count variable, such that the sensitivity remains independent of the detector frequency and hence independent of the loop and lead-in cable inductance.

Table 6-5. Advantages and disadvantages of preformed loops.

Advantages	• Supplier normally guarantees electrical characteristics of this factory-assembled, heavy-duty installation • Avoids installation errors typical of saw-cut embedded loops • Longer physical life • Improved environmental stability • No problems from wire movement • Higher dielectric characteristics when tested with a 500-volt megger to ground • Total installed cost likely to be lower than standard loop
Disadvantages	• PVC pipe may shatter in extremely cold weather, particularly in presence of heavy equipment traffic. (Alaska uses extra heavy duty PVC (schedule 80) to alleviate this problem.) • Shipping and handling somewhat inconvenient • When used in wide saw cuts, caution must be exercised in sealing to preserve pavement integrity

With the exception of digital frequency shift type detectors, the response times of all digital detector units are proportional to the sensitivity selections. The more sensitive the selection, the longer the response time.

During the 1980s, digital detector systems incorporated several refinements. Recognizing the heavy demand on maintenance dollars, some manufacturers added circuitry designed to reduce trouble calls. These features can reduce maintenance costs and maximize performance. For example, the Open Loop Test capability determines whether an open loop circuit has recently occurred. Automatic and Remote Reset features allow resetting the detector (removing a call indication which has persisted for some time).

NEMA Standards define 2 basic types of detector unit configurations (2) :

- Shelf-mounted, and
- Card rack-mounted.

Shelf-mounted units are commonly used in NEMA controller installations, and come in both single - and multi-channel (2 or 4 channel) configurations. The 120 volt AC supply in the cabinet powers these shelf-mounted units.

Card rack-mounted detector units fit into a multiple rack and operate off external 24 volt DC power generated in the rack assembly or elsewhere in the controller cabinet. These devices effectively reduce cabinet space requirements for large numbers of detectors.

NEMA has developed functional standards for loop detector units including (2):

- Operation,
- Modes of operation,
- Output types,
- Tuning,
- Self-tracking,
- Crosstalk,
- Timing features (delay/extension), and
- Controls and indicators.

Table 6-6 describes these standards.

Model 170 Specification — Section 7.8 describes the characteristics of the Model 170 controller. Detector Models 222 and 224 are 2- and 4-channel detector units that are compatible with this controller.

The detector unit mounts on an edge-connected, printed circuit board. Two channel detectors take up one card slot; 4 channel detectors take 2 slots. The detector module front panel has a hand pull for insertion and removal from the input file.

Each detector channel has panel-selectable sensitivity settings for both presence and pulse modes of operation. In keeping with NEMA Standards, the Type 170 Specification requires a means of preventing crosstalk with other modules. It also requires that the detector channel not detect moving or stopped vehicles at distances of three feet or more from any loop perimeter. Timing features are incorporated into the various Type 170 software programs.

Loop Electronics with Processing — Most digital detector manufacturers offer detector electronics that can process 4 or more loops. Some models address the crosstalk problem by providing a frequency separation switch, while others separate the loops by a time-division *scanning* process.

One manufacturer's scanning detector energizes and analyzes each of the 4 or more channels sequentially, 1 at a time, up to 100 times per second. The digital period shift type of detector is inherently fast enough to permit scanning. The time required to analyze a channel depends on the sensitivity desired, as high precision in thresholding demands more time for counting reference pulses.

Another manufacturer uses a much higher clock speed to provide much faster scanning rates. For example, on the lower sensitivity settings, the sample time is 0.5 ms per channel. Therefore, the total time to scan all 4 channels is 2 ms. Also, when a channel is switched off, the scan time for that channel is 0 (1).

Microloop — The Microloop Probe is a small, cylindrical, passive transducer of earth's vertical magnetic field intensity into inductance. It transforms changes in magnetic field intensity into inductance changes that loop detector units can sense. Intended for point detection (passage), 1, 2, or 3 microloops installed across a lane will replace a typical 3-turn 6- by 6-ft (1.8- by 1.8-m) wire loop for those applications. The number of probes required per lane and their optimum cross-lane position is determined by the lane width and the size (height) of vehicles to be detected. As a general rule, if some portion of a vehicle passes over a probe, it will be detected. A single probe centered in a lane will detect most vehicles; however, 2 or more at 3 to 4 ft (0.9 to 1.2 m) intervals are preferable for detection of small motorcycles and bicycles. Probes should be located vertically in 1-in (2.54-cm) holes and 16 to 24 in (40.6 to 61 cm) below the roadway surface. Microloop probes can be connected in series with other microloop probes or conventional wire loops (7).

Table 6-6. NEMA loop detector functional standards.

Standard	Specification
Operation	The loop detector unit responds to changes in the inductance of the detector loop/lead-in combination(s) connected to its loop input terminals. It develops a detection output upon a sufficiently large decrease in the magnitude of the connected inductance.
Modes of Operation	There are 2 modes of operation selectable for each detector channel: *presence* and *pulse.* *Presence* detection implies that a detector output remains *on* while a vehicle is over the loop. The detector unit must sustain a presence output for a minimum of 3 minutes before tuning out the vehicle. Most units maintain the call up to 10 minutes. This mode is typically used with long loop installations on intersection approaches with the controller in the *non-locking detection memory* mode. (Non-locking detection memory is a controller function whereby the controller retains a call (vehicle detection) only as long as the presence detector is occupied (vehicles are passing over or stopped on the detector). If the calling vehicle leaves the detector, the call is dropped (forgotten) by the controller). *Pulse* detection requires the detector to generate a short pulse (between 100 and 150 ms) every time a vehicle enters the loop area. If this vehicle remains in the zone of detection, the detector unit becomes responsive within a maximum of 3 seconds to additional vehicles entering the zone of detection. The detector unit produces one and only one output pulse for a test vehicle traveling at 10 mi/hr (16.1 km/hr) across the zone of detection of the single sensor loops. This mode is typically used with detectors well upstream of the intersection and the controller in the *locking* detection mode. (The vehicle call is not dropped by the controller when the calling vehicle leaves the detector.)
Output Types	Two types of output are available for detector units: *relay* and *solid state.* Relay outputs use electromechanical relays to generate a circuit closure, and thus a detection call to the controller. Relay outputs fail *on* (contacts closed) when power is interrupted. Relay output proves more desirable for intersection actuation, because a constant-call is safer than a no-call. Solid-state outputs have no moving parts, and therefore prove generally more reliable and considerably more accurate in tracking vehicle presence. This may be a factor where data is sampled or processed by communications or computer equipment in system applications. The solid-state output fails *off* (non-conducting) when power is interrupted. Solid-state output provides more accurate presence detection.
Tuning	Detector channels must accommodate the range of detector loop/lead-in inductance. The unit automatically tunes upon application of power and operates with at least 90 percent of its selected sensitivity within 2 seconds after application of power.
Self-Tracking	The detector unit automatically accommodates those after-tuning changes in the loop/lead electrical characteristics.

Table 6-6. NEMA loop detector functional standards (continued).

Standard	Specification
Crosstalk	Two loops of the same size, number of turns and lead-in length have the same resonant frequency. Should these 2 loops or their lead-ins be in close proximity (perhaps running in the same conduit), *crosstalk* can occur. This is an electrical coupling between the 2 loop channels which often manifests as brief, false, and/or erratic actuations with no vehicles present. NEMA Standards require a means to prevent crosstalk. Prevention may be inherent, automatic, or manual. Most units feature a frequency selection switch to vary operating frequency of the adjacent loop channels.
Timing Features	Includes *delay* and *extension* timing. *Delay* timing can be set from 0 to 30 seconds, indicating the time the detector waits from the start of the continuous presence of a vehicle until output begins. The output terminates when the vehicle leaves the detection area. If the vehicle leaves the loop before the delay time has expired, no output is generated. *Extension* time defines the time the output is extended after the vehicle leaves the zone of detection, and can be set from 0 to 15 seconds. The time can be controlled by external inputs to the detector. For detectors with relay outputs, a Delay/Extension Inhibit Input is provided and requires 110 volts to activate. Detectors with solid state outputs have a Delay/Extension Enable Input that requires a *low* state DC voltage (0 to 8 Volts). A delay call installation is typically found in a semi-actuated intersection with heavy right-turns-on-red from a side street that has long loop presence detection. Using a relay output detector, the side street green field output (110 volts AC) is connected to the Delay/Extension Inhibit Input. Thus, a delay is timed, allowing right-turns-on-red to be made without unnecessarily calling the controller to the side street. (Heavy right-turn movements will bring up the green anyway, as the loop will be occupied by following vehicles.) However, when the side street shows green, the delay is inhibited, permitting normal extensions of the green. Conversely, extended call detectors could be used on high-speed approaches to an intersection operated by a basic non-volume-density actuated controller. Using this technique, the apparent zone of detection is extended, and a different *gap* and *passage* time can be created without the need for volume-density controllers (this does not, however, replace volume-density functions). The Delay/Extension Enable Input on a solid-state output detector could be tied to the controller's *Phase-On* output.
Controls and Indicators	Specifications include: • *Output Indicator* Visually indicates the output state of each channel • *Sensitivity Control* Permits selection of the sensitivity of each channel • *Reset* Unconditionally causes the detector or detection channel to return to a non-vehicle present condition • *Mode Selector* Provides for selection of pulse or presence mode operation of each channel

Selection Factors **—**Several important considerations should enter into the selection of an appropriate loop detector unit. The importance of these factors depends on specific requirements.

Depending on a unit's application, users should review the following ILD specifications:

- Tuning range,
- Loss of detection on long loops during saturated flow,
- Loss of sensitivity with increasing length of lead-in cable,
- Loss of sensitivity from pavement overlay,
- Pulse-mode reset,
- Response time,
- Recovery from sustained occupancy,
- Fail-safe operation with loops that are grounded, open, or shorted,
- Lightning damage and other electrical interference,
- Delay/extension control, and
- Cabinet space.

Magnetometer Detectors

Principles of Operation. The magnetometer detects a change in the vertical component of the earth's magnetic field caused by presence or passage of a vehicle over a magnetic probe installed within the pavement. When a vehicle passes over the probe, a voltage change causes closure of the output relay. The unit detects vehicles traveling at speeds from 0 to 100 mi/hr (0 to 161 km/hr). A magnetometer detector, illustrated in figure 6 -5, consists of the (8):

- Probe,
- Probe cable,
- Lead-in cable, and
- Electronic unit.

Magnetometers provide an alternative to the ILD for several applications. However, the magnetometer primarily obtains vehicle count and passage information at individual intersections, where the device senses a vehicle in a small area. A large area presence detection application requires a series of probes, which may prove more costly than the ILD. Magnetometers may find application:

- Under bridge decks when damage to the reinforcing steel becomes a concern, or

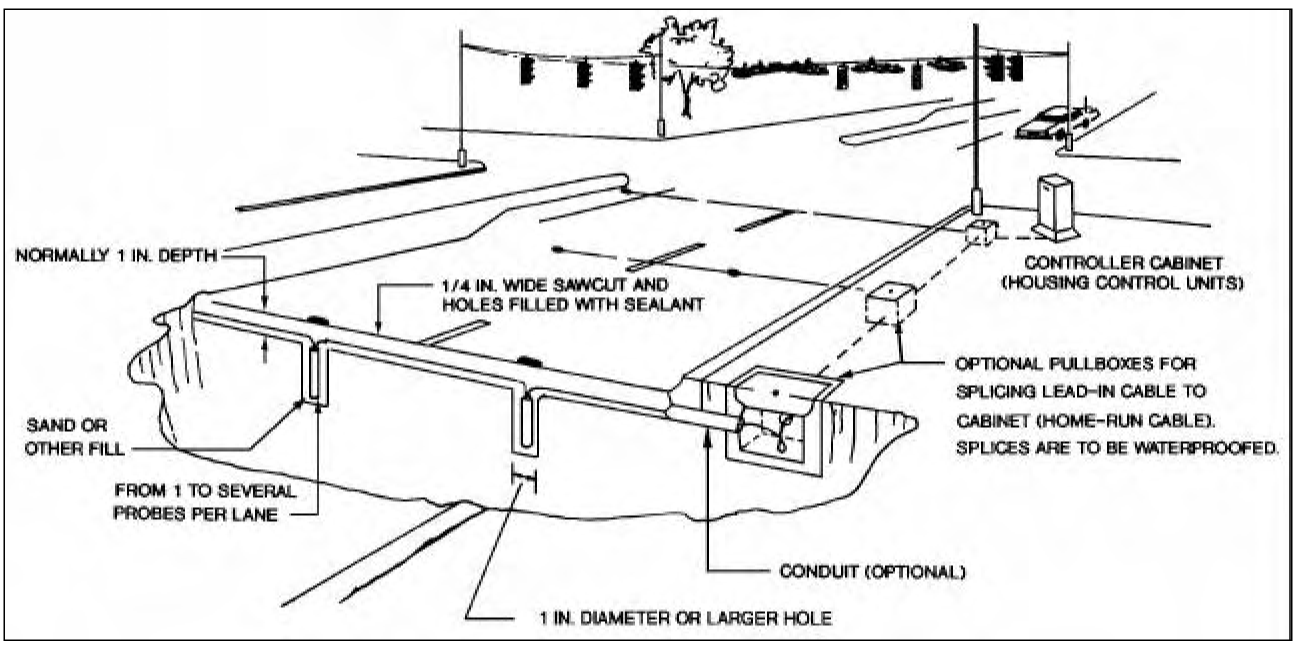


Figure 6-5. Magnetometer detectors.

- In roadways where deteriorating pavement dictates minimizing saw cut.

Unlike inductive loops or magnetic detectors, probes and/or electronic units for magnetometer detectors are not interchangeable among different manufacturers.

Probe Characteristics. The magnetometer probe is a small cylindrical device, installed vertically in a drilled hole in the pavement, usually 1 -ft (0.3-m) deep. Since the detector measures only changes in the earth's magnetic field, the detector itself establishes no active field. A single magnetometer probe may not accurately define vehicle speed and occupancy in a monitoring application. This occurs because of the inexact detection of the vehicle perimeter. The magnetometer detector can prove very sensitive. Depending on the manufacturer, as many as 12 probes can be connected in series to one channel of a detector unit. However, as the number of probes per channel increases, sensitivity at each probe decreases (1). The Model 170 Controller equipment suite specifies Magnetometer Sensing Element Model 227 and 2 Channel Detector Controller Unit Model 228.

Magnetic Detectors

Principles of Operation. Magnetic detectors were among the early vehicle detection devices produced. They still see use where:

- Deteriorated pavement and frost activity tend to break the ILD wire, or
- It is desirable to install detection without cutting the pavement.

Magnetic detectors operate based on a *change* in *lines of flux* from the earth's magnetic field. A coil of wire with a highly permeable core is placed below the surface of a roadway. When in proximity to or passing over the coil, a vehicle deflects the constant lines of flux passing through the coil, thus causing an induced voltage. This voltage, passing through a high-gain amplifier, operates a relay which signals the controller that a vehicle has passed.

Figure 6-6 illustrates a magnetic detector (probe) tunneled under the roadway and protected in a non-conducting waterproof material (9). Normally, a magnetic detector detects from 1 to 3 lanes of traffic,

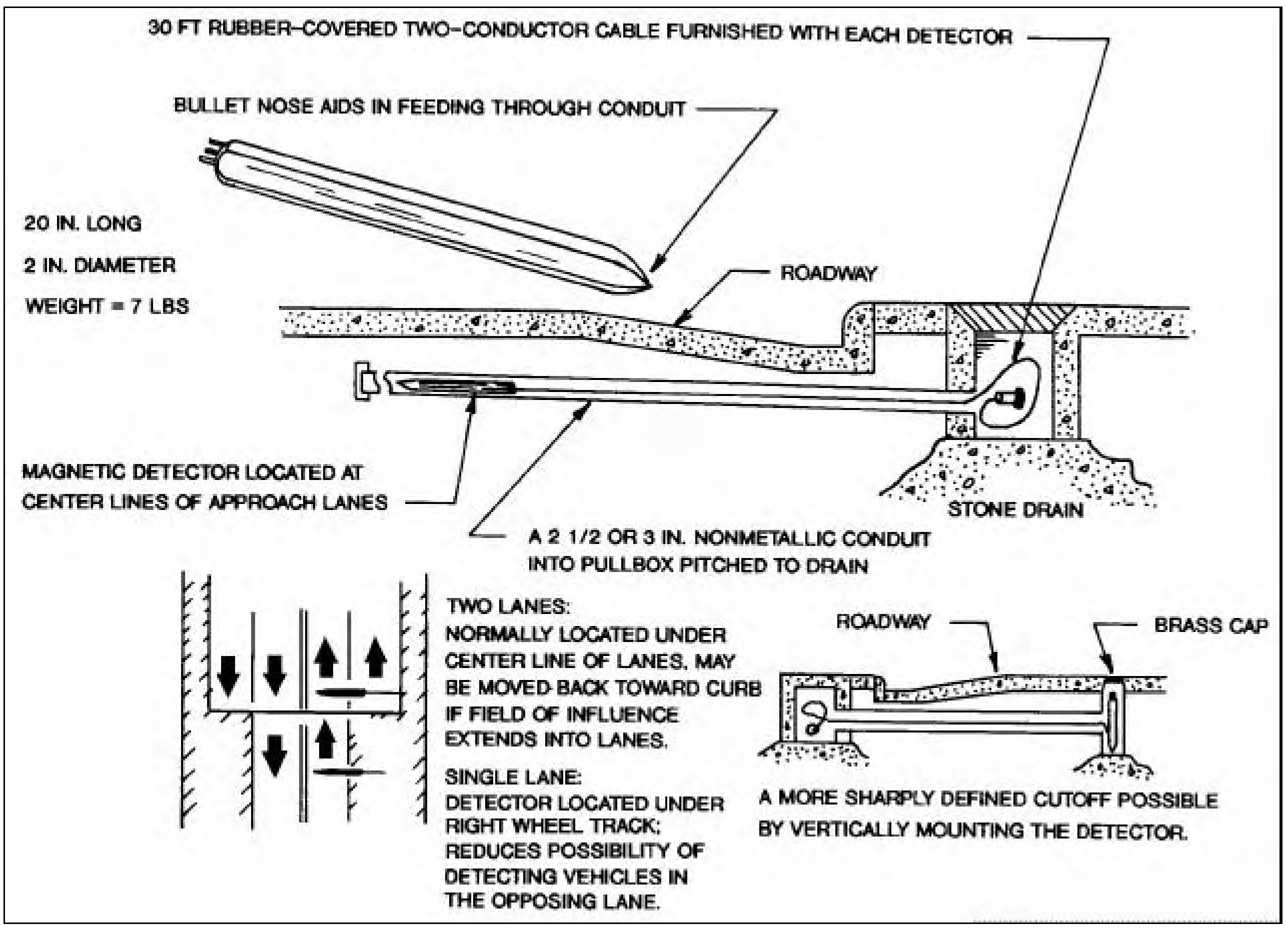


Figure 6-6. Non-directional uncompensated magnetic detector.

depending on the sensitivity setting of the amplifier relay assembly. The type of magnetic detector illustrated in figure 6-6 is *non-directional*; i.e., it cannot distinguish between vehicles traveling in opposite directions.

Probe Characteristics. The magnetic detector is a passive device; it does not create a field. Vehicles must move through the zone of influence to produce detector output. This detector type does not suit applications that require vehicle presence detection, because at very low speeds (less than 3 to 5 mi/hr (4.8 to 8.1 km/hr)), it may not generate a usable signal. Magnetic detectors typically apply:

- On high-speed approaches where small area detection combines with locking memory on the controller unit phase, and
- For areas with poor pavement conditions where previous loop detector installations have proven unsuccessful.
- Two available magnetic detector types include:
- Installed flush with pavement (*surface* mount), and
- 12 to 30 in (305 to 762 mm) below pavement (*subsurface* mount).

While magnetic detectors are inexpensive, reliable, and simple, they only suit pulse output applications in actuated signal control and traffic counting. The Model 170 controller equipment suite specifies Magnetic Detector Sensing Element Model 231 and Magnetic Detector Amplifier Models 232 and 234.

Pressure Detectors

Pressure detectors saw wide application before development of the now frequently-used loops and magnetometers.

Pressure detectors are activated by vehicle *weight*. The weight closes contact plates sealed in a rubber pressure plate and the closure signals a controller. Contact plates normally close at 100 lbs (45 kgs) pressure or less, so the detector operates satisfactorily for virtually all vehicle types. A metal frame installed in the pavement provides support and holds the pressure plate in place.

Although pressure detectors saw wide use for many years, current applications prove rare because the detectors:

- Provide only count data,
- Are expensive to install,
- Require a lane closure for extended periods during installation, and
- Result in a dip when resurfacing a roadway.

Non-Pavement Invasive Detectors

Radar/Microwave Detectors transmit microwave energy toward the roadway from the detector's antenna. The presence of a vehicle causes a reflection that is returned to the antenna. Many microwave detectors sense the frequency change of the reflected energy (*Doppler* frequency) and obtain vehicle speed from this signal. Other detectors use other properties of the reflected signal. Detectors that only use the Doppler frequency can sense only speed and passage, not presence.

Vehicle detectors use 2 types of radar units:

- Antenna and detection electronics fabricated as one unit located over the roadway or in a side-fire position, and
- Separate antenna and detection electronics.

The latter is pole-mounted at a height that allows for easy maintenance from the ground.
Radar detectors require a Federal Communications Commission (FCC) radio station license, obtainable by a state or municipality free of charge, and renewable every 5 years. A single FCC license covers all radar detectors in a given city or State.

Newly developed radar detectors:

- Detect moving vehicles as well as stopped vehicles,
- Cover single or multiple -lanes,
- Provide digital speed information, and
- Sense multiple locations (10).

Sonic Detectors. The *active* sonic detector transmits pulses of ultrasonic energy through a transducer toward the roadway. The presence of a vehicle causes these beams to reflect back to the transducer. The transducer:

- Senses the reflected wave,
- Converts it to electrical energy, and
- Relays this energy to a transceiver, that provides vehicle presence information.

Transducers may be mounted over the roadway or in a side-fire configuration, while transceivers are installed in a separate controller cabinet. The maximum pulse repetition frequency (PRF) of the sonic detector is approximately 12 to 15 pulses per second. This limits the fidelity of the occupancy measurement. Where a system requires accurate occupancy at moderate or high speeds, such as for freeway monitoring or platoon speed measurements, this detector type is not recommended.

Passive sonic detectors essentially act as sensitive acoustic microphones *listening* to the noise of vehicles as they pass through the detector's range. This technology stems from anti-submarine warfare (ASW), where the noise of a submarine's engine or wake is sensed. This detector type is currently in limited production.

Video Image Processing System (VIPS) uses video technology and image processing techniques for vehicle detection. The Federal Highway Administration initially promoted and funded investigation of this technology during the mid-1970s.

This initial project combined television with video processing technology to identify and track vehicles traveling within the camera's field of view. The initial system saw limited success because of tracking difficulties under varying background and lighting conditions.

During the 1970s and 1980s, Japan, the United Kingdom, Germany, Sweden, and France undertook parallel efforts. These activities:

- Addressed the problems and limitations of existing roadway detectors, and
- Explored the requirements of modern control technology for improved detection.

Following the initial FHWA research project, the University of Minnesota developed the Video Detection System (VIDS) (11). This system uses a single video camera with associated processing hardware and software to provide output equivalent to multiple loop detectors.

Figure 6-7 depicts the operation of this real-time video imaging detection system (1). Video cameras installed at selected locations on the freeway and/or signalized intersections collect traffic data in real-time.

The system can detect traffic at a number of locations (multiple spots) within the camera's field of vision. The user specifies these locations with interactive graphics and can change them as desired. To achieve this flexible detection point placement, the user inserts detection lines along or across the roadway lanes (as depicted on the TV monitor) by means of a mouse or keyboard. A vehicle crossing a detection line generates a signal.

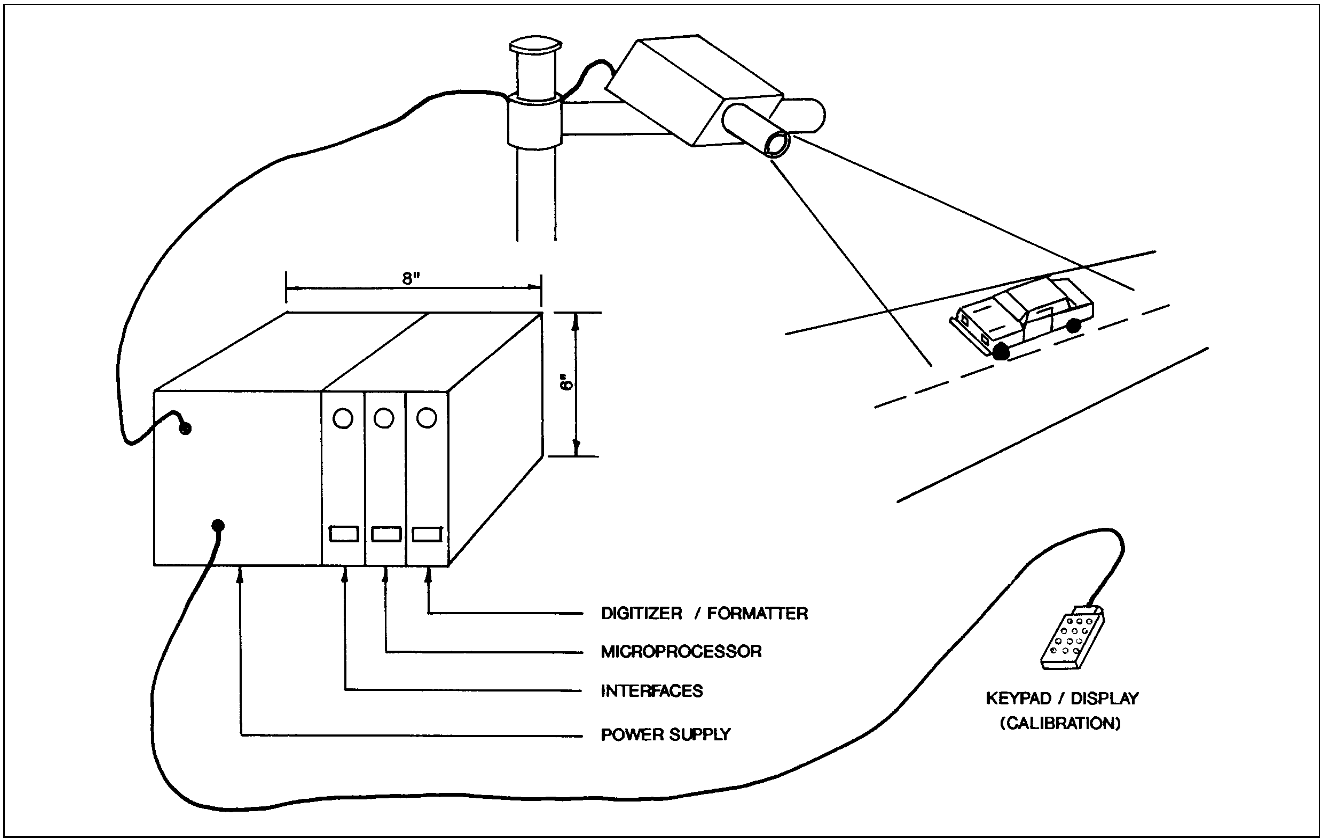


Figure 6-7. Wide-area video imaging system.

The processing system can provide output comparable to loop detectors in the identification of factors such as vehicle presence. It can also process the data to provide indications of volume, occupancy, and speed, as well as other variables.

The system output can connect to a:

- Control system (either freeway or signal control), or
- Local signal controller where traffic control application software processes information on detected traffic.

A single camera can replace a number of loops, thereby providing wide-area detection. Lancaster, CA, Long Beach, CA, Oakland County, MI and Minnesota DOT currently use image processing technologies. Minnesota DOT is conducting an extensive evaluation for possible freeway applications.

Video image processing (VIP) detectors have been developed and successfully demonstrated for a variety of roadway, environmental, and traffic conditions (12). Algorithms generate presence and passage detection and vehicle speed for multiple detection spots in the camera's field-of-view. One implementation reduces the image data from the video digitizer with a microprocessor called a *formatter*, so that only data needed for detection is processed. This reduces the amount of data processing by 2 to 3 orders of magnitude.

Once the formatter reduces the data, spatial and temporal features are extracted for each detection location. These spatial and temporal elements are combined using sequential decision processing to generate either presence or passage signals. Speed is estimated by using pairs of closely spaced detection lines and measuring the time between adjacent passage signals for these detection spots. This is similar in concept to loop detector speed traps.

The processing algorithms have been optimized to deal with *artifacts* such as:

- Shadows,
- Illumination changes, and
- Reflections.

A typical commercially-available VIP system accepts input from several cameras viewing the roadway. Detectors are drawn on a video monitor using a mouse. Different detector sizes can be selected, and detection zones may be placed anywhere and in any orientation within the combined field of view of the cameras. Special speed trap detectors can extract vehicle speed and vehicle classifications as defined by length. The processor may be located in the field, or video signals may be transmitted to a control center for processing.

The availability of multiple detector locations in a single processor, in combination with other data processing capabilities, enables video image processors to develop traffic variables and perform operations that may be beyond the capabilities of loop detector-based monitoring.

California State University (Cal Poly) at San Luis Obispo, CA, identified and tested 3 *turnkey* (available commercially) and 5 *prototype* VIPs (13). The test procedure evaluated the effectiveness of these products under likely conditions on the congested California highway system. The test examined variables such as:

- Camera positioning,
- Traffic volumes,
- Weather, and
- Lighting conditions.

Approaches by the different systems vary from vehicle tracking throughout the video image to analyzing only specific regions for vehicle presence.

Initial results show sufficient accuracy for traffic control purposes was achieved by most systems in typical low, moderate, and high traffic intensities, with minor problems created mainly by occlusion. Some systems had problems with stop and go traffic, particularly when initialized during periods of heavy congestion.

The transition from day to night and vice-versa often reduced accuracy. For most systems, this occurs because different algorithms apply to the 2 lighting conditions. Switching from one to the other required refinement in most systems. This may prove to be a significant problem, since peak periods frequently coincide with such transitions. However, much of the equipment tested has subsequently undergone improvement.

Infrared detectors are used extensively in England for both pedestrian crosswalks and signal control. The San Francisco-Oakland Bay Bridge also uses these devices. On the Bay Bridge, they are side-mounted at 600 ft (180 m) intervals on the upper bridge deck. The detectors establish the presence of vehicles across all 5 lanes, thus providing an occupancy measurement.

Users often cite the following disadvantages of infrared detectors. Changes in light and weather will cause scatter of the infrared beam. The lens system may also prove sensitive to water and environmental constraints. Their reliability in high flow conditions has been questioned as well. In addition, some earlier infrared detectors were not capable of providing vehicle counts (14).

One infrared detector product line consists of both *active* and *passive* models. The *active* system illuminates detection zones with low power infrared light. An optical system focuses the infrared light reflected from vehicles traveling through the zone of detection onto a sensor matrix. Real-time signal processing then analyzes the received signal and determines the *presence* of a vehicle. The unit automatically tracks environmental shifts. One version of this active infrared detector primarily applies to stopline presence detection, while a second version applies to presence detection in the intersection approach (e.g., a detection zone 68 to 100 ft (20.7 to 30.5 m) in advance of the stopline).

The manufacturer reports that its *active* infrared detectors can provide vehicle presence detection for traffic signals, vehicle counting, speed measurement, length assessment, and queue detection information. Their units accommodate mounting heights of between 15 to 30 ft (4.5 to 9.1 m). Multiple units can be installed within the same intersection without interference and with no interaction between units. The optical system design provides sharp-edged zones of detection. Vehicles outside of the defined zone have no effect (15).

The *passive* system measures passage (motion) only. The unit contains a lens configuration that provides detection of moving vehicles within a 3° zone of detection up to 300 ft (91.4 m) from the unit. Wider detection zones become possible by selecting the optional medium or short focal length lenses. To eliminate adjacent lane detection when detecting vehicles over 100 ft (30.5 m) from the unit, the long length lens option is recommended. For detection close to the unit (e.g., for side-fire detection), use of a medium or short focal length lens is preferred.

A device recently became available that offers vehicle presence sensing and thus serves as an alternative to the inductive loop. This new device examines different areas in the field of view for uniformity of thermal contrast and for continuity of contrast in time. It is microprocessor-based and can thus compare *present* to *preceding* contrasts using proprietary algorithms. Moreover, it adjusts to thermal changes in the background (a road) produced by rain, wind, sun-going-behind-cloud, etc. As currently configured, this device will detect the presence of a vehicle for over 6 minutes. The passive infrared vehicle-presence sensor is self-contained within a NEMA 4X housing and mounts to a corner pole, mast arm, or other stable structure, looking down at the lane to be controlled. (It cannot be mounted from a span wire because movement in the wind will alter the view, causing false actuation.) (16)

Special Purpose Detectors

This section discusses *special-purpose* detectors for:

- Buses,
- Automatic vehicle identification/electronic toll and traffic management,
- Overheight vehicles,
- Environmental conditions,
- Pedestrians, and
- Preemption.

Bus Detector. An *active* bus detector system consists of a:

- Radio frequency transmitter,
- Receiving loop buried in the pavement, and
- Curbside receiver unit.

Detection occurs with the vehicle over the loop, which establishes bus position and direction of approach. This in turn enables automatic initiation of a control action.

To eliminate the transmitter, *passive* systems do not require equipment on board the vehicle. Currently marketed systems use a conventional loop buried in the roadway and a specially adapted digital detector that transmits a unique wave form (also termed *signature* or *footprint*) for each vehicle. Bus detection systems transfer the digital signal to a microprocessor module that:

- Analyzes the shape and characteristics of the signature,
- Compares the signature to known stored bus profiles, and
- Generates an output to provide priority treatment.

Automatic Vehicle Identification (AVI) Detectors identify specific vehicles at predetermined points on the highway, without requiring any action by the driver or an observer (17). AVI systems commonly assist in toll collection. This type of AVI system includes three functional elements:

- Vehicle-mounted transponder or tag,
- Roadside reader unit, with its associated antennas, and
- Computer system for data processing and storage.

At the simplest level, information that identifies the vehicle is encoded into the transponder. The information normally consists of a unique identification number, but can also include other coded data. A vehicle passing the reader site triggers the transponder to send coded data to a receiving antenna at the roadside reader. The reader checks data integrity and transmits it to the computer system for processing and storage.

Some AVI systems permit *two-way* communication. Here, data flows in both directions, with coded messages transmitted between the reader and vehicle-mounted transponders. Vehicles could potentially be warned of congested areas, accidents, or adverse weather conditions, enabling drivers to take alternative routes. This type of system requires more sophisticated technology, with additional capabilities in both roadside and vehicle-based equipment.

One application provides real-time travel speed information, which can be used by traffic information systems. The system determines speed by transmitting the coded vehicle identification number to the roadside at each reader. The central computer processes this identification data to obtain journey times between readers in an AVI network, indicating traffic conditions between these points. Vehicles used in this manner are sometimes called *probes*.

A number of approaches to AVI have been performed since the first investigations in the 1960s. Recent advances in vehicle detection and data processing techniques have made AVI systems both technically and economically feasible. AVI systems can be divided into 5 main categories, described in table 6-7.

Overheight Vehicle Detectors and overheight vehicle control systems are discussed in section 3.10.

Environmental Detectors detect adverse environmental conditions, so that systems can appropriately control or advise travelers. These detectors yield weather information and data and can activate an early warning or traffic control system, typically in conditions such as ice, wet pavement, or fog.

Environmental detection devices can provide accurate surface and atmospheric data from selected locations so the traffic or maintenance engineer can plan efficient and safe operations. In deploying maintenance forces, an early warning system for detecting icy conditions on critical roadway sections can save:

- Response time,
- Staffing levels, and
- Anti-icing material.

Systems for detecting adverse environmental conditions can remotely detect pavement slickness due to rain, snow, ice, sleet, or commodity spillages. A number of commercial detection systems exist, such as those manufactured by SCAN in the United States (20).

Pedestrian Detectors provide input to the controller to allow time for pedestrian and bicyclist crossings at signalized intersections. The *pushbutton detector* has proved the most widely used pedestrian demand detector. It consists of a button that causes a contact closure when pushed by the pedestrian. The closure allows low voltage current to flow to the actuated controller, which registers a demand for serving the pedestrian phase. At the first appropriate opportunity, the controller displays the WALK indication. An environmental enclosure houses the pushbutton to protect it from weather or vandalism. The device is mechanically simple and generally reliable. The intersection controller contains all response and pedestrian timing data.

Preemption Devices provide priority for fire and emergency vehicles by detecting the vehicle and sending the preemption command to the controller.

- *Optical* preemption devices have two elements:
- Optical emitter on the vehicle to generate optical signals, and

Optical detector near the intersection to receive the signals.

The information goes to a phase selector in the controller cabinet that processes the electronic impulse and commands the controller to provide a green signal.

Recently introduced preemption systems use spread spectrum, UHF, and digitally-coded radio from the vehicle to the intersection.

A commercially-available radio preemption system (EMTRAC) consists of (21):

- Transmitter with a directional antenna and an electronic auto-compass in each vehicle, and
- Receiver with an omnidirectional antenna at each intersection.

The receiver comes in a shelf-mount version, powered directly by 120 VAC, and provides a simple 5-wire connection to all NEMA controllers with preemption inputs. It also comes as a plug-in module, which fits directly into 2 card slots of a Model 170 controller cabinet.

Table 6-7. Categories of AVI/ETTM systems.

Category	Description
Optical Systems	Early AVI technology developed in the 1960s in the United States and Europe. Optical systems require clear visibility, as performance is degraded by snow, rain, ice, fog, or dirt. Also sensitive to: • Reader/tag misalignment • Focusing problems • Depth of field limitations Improvements in performance have been achieved in recent years. A recent project undertaken at the University of Arkansas investigated bar code optical AVI systems. Results suggest that, even with modern technology, reliability of optical AVI remains too low for most highway transportation applications. Largely abandoned approach (17).
Infrared Systems	Tried during the 1970s as a substitute for earlier optical approaches. Found to share many of the problems of earlier optical systems. Also proved sensitive to environmental conditions. High read reliability not achieved. Largely abandoned approach.
Inductive Loop	Uses conventional traffic detection and counting loops in pavement to detect signals from transponders mounted on the underside of vehicles. Approaches include: active, semi-active, and passive systems, according to the power source used by the vehicle-mounted transponder. For example, INRAD is a two-way system used for both communication to the vehicle and vehicle identification (18).
RF and Microwave	Roadside-mounted or in-pavement antennas, transmitting or receiving on a wide range of frequencies in the kilohertz, megahertz, and gigahertz ranges. These systems include: active, semi-active, and passive approaches. Because they operate at higher frequencies, these systems can transmit data at much higher rates than inductive loop systems. A potentially serious problem concerns the power levels transmitted to energize vehicle-mounted tags. In many countries, these may violate accepted safe operating levels for microwave systems. Semi-active systems offer a compromise, using a sealed unit transponder with an internal lithium battery. These allow great reduction in radiated power levels, while providing a transponder design life of several years.
Surface Acoustic Wave (SAW)	A SAW tag consists of 2 elements: an antenna and lithium niobate SAW chip that serves as a multi-tapped electronic delay line (19). The SAW chip: • Receives an interrogation signal through the attached antenna • Stores it long enough to allow other reflected environmental interference to die out • Returns a unique phase-encoded signal The key operating characteristic of the SAW chip is conversion of the electromagnetic wave into a surface acoustic wave. SAW tags overcome concerns over high microwave power levels, but are limited to purely fixed-code applications.

The *auto-compass* can automatically set the preemption direction by sensing the vehicle's travel direction. The direction can also be set manually from the transmitter and can differ from the current direction of travel. This feature allows clearance of congested traffic in any direction.

EMTRAC normally operates in a fully automatic mode using the auto -compass, with no need for driver intervention. Preemption automatically initiates with power applied to the light bar. It automatically terminates when the air brake is set or the driver's door opens.

Preemption can initiate directly from the fire station with the apparatus still parked. The system does not require direct line of sight to the intersection.

Each EMTRAC receiver automatically keeps preemption logs. These allow analysis of emergency response times and provide backup in case of litigation.

Comparison of Vehicle Detectors

Table 6-8 compares the functional capabilities of vehicle detectors that are suitable for general traffic control purposes, are commercially available, and are manufactured and installed in significant quantities (22). Detectors using other technologies such as active and passive infrared and passive acoustic monitoring are in various stages of development, evaluation, and limited quantity manufacture, but may play a significant future role.

6.3 Detector Operations Summary

This section describes the detector controller relationship and techniques for using detectors on low-and high -speed approaches. An understanding of this section will allow appropriate selection of a detector type for a given application.

Detector-Controller Relationship

A vital relationship exists between a controller's timing intervals and the detection techniques it employs. The appropriate combination of detector type, placement and controller settings can improve an intersection's efficiency and safety. The following discussion highlights this relationship, and is based on *Guidelines for Selecting Traffic-Signal Control at Individual Intersections*, Vol. II (23).

Low-Speed Approaches experience speeds less than 35 mi/hr (56.3 km/hr). Detection system requirements depend on whether the controller unit phase has been set to *locking* or *non-locking* detection memory (sometimes termed *memory ON* or *memory OFF*, respectively).

Locking Detection Memory enables a controller to *remember* or hold a vehicle call (even after the calling vehicle leaves the detection area) until satisfied by the appropriate green indication. Locking detection memory often uses small -area or point detection such as a 6- by 6-ft (1.8- by 1.8-m) loop or magnetometer. Often called *conventional* control, this approach minimizes detection cost. However, it cannot *screen out* false calls (such as those occurring with a right turn on red).

Most traffic engineers desire the allowable gap to range from 3 to 4 seconds, which requires locating the detector 3 to 4 seconds of travel time back from the stopline. This approach efficiently positions the detector to accurately time the end of green, after passage of the first vehicle of a queue or platoon.

However, the above technique applies only to low-speed approaches and intersections controlled by an actuated controller (without gap reduction). Using a practical allowable gap of 3 to 4 seconds, the detector setback should not exceed 120 ft (36.5 m) See table 6-9 for a summary of this principle (1).

Non-locking Detection Memory sets phases through *loop-occupancy control* using large-area presence detectors, such as 6- by 70-ft (1.8- by 21.3-m) loops or multiple magnetometer detectors (24). In this non-locking mode, the controller phase drops (or *forgets*) a waiting call when the vehicle leaves the detection zone. This greatly simplified control strategy responds to the presence/non -presence of vehicles. The non -locking feature reduces delay by avoiding diversion of the right -of-way to an empty approach.

Loop-occupancy control was first used at intersections with a separate left -turn control, in addition to locations that permitted right -turn-on-red. In this application, a call placed during the yellow change interval cannot restore the green to an empty approach. Another potential advantage exists at intersections that permit a left -turn during the through movement (permissive left). To enhance this operation, a delay detector unit outputs a call to the controller only if a vehicle is continuously detected beyond a preset time period. The NEMA TS2 specification includes an optional delay/extension capability (2). The Model 170 can achieve this capability using appropriate controller software. During light traffic conditions, left -turn and right-turn-on-red vehicles in transit over the loop are

Table 6-8. Types of detectors for general traffic control use.

Detector	Measuring Capability: Count	Presence	Speed	Occupancy	Method of Operation	Advantages	Disadvantages
Loop	Yes [1]	Yes	Yes [2]	Yes	Vehicle passage cuts magnetic lines of flux generated around the loop. Resulting inductance change is detected and transmitted to an amplifying circuit.	• Size and shape of detection zone can easily be set by size of loop • Excellent presence detector • Capable of measuring all traffic parameters • Relatively easy to install • Capable of detecting small vehicles	• Requires sawcutting of pavement • Installation requires closing of traffic lane or lanes for short periods of time
	[1] Short loops may be used to count. Long loops (e.g., 20 ft (6.1 m)) do not count accurately, due to multiple occupancy on the loop. [2] See section 3.2 for speed determination techniques						
Magnetometer	Yes	Yes	No	Yes	Measures change in earth's magnetic field caused by vehicle; makes use of small cylindrical sensing head placed below pavement surface.	• Relatively easy to install • Capable of measuring count or presence • Reliable • Not affected by DC lines in vicinity • Under roadway location and not subject to damage	• Requires closing of traffic lane for installation • May double-count some vehicles due to magnetic material distribution • Poorly defined detection zone
Magnetic, non-directional	Yes	No	No	No	Vehicle passage over wire coil embedded in roadway disturbs earth's lines of flux passing through coil and induces a voltage in the coil; voltage is amplified by high-gain amplifier to operate detector relay.	• Under roadway location and not subject to damage • Relative ease of replacement • Low maintenance	• Non-directional • Difficult to set detection zone • Subject to false calls when located near large DC lines • Cannot detect presence • Necessitates closing of traffic lanes for installation
Magnetic, directional (two-coil version)	Yes	No	No	No	(Same method of operation as non-directional magnetic detector.)	• Directional • Not affected by DC lines in vicinity • Low maintenance • Under roadway location and not subject to damage • Relative ease of replacement	• Requires closing of traffic lane for installation • More expensive than non-directional magnetic detector • Cannot detect presence

Table 6-8. Types of detectors for general traffic control use.

Detector	Measuring Capability				Method of Operation	Advantages	Disadvantages
	Count	Presence	Speed	Occupancy			
Pressure	Yes	No	No	No	Weight of vehicle closes metallic contacts to complete a circuit.	• Well-defined detection zone • Rugged construction • Reliable • Capable of detecting all moving vehicles, regardless of speed	• Counts axles, which yields poor count accuracy • Does not measure presence • Installation may disrupt traffic for excessive period of time • Major resurfacing requires the use of a frame extension
Radar/Microwave	Yes	Dependent on design of specific unit	Yes	Dependent on design of specific unit	Passage of vehicle reflects microwaves back to antenna. May use Doppler principle as well as other techniques.	• May not necessitate closing of traffic lanes to install • Non-pavement or roadway invasive	• Requires FCC license to operate • Antenna alignment required
Sonic, active	Yes	Yes	Poor accuracy	Yes	Emits bursts of ultrasonic energy at a rate of approximately 12 to 20 times per second; detects reflected ultrasonic pulse.	• May not necessitate closing of traffic lanes to install • Can be used at locations with unstable pavement • Can classify vehicle by height • Non-pavement or roadway invasive	• Low Pulse Repetition Frequency (PRF) limits accuracy of occupancy and speed • May be difficult to get complete lane coverage and avoid adjacent lane detection • May be sensitive to temperature variations • Cannot be used in certain high wall locations
Video image processing	Yes	Yes	Yes	Yes	TV cameras transmit their images to processor; processor detects vehicles crossing line drawn across lane by analyzing image pixels.	• Provides wide-area detection • Can provide traffic information beyond capability of spot detectors	• May be relatively expensive for simple applications • Subject to phenomenological error sources such as shadows, occlusion and background lighting

Table 6-9. Summary of detection locations and related timing for basic actuated Controller operating in locking detection memory mode.

Approach Speed		Detector Setback Stopline to Leading Edge of Loop		Minimum Green	Passage Time
mi/hr	km/hr	ft	m	seconds	seconds
15	24	40	12	9	3.0
20	32	60	18	11	3.0
25	40	80	24	12	3.0
30	48	100	30	13	3.5
35	56	135	41	14	3.5
40	64	170	52	16	3.5
45 +	72 +	Volume Density or Multiple Detectors Recommended			

Note: Volume density could be considered at speeds of 35mi/hr (56 km/hr) or above.

detected, but no call is placed until the preselected time delay has expired, thus reducing intersection delay by omitting unnecessary phase changes.

Often, loop-occupancy control is used for through-phase detection on approaches with low-approach speeds. This technique minimizes delay by allowing the use of a short extension interval in the range of 0 to 1.5 seconds.

The length of the detection area depends on the approach speed and the controller timing settings. For approach speeds below 30 mi/hr (48.3 km/hr), figure 6-8 indicates a detection area length for various unit extension time settings (1). Approach speeds above 35 mi/hr (56 km/hr) require a different technique to alleviate driver indecision caused by the yellow change interval.

High-Speed Approaches experience speeds of 35 mi/hr (56 km/hr) or greater. If the yellow change interval begins with a vehicle in an indecision zone, the driver may have difficulty deciding whether to stop or proceed through. An abrupt stop may produce a rear-end collision, while going through on red may produce a right-angle accident. Table 6-10 shows the boundaries of the dilemma zone (25). The data indicates that the upstream boundary of the dilemma zone, where 90 percent of motorists will decide to stop, lies 4.5 to 5 seconds from the intersection. The lower boundary, where 10 percent of the motorists will decide to stop, is 2 to 2.5 seconds from the intersection. Therefore, the duration of the dilemma zone does not exceed 3 seconds, starting approximately 2 seconds in advance of the stopline.

An actuated controller with appropriate detection can minimize inappropriate yellow change intervals. A research project examined a number of advanced detector-controller designs for high-speed, isolated approaches (24). Table 6-11 shows conventional detector-controller designs enhanced with multiple-point detection and/or a density-actuated controller (26). For details of the applications of these designs, see chapters 10 and 11 of reference 24. Table 6-11 demonstrates various combinations of detector-controller hardware that improve safety at high-speed intersections.

Studies by the University of Texas and the Texas Department of Highways and Public Transportation comparing multiple-point vehicle detection with single-point detection at 10 locations have shown (27):

- A significant reduction of accidents at speeds of 45 mi/hr (72 km/hr) and above, and
- No significant delay reduction using multiple loops instead of a single-point detector.

A similar study by Parsonson/Tarnoff does not agree with these conclusions, however (23).

When comparing alternatives for high-speed approach detector designs, the traffic engineer should give more weight to operational features and

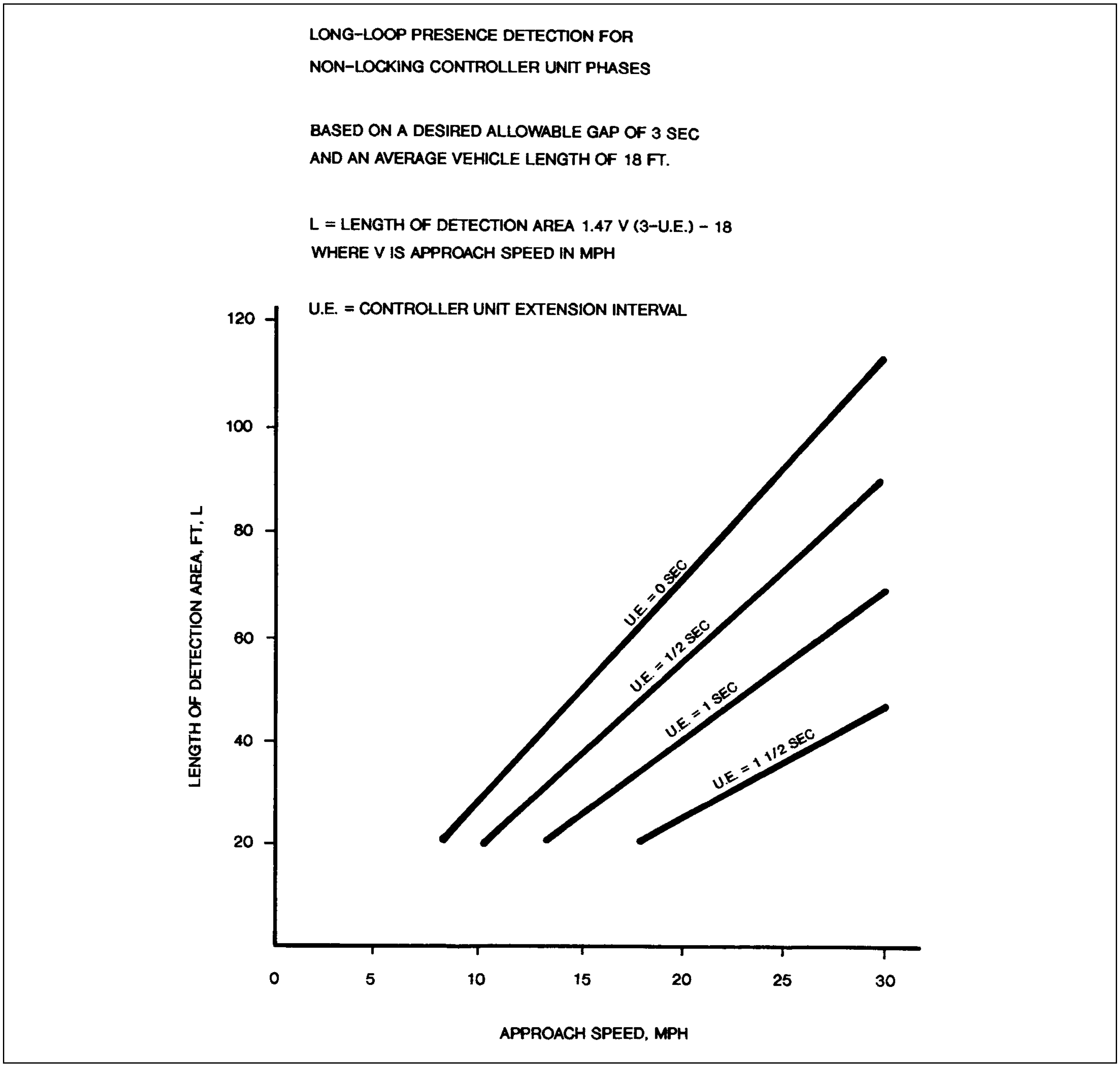


Figure 6-8. Loop length for low-speed approaches.

Table 6-10. Dilemma zone boundaries.

Approach Speed		Distance from Intersection for Probabilities of Stopping			
		10 percent probability		90 percent probability	
mi/hr	km/hr	ft	m	ft	m
35	56	102	31	254	77
40	64	122	37	284	86
45	72	152	46	327	100
50	80	172	52	353	108
55	88	234	71	386	118

Table 6-11. Conventional detector-controller unit configurations for high-speed approaches.

Type of System	Design	Memory	Detection Type	Controller Comments
1. Green-extension systems for semi-actuated controllers	A. 2-loop B. 3-loop	Locking	Semi-actuated	Composed of extended-call detectors and auxiliary logic units to hold the controller in main street phase A, until the approaching vehicle has cleared the dilemma zone. Vehicles traveling slower than design speed or termination of green by gapout may be trapped in the dilemma zone. Increasing the passage time for protection results in an intolerable allowable gap.
2. Extended-call detection systems for basic controllers	A. Extended-call (EC) design uses 70 ft (21.3 m) loop at the stopline (normal detector output) supplemented by extended-call detector 5 seconds before the stopline B. Extended-call and delayed-call (EC-DC) design uses 25 ft (7.6 m) loop at stopline (delay-call output) supplemented by extension detector 5 seconds before stopline and a third detector between them (see figure 6-9 (30))	Non-locking	Basic full-actuated	A. The stretch setting on the extended-call detectors requires compromise between rapid operation and protection for slower vehicles. The allowable gap of the EC design is typically 5 seconds because of the stretch detector and long loop at the stopline. Appears limited to routes carrying less than 10,000 ADT. Design has lowest initial cost. B. A stretch setting of 2.2 seconds on the upstream loop will carry vehicles approaching within the speed range of 40 to 55 mi/hr (64.4 to 88.5 km/hr) through the dilemma zone. A vehicle traveling less than 40 mi/hr (64.4 km/hr) will also be protected because the yellow will appear before the vehicle has reached its dilemma zone. The 2.2 second extension time produces an allowable gap for traffic of 3.8 seconds (55 mi/hr (88.5 km/hr)) and 4.4 seconds (40 mi/hr (64.4 km/hr). The allowable gap is actually greater than the 1 second difference of the EC design. The EC-DC design disables the stopline loops to give a decided superiority to EC design in real-world operation.
3. Multiple-point detection systems for basic controllers	A. Bierele modified method uses 5 detectors for 55 mi/hr (88.5 km/hr) approach speeds, with farthest detector placed 349 ft (106.4 m) from the stopbar. Uses special detector logic to determine approach speed and disable first 3 loops (see figure 6-10b (29))	Locking	Basic full-actuated	A. Bierele has modified his design for speeds greater than 40 mi/hr (64.4 km/hr). The first 3 detectors from the stopline are based on 40 mi/hr (64.4 km/hr) speeds and operate on 1 amplifier (speed detector). 2 additional detectors are placed at 1 second intervals for 40 mi/hr (64.4 km/hr) until a distance of 349 ft (106.4 m) is reached, and tied to the second amplifier (standard detector). For speeds greater than 40 mi/hr (64.4 km/hr), the special detectors are disabled, and only the standard detectors extend the green to maintain a tolerable gap.

Table 6-11. Conventional detector-controller unit configurations for high-speed approaches (continued).

Type of System	Design	Memory	Detection Type	Controller Comments
3. Multiple-point detection systems for basic controllers *(Continued)*	B. Texas Department of Highways and Public Transportation uses primary loop detector placement designs for 45 to 55 mi/hr (72.5 to 88.5 km/hr) (see figure 6-10a (29))	Locking	Basic full-actuated	B. This method used AASHTO stopping sight distances (based on 1 second perception-reaction time) for approach speeds up to 55 mi/hr (88.5 km/hr). This design is based on the assumption that a vehicle entering the loop field at the design speed will guarantee a safe stopping distance and a green if the speed is maintained or reduced by no more than 10 mi/hr (16.1 km/hr) between successive loops.
	C. Winston-Salem method employs 3 sensors for 50 mi/hr (80.5 km/hr) approach	Locking	Basic full-actuated	C. This method for detector placement is derived from the Bierele method, and uses stopping sight distances computed from the Traffic Engineering Handbook. The outermost point of initial detection is 240 ft (73.2 m) for a 50 mi/hr (80.5 km/hr) approach speed, which may not detect a vehicle before it reaches the dilemma time. Attempts to improve the design in that respect result in an allowable gap that is too long and frequently causes the controller to max-out.
	D. SSITE method uses 6 sensors for 50 mi/hr (80.5 km/hr) approach	Non-locking	Basic full-actuated	D. This multisensor design will adequately protect the driver from the dilemma zone, with its farthest detector set back 5 seconds from the stopline. However, with its 2 second vehicle interval, two-50 mi/hr (80.5 km/hr) vehicles will cause an allowable gap of 7 seconds; too long to be a design of choice.
4. Extended-call systems for density controllers	A. Single-point method composed of a presence loop at the stopline and one upstream detector	Non-locking	Density full-actuated	A. This method provides dilemma zone protection to vehicles operating at the design speed. The suggested 2 second vehicle interval may be insufficient for a slower vehicle to enter the usable yellow line.
	B. Multiple-point method employs a presence loop at the stopline and several upstream sensors	Non-locking	Density full-actuated	B. The multiple-point method can be configured to afford dilemma zone protection for a variety of approach speeds and operating conditions. A queue can get into motion without gapping out and false calls can be screened out because of detection at the stopline.

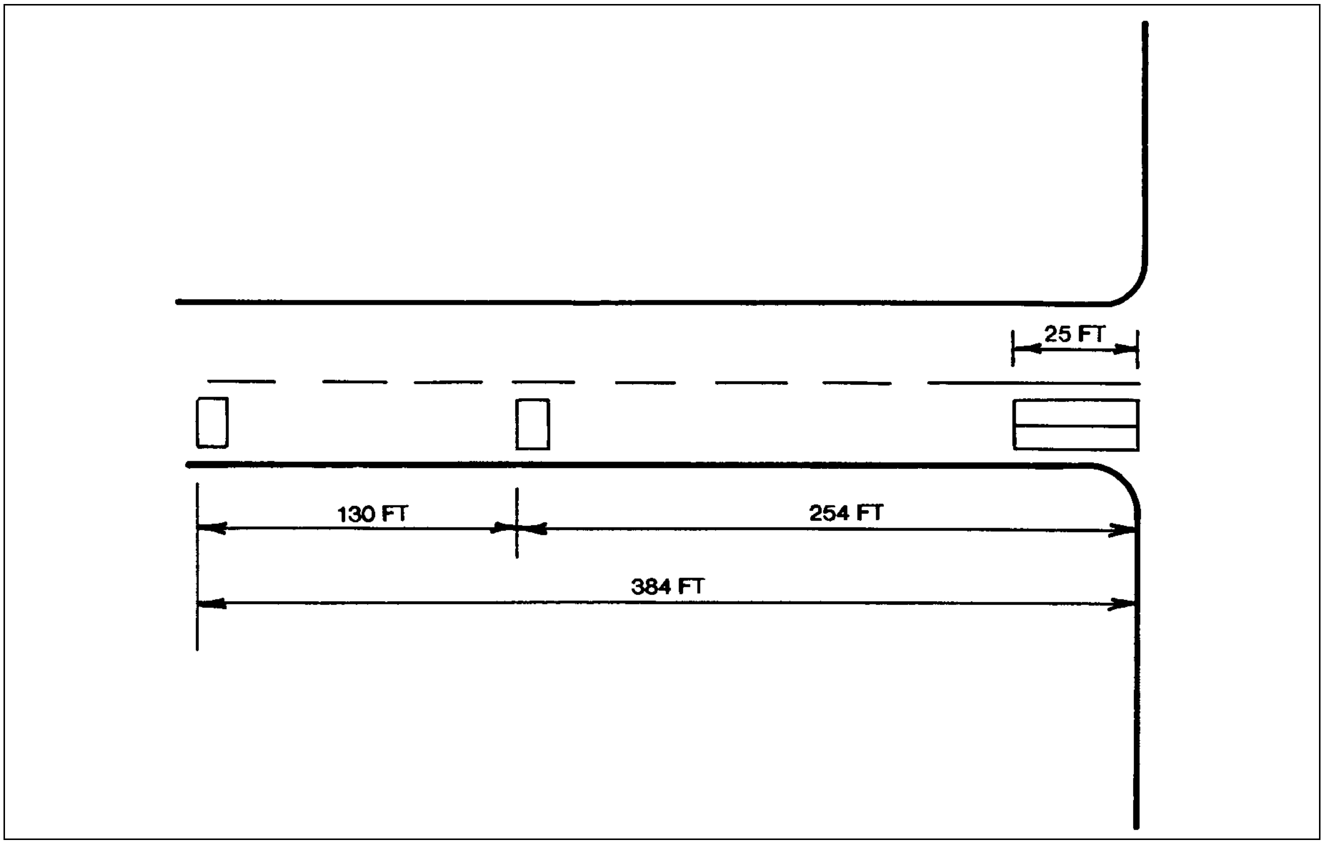


Figure 6-9. Loop location for extended call-delay call design with55 mi/hr (88.6 km/hr) approach design speed.

maintainability than initial cost. The engineer must consider the capabilities of maintenance staff and the difficulty of keeping loops in service. Parsonson applies the following criteria to judge the effectiveness of a proposed detector configuration for high-speed intersections (26):

- Does the design detect a vehicle approaching at the design speed before it reaches the dilemma zone? The design should detect the design -speed vehicle before it reaches the dilemma zone in accordance with Zegeer's data (see table 6-10).
- What is the allowable gap imposed by this design? A short allowable gap will cause the green to terminate in a rapid, traffic -responsive manner. A long allowable gap will often prolong a green until terminated by the maximum setting of the controller. This proves undesirable, because a vehicle may be caught in the dilemma zone. Dilemma zone protection can be provided by a last car passage feature or appropriate yellow change/red clearance intervals.
- On termination of the green by gap -out, will vehicles approaching at the design speed clear the dilemma zone? The last vehicle should be no more than 2 seconds from the stopline, so the driver can decide with no difficulty to go through the intersection.
- On termination of the green by gap -out, will vehicles traveling slower than the design speed clear the dilemma zone? A trade -off exists between rapid operation and protection afforded the slower vehicles; one can be obtained only at the expense of the other.
- Can a queue waiting at the stopline get into motion without a premature gap? Premature gap-out can occur with very heavy traffic. Configurations using a stopline loop assure that a queue can discharge without this problem.
- Can the design screen out false calls for green (as, for example, with a right -turn-on-red)? A delayed-call design of the stopline loop improves the ability to screen out false calls for the green.
- During the green interval, can a queue of left-turning vehicles hold the green as they wait to filter through gaps in oncoming traffic (on an approach without a left-turn lane and a protected left-turn phase)? Again, a stopline loop permits a queue of left-turning vehicles to hold the green as they wait for a gap in oncoming traffic.

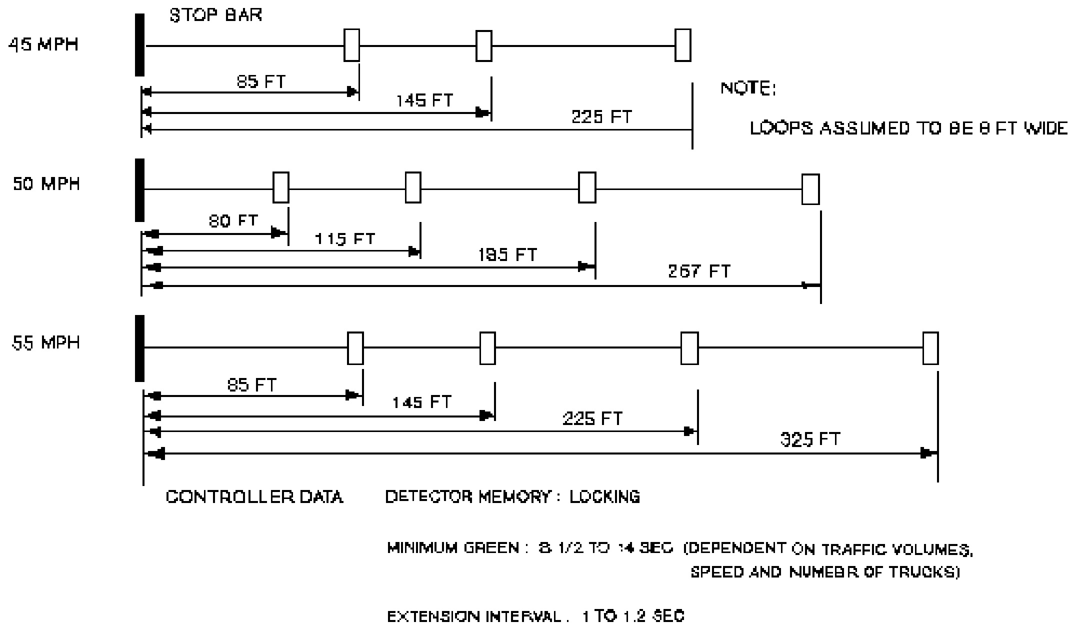


Figure 6-10 (a)

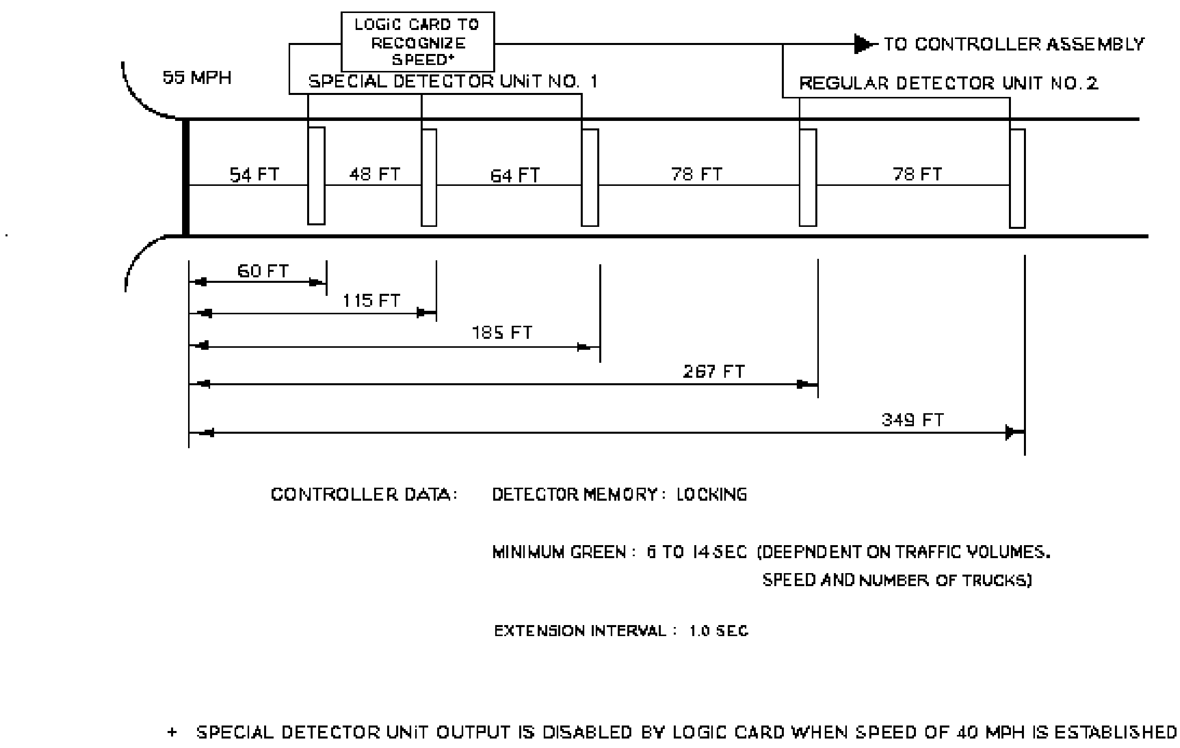


Figure 6-10 (b)

Figure 6-10. Two methods of multiple point detection systems for approach speeds up to 55 mi/hr (88.6 km/hr).

6.4
Vehicle Detector Location and Configuration

This section focuses on alternative detector designs and their appropriate application to:

- Isolated actuated intersection control,
- Urban system control, and
- Freeway monitoring and control.

Isolated Actuated Intersection Control

Since vehicle arrivals fluctuate at individual intersections, efficiency depends on responsiveness to minute-by-minute demand variations. The actuated green interval is changeable and can be tailored to actual arrivals. This varying green interval (from minimum to maximum controller settings) is determined by the unit extensions generated by vehicles crossing the detectors. For most volume levels, full actuated control proves to be the most cost-effective method (28). Full vehicle actuation is normally preferable to pretimed or semiactuated control.

Small-Area Detectors simply detect the passage of a vehicle at a spot location (e.g., upstream of the stopline). Small-area detectors are often called short-loop, point, or passage detectors. The magnetic detector can only be used for point detection, because it covers a small area. Short-loop detectors (less than 20 ft (6.1 m) long) are the simplest and most common type.

As previously discussed, small-area loops back from the stopline act as calling detectors for high-speed approaches. Figure 6-10 illustrates a high-speed detector design using multiple short loops (27). Magnetometers also cover small areas. Some agencies use a single 6 ft (1.8 m)-long loop to cover 2 or more lanes. Single point detection is relatively inexpensive, but gives no information on traffic between the downstream detector and stopline. Figure 6-11 illustrates the contrast between small- and large-area detection (28).

Large-Area Detectors, usually long loops, register presence of a vehicle in the detection zone as long as the detector remains occupied. In this mode, the controller holds in the extension interval until the detector clears. Thus, a very short extension interval is used. Figure 6-12 illustrates various detection designs, including both small- and large-area detection (29).

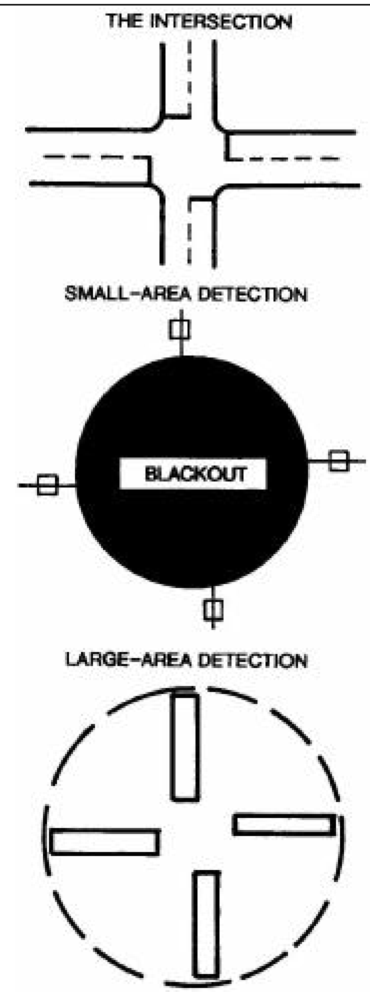


Figure 6-11. Contrast between small-area and large-area detection.

As previously discussed, loop occupancy control uses large-area detection and non-locking detection memory. This design operates best with well-formed platoons on low-speed approaches. However, random vehicles may cause the controller to max-out when vehicle headways permit one vehicle to enter the detection zone just as the previous one leaves. Figure 6-9 shows detector placement for the extended and delayed call (EC-DC) design using large-area detection at the stopline with two small-area detectors upstream for high-speed vehicles (30). This detector configuration has proven very effective.

Disadvantages of large-area detection include:

- Higher installation costs, and
- Greater maintenance problems with long loops.

To reduce long loop problems, use a series of 6-ft (1.8-m) wide loops placed parallel to the stopline and separated by approximately 10 to 12 ft (3 to 3.6 m). This design allows:

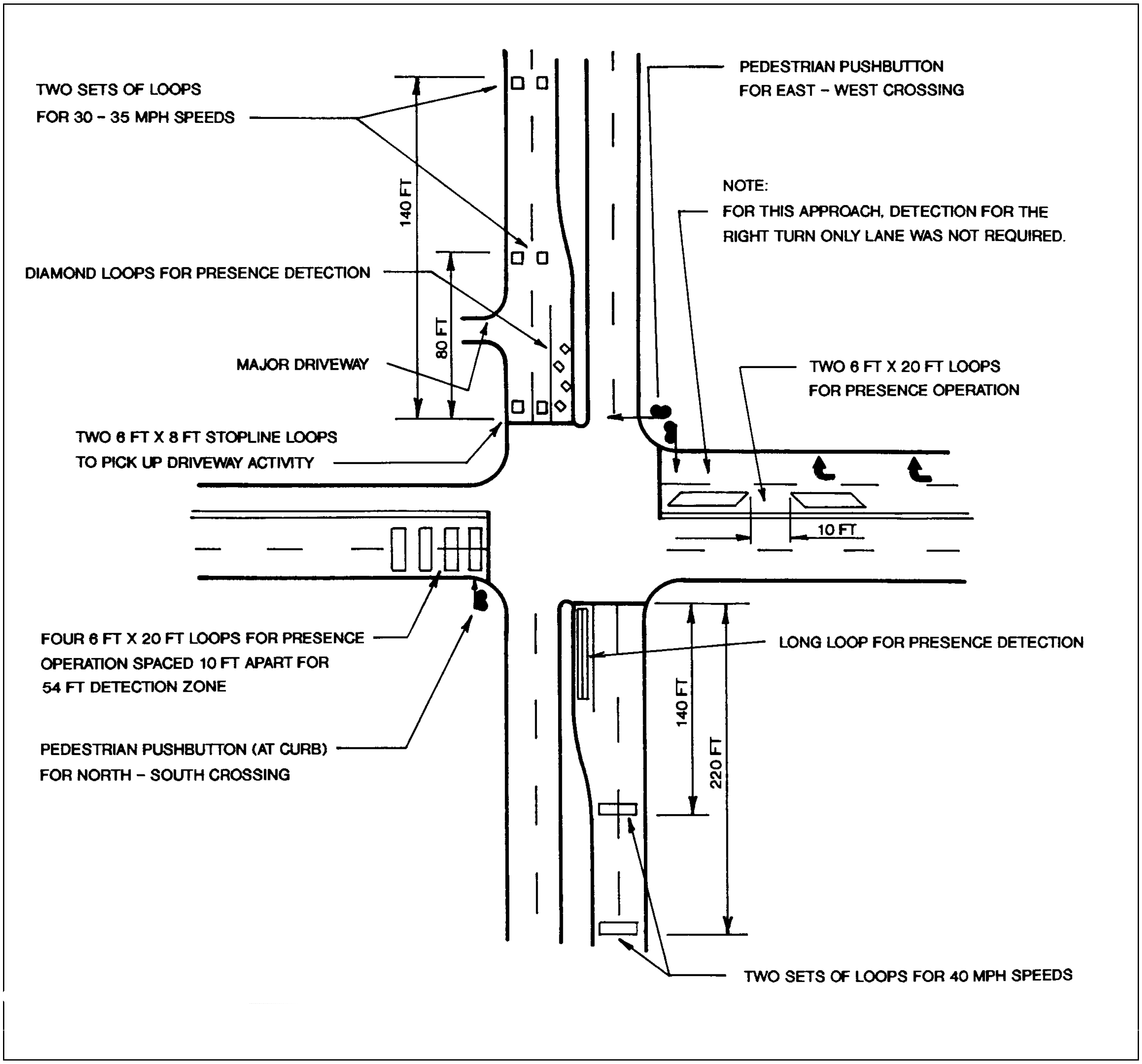


Figure 6-12. Typical detector designs.

- Higher loop sensitivity and protection against losing a lane of detection, and
- Operation with one or more failed loops.

Left-Turn Lanes. Efficient vehicle detection in left-turn lanes can increase intersection capacity by reducing lost green time. The Illinois Department of Transportation has designed a loop configuration for left-turn lanes that improves intersection efficiency and safety (31). Efficient presence actuation must account for:

- Driver start-up time averages 3 to 4 seconds for the first vehicle in a queue while headway averages 2 to 3 seconds between following vehicles. Loop length must accommodate longer than average reaction times to maintain green for starting vehicles.
- Trucks and other slow vehicles require a longer start-up time, often leaving a 3 to 4 car length (6 to 12 second) gap ahead of them. At locations with a relatively high percentage of trucks, loop length must account for these gaps.

- One or 2 vehicles require only a short green time. The detection zone length, however, must allow the following car either to reach the loop in time to maintain the green or decelerate to a stop.
- A vehicle extension interval of 1.5 seconds permits drivers to almost complete their turning radius before yellow occurs. Any additional extension becomes lost time. A shorter vehicle extension interval disturbs drivers when the yellow appears.
- A minimum loop length from the stopline of 80 ft (24.4 m).
- Vehicles allowed to turn left on the through green (permissive), normally proceed past the stopline and wait for a gap in the opposing traffic to complete their turns. Lack of a gap can strand the left-turner ahead of the detection zone that ends at the stopline. The controller will then skip the protected left-turn phase in the next cycle, if no other vehicles are waiting to turn left. The driver may complain of a malfunctioning signal resulting in an unnecessary service call. Extending the detection zone beyond the stopline may resolve this problem.

Figure 6-13 shows a minimum left-turn loop design that addresses the above requirements (31).

The loop layout should include *advanced detection* when:

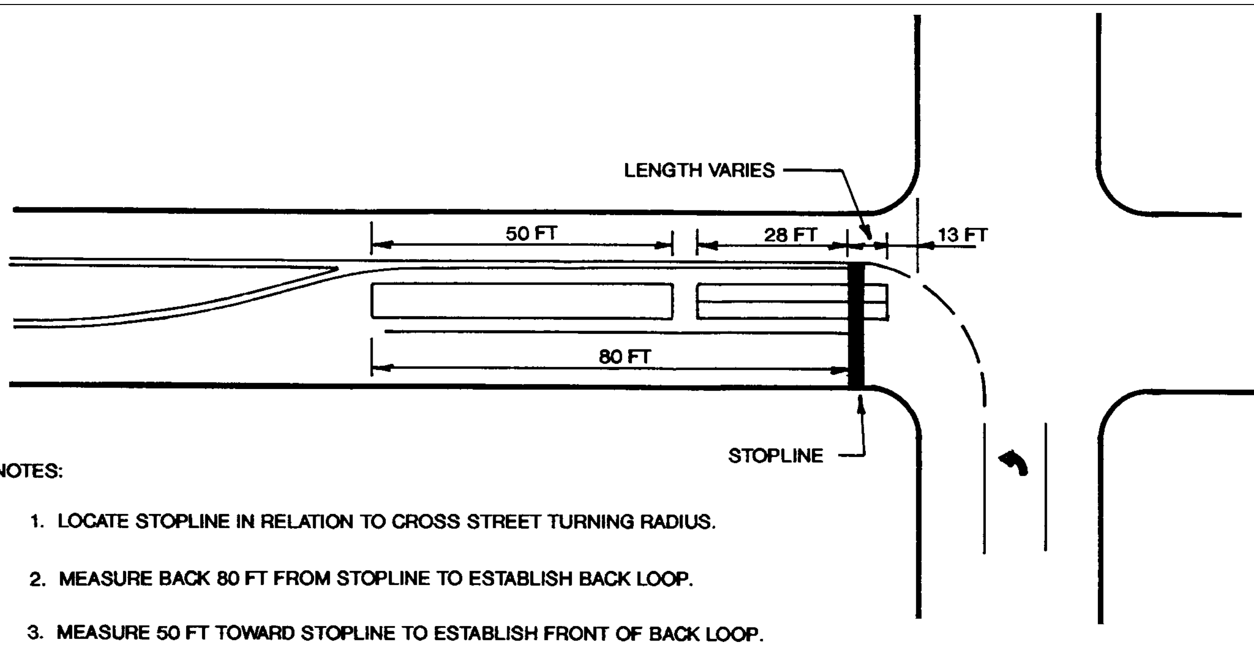
- Left-turn demand requires storage of 15 0 ft (45.7 m) or more, or
- Approach speeds require a safe stopping distance.

Advanced detection using a call-extension feature, will extend the effective detection zone to accommodate heavy vehicle or truck volumes and provide for safer operation (see figure 6-14 (31)).

In many instances, one 30 to 40 ft (9 to 12.2 m) presence loop suffices for left-turn detection and provides rapid initiation of the left-turn phase. Left-turn loop design varies with:

- Approach speed,
- Presence of heavy trucks, and
- Grade and intersection geometries.

OPAC Detection Scheme. Under a Federal Highway Administration research grant, Dr. Nathan Gartner of the University of Massachusetts developed the Optimized Policies for Adaptive Control (OPAC) strategy for isolated intersection control. This strategy, when implemented using an individual signal controller, includes:



NOTES:

1. LOCATE STOPLINE IN RELATION TO CROSS STREET TURNING RADIUS.
2. MEASURE BACK 80 FT FROM STOPLINE TO ESTABLISH BACK LOOP.
3. MEASURE 50 FT TOWARD STOPLINE TO ESTABLISH FRONT OF BACK LOOP.
4. ALLOW 2 FT GAP BETWEEN LOOPS AND MEASURE 28 FT TO STOPLINE.
5. FRONT LOOP SHOULD BE WITHIN 13 FT OF CROSS STREET TRAFFIC LANE. FRONT LOOP SHOULD BE QUADRUPOLE DESIGNED TO DETECT SMALL VEHICLES.

Figure 6-13. Detection in left-turn lanes.

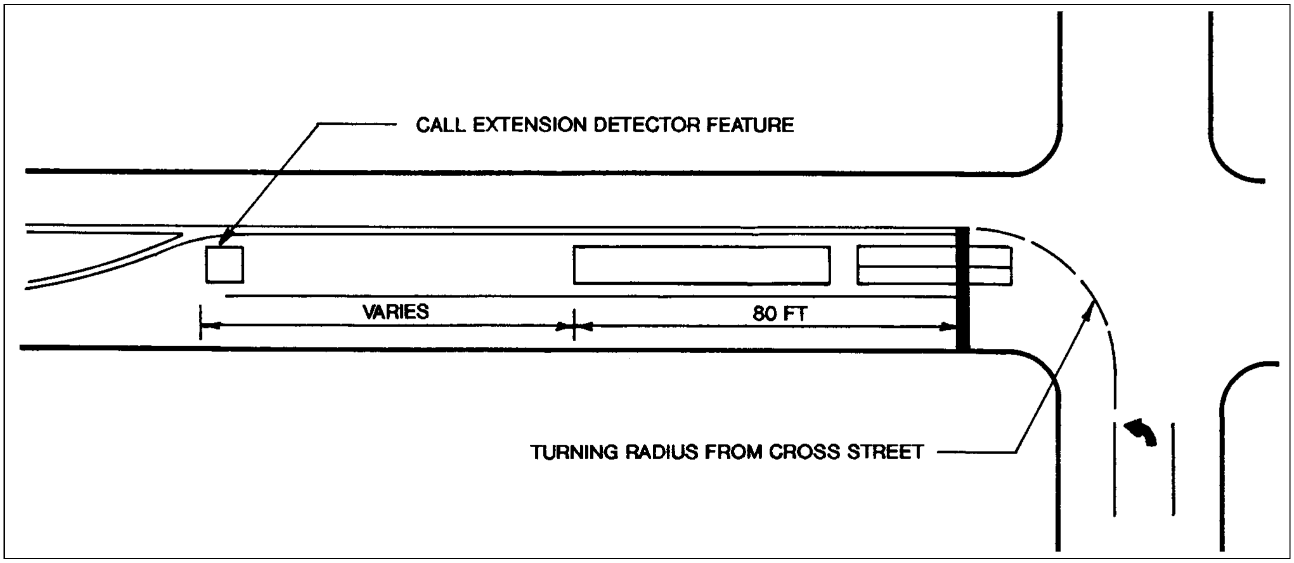


Figure 6-14. Extended detection on left-turn lanes.

- The measurement of traffic flow from upstream detectors, and
- The projection of vehicle arrivals during a period equal to the travel time from these detectors to the intersection (32).

Section 3.13 further describes this strategy.

OPAC uses detectors considerably upstream to predict a profile of platoons arriving at the downstream intersection. Generally, positioning detector locations further upstream leads to better system performance. Detector placement should leave a minimum number of traffic sources and sinks (driveways) between the detector and the downstream intersection so as to minimize queue simulation error. Maximizing upstream detector distance and minimizing intervening sources and sinks requires a tradeoff to optimize loop placement.

MOVA Detection Scheme. Modernized Optimization Vehicle Actuation (MOVA) requires 2 sets of loops on each approach at distances of 130 ft (39.6 m) and 330 ft (100.6 m) from the stopline (33). MOVA schemes work on *approach occupancy*, and constitute a trade-off between stopping approaching vehicles and holding already stopped vehicles for a few more seconds. Section 3.13 further describes this strategy.

Detection of Small Vehicles. A large-area detector should detect all licensed vehicles (including a small motorcycle) and hold its call until a display of green to the phase. A hold time of 3 minutes is commonly specified. A conventional long-loop configuration (longer than 20 ft (6.1 m)) may not detect a small motorcycle. However, several loop configurations can enhance a detector's small-vehicle detection capability.

Some modified long loops include *powerheads* and *angled* powerheads — small internal loops with additional turns of wire at the end of long loops. This refinement causes a motorcycle to cut the lines of flux more efficiently, thereby increasing inductance by as much as 25 percent (1). Figure 6-15 illustrates this technique (34). Unless clearly indicated by paint, a motorcycle may not stop on the powerhead.

Another technique, termed *Quadrupole, detects small vehicles by adding a longitudinal sawcut along the center of the lane* (35). The loop wire is installed in a figure-8 pattern, so that the 2 center wires have currents flowing in the same direction. Their fields reinforce each other and improve small vehicle detection. This layout diminishes the outer wire's field of influence, thus reducing the possibility of detecting vehicles from adjacent lanes. Figure 6-16 shows the single-wire configuration (1-2-1) (34). For detecting bicycles and smaller motorbikes, wind the loop wire twice for a double-wire design (2-4-2).

Multiple small loops, magnetic detectors, and magnetometers have also proven effective in detecting small vehicles.

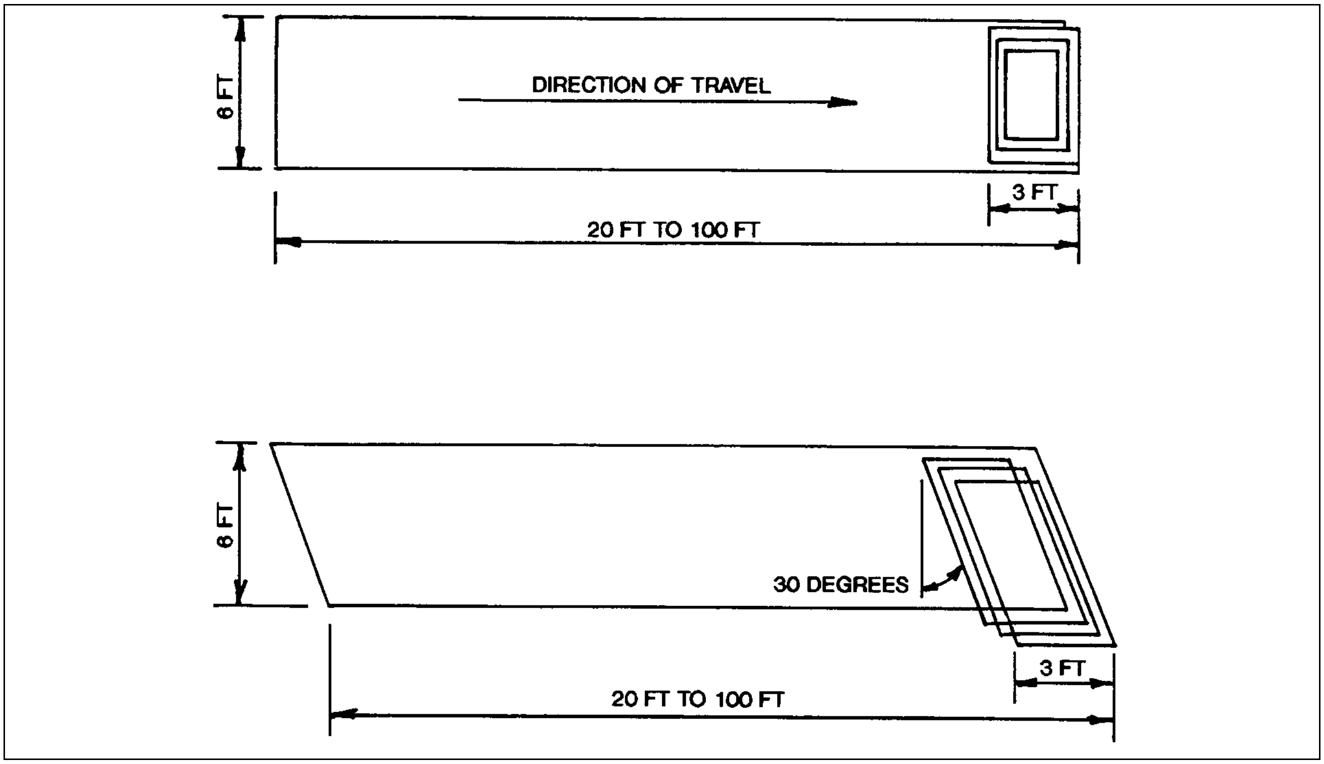


Figure 6-15. Powerhead loop configurations.

Control of Arterial and Network Intersections

This section describes the data monitoring subsystem for traffic signal systems and includes the control of:

- Arterial streets,
- Diamond interchanges,
- Closed networks (such as a central business district), or
- An area consisting of networks and arterial streets.

System detectors are normally located in strategic locations within the system and usually require count and presence capability.

ILD Applications for System Detectors

The inductive loop detector provides a broad range of system detection requirements, although many other types have recently seen application. Loops detect both presence and passage; with these outputs and knowledge of signal timing, a system can derive the following variables with varying degrees of accuracy:

- Volume,
- Occupancy,
- Speed,
- Delay,
- Stops,
- Queue length, and
- Travel time.

Volume and occupancy are the most commonly -used variables in traffic control and are the most important factors in traffic-responsive plan selection and other real-time traffic-responsive algorithms. Volume proves to be the most easily obtained and accurate variable. Occupancy, as defined in chapter 3, generally proves less accurate, since it can depend on vehicle profile and other factors. Measuring and detecting occupancy is extremely important, since it will continue to increase as intersections become saturated. (Volume measures level off to a constant, proportional to green time divided by average vehicle headway.)

It has been observed that occupancies over 25 percent reliably indicate the onset of congestion (36). Accurate determinations of occupancy depend on the repeatability of the pickup and dropout characteristics of vehicles entering the detection zone and on

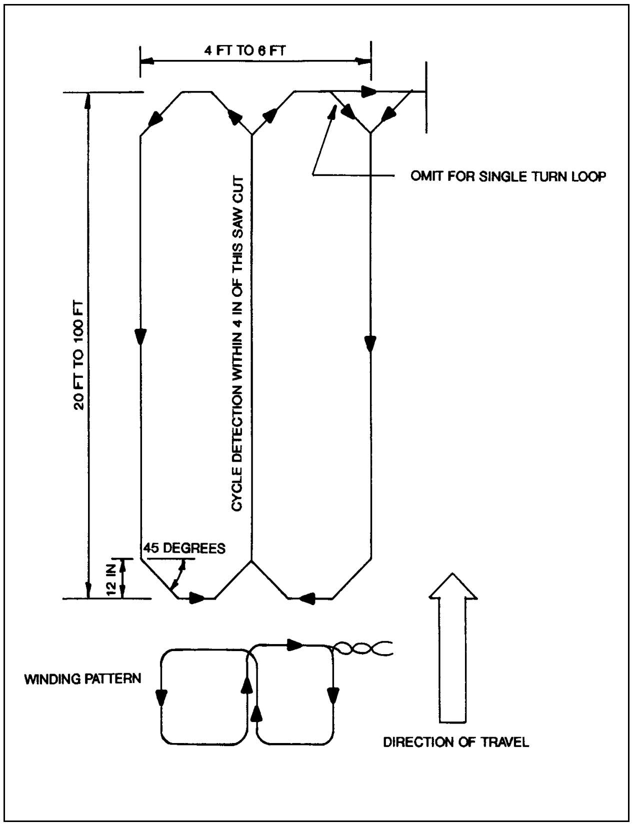


Figure 6-16. Quadrupole-loop configuration Design.

variations in vehicle characteristics. An occupancy error is also introduced as a result of detector output being sampled by a communications unit or field microprocessor, rather than by continuous measurement. Therefore, occupancy measurements (in terms of percentage of error) tend to be more accurate at lower speeds. Chapter 3 describes several data-filtering and smoothing techniques relating to occupancy measurement.

The remaining quantities (delay, stops, travel time, and queue length) are normally calculated from volume and occupancy. Loop detectors cannot accurately measure these variables, thus limiting their effectiveness for control. Unless multiple detectors are installed in each lane, queue length and stops are also difficult to compute.

A distinction should be made between *system* detectors and *local actuation* detectors. A local intersection detector connects directly to an actuated controller, whereas the system detector connects to the central computer or arterial master.

Arterial Street Systems

Volume and occupancy represent the 2 basic variables used in arterial street system control. These systems aim to adjust signal timing to accommodate the predominant traffic flow as described in table 3 -2. Separate detectors may control cycle, split and offset volume, and weighted occupancy may be used. The arterial master usually selects cycle and offset by using arterial detectors, whereas split selections use both arterial and cross street detectors.

Network Control Systems

Data monitoring requirements for areawide traffic-responsive control depend on the control type. Section 3.9 discusses detector requirements for UTCS first generation control and the SCOOT and SCAT systems.

Detector location for UTCS and UTCS derivative systems consists of a 3-step process that selects:

- Links,
- Longitudinal placement, and
- Lateral placement.

Link Selection is important, since cost increases in proportion with the number of detectorized links. A *link* is a section of roadway carrying a single direction of traffic flow between 2 signalized intersections. Its inclusion in the system depends on several factors, including:

- Type of control strategy,
- Intersections requiring critical intersection control (CIC),
- Major traffic flow patterns occurring throughout the day,
- Distance between adjacent intersections,
- Number of major generators between intersections,
- Special-event timing, and
- Automation of traffic counts.

To implement timing plan selection by the UTCS algorithm, at least 8 system detectors on different approaches in a single section are recommended. After 20 to 25 detector locations have been selected for a section, the value of information provided by additional detectors becomes marginal in terms of timing plan selection.

Link selection begins by identifying candidates for Critical Intersection Control (CIC). Candidate intersections have sufficiently disparate traffic demand to benefit from variable split, and yet continue to operate in an unsaturated condition. When an intersection operates under CIC, all approaches served by phases with variable green times must be detectorized. (Reference 6 details a step-by-step procedure for determining CIC candidates.)

After CIC selection, other links should be examined. Links that experience high volume and/or occupancy during certain periods will be more beneficial to the UTCS First Generation algorithm's signature matching process than detectors with lower values. Therefore, detector selection should favor links with high values of occupancy and per-lane volume.

Longitudinal Placement for First Generation Control requires an accurate occupancy measurement to support the software. Kay recommended not locating detectors near either the upstream or downstream intersections (6). Since lane discipline deteriorates in the vicinity of the intersection, lane-changing maneuvers (especially upstream) can produce significant errors in both volume and occupancy.

Reference 6 recommends a distance of approximately 230 ft (70.1 m) from the upstream intersection stop-line. Detectors should not be placed where standing queues from the downstream intersection typically extend. This distance depends on cycle length, split, and offset, but the following minimum distances are recommended:

- Urban grid areas: 200 to 250 ft (61 to 76.2 m)
- Suburban arterials: 300 to 350 ft (91.4 to 106.7 m)

The criteria based on typical queue size is considered more critical and should govern in the event of a conflict (6).

Another longitudinal-detector placement issue concerns traffic *sinks* and *sources*. Research indicates that a sink/source only minimally affects traffic in the critical lane when a facility operates as a sink; e.g., a parking garage during the morning peak. This results because vehicle turns into the sink usually occur from the curb lane, rather than the critical lane. Measurable effects on the critical lane were observed only during the evening peak, when the facility functions as a source.

Most vehicles exiting a source wait for a sufficient gap in their target lane before entering traffic. Therefore, a critical lane detector should be located at least 50 ft (15.2 m) downstream from the source, provided that this meets the downstream intersection criteria described earlier. In general, unless the source contributes more than 40 v/hr to the critical lane, its effects on link demand are insignificant.

Lateral Detector Placement. The lateral positioning of detectors refers to the lane or lanes in which they are to be installed. In general, detectors must be capable of measuring the highest lane volume at the intersection approach. The work of Henry, Smith, and Bruggerman indicates that at the midblock location, the lane designated as the critical lane did not change over the entire daytime period for approximately 65 percent of the cases (37). To identify the high volume lane on all links when not directly obvious, recommended steps include (6):

- Identify the intersection approach requiring detectorization,
- Conduct measurements for 20 signal cycles during the a.m., p.m., and midday periods at each intersection approach,
- Collect the data by positioning manual observers at the longitudinal detector position,
- Record volume data on a 5-minute basis, and
- Analyze the data by comparing the total volumes measured for the approach lanes.

In many cases, simple observation of an intersection will establish the high volume lane. These more detailed measurements will only prove necessary in areas where short-term observation of intersection operation does not permit critical lane selection.

General Guidelines for Spotting Detectors. Previous sections describe:

- Selecting links to be detectorized,
- Appropriate longitudinal location, and
- Detector lane placement.

After completing a detectorization plan, the engineer should walk through each link to select final detector locations. This field check should also consider:

- Access to the controller cabinet,
- Special driveway problems,
- Pavement conditions and special situations, such as pavement construction joints, and
- Manhole locations.

General guidelines concerning field location of individual loop detectors include (6):

- Locate a detector in the center of traffic flow, not necessarily in the center of the marked lane. Identify the center of traffic flow by oil markings or tire tracks on the pavement.

- Locate the detector in areas of stable traffic flow. Avoid sections of a link with excessive weaving or entering and exiting driveways.
- When a major driveway occurs within a link, locate the detector at least 50 ft (15.2 m) downstream from the driveway, provided the detector is at least 200 ft (61 m) upstream of the stopline.
- Traffic detectors should not be located within 10 ft (3 m) of any manhole, water valve, or other appurtenance located within the roadway. This distance permits sufficient clearance for work in the manhole without disturbance to the detector.

The final location of detectors for advanced traffic control strategies blends analytical procedures and engineering judgment. Not all links yield measurements within the algorithm's required accuracy. Short links, and links with poor lane discipline, typify those not amenable to accurate instrumentation.

Freeway Monitoring and Control

Freeway monitoring and control requires detection of 2 types of congestion: recurrent and non-recurrent, as described in chapter 4.

That chapter also discusses control techniques that mitigate the 2 types of congestion. This section describes detection requirements for freeway monitoring and control techniques such as:

- Mainline detection,
- Incident detection, and
- Ramp metering.

Inductive loop detectors are most prevalent in freeway monitoring and control systems. Mainline detector stations are commonly spaced at intervals ranging from 0.25 to 0.5 mi (0.4 to 0.8 km). Closer spacing is sometimes used for special applications, such as tunnels and covered roadway sections. Detectors are often placed in such a way as to assure coverage of each mainline roadway section between ramps, junctions, and bifurcations. Figure 6-17 shows typical freeway mainline loop detector installations. Table 6-12 shows the information obtainable from these configurations. The use of full-lane coverage deployments enable information to be provided from the remaining detectors in the event that one detector fails.

Section 3.2 describes many of the algorithms used to obtain surveillance parameters.

Surveillance systems are sometimes planned with full lane coverage stations interspersed at prescribed intervals. If the vehicle mix and roadway vertical alignments (and in some cases, horizontal alignments) of both stations are similar, data from the speed trap can calibrate the vehicle length and loop length parameters in equations 3.2 and 3.4.

Figure 4-13 shows detector locations for a typical ramp metering installation and section 4.2 describes the functions of ramp detectors. Section 4.2 also discusses the requirements for mainline detector stations summarized by table 6-13.

6.5 A Look to the Future

The last decade has witnessed the emergence of a wide variety of non-pavement invasive traffic detectors, including the following technologies:

- Video image processing,
- Ranging microwave radar,
- Passive infrared detection,
- Active infrared detection, and
- Passive sonic detection.

While some of the technologies have seen operational use, others are in various stages of evaluation by FHWA, as well as by traffic system operators.

Operational Use of New Detectors

Most users have some understanding of the capabilities and limitations of inductive loop detectors. Emerging detector technologies have not had the benefit of broad-based practical application, and so a number of issues are yet to be resolved. These include:

- Occlusion effects,
- Effects of weather,
- Effect of variations in scene illumination,
- Mounting restrictions,
- Sensitivity to movement of the mount,
- Multipath effects, and
- Suitability for special applications, such as tunnels.

It is expected that the experience gained through deployment in real-world settings will provide an improved basis for the selection, specification, and installation of these emerging detectors.

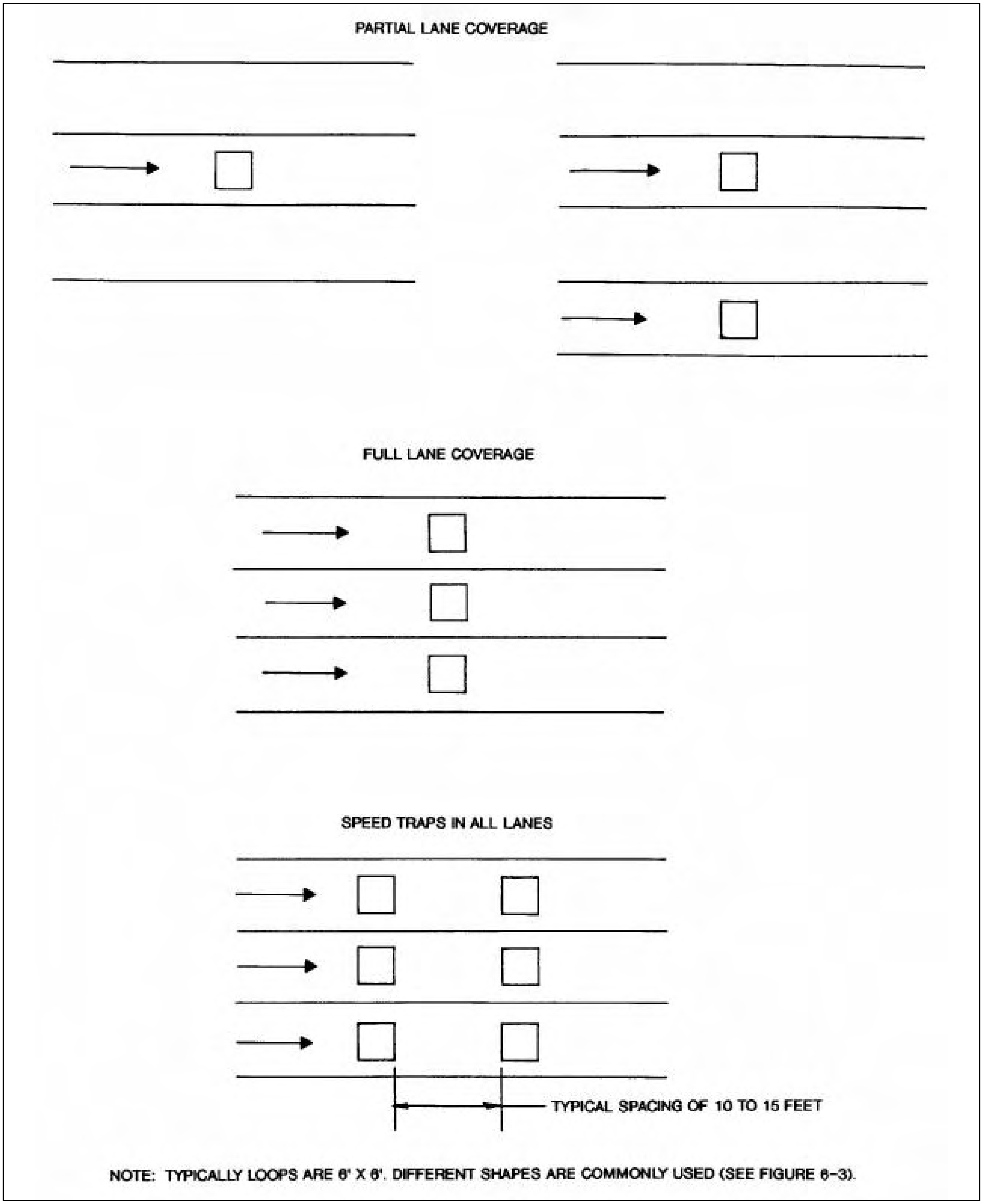


Figure 6-17. Typical freeway mainline loop detector installations.

Table 6-12. Information obtainable from mainline detector station.

Installation Configuration	Type of Information	Application
Partial Lane Coverage	• Lane volume • Lane occupancy • Lane speed (moderate accuracy)	• Real-time (online) - indication of congestion
Full Lane Coverage	• Volume in all lanes • Occupancy in all lanes • Speed in all lanes (moderate occupancy)	• Real-time (online) - congestion indication - ramp metering - incident detection • Planning (offline) - volume - speed, level of service - land use - day of week, month factors
Speed Traps in All Lanes	• Volume in all lanes • Occupancy in all lanes • Speed in all lanes (high accuracy) • Vehicle classification by length	• Real-time (online) - congestion indication - ramp metering - incident detection - calibration of vehicle length for speed estimation at nearby full lane coverage stations • Planning (offline) - volume - speed, level of service - lane use - day of week, month factors - percent of vehicles by length classification

Table 6-13. Mainline detector requirements for traffic-responsive ramp metering.

Ramp Meter Strategy		Requirement
Isolated	Demand Capacity Control	Full lane coverage station upstream of ramp merge. Additional station downstream (at bottleneck location) if real-time capacity measurement used.
Isolated	Downstream Occupancy Control	Full lane coverage station downstream of merge at bottleneck location
Isolated	Upstream Occupancy Control	Full lane coverage station upstream of ramp merge
Integrated	Integrated	See figure 4-12 • Full lane coverage station upstream of ramp merge • One or more full lane coverage stations downstream of merge

Additional Capabilities of New Detectors

It is expected that new sensor technologies will concentrate on functions not easily performed by currently available equipment. For example, certain control concepts require multipoint or continuous detection over wider areas or distances than is practicable with current sensors. Active scanning microwave-based sensors, for example, might satisfy this requirement.

It is also anticipated that the use of weather sensors for traffic control applications will increase in the next few years (38).

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CHAPTER 7
LOCAL CONTROLLERS

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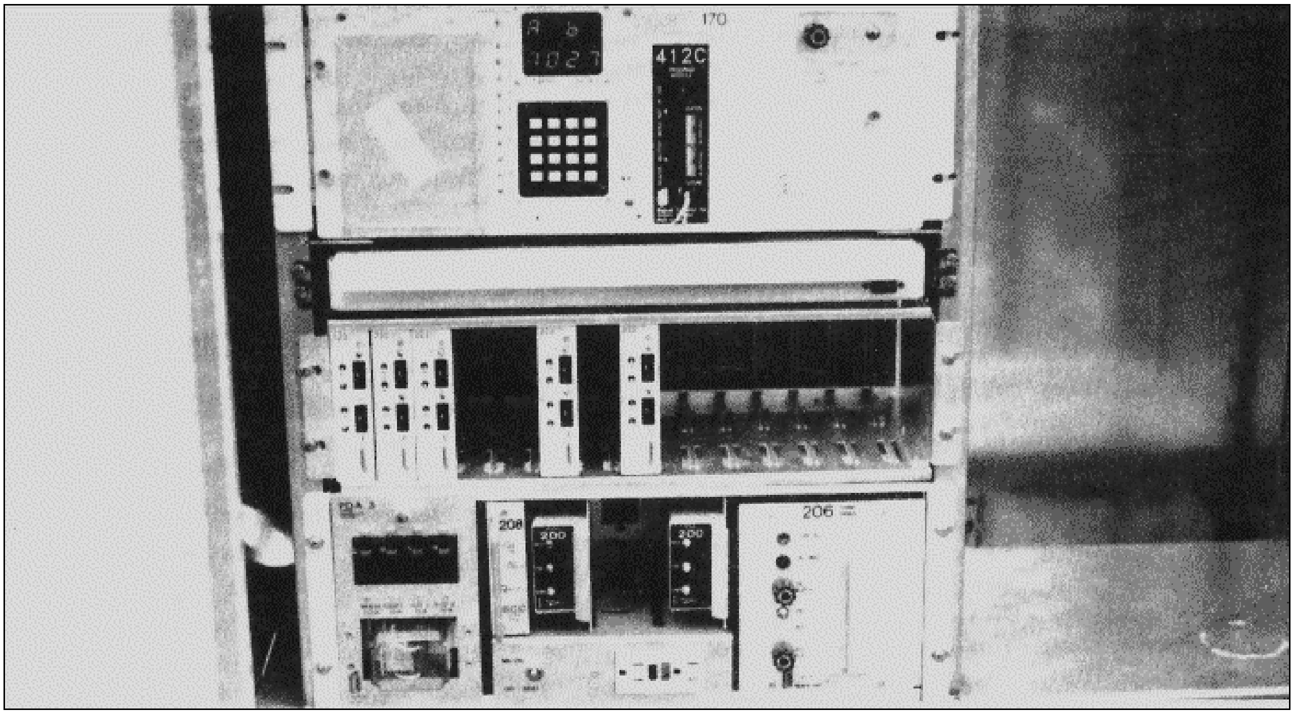


Figure 7-1. Type 170 controller.

7.1 Introduction

This chapter provides detailed information on intersection controllers so that the user can:

- Understand the principles of controller operation,
- Become familiar with various controller types, and
- Select controllers for specific applications.

Table 7-1 shows the organization of this chapter.

Table 7-2 presents some basic definitions used throughout the chapter, while table 7-3 summarizes functions performed by a local controller. Table 7-4 summarizes the 2 distinct modes of local controller operation.

A subsequent section of this chapter discusses special controller units and their range of applications. See also chapters 3 and 4 of this Handbook for additional information on some special control concepts.

7.2 Types Of Operation

Despite the many variations in their design, intersection controller units can be classified according to operational type as:

- Pretimed,
- Full-actuated, and
- Semi-actuated.

Table 7-5 describes characteristics and applications of each of these types.

7.3 Range Of Applications

Types of Intersection Control

Table 7-6 summarizes applications of controller types to intersection control. This section further describes each application.

Isolated intersection control operates a signal independently of any adjacent control. Factors used in determining the appropriate type of intersection control include roadway characteristics such as (2):

- Number of approach lanes,
- Traffic volumes,
- Arrival patterns, and
- Number of intersection approaches.

Table 7-1. Chapter 7 organization.

Section Title	Purpose	Topics
Types of Operation	Describes types of controllers, characteristics and operation	• Pretimed • Full-actuated • Volume-density full-actuated • Semi-actuated
Range of Applications	Describes applications of controller types	• Types of intersection control - isolated intersection - pretimed - arterial system - network system • Protected, protected/permissive and permissive operation • Special controls - lane-use control signals - freeway entrance ramp - overheight vehicle
Controller Evolution	Describes evolution of traffic controllers	• Hardware • Electronics - analog - digital • Microprocessors
Types of Local Controllers	Describes controllers currently available	• Pretimed • Full-actuated • Model 170 • NEMA
Pretimed Controllers	Describes operation and characteristics	• Timing • Solid-state controller hardware • Electromechanical controller hardware • Coordination requirements
Full-Actuated Controllers	Describes operation and characteristics	• Controller operation • Controller detection modes • Timing and phasing characteristics • Single and dual-ring operation • Basic interval timing functions • Special operational features • Hardware characteristics - environmental and operating requirements - conflict monitor • Phasing other than for 8-phase control • Single point freeway interchange operation • System capabilities • Downloading capabilities

Table 7-1. Chapter 7 organization (continued).

Section Title	Purpose	Topics
Model 170 and NEMA Controllers	Describes operation and characteristics	• Model 170 based controller systems • NEMA controllers • Comparison of NEMA and Model 170 controllers
Local Controller Coordination	Describes operation and concepts	• Function • Time-base coordination
Factors in Controller Selection	Describes process of selecting controllers	• Operating requirements and constraints • Anticipated effects and costs • Maintainability and reliability • Human factors
A Look to the Future	Describes advanced controllers and continuous flow intersections	• Advanced Transportation Controller (ATC) • Model 2070 Advanced Transportation Management System Controller • Continuous Flow Intersection

Pretimed control best suits locations where traffic proves highly predictable and constant over a long period of time. These situations do not usually exist at isolated intersections (2).

Full-actuated control usually proves the most efficient operation at isolated intersections. On making the decision to install a traffic signal, first consider full-actuated control. Its traffic-responsive capability adjusts cycle and phase (split) lengths to fit changing demands from cycle to cycle. Rarely do approach traffic volumes at an isolated intersection remain predictably constant over a long period.

Because all phases usually do not peak simultaneously, it should not be assumed that a full-actuated signal operates on a fixed cycle length even with high traffic demand.

Full-actuated control applies to a variety of signal phasing and detection schemes ranging from a simple 2-phase operation to an 8-phase dual-ring configuration. Because of its skip-phase capability, the 8-phase dual-ring controller may operate as a basic 2-phase controller under light traffic conditions; in the absence of demand, the controller unit ignores that phase and continues around the ring seeking a serviceable phase (2).

Table 7-2. Local controller definitions.

Term	Definition
Controller Assembly	The complete electrical mechanism mounted in a cabinet for controlling signal operation. The controller assembly generally includes the cabinet.
Controller Unit	Portion of a controller assembly which selects and times signal displays
Intersection Controller Unit	The traditional and original usage, most commonly referred to as *traffic signal controller*
Special Controller	Includes units for freeway control and monitoring, lane-use control and other applications not involving the traditional assignment of right-of-way for vehicles and pedestrians at intersection or midblock locations.

Table 7-3. Local controller functions.

- **Can control:**
  - single intersection
  - closely spaced multiple intersections
  - midblock crosswalk
- **Electrically switches signal indications:**
  - red
  - yellow
  - green
  - WALK
  - DONT WALK
  - OTHER
- **Assures appropriate right-of-way assignments in accordance with pretimed or actuated intervals**
- **Times fixed clearance intervals such as:**
  - flashing DONT WALK
  - all red
- **Times greens and green arrows for:**
  - fixed-duration (pretimed control)
  - variable duration (up to a pre-determined maximum) according to traffic demand (actuated control)
- **Can operate under the supervision of central computer or master controller which can alter intervals in local controller.**

Single-intersection control is not limited to the intersection of 2 or more streets.

Pedestrian signal control may be located midblock when a pedestrian crossing cannot be supplied (or is impractical because of the distance) at an adjacent, signalized intersection. Control may also be warranted at intersections or midblock locations to give emergency vehicles access to a major street (2).

Arterial system intersection control applies when 2 or more traffic signals have time-related operation. The system supervises local controllers along an arterial street to ensure progressive traffic flow. An arterial system can use any previously described operation type at the local control level.

The basic concept of arterial street control recognizes that vehicles release in platoons and travel progressively from signal to signal with little or no impediment. Depending upon prevailing traffic demand, the system can orient this progression to one or both travel directions. The system establishes and ensures a desirable time relationship between the onsets of arterial green at each intersection compatible with progressive flow speed and desired direction. As a result, continuous traffic flow in defined platoons reduces stops and delay.

In a ***network system***, such as a typical central business district (CBD), crossing arterials form a grid pattern with virtually every intersection requiring local control. The most prevalent form of local control is pretimed operation because of the closely spaced signals and a desire to provide progression on all streets in each travel direction.

The network system provides optimal time relationships between the onsets of green at each of the locally controlled intersections. A timing plan optimizes traffic performance for a given traffic pattern (inbound peak, balanced light flow, etc.). In some network systems semiactuated control is used at midblock pedestrian signals and, less often, at lighter traveled T intersections, to provide left-turn protection on demand only.

Protected, Protected/ Permissive and Permissive Operation

Traffic operations should aim to eliminate unnecessary delays at signalized intersections. Appropriate use of *protected/permissive* and

Table 7-4. Controller modes.

Mode	Definition
Isolated Control	Local controller acts as a standalone unit and times right-of-way assignments independently, unaffected by other devices
Supervised Local Control	A device, ranging from a time-base coordination unit to a remote master controller or central computer, determines or alters interval durations and/or maintains timing relationships in a group of local controllers. Under supervised local control, the local intersection controller units may either serve as part of an arterial or grid network system or simply as a small system comprised of 2 local units: 1 supervising master and 1 secondary controller.

Table 7-5. Types of operation.

Operation	Characteristics
Pretimed	• Duration of all intervals pre-determined • Local controller unit times intervals • Under supervised control, master controller or other remote device determines duration of certain intervals • May have actuated left-turn capability. Left-turn phase interval can only extend to maximum. Unused left-turn time given to associated thru phase. With no left-turn actuation, normal left-turn time given to associated thru phase. May have actuated phase capability for cross streets and pedestrians.
Full-Actuated	• All signal phases actuated • Change and clearance intervals have predetermined duration • Length of each variable interval (e.g., green and green arrow) determined by controller unit based on detected traffic demand on the associated approach • Each variable interval limited by preselected maximum timing set in controller • Phase-associated WALK intervals have guaranteed duration, but are timed and displayed only upon respective pedestrian push button actuation
Volume-Density Full-Actuated	• Programmed to operate with an added initial interval and a reducible gap feature • Certain phases selected; left-turn phases usually not included. Varies green interval based upon evaluation of approach traffic conditions. Maximum green extension functions as full actuated controller unit (1). • Detectors are located on all approaches. Detectors may be placed further from stopline. With single detector, initial interval is time required for standing queue between detector and stopline to start moving through intersection. To avoid long minimum green intervals, counts vehicles arriving during yellow and red and varies each volume-density phase minimum green interval by added initial, computed initial, or extensible initial. - *Added initial timing* adds time to minimum green interval portion based on time increments derived per vehicle from number of actuations counted. Minimum timing used as set in the controller unit until a preset number of counted actuations reached. When that number is exceeded, minimum green interval expanded accordingly. - *Computed initial timing* uses a preset minimum and maximum timing. Minimum green interval expanded (up to the preset maximum) based on a preset number of vehicles detected during the period. - *Extensible initial timing* similar to computed initial technique except that minimum green interval expanded (up to a preset maximum) based on preset time increments per vehicle detected during the period (1) • Vehicle extension interval is extended green time created by each additional actuation after minimum green interval time has elapsed • Maximum green or extension limits preset for each phase • *Extensible (gap reduction)* timing reduces the allowable gap between successive vehicle actuations by decreasing extension time depending on vehicle waiting time on opposing phase. Uses the following functional settings:

Table 7-5. Types of operation (continued).

Operation	Characteristics
Volume-Density Full-Actuated **(continued)**	- *Time before reduction* begins in the green interval when a serviceable conflicting call occurs. If call withdrawn while timing in this period, timer is reset and remains so until next serviceable conflicting call. Upon completion of this period, linear reduction of the allowable gaps begins. - *Passage time, minimum gap, time to reduce* - Rate of reduction based on setting of these 3 controls. Allowable gap reduced at a rate equal to the difference between passage time and minimum gap settings, divided by setting of time-to-reduce control. Reduction of allowable gap continues until gap reaches a value equal to, or less than, minimum gap control setting, after which allowable gap remains fixed. In the presence of a continuous vehicle actuation, phase does not gap out even if minimum gap is set at 0. If serviceable conflicting call withdrawn, gap length returns to passage time setting, and time before reduction timer reset to remain so until next serviceable conflicting call. • Usually effective at high speed or high volume intersections. Detectors must be carefully located and proper timing settings used to achieve efficient and safe control. • Most full-actuated controller units currently manufactured capable of volume-density type operation (1)
Semi-Actuated	• Detectors located only on actuated-phase approaches • Non-actuated phase receives minimum green interval • Non-actuated phase green extends indefinitely until interrupted by actuation on other phases • Actuated phase receives green upon actuation provided that the non-actuated phase has completed its minimum green interval • Actuated phase has minimum green interval • Additional vehicle calls will extend actuated phase green until the preset maximum is reached or a gap in actuations exceeds the unit extension (passage) interval portion • If locking detection memory used on the actuated phase, unit will remember additional actuations if the maximum is reached; controller will reservice actuated phase after non-actuated phase minimum green reached • Yellow change and red clearance intervals preset for each phase (1) • Actuated phase green interval terminates when: - vehicle passage times out - reaches maximum green - force-off is applied - change and clearance intervals timed - for multiple actuated phase operation, displays green to next calling phase for minimum green interval - for 2-phase operation, displays green for non-actuated major street phase (1) - minimize delays on major street when shortest practicable timing settings for actuated phase intervals are used (1)

Table 7-6. Applications of intersection control types.

Type of Control	Isolated Intersection	Arterial System (Open Network)	Network System (Closed Network)
Pretimed	Usually not appropriate	Could be applicable if cross street carries consistent substantial traffic volumes	Prevalent type used
Semi-Actuated	Usually not appropriate unless side street volumes are less than 20 percent of those on major street	Applicable for intersections with lighter cross street volumes. Also used at mid-block pedestrian	Sometimes used at mid-block pedestrian crossings
Basic Full-Actuated	Most widely used control type for isolated intersections; use ranges from simple 2-phase through dual-ring 8-phase configuration. Also applies to mid-block and T-intersection pedestrian crossings. Applicable for high-type intersection with heavy, fluctuating demand which requires multiple phasing on cross street.	Can operate as isolated intersection during light traffic periods	Applicable for isolated operation during light traffic periods in corridor networks in outlying areas
Volume-Density	Provides benefit with approach speeds above 35 mi/hr (56.3 km/hr) or where detector setback exceeds 125 ft (38.1 m)	Sometimes applicable when volume-density concept limited to major street	Not appropriate

Source: Reference 2 (Modified)

permissive only traffic operation provides one means of reducing left- turn movement delay.

Provide separate left-turn phases only where needed, because unnecessary separate left-turn movements increase cycle length and traffic delays. Traffic control without separate left-turn operations can minimize delay for all movements including left-turns. However, conditions exist that require protected/permissive operation or justify protected (only) operation. Asante, et al. provides a set of guidelines for left-turn protection (3). The report provides guidance on:

- Justification of some form of protected left -turn phasing,
- Selection of type of left-turn protection, and
- Sequencing of left-turns.

Permanent changes from one type of operation to another may prove appropriate. In such a case, observe the intersection for a period of time to ensure:

- Proper operations and
- Proper motorist response.

Traffic operation can also change from protected to protected/permissive or permissive operation as traffic patterns change during the day and/or week.

Special Controls

A number of applications use special-purpose controller assemblies with electrical switching of signal indications akin to intersection controllers. Some of these applications include:

- Flashing beacons for various applications such as:
  - Roadway hazard identification,
  - Enforcement time definition for speed limits,
  - Intersection hazard identification with stop control, and
  - Use of visual-attention device with individual stop signs.

- Lane control signals,
- Changeable lane use signs at intersections,
- Movable bridge signals and 1-lane, 2-way operation signals,
- Traffic controls (metering) at freeway entrance ramps,
- Overheight vehicle controls, and
- Audible pedestrian controls.

Table 7-7 summarizes usage of lane control signals, changeable lane use signs, controls at freeway ramps, overheight vehicle controls, and audible pedestrian controls. See reference 4 for further information on design of all listed special controls.

7.4 Controller Evolution

The evolution of traffic signal controllers parallels the evolution in related electronics industries.

Signal controller unit hardware has evolved from the days of motor-driven dials and camshaft switching units to the adaptation of general-use microprocessors for a wide variety of intersection and special control applications.

In the early years of traffic signal control, virtually the only commercially available controller units were the electromechanical type. Later, several manufacturers introduced semi- and full-actuated controllers equipped with vacuum tube circuits for timing functions. The traffic engineer adjusted interval and phase timing via knobs on a control panel. Transformers and vacuum tubes in these *analog* units generated considerable heat, requiring forced-air circulation and filtering in controller cabinets. Some manufacturers retained solenoid-driven camshafts for lamp switching, while others used stepping relay-driven stacked rotary switches and encapsulated relays. Short component life and timing drifts characterized these controllers.

Replacement of the vacuum tube with the transistor introduced low-voltage circuitry with only a fraction of the former heat generation. The high-amperage heater circuits and high-voltage B plate circuits once required for vacuum tubes passed from the scene. The mid-1960s saw transistorized circuits first used for timing and phasing functions. Lower operating temperatures increased component life, and digital timing ensured timing accuracy and eliminated fluctuations. During this period manufacturers also introduced the solid-state load switch for lamp circuits. Wide variations in component and equipment arrangements from manufacturer to manufacturer also prevailed during the 1960s.

Designs varied from those in which all timing and phasing components were placed on a single circuit board to those that used modular, plug-in phase and function-oriented designs.

The integrated circuit (IC) proved the next major step in controller evolution as microchip technology significantly reduced component size. These very small chips were linked together in circuits and sealed within an IC envelope to form the microprocessor. This development led to microcomputers — small, lightweight, low-cost units still used practically everywhere today.

Industry quickly incorporated microprocessors into new signal controller designs. They are, today, the heart of solid-state controller units.

Microprocessor controllers and related equipment provide features:

- That older controllers could not provide
- At a much lower cost than older controllers.

Table 7-8 summarizes these features.

7.5 Types of Local Controllers

Functionally, controllers for intersection signal control may be considered as either pretimed or actuated (semi-actuated or full-actuated). In earlier years, there was a strong correspondence between the controller's functional requirements and its physical implementation. Many of these special purpose controllers are currently in use and will continue to be in use for many years.

The 2 major controllers currently available in the U.S. are the Model 170 controller and the NEMA TS2 controller (8, 9). Both can perform all of the pretimed and actuated controller functions described in sections 7.6 and 7.7. Section 7.8 describes specific characteristics of Model 170 and NEMA controllers.

7.6 Pretimed Controllers

Timing Characteristics

Pretimed controllers operate on predetermined, fixed intervals and phase timings. The number and sequence of right-of-way assignments (phases) and the cycle length are also fixed. These timing features

Table 7-7. Special controls.

Type	Application	Technique
Lane Control Signals (see figure 7-2)	• Permits or prohibits use of specific lanes of a street or highway • Indicates impending prohibition of use • Most commonly used for reversible-lane control to increase roadway capacity during periods of directional peak traffic flow • Used on freeway to: - keep traffic out of certain lanes at certain hours - indicate that a lane ends	Uses combination of overhead signals and signing. Signals consist of: • A red X on an opaque background • A green arrow (pointing down) on an opaque background A yellow X may also be used. Uses 2-way left-turn indication where a reversible lane operates as a 2-way left-turn lane during off-peak hours. Only 1 of the 4 indications displayed at a time per lane, per direction. Operation mode changes usually done on a time-of-day basis commensurate with peak traffic demands. Control equipment consists of: • Switching equipment, electrically or mechanically interlocked, to prevent conflicting display • Appropriate clock/switch devices Some longer distance systems (several miles or more) use progressive lane variation overhead indications switched individually or in small groups in directional patterns along the arterial. Operation minimizes possible vehicle conflicts if all common indications in the system were abruptly switched. Employ lane use control only when an engineering study verifies need and practicability, and safe operation can be assured (4). Can locate changeable lane use signs at intersections to permit flexible allocation of lane use based on changing traffic patterns. For example, 2 left lanes at a freeway off ramp or frontage (service) road approach to an intersection may be needed for *left-turn only* movement during morning peak. The second lane from the left could best operate as a thru lane the remainder of the day. Changeable lane use signs at intersections can be changed by either time-of-day or real-time control. Field observations needed to assure that: • Motorists understand meaning of the sign • Use provides desired and safe operation

Table 7-7. Special controls (continued).

Type	Application	Technique
Freeway Entrance Ramp Control		See chapter 4 for a discussion of ramp metering and ramp closure
Ramp Metering	Controls flow rate of entering traffic	
Ramp Closure	Automatic or manually placed barriers or gates used in conjunction with a ramp-type signal. Gates also used during certain portions of the day to close freeway entrance ramps to improve operations on the mainline. May require trail blazer signs to an adjacent ramp along an alternate route	
Overheight Vehicle Control	Can avoid structural damage by overheight commercial vehicles Can use overheight detection with advance warning controls at: • Tunnel portals • Critical structures • Structures with a lower clearance height than others	See chapter 6 for discussion on overheight vehicle detectors
Audible Pedestrian Signals (5, 6, 7)	Audible signal which indicates the display of a walk interval or phase to the visually impaired. Guidelines for implementation include: • Signalized intersection • Capability of retrofitting audible signals to existing signal • Suitable location for installation • Demonstrated need	A buzzer or chirp sound most commonly used. Different tones or chirp sounds often used to indicate different crossing directions.

Figure 7-2. Lane control signals.

Table 7-8. Microprocessor controller features.

Feature	Description
More Robust Data Storage	Ability to store more timing plans and database parameters which a traffic operations center or on-street system master can implement
More Powerful Data Processing	Ability to process detector data and consolidate traffic data collection and analysis
Ability to Serve as Communications Terminal	Enables use of a wide variety of communications technology and standard interfaces and protocols
Use in Various Types of Control	Software changes allow 8-phase intersection controller, diamond interchange controller and others
More Intersection/ Interchange Control Functions at Intersection	Includes ability to change between: • Multiphase and 2-phase operation • Various dual left and lead-lag phasing sequences
Ramp Control	Can function as ramp metering and gate controller
Multiple Use Control	Can function at interchange for signal control, ramp control and detector processor in 1 unit to reduce installation and maintenance cost
Functional Modifications	Can change via software instead of hardware
Control of Supplementary Devices	Enables control of flashers, blank out signs, changeable message signs and other motorist information devices, changeable lane use signs at intersections, lane use control signals, gates, and overheight vehicle control. Can provide functional check on these devices

do not, however, make the pretimed controller completely inflexible. Each set of predetermined time increments applies to a single timing plan or dial used in the controller. In solid-state units, selecting a different timing plan can cause changes in:

- Cycle length,
- Phase split,
- Phase sequencing, and
- Minor movement availability.

A time clock or time-base coordinator can *internally* change the timing plan or dial in use, or a computer or master controller supervising the controller can *externally* change the timing plan.

Offset timing becomes important when the pretimed controller represents part of a coordinated or otherwise supervised system. See chapter 3 for a definition of *offset*.

Solid -State Controller Hardware Characteristics

Solid state controller assemblies include:

- A controller unit,
- A conflict monitor,
- Auxiliary devices (e.g., flasher, load switch), and
- Terminals.

For traffic actuated phasing, detector units are also provided. The controller operates at 12-24 DC volts furnished by a power supply module. Most controller units currently being manufactured use keyboard entry.

The conflict monitor checks the green and yellow indications for each phase to protect against improper or conflicting signals. It also protects against improper operating voltages. NEMA TS2 refers to conflict monitors as malfunction management units. It also requires that NEMA pretimed controllers meet the same standards as traffic actuated controllers.

Features incorporated into solid state pretimed controllers include:

- Time-base coordination,
- Programmable preemption sequences,
- Capability to program specific output circuits to be in modes ON, OFF, or FLASH during each interval,
- Alternate phase sequencing,
- Detector actuation input for phase selection, and
- Ability to select different offset seeking techniques.

The low DC voltage used in solid-state controller units mandates the use of load switches for 110-v lamp circuits. Timing modifications and maintenance prove relatively easy.

Electromechanical Controller Hardware Characteristics

Until the late 1970s, the electromechanical controller served as the standard pretimed traffic signal controller. Many of these controllers still operate, but more flexible solid-state controllers are generally replacing them.

An electromechanical controller includes the following devices:

- The dial unit, consisting of:
  - A synchronous motor,
  - A manually changeable cycle gear,
  - A dial cycle,
  - Timing keys, and
  - A bank of key-operated switches.

- The camshaft or switching drum, consisting of:
  - A solenoid or motor for incremental rotation,
  - Individual cams with appropriate switch breakouts, and
  - A bank of switch contacts for activating lamp circuits and other dial/camshaft mutual functions.

The dial unit times the selected intervals. Pretimed controllers generally come equipped with from 1 to 3 dial units. Three dials can provide 3 different cycle lengths for the:

- A.M. peak,
- P.M. peak, and
- Off-peak period.

The camshaft or drum serves as the other basic part of the signal timing unit. Timing keys activate the camshaft, which rotates to change the signal indications. As the timing key reaches the 12 o'clock position on the dial, it activates the camshaft impulse switch, which rotates the camshaft 1 position. At this point the cams, broken out to allow a contact arm to drop into a cam slot, either actuate relays (which change signal indications) or change indications by direct contact. Some controllers use cam inserts instead of breakouts.

Multiple-dial pretimed controllers have extra keys to initiate the transfer from 1 dial to another. Each dial can be equipped with 3 splits and 3 offsets. Thus, a 3-dial controller can provide 3 different cycle lengths, 3 sets of splits, and 9 different offsets (3 offsets per dial). Some controller units provide 3 splits for each of the 3 dials.

Coordination Requirements

Both open and closed network systems widely use the pretimed controller. Systems operate by either *time-base* or *explicit* coordination.

- ***Time-Base Coordination***

  This technique changes timing plans on a time-of- day basis and does not use wireline based communications or interconnect. See section 8.5 for further details.

- ***Explicit Coordination***

  Explicit coordination links local controllers with a twisted pair cable or other medium, as described in chapter 9. A master controller or central computer establishes the coordination (sync) pulse for all controllers in the system. The central computer or master controller performs other functions, such as selection of timing plans or parameters, and transmits them via the communications medium to each local controller.

7.7 Full-Actuated Controllers

For Model 170 and NEMA controllers, this section discusses:

- Modes of operation,
- Controller characteristics, and
- Common features.

Subsequent sections describe attributes of both controller types. Full-actuated controllers can also operate in a semi-actuated mode.

Controller Operation

To reflect relative approach volumes or the presence of pedestrians, a full-actuated controller unit provides variable vehicle green intervals and allows user selection of:

- Pedestrian interval(s),
- Phase sequences, and
- Durations.

The timing of certain intervals and phase durations are determined (within the limits of the respective maximum times set in the controller) by outputs from vehicle detectors strategically placed in the roadway. The display of pedestrian indications depends upon pedestrian actuation of the respective pushbuttons.

Other previously described types of actuated control operation are:

- Semi-actuated and
- Volume-density.

Controller Detection Modes

Locking Detection Memory locks vehicle actuations into the controller for subsequent service of the called phase. Chapter 6 discusses this mode.

In ***Nonlocking Detection Memory***, once a vehicle leaves the detector, the controller *forgets* its call. Chapter 6 also describes this mode.

Timing and Phasing Characteristics

Full-actuated operation requires detectors on all approaches assigned, respectively, to each controller unit phase. The full-actuated controller, in the absence of calls on opposing phases, dwells in the green interval of the last serviced phase, unless:

- One of the recall features is set, or
- Red rest is set for the respective ring.

Activation of one of the recall features causes the controller unit to return and service the designated phase even in the absence of detector actuations. The controller can also dwell in an all-red state (red rest), in the absence of demand from any of the phase detectors.

Maximum green time on a respective phase does not begin timing until a serviceable opposing phase detector call. Therefore, a phase with continuing demand may remain green for some time before a conflicting call is registered that starts the timing of the maximum green. Depending on the duration of the continuing detector actuations for the active phase, the controller unit may, upon receipt of opposing detected demand, respond as follows:

- Immediately begin the sequence to serve the opposing phase, if opposing demand coincides with the termination of demand on the phase currently being served.

- Immediately begin timing maximum green, and with continuing demand on the phase currently being served, begin the sequence to serve the opposing phase only when the maximum green times out.

The timing and phasing characteristics of full-actuated controller units follow:

- Each phase has a preset minimum green interval to provide starting time for standing vehicles.
- The green interval extends for each additional vehicle actuation after the minimum green interval has timed out, provided that a gap in traffic greater than the present unit extension setting does not occur.
- A preset maximum limits green extension. All NEMA-type controller units provide 2 selectable maximum limits (commonly referred to as MAX I, and MAX II).
- Yellow change and red clearance intervals are preset for each phase. Red clearance is not always needed in controller unit operation.
- Each phase is provided with a means of placing a call for minimum, maximum, or pedestrian recall.

Single - and Dual -Ring Operation

Understanding different controller operating modes requires knowledge of several terms. Table 7-9 describes these terms, as defined in the NEMA Standards and common to both Model 170 and NEMA-type units.

Basic Interval Timing Functions

Table 7-10 describes the timing settings per phase provided by full-actuated controllers units.

State-of-the-art full-actuated controller units implement (per phase) all settings in table 7-10.

Special Operational Features

In dual-ring operation, full-actuated controller units are capable of a number of different phasing sequences between barriers (compatibility lines). For each of the 2 major phase groups, there are 3 basic phase sequences:

- Left-turns first,
- Lead-lag left-turns, and
- Through movements first.

Table 7-11 describes each of the phase sequence options shown in figure 7-5, and assumes that demand is present to initiate each phase.

Figure 7-5 shows identical phase sequences for each phase group in respective phase sequence options. In practice, a given sequence, such as left-turns first, could be applied to 1 phase group (phases 1, 2, 5, and 6), and a different sequence, such as lead-lag left-turns, applied to the other phase group (phases 3, 4, 7 and 8).

Through *internal* or *external manipulation*, NEMA-type controller units are capable of the sequences described in table 7-11. Sequencing thus can be selected by the user through software or controller interface units.

The external control functions (inputs) that characterize NEMA traffic signal controller units, and the manner in which they operate, are discussed below. They are grouped into 3 categories:

- Inputs per phase (see table 7-12),
- Inputs per ring (see table 7-13), and
- Inputs per controller unit (see table 7-14).

Table 7-15 summarizes controller unit terminals.

Hardware Characteristics

Environmental and Operating Requirements

Environmental and operational requirements and procedures for control equipment conformance testing appear in table 7-16.

Conflict (Malfunction) Monitor

By detecting the presence or absence of voltages at field terminals, the *conflict monitor* detects conflicting signal indications. The monitor also ensures the presence of satisfactory operating voltages within the controller unit and within itself. Upon detection of conflicting indications or an unsatisfactory operating voltage, the monitor will cause immediate transfer of the signal operation to a preprogrammed flashing condition. The NEMA Standards Publication TS2 terms the conflict monitor the *malfunction monitor*.

Phasing Other Than for 8-Phase Control

Software may perform phasing applications other than the basic 8-phase full-actuated operation. The standard phasing of an 8-phase, full-actuated controller is converted into unique phase sequencing

Table 7-9. Full-actuated controller definitions.

Term	Description
Single-Ring Controller Unit	Contains 2 to 4 sequentially timed and individually selected conflicting phases arranged to occur in an established order. Phases may be skipped in 3 and 4-phase controllers. The phases within a ring are numbered as illustrated in figure 7-3.
Dual-Ring Controller Unit	Contains 2 interlocked rings arranged to time in a preferred sequence and allow concurrent timing of respective phases in both rings, subject to the restraint of the barriers (compatibility lines). Each of the respective phase groups must then cross the barrier simultaneously to select and time phases in the phase group on the other side. The phases within the 2 timing rings are numbered as illustrated in figure 7-4.
Barrier (compatibility line)	A reference point in the designated sequence of a dual-ring controller unit at which both rings interlock. Two reference points or barriers (1 for each phase group) assure that conflicting phases will not be selected or timed concurrently. Both rings (in 1 phase group) time out and then cross the barrier simultaneously, as illustrated in figure 7-4.
Dual Entry	A mode of operating in a dual-ring controller unit in which one phase in each ring must be in service. If a call does not exist in 1 of the rings when the barrier is crossed (from the other phase group), a phase is selected in that ring to be activated by the controller in a predetermined manner. For example, referring again to figure 7-4, in the absence of calls on Phases 7 and 8, Phase 2 and Phase 6 terminate to service a call on Phase 3. Programming for dual entry determines whether Phase 7 or Phase 8 will be selected and timed concurrently with Phase 3, even though no call is present on either Phase 7 or Phase 8.
Single Entry	A mode of operation in a dual-ring controller unit in which a phase in 1 ring can be selected and timed alone when there is no demand for service in a non-conflicting phase on a parallel ring. For example, referring to figure 7-4, after the termination of Phase 2 and Phase 6, the controller unit will service a call on Phase 3 in the absence of calls on either Phase 7 or Phase 8. While Phase 3 is selected and timed alone, Phases 7 and 8 (in Ring 2) will remain in the red state.

for special applications. Table 7-17 shows 2 examples of special phase sequencing.

NEMA controller units, modified by software for the 3-phase and 4-phase sequences described in table 7-17, are currently in service in Texas (10). The operation can change between the sequence options in response to external commands. The City of Dallas provides for 4 sequence variations. The 2 sequence variations shown in figure 7-8 are used by the Texas Department of Transportation. Typical detector locations for operation of the controller unit in 3-phase, lag-lag, or 4-phase (with overlaps) sequencing, with locally produced external data, are shown in figure 7-9. Software also provides the option for use of any compatible combination of phases at the ramp intersections, in response to computer-issued command data, as shown in figure 7-10.

Diamond Interchange Operation

An interconnected signal system, consisting of 6 diamond interchanges under computer supervision, has been installed in Texas. When computer-issued commands are lost, or computer operation is intentionally discontinued, local interchange controller units revert to a preselected 3-phase or 4-phase full-actuated operation (figure 7-8) based on local detector data (figure 7-9).

A model 170 controller unit provided with the proper software is also capable of the operations described in table 7-14.

The 3-phase sequencing shown in figures 7-7 and 7-8 can provide a shorter cycle length than the 4-phase sequencing shown in figure 7-8. For example, Texas

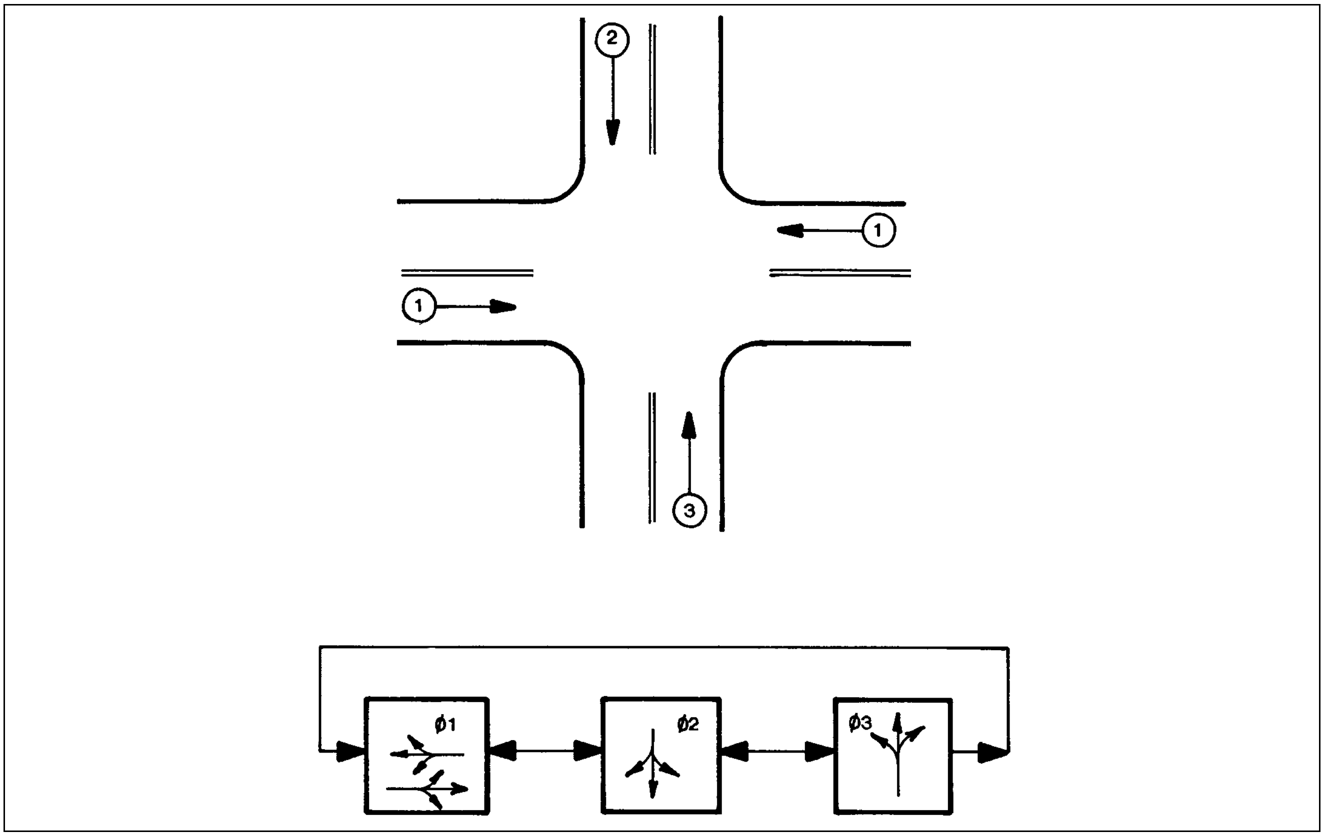


Figure 7-3. Three-phase controller phase sequence for single-ring controller.

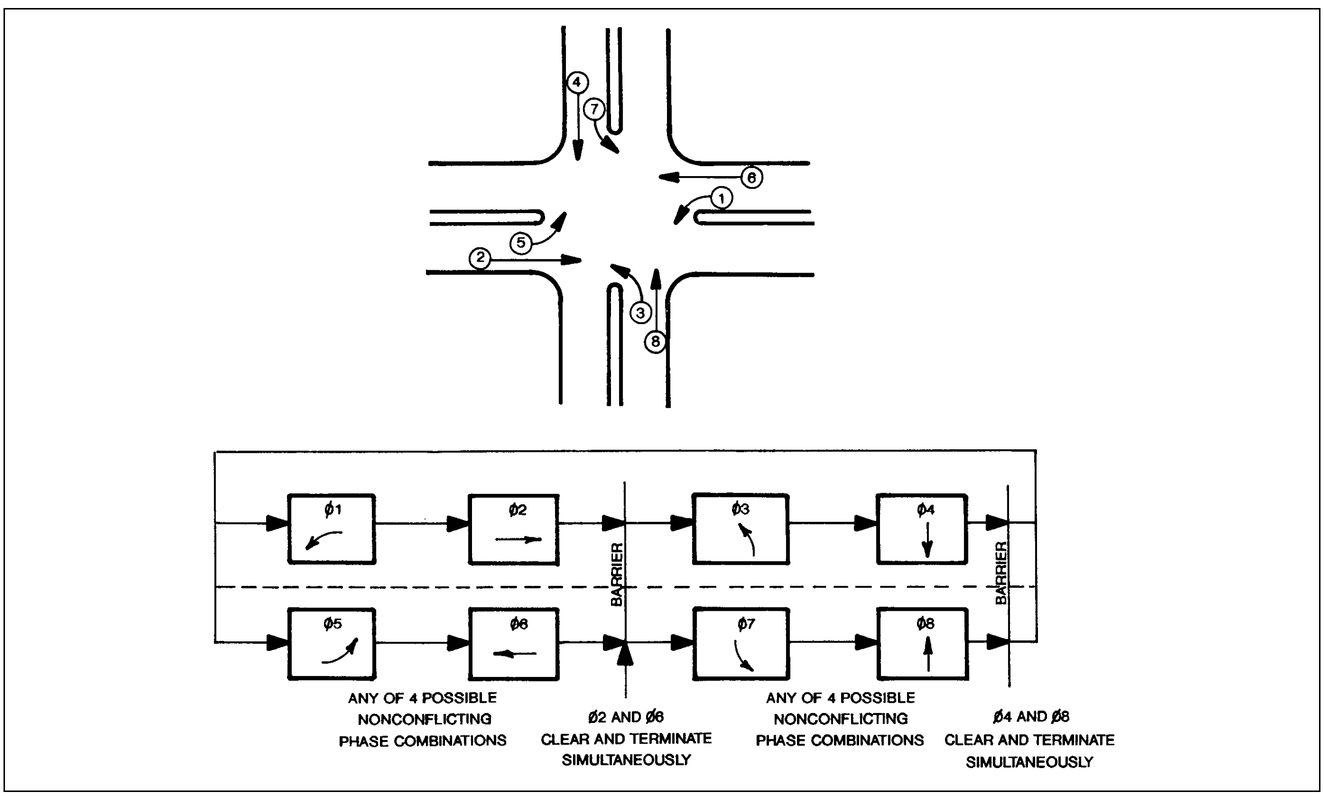


Figure 7-4. Phase sequence for dual-ring controller.

Table 7-10. Full-actuated controller timing settings.

Setting	Description
Minimum Green Interval	The first timed portion of the green interval. Set considering the waiting vehicles between the approach detector and the stopline. Thus, minimum green equals either: • Initial portion of the green interval • Initial portion of the interval plus one extension interval • WALK interval plus pedestrian clearance • WALK interval plus pedestrian clearance plus one extension interval (9)
Extension (gap) Interval	Portion of the green interval in which: • Timing resets with each subsequent vehicle actuation • Does not commence to time again until vehicle actuation signal removed This extensible portion of the green interval subject to termination by the maximum of extension limit time function (9)
Maximum (extension limit)	Determines the length of time that the respective phase may be held in green in the presence of an opposing serviceable call. In the absence of a serviceable conflicting call, the maximum timer is held reset (9). This maximum (extension limit) can be modified by selection of preset, alternate green interval extension limits (MAX I, MAX II, etc.).
Yellow Change Interval	The interval following green which alerts motorists to imminent phase termination
Pedestrian (WALK) Interval	The interval used to initiate the assignment of pedestrian crossing time. Guarantees a minimum fixed time for the WALK display.
Pedestrian Clearance (DONT WALK) Interval	Follows the pedestrian WALK indication. Provides time for the pedestrian(s) to leave the curb and travel to the center of the furthest traveled vehicle lane before opposing vehicles receive a green indication.
Red Clearance Interval	When selected, follows the yellow change interval. Both the terminating phase and the next (conflicting) phase display red.

DOT conducted a study in which the 2 phase sequences shown in figure 7-8 were compared at a number of intersections during isolated full-actuated control. The cycle lengths for the 4-phase sequence were 40 to 80% longer than for the 3-phase sequence. Expect similar reductions in cycle lengths at locations in other isolated and interconnected systems, as long as the left-turn movements remain within reasonable limits, and storage is available between the off-ramp (frontage road) connections. Where turning movements are high onto and/or off of the ramp connections (frontage roads), the 4-phase sequence provides the best operation.

One of the 3 phase sequences shown in Figure 7-7 can also apply when certain turning movements prove heavy. If the controller includes more than 1 phase sequence, the sequences can be changed to accommodate operational requirements.

Single Point Freeway Interchange Operation

The single point urban interchange (SPUI) shown in figure 7-11 has been installed at a number of freeway locations. The design provides a basic 6 movement operation as shown in figure 7-12.

The Texas Transportation Institute studied the single point design, which resulted in warrants and guidelines (11). The SPUI and the tight urban diamond interchanges with a distance of 250 to 400 ft (76 to 122 m) between ramp connections (or frontage roads) were judged viable competitors.

Table 7-11. Phase sequence options.

Sequence	Description
Left-Turns First	Sequence begins with Phase 1 and Phase 5, the opposing turns moving together. As demand ends or maximum green is reached on either Phase 1 or Phase 5, the respective left-turn is terminated after the proper change and clearance intervals, and the opposing thru movement (Phase 2 or Phase 6) is given a green indication concurrent with its accompanying left-turn. As demand ends or maximum green is reached on the remaining left-turn movement, it is terminated after the proper change and clearance intervals, and its opposing thru movement is released. Phases 2 and 6 then run together until demand ends or maximum green time for both phases is reached. The phases then, after display of proper change and clearance intervals, terminate simultaneously at the barrier line. As shown in figure 7-5, the above phase sequence also applies to the phases beyond the barrier line (Phases 3, 4, 7 and 8) in the other phase group.
Lead-Lag Left-Turns	Sequence begins with Phase 5, a left-turn, and its accompanying Phase 2, moving concurrently. As demand ends or maximum green is reached on Phase 5, that left-turn is terminated after the proper change and clearance intervals. The opposing thru movement, Phase 6, is released to run with Phase 2. As demand ends or maximum green for Phase 2 is reached, it is terminated after the proper change and clearance intervals. Its opposing left-turn, Phase 1, is released to run with accompanying thru movement, Phase 6. When demand ends or maximum green is reached on Phase 1, both phases terminate, after proper change and clearance intervals, at the barrier line. As shown in figure 7-5, the above phase sequence also applies to the phases beyond the barrier line (Phases 3, 4, 7 and 8), in the other phase group. Also, it must be noted that either of the opposing left-turns in each phase group may lead the phase sequence.
Thru Movements First	Sequence begins with the opposing thru movements, Phases 2 and 6. As demand ends or maximum green is reached on one of the thru movements, that phase (2 or 6) is terminated after the proper change and clearance intervals, and its opposing left-turn (Phase 1 or 5) is released to run concurrently with the accompanying thru movement. As demand ends or maximum green is reached on the thru movement, that phase (2 or 6) is terminated after the proper change and clearance intervals, and its opposing left-turn (1 or 5) is released. Both left-turns run together until demand ends or maximum green on the latest released phase is reached. Phases 1 and 5 then terminate simultaneously after the proper change and clearance intervals at the barrier line. As shown in figure 7-5, the above phase sequence also applies to the phases beyond the barrier line (Phases 3, 4, 7 and 8), in the other phase group.

The study recommended the following guidelines for the SPUI:

- Equivalent left-turn volumes exceed 600 v/hr as large truck volumes are anticipated from off- ramps having left-turn volumes exceeding 300 v/hr

- SPUI becomes a good candidate with:
  - Restricted right-of-way,
  - High volumes with major congestion,
  - High incidences of left-turns and large truck volumes (see above), and
  - High accident incidence locations.

- SPUI is *not* a candidate at sites with:
  - Severe skew angles,
  - A wide overcrossing roadway,
  - Adverse grades on the cross street,
  - Moderate-to-high pedestrian crossing volumes, or
  - A combination of high through-volumes and low turning volumes on the cross street.

Freeway incident management often makes use of continuous frontage roads. Due to longer cycle lengths and increased delays, the SPUI is not recommended where continuous frontage roads exist when the SPUI and the frontage roads are grade-separated with one elevated above the other.

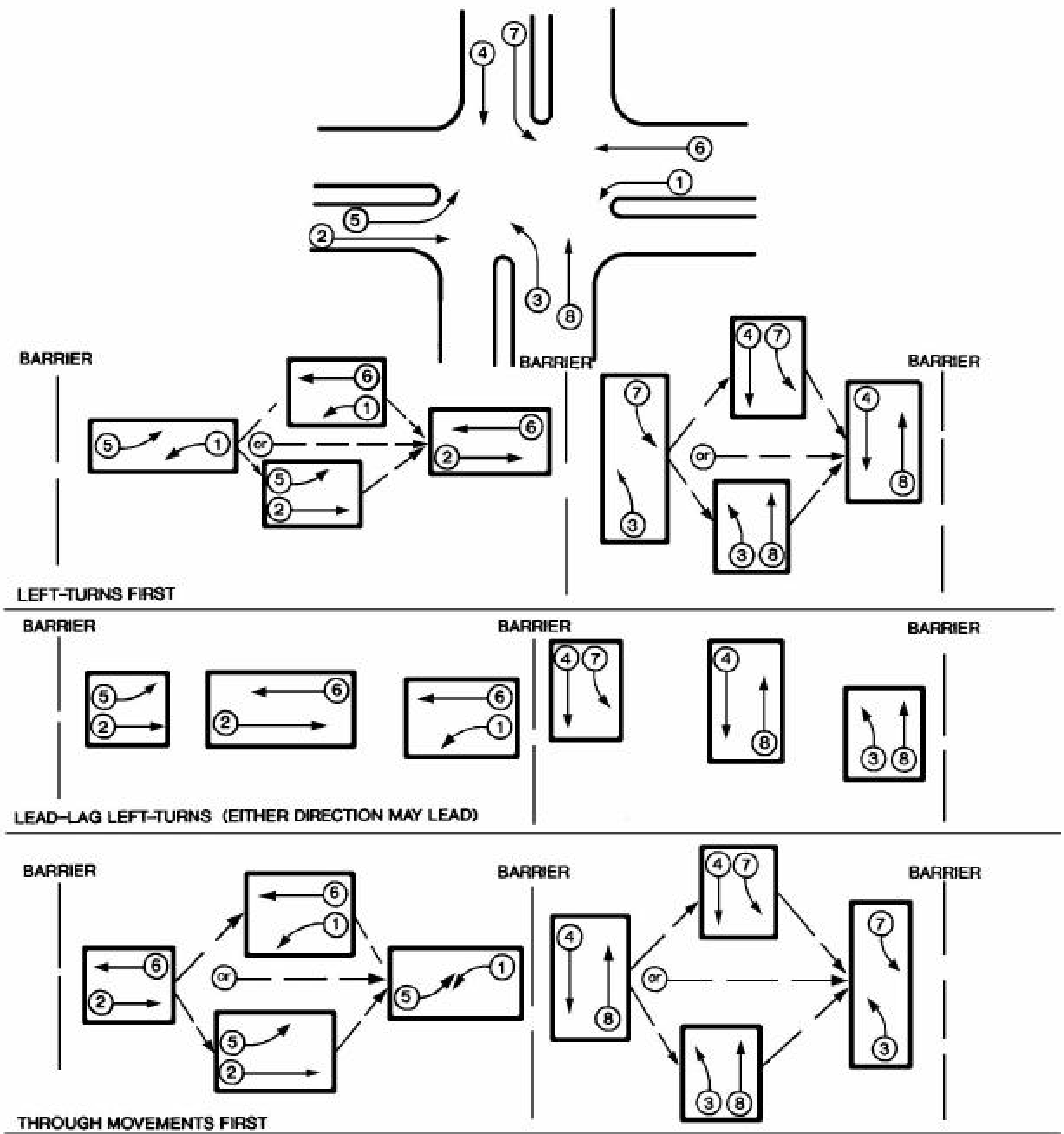


Figure 7-5. Dual-ring basic phase sequence options.

Table 7-12. Inputs per phase.

Input	Description
Vehicle Detector Call	Enters a vehicle demand for service into the appropriate phase of the controller unit
Pedestrian Detector Call	Enters a pedestrian demand for service into the associated phase of the controller unit
Hold	Command that retains the existing right-of-way and has different responses, as follows depending upon operation in the vehicle non-actuated or actuated mode: • For a non-actuated phase, energization of the hold input maintains the controller unit in the timed out walk period with green and walk indications displayed. Energization of the hold input while timing the WALK portion of the green interval does not inhibit the timing of this period. De-energization of the hold input and with the WALK interval timed out causes the controller unit to advance into the pedestrian clearance interval. Re-application of the hold input while timing the pedestrian clearance portion of the green interval neither inhibits the timing of this period nor the termination of the phase. • For an actuated phase, energization and de-energization of the hold input operates as follows: (a) Energization of the hold input allows the controller unit to time normally but inhibits its advance into the yellow change interval. Energization of the hold input inhibits the recycle of the pedestrian service unless the pedestrian recycle input is active and a serviceable pedestrian call exists on the phase. The rest state signal indications for that phase are green and DONT WALK. (b) De-energization of the hold input allows the controller unit to advance into the green dwell/select state when all green periods are timed out. (c) De-energization of the hold input with all intervals timed out allows the controller unit to recycle the walk interval if there is no conflicting demand for service and a pedestrian call exists for that phase. However, if there is any serviceable demand on an opposing phase with the hold input de-energized, and with all intervals timed out, the controller unit advances into the yellow change interval and does not recycle the walk on that phase until those demands have been served.
Phase Omit	Command which causes omission of a phase, even in the presence of demand, by the application of an external signal, thus affecting phase selection. The omission continues until the signal is removed. The phase to be omitted does not submit a conflicting call to any other phase but accepts and stores calls. The activation of Phase Omit does not affect a phase in the process of timing.
Pedestrian Omit	Command which inhibits the selection of a phase resulting from a pedestrian call on the subject phase, and it prohibits the servicing of that pedestrian call. When active, the Pedestrian Omit prevents the starting of the pedestrian movement of the subject phase. After the beginning of the subject phase green, a pedestrian call is serviced or recycled only in the absence of a serviceable conflicting call and with Pedestrian Omit on the phase non-active. Activation of this input does not affect a pedestrian movement in the process of timing.

Table 7-13. Inputs per ring.

Input	Description
Force-Off	Command which provides for the terminations of green timing or WALK hold in the non-actuated mode of the active phase in the timing ring. Such termination is subject to the presence of a serviceable conflicting call. The Force-Off is not effective during the timing of Initial, WALK or pedestrian clearance. Force-Off is effective only as long as the input is sustained.
Red Rest	Requires the controller unit to rest in red in all phases of the timing ring(s) by continuous application of an external signal. The registration of a serviceable conflicting call results in the immediate advance from Red Rest to green of the demanding phase. The registration of a serviceable conflicting call before entry into the Red Rest state results in the termination of the active phase and the selection of the next phase in the normal manner, with appropriate change and clearance intervals. The registration of a serviceable call on the active phase before entry into the Red Rest state even with this signal applied, results (if Red Revert is active) in the continuation of the termination of the active phase with appropriate yellow change interval and Red display for the duration selected in Red Revert. The formerly active phase is then reassigned right-of-way.
Inhibit Maximum Termination	Disables the maximum termination functions of all phases in the selected timing ring. This input does not, however, inhibit the timing of Maximum Green.
Omit Red Clearance	Causes the omission of Red Clearance timing intervals
Pedestrian Recycle	Controls the recycling of the pedestrian movement. The operation depends on whether the phase is operating in the actuated or non-actuated mode: • In the actuated mode, if a serviceable pedestrian call exists on the subject phase and the Hold input is active, the pedestrian movement is recycled when the Pedestrian Recycle input is active, regardless of whether a serviceable conflicting call exists. • In the non-actuated mode, if the subject phase has reached the Green Dwell/Select state, the Pedestrian Omit is not active on the phase and a serviceable conflicting call does not exist, the pedestrian movement is recycled when the pedestrian recycle input is active.
Stop Timing	When activated, causes cessation of controller unit ring timing for the duration of such activation. Upon the removal of activation from this input, all portions which are timing, will resume timing. During Stop Timing, vehicle actuations on non-Green phases are recognized; vehicle actuations on Green phase(s) reset the Passage Time timer in the normal manner, and the controller unit does not terminate any interval or interval portion or select another phase, except by activation of the Interval Advance input. The operation of the Interval Advance with Stop Timing activated clears any stored calls on a phase when the controller unit is advanced through the green interval of that phase.
Maximum II (Selection)	Allows the selection of an alternate maximum time setting on all phases of the timing ring

Table 7-14. Inputs per controller unit.

Input	Description See section 3.5.5.5 of NEMA TS2 Standard (9)
Interval Input Advance	A complete On-Off operation of this input which causes immediate termination of the interval in process of timing. When concurrent interval timing exists, use of this input causes immediate termination of the interval which would terminate next without such actuation.
Manual Control Enable	Places vehicle and pedestrian calls on all phases, stops controller unit timing in all intervals, and inhibits the operation of the Interval Advance input during vehicle change and clearance intervals
Call to Non-Actuated Mode (Two per Controller Unit)	When activated, causes any phases appropriately programmed to operate in the non-actuated mode. The 2 inputs are designated Call to Non-Actuated Mode I and Call to Non-Actuated Mode II, respectively. Only phases equipped for pedestrian service are to be used in a non-actuated mode.
External Minimum Recall to All Vehicle Phases	Places recurring demand on all vehicle phases for a minimum vehicle service
External Start	Causes the controller unit to revert to its programmed initialization phase(s) and interval(s) upon application of the signal. Upon removal of this input, the controller unit commences normal timing.
Walk Rest Modifier	When activated, modifies non-actuated operation only. Upon activation, the non-actuated phase(s) remain in the timed-out WALK state (rest in WALK) in the absence of a serviceable conflicting call without regard to the Hold input status. With the input nonactive, non-actuated phase(s) do not remain in the timed-out WALK state unless the Hold input is active. The controller unit recycles the pedestrian movement when reaching the Green Dwell/Select state in the absence of a serviceable conflicting call.

Table 7-15. Controller unit terminals.

AC + (Line Side)	Fused side of the 120-VAC, 60-Hz power source to the controller unit
AC- (Common)	Unfused and unswitched side of the 120-VAC, 60-Hz power source taken from neutral output of the AC power source. This input is not connected to Logic Ground or Chassis Ground within the controller unit.
Chassis Ground	Provides grounding of the controller. Chassis Ground is electrically connected to the shell of the connector, but it is not connected to Logic Ground or AC-(Common) within the controller unit.

Table 7-16. Controller specifications.

Controller	Specification
Model 170	Traffic Signal Control Specifications (as amended) California Department of Transportation January 1989 (8)
NEMA	Traffic Control System Standards Publication No. TS2-1992 National Electrical Manufacturers Association (9)

Table 7-17. Special phase sequencing.

Operation	Description
Left-Turn Restoration	In the operation of a standard 8-phase controller unit, the service of a left-turn can be restored without first cycling through the barrier line. In this operation, the controller unit monitors the time remaining on any thru movement phase which is opposed by a thru phase which has gapped out. If the time remaining on the non-gapped phase is sufficient for at least a minimum service of its associated (parallel) left-turn phase, the controller unit terminates the gapped-out phase and reservices the left-turn. Figure 7-6 illustrates the phase sequence.
Full Diamond Interchange	The operation of 1 standard 8-phase controller unit with modified software for signalization of a full diamond interchange. Figures 7-7 and 7-8 show 4 sequence variations: • A 3-phase lead-lag operation in which traffic on both ramp approaches begins simultaneously (Phase 1). Phase 2 follows Phase 3 if there is a demand (detector activation) for the phase. Phase 3 follows Phase 2 if there is a demand for the phase, and Phase 1 follows Phase 3 if there is a demand for that phase. • A 3-phase operation in which traffic on both cross street approaches begins simultaneously and is followed subsequently by Phases 2 and 3 if there is a demand for each of these phases. • A 3-phase, lag-lag operation in which the traffic on both ramp approaches is released simultaneously (Phase 1). Subsequent vehicle actuations and/or maximum green time-outs determine diagram flow from Phase 1 to 1 of the 4 overlap phases, or directly to Phase 2. Depending upon demand registered and which Phase 1 overlap was previously served, the controller unit will move to serve 1 of the 2 Phase 2 overlaps or go directly to Phase 3. In the absence of demand from either ramp approach, the controller unit may proceed from Phase 3 back to Phase 2, or to 1 of the 2 Phase 2 overlaps. • A 4-phase operation with 2 overlaps, in which traffic on one of the ramp approaches is released simultaneously with thru and left-turn traffic (on the intersecting arterial) at the other ramp intersection, thereby clearing any possible internal queue for the traffic turning left from the ramp (Phase 1). As shown in the diagram in figure 7-8, several optional flow paths are available, any of which could be followed, based upon registered demand and/or maximum green time-outs on certain approaches. For purposes of illustration, the following flow sequences assume continuing demand on all detectors. From Phase 1, the controller unit moves to Phase 1 overlap, in which the opposing traffic on the arterial (at the, as yet, unserved ramp intersection) is released while the ramp approach green continues. The Phase 1 overlap phase must be of fixed time duration since the running ramp green must be terminated to accommodate the progressive movement of the arterial traffic released at the start of the overlap phase. This fixed time period is determined by the travel time of accelerating arterial traffic from a stop at one ramp intersection, and through the other ramp intersection. The controller unit proceeds then to Phase 2 green to accommodate the above described approaching arterial traffic (thru and left-turns). For Phase 3 initiation, traffic on the arterial (at the, as yet, unserved ramp) is cleared and terminated for release of traffic on the ramp approach. As the diagram shows, flow continues to Phase 3 overlap and on to Phase 4, serving remaining traffic movements. The phase sequence described for each of the 4 sequence variations assumes that there is demand for each phase. Since the controllers are full traffic actuated, it is possible for phases to be skipped. The array of flow lines and arrows on the diagram represents all possible sequence paths the controller unit can take. The different sequence variations shown in figures 7-7 and 7-8 are applicable and depend on the traffic patterns at the interchange. The software for 2 or more of the sequences can be provided in the same controller unit and changed by time-of-day or on a real-time basis as traffic patterns change.

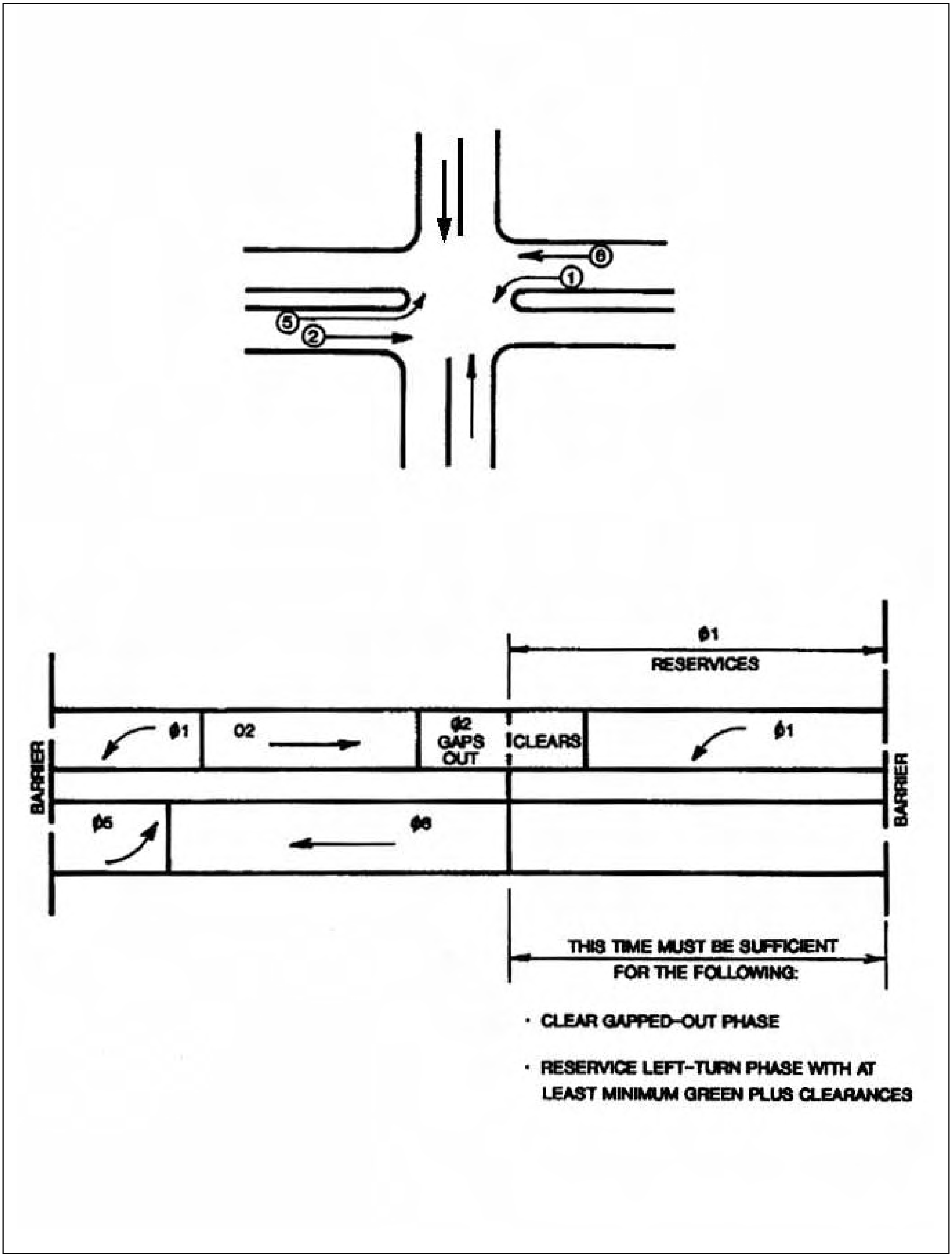


Figure 7-6. Example of special phase sequence for conditional service of left-turn phase.

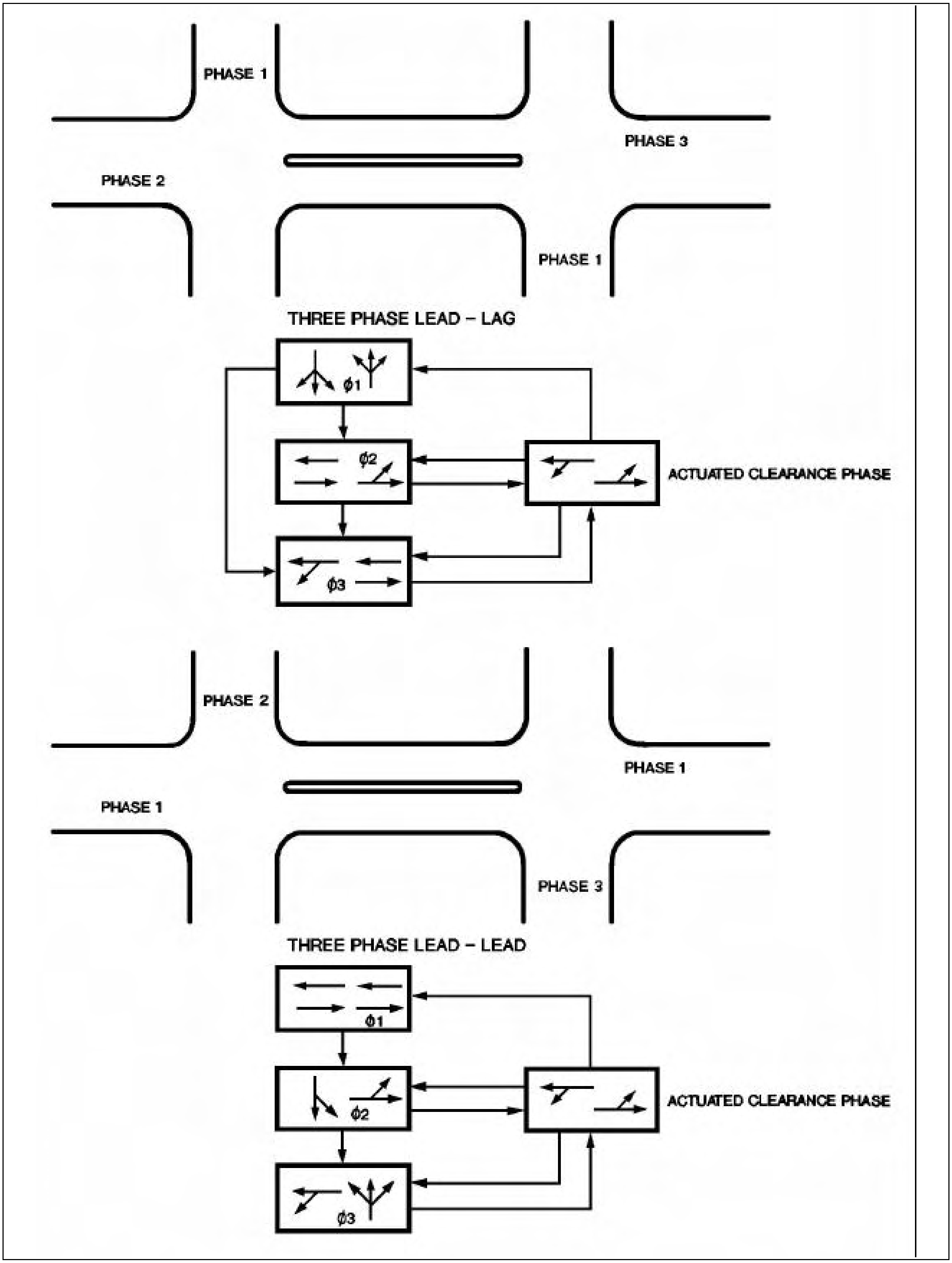


Figure 7-7. Diamond interchange phasing (3-phase).

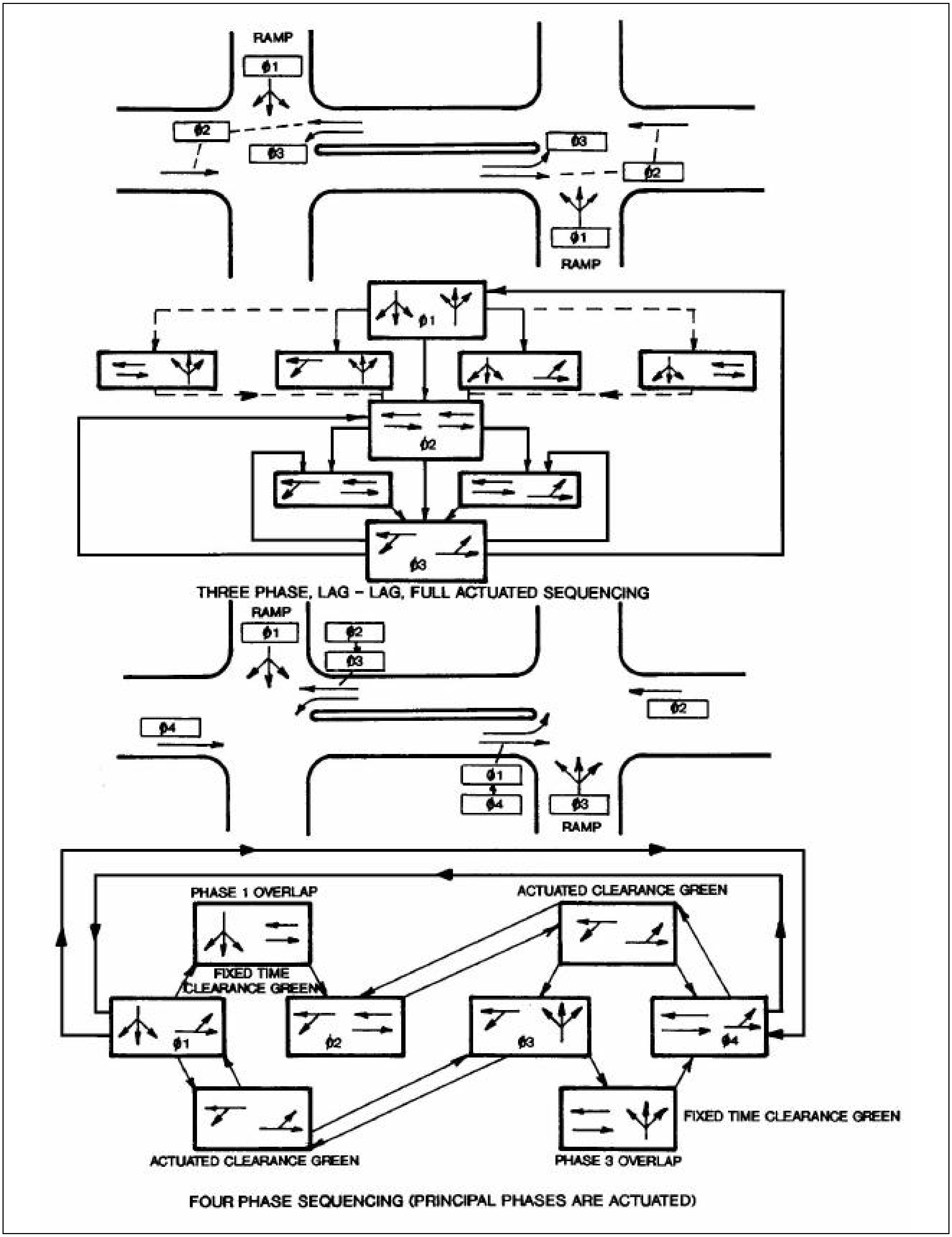
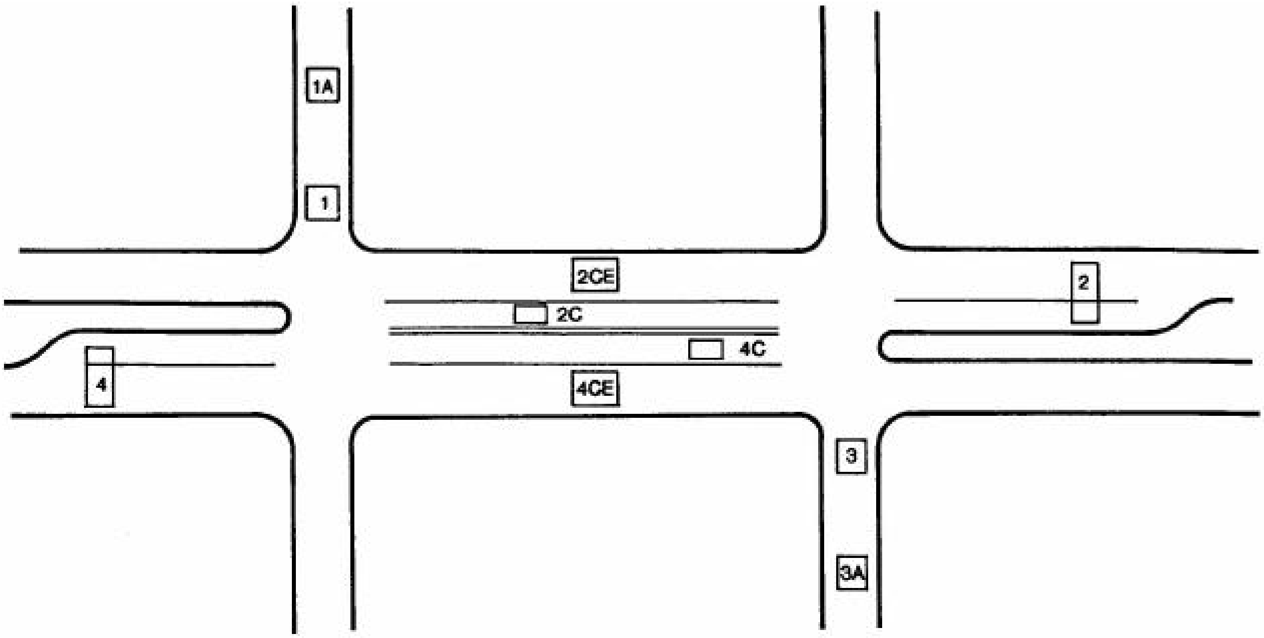


Figure 7-8. Diamond interchange phasing (3- and 4-phase).



DET. NO.	ASSOC. PHASE	FUNCTIONS FOR:		DET. NO.	ASSOC. PHASE	FUNCTIONS FOR:	
		3φ LAG-LAG	4φW/OVERLAP			3φ LAG-LAG	4φW/OVERLAP
1	1	PHASE DETECTOR	PHASE DETECTOR	3	3	PHASE DETECTOR	PHASE DETECTOR
1A	1	(NOT USED)	PHASE DETECTOR DURING φ1 WHEN CALL IS RECEIVED FOR φ2	3A	3	(NOT USED)	PHASE DETECTOR DURING φ3 WHEN CALL IS RECEIVED FOR φ2
4	4	PHASE DETECTOR	PHASE DETECTOR	2	2	PHASE DETECTOR	PHASE DETECTOR
4C	4	DETECTOR FOR LEFT TURN AND INTERVAL CLEARANCE GREEN	SWITCHED ON FOR CALLING ONLY DURING φ2 AND φ3 EXTENDING DETECTOR DURING CLEARANCE GREEN	2C	2	DETECTOR FOR LEFT TURN AND INTERVAL CLEARANCE GREEN	SWITCHED ON FOR CALLING ONLY DURING φ1 AND φ4 EXTENDING DETECTOR DURING CLEARANCE GREEN
4CE	4	EXTENDING DETECTOR	SWITCHED ON FOR CALLING ONLY DURING φ3 EXTENDING DETECTOR DURING CLEARANCE GREEN	2CE	2	EXTENDING DETECTOR	SWITCHED ON FOR CALLING ONLY DURING φ1 EXTENDING DETECTOR DURING CLEARANCE GREEN

Figure 7-9. Typical detector configuration for 3-phase, lag-lag and 4-phase (with overlap) special sequences.

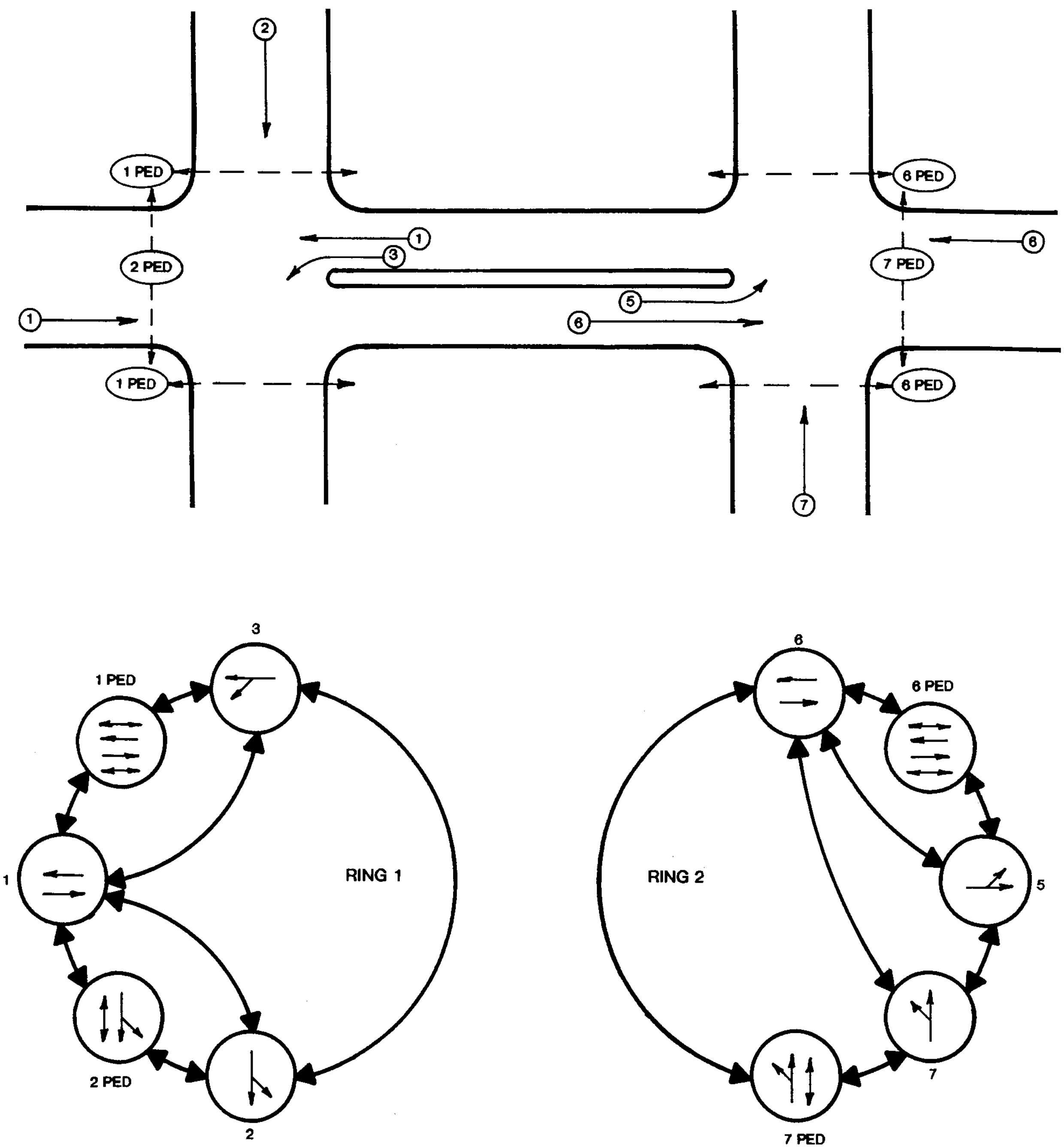


Figure 7-10. Computer controlled diamond interchange operation.

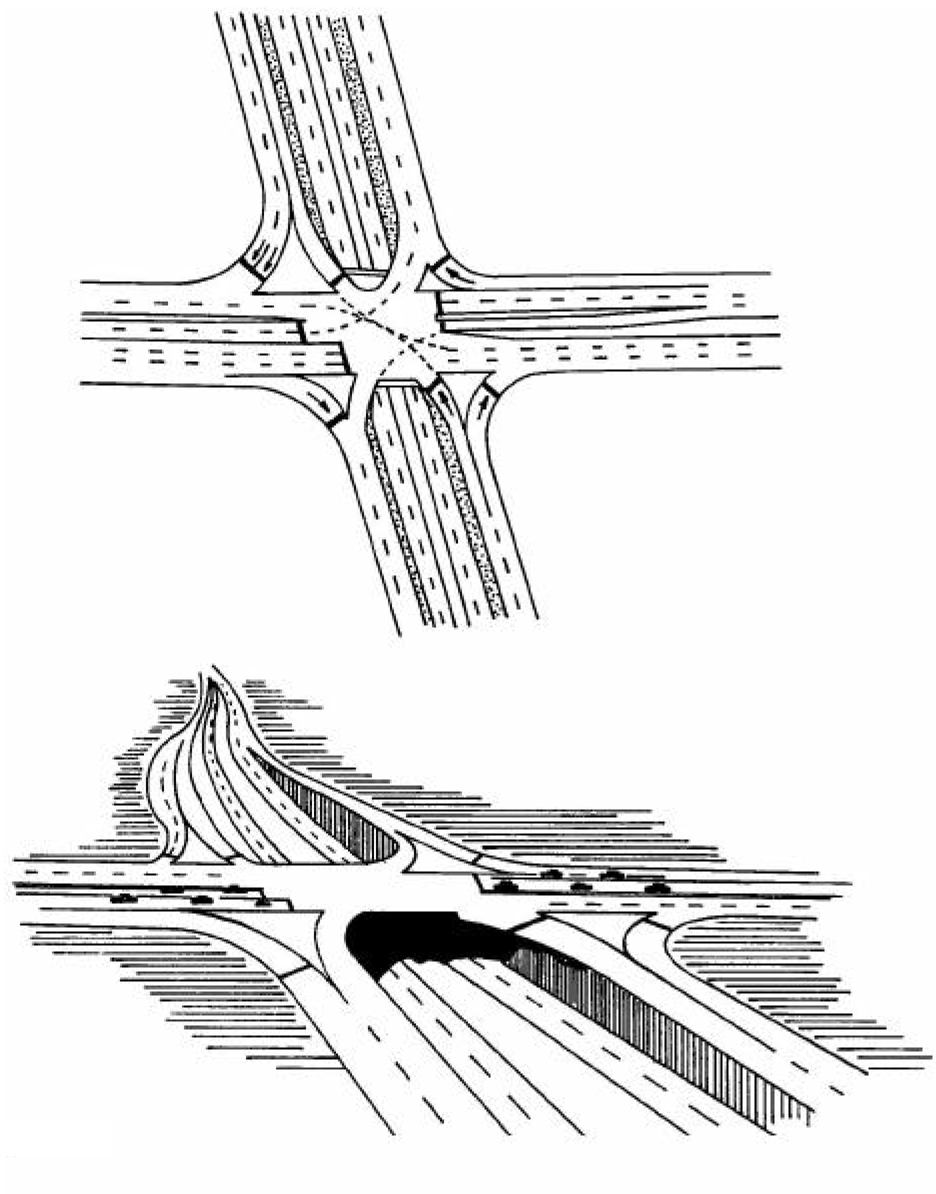


Figure 7-11. Single point urban interchange (SPUI).

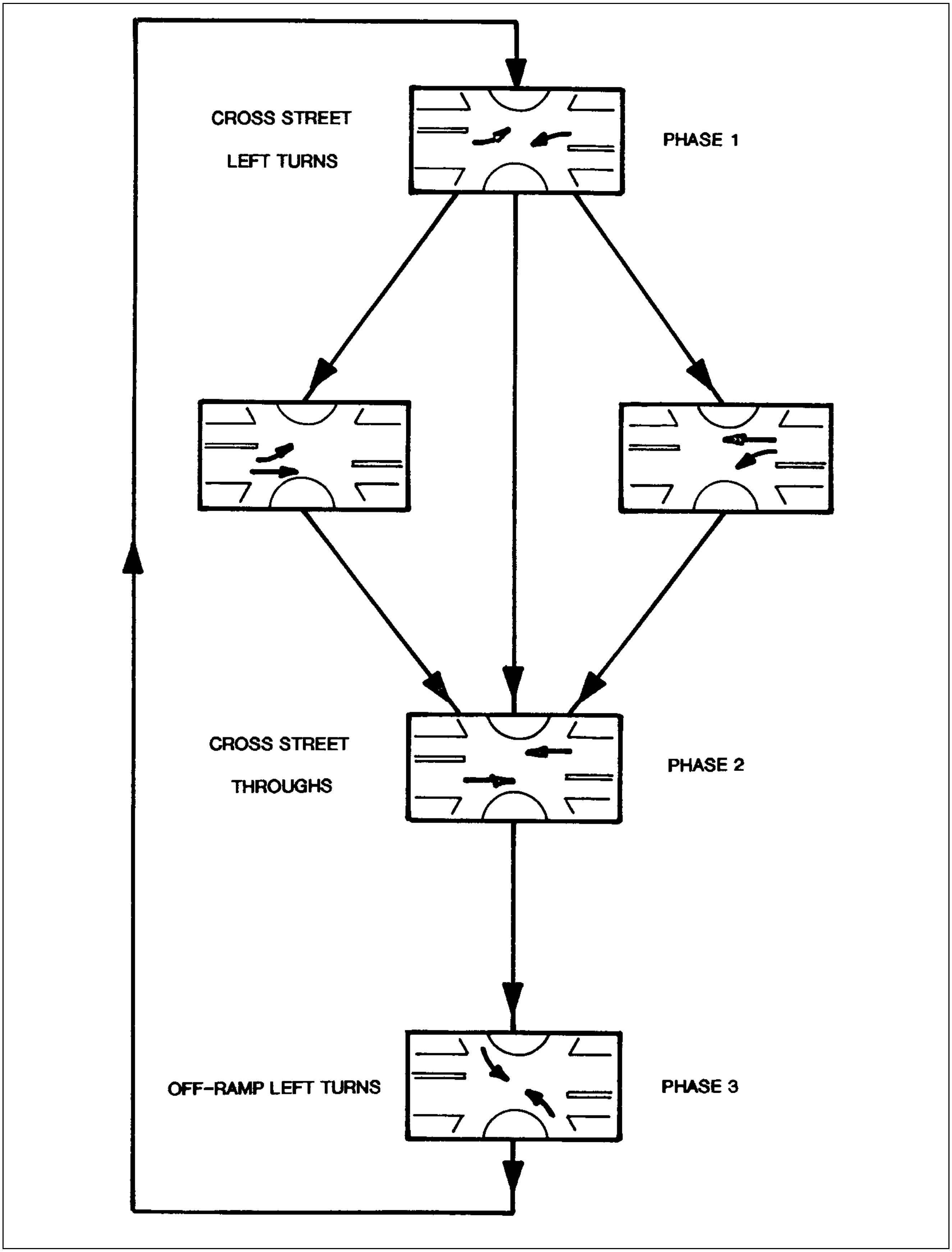


Figure 7-12. Typical SPUI 3-phase sequence.

System Capabilities

The full-actuated controller, when used as a local unit in a traffic signal system, can provide additional functions other than previously described. Through the use of communications to a supervising master or central computer, the controller receives and implements a variety of commands. In closed-loop systems or central computer control systems, a 2-way communications system returns information from the local unit to the central facility. The control status of the local controller and timing plan in effect exemplify returned local-oriented information. In many systems using 2-way communications, system detector information is also returned to the supervising master unit or central computer.

Downloading Capabilities

With *downloading*, the master unit or computer, via communications interface, can access the contents of the local controller unit's random access memory (RAM). The master can alter any stored existing signal timing plan, or load new plans. It can also modify other controller parameters. Thus, the master can access and/or manipulate:

- Phase sequencing,
- Interval timing,
- Number of intervals,
- Offset points, and
- Other timing plan characteristics.

The operator may also manually access via the central facility, individual intersection parameters stored in the local controller unit's RAM, thereby overriding previous changes or commands. Downloaded interval durations and phase sequences may be subject to local minimums or maximums stored in PROM (Programmable Read Only Memory) or RAM locally, or the downloaded data may overwrite existing data without restraint. Methods vary from system to system, and traffic engineers must remain aware of the resulting impacts on traffic flow and operations safety. The capability to access this data and transfer it to the master or central computer is called *uploading*.

The downloading of signal timing plans becomes possible when microprocessor-based controller units serve as local controllers in a master- or computer-supervised control system. A communications unit associated with the controller can also store downloaded timing plans.

7.8 Model 170 and NEMA Controllers

Model 170 Based Controller Systems

A specification jointly developed by the states of California and New York describes the Model 170 controller system (8). Since its introduction, many states and other traffic organizations have adopted the Model 170 controller, which along with NEMA have become de facto national standards. The Model 170 system includes a set of equipment specifications for:

- Electronic modules,
- Connectors,
- Wiring harnesses, and
- Cabinet enclosures.

Figure 7-13 shows a typical front panel display for the Model 170 controller.

The controller unit contains a microcomputer which, with the addition of appropriate software, can provide a variety of control applications. Thus, the controller unit can adapt to the user's needs by:

- Incorporating an existing software program,
- Modifying an existing software program, or
- Developing a new program.

Some manufacturers provide variations of the Model 170 controller which include:

- Improved front panels,
- Improved communications capability, and
- Other enhancing features.

A number of states, Canadian provinces, and other traffic organizations have developed software for the Model 170 controller. A number of firms also develop and market related software. Software for the Model 170 requires a low level computer language and is implemented through the use of PROM computer chips.

Organizations choosing not to develop their own software can obtain it from firms which market it. Software is available for the following applications (12, 13):

- Pretimed Controller,
- Actuated Controller,

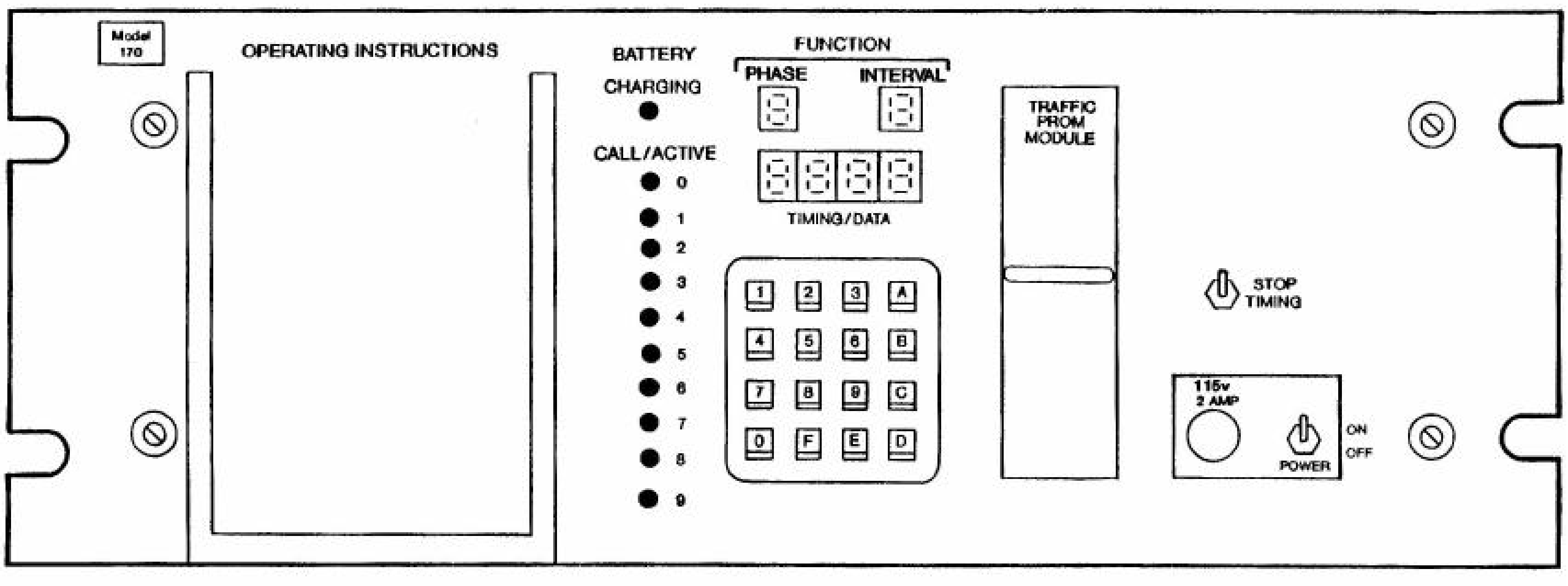


Figure 7-13/ Model 170 typical front panel display.

- Time-Base Coordination,
- Field Masters,
- Closed-Loop Systems,
- Ramp Metering, and
- Diamond Interchange Control.

Freeway monitoring and ramp metering applications commonly use the Model 170 controller, together with appropriate software. Cabinet arrangements for these applications (such as Model 334) make it possible to (8) :

- Eliminate equipment such as conflict monitors and flashers (not needed for freeway applications), and
- Reduce the number of switchpaks.

A number of firms provide modules that plug into the Model 170 Controller Unit chassis and provide enhanced functions, particularly input/output and communications functions.

The New York State Department of Transportation uses a similar controller, the Model 179 (12). Although using a somewhat more powerful microprocessor, the Model 179 has not achieved the same acceptance as the Model 170.

NEMA Controllers

Some electrical equipment manufacturers have agreed to conform to NEMA Standards Publication No. TS2 - 1992 with respect to the traffic signal controller units they manufacture (9). These standards reflect inputs from:

- Installers of traffic signal equipment,
- Traffic engineers, and
- Other professionals in the field of traffic control.

They describe physical and functional requirements for full-actuated traffic signal controller units and ancillary equipment. The controller unit functions described in the standards include 2- through 8-phase, single- and dual-ring operation. The standards, developed to provide compatibility and interchangeability among controller units, also cover input and output formats, environmental standards, and test procedures.

The NEMA TS2 - 1992 standard provides numerous operational and electrical requirements for pretimed and 2 designs for full traffic actuated controllers. The 2 full traffic actuated controllers are Type 1 and Type 2.

The Type 2 controller upgrades the controller described in the NEMA TS1 - 1983 standard, but maintains downward compatibility through continued use of the standard MS A, B, and C connectors. In addition, the Type 2 controller can be provided with software options and non-standard pin connector designation, which could apply to special interface needs.

The Type 1 controller is based on a new performance oriented standard that uses communications ports in place of the MS connectors. The communications ports make the controller more flexible for different applications. Port 2 is an EIA-232C connector that can interface to a personal computer and printer. Remote controller and detector diagnostics can also be included.

The NEMA TS2 - 1992 standard encompasses a much broader scope than NEMA TS1 - 1983. In addition to those items included in TS1, TS2 includes specifications for:

- Pretimed control,
- Communications, and
- An additional (Type 1) controller design that includes remote diagnostics.

In addition, NEMA is in the process of developing a standard communications protocol for system operation.

Although manufacturers of NEMA controller units must produce equipment that functionally satisfies the standards, many state-of-the-art units have additional operational features. Some of the special operations that NEMA controller units perform were covered earlier in this chapter.

Comparison of NEMA and Model 170 Controllers

The NEMA and Model 170 concepts are quite different from one another. NEMA controller units are designed and manufactured in various physical packages, but all must conform functionally to NEMA Standards. Certain physical requirements for auxiliary and ancillary equipment must also be met to maintain compatibility between certain components. Model 170 controller units, on the other hand, are microprocessors conforming to the Model 170 equipment specification, which describes the physical performance and mechanical requirements of the unit. The user must provide (or procure from other sources) a software program, and install it in the traffic PROM module of the unit.

For the sake of comparison, table 7-18 describes some aspects of the Model 170 and NEMA controller units.

Potential users should realize that each approach has its own variation in:

- Range of applicability,
- Procurement ramifications,
- Staffing requirements for maintenance,
- Spare equipment requirements, and
- Overall costs.

These must be studied prior to use in a particular location or by a specific entity. Prospective users should give careful consideration to both concepts, and should recognize that standardization, however conceived or applied, aims to achieve safe, effective, and energy-efficient traffic control.

7.9 Local Controller Coordination

Function

The coordination of local controllers in a signal system can be accomplished by using one of the following basic concepts:

- Supervision of the local units by a master controller or central computer. Interconnection of the master and locals is required, either by physical means or by the use of radio or other air-path communication media.
- Supervision of each local controller by an internal device, which has the capability of retaining a very accurate time relationship with like devices that are supervising other local units in the system.

Some systems use a combination of these concepts, wherein the master controller or computer provides periodic updates of timing plans and checks the time relationship with adjacent intersections by use of a non-continuous communication channel such as dial-up telephone lines. The local controller then maintains the proper time through its internal device.

Chapter 9 discusses the forms of permanent channel communication required by the first concept.

Time-Base Coordination

In this form of signal system coordination, a very accurate time-base device supervises each local controller. Cycle pulse reference or timing plan changes, and other commands which normally flow from a computer or master-driven coordination unit are produced by a unit located in the field controller cabinet, or by specific software in the controller unit.

Table 7-18. Comparison of NEMA and Model 170 controller units.

Basis for Comparison	NEMA TS2	Model 170
Design	Microprocessor-based and must functionally conform to NEMA standards of operation for traffic signal controller	Microprocessor-based, but functions are a result of the specific software program installed in PROM module
Standards/ Specifications	Non-hardware specific: • Defines functional, environmental, electrical interface and overall physical dimensions • Provides for standard operation and performance as traffic signal controller	Hardware-oriented: • Defines environmental, physical, self-diagnostics, and interface • Interchangeability of module in controller • User and/or vendor are responsible for operation and software program used
Software	Tested and supplied by vendor	Vendor or user (or other source) may supply
Monitoring	Internal diagnostics and event reporting in addition to conflict monitoring	Conflict monitoring provided by hardware. Other features, if desired, may be programmed
Cabinet Layout	Manufacturer specific general layout defined	Fixed (by specification)

The time-base coordinator is equipped with a rechargeable battery capable of about 30-day usage. In case of local power failure, it retains memory and clock time, allowing resumption of correct operation when power is restored. In normal operation, these devices derive their clock accuracy from the 60 Hz alternating power line current. The internal device timing may be periodically checked and updated by the master controller. The time-base coordinator may be a separate piece of hardware or may be integral to the controller unit (as in the Model 170 and NEMA TS2 controller units). (See chapter 8 for a more detailed discussion.)

7.10 Factors in Controller Selection

Selection of the proper type of control can prove a difficult and time-consuming process. In 1981, the National Cooperative Highway Research Program (NCHRP) published Report 233, which contains information to aid the traffic engineer in an evaluation of the various control alternatives (2). The *Manual on Traffic Signal Design* and the *Manual on Uniform Traffic Control Devices* also provide guidance in this regard (1, 4). These reports contain information needed to select the most appropriate type of signal equipment for an individual intersection in urban or rural areas. Emphasis is placed on traffic control at isolated intersections. Adjacent intersections are considered in identifying the need for coordinated operation (1, 2, 4).

Controller selection ultimately depends on computed benefits and costs. These in turn depend on:

- Roadway characteristics,
- Traffic characteristics, and
- Control requirements.

The final selection of control type should be made by comparing costs and benefits of alternative control techniques (1, 2, 4).

Benefits should be in the areas of:

- Safety,
- Traffic flow,
- Fuel consumption, and
- Vehicle emissions.

Traffic flow variables include stops and delays at the intersection.

Cost consideration elements should include:

- Design,
- Installation,
- Operation,
- Maintenance of the basic controller equipment,
- Equipment,
- Labor, and
- Detectors in the case of actuated equipment.

Do not include signal displays, cabinets, and other equipment common to all forms of control in the cost comparison (1, 2).

Operating Requirements and Constraints

Control options are determined by the specific needs at the intersection, with modifications to reflect policy considerations. To define intersection operation requirements, analyze:

- Existing geometry,
- Approach demand,
- Turning movements,
- Accident profiles,
- Approach speed,
- Delays,
- Expected future conditions,
- Constraints, and
- Other factors.

An analysis of intersection traffic flow characteristics and requirements yields information on:

- Appropriate type of control,
- Proper phasing, and
- Appropriate cycle length(s) and associated interval timings.

This information is best obtained from traffic counts, including turning movements. Various phasing options will likely become apparent, especially if left-turn phasing is required. All options should be thoroughly investigated and analyzed for their effect on intersection capacity and accident potential (1, 2, 4).

Chapter 3 discusses computer models available to the traffic engineer for developing signal control plans at isolated intersections.

Using these models can enable the engineer to determine the optimal signal timing and phasing and obtain several measures of effectiveness (MOEs), including:

- Delay,
- Stops,
- Fuel consumption,
- V/C ratio, and
- Left-turn conflicts.

Anticipated Effects and Costs

To assess benefits and costs, identify the anticipated effects from the implementation of each candidate signalization plan. Although economic benefits usually prove high, perform a conservative analysis for feasibility assessment.

The second element of benefit/cost analysis compares benefits with costs. Estimates should include costs for:

- Design,
- Procurement,
- Maintenance, and
- Operation.

Controller reliability, versatility, and innovative features have increased in recent years, with relatively little price impact. Generally, a small price gap exists between a *minimum* controller and one expandable to changing traffic patterns. In this case, opt for the more capable unit.

Maintainability and Reliability

Consider the capability of the agency's maintenance and operation staff when making controller selections. Training requirements associated with procuring any new equipment become critical. One approach to this problem is standardization to avoid continual retraining. Packaging several projects together can maximize hardware commonality, and lower procurement cost. Some agencies use the annual procurement process to minimize costs and inventory.

Reliability depends not only on design, but also on quality control during manufacture. Emphasize assurance of electronic component requirements, and use test procedures to guarantee quality control during fabrication. Controller selection should include consideration of the reliability of similar equipment previously furnished. Maintenance records should be provided for each controller. For users of the Model 170 controller system, the Self-Testing Evaluation Program is available for such procedures (15, 16, 17). Bid proposals for equipment might contain requirements for acceptance testing before units become approved for purchase.

Human Factors

Equipment under consideration should be engineered for simplicity and ease of human operation and maintenance; it should be *user friendly*. Perhaps human factors are best measured in terms of the experience, capabilities, and attitudes of traffic engineers, technicians, and other maintenance personnel. Their interface with the equipment under consideration virtually constitutes the human factor.

7.11 A Look to the Future

Advanced Transportation Controllers

Advanced technology has permitted the development of controllers with greater enhanced memory, speed and input/output capability. These controllers are being developed by firms and operating traffic organizations. The California Department of Transportation initiated the development of the Advanced Transportation Controller (ATC), which has evolved into the Model 2070 Advanced Transportation Management System Controller (18, 19, 20). Table 7-19 describes key features of this controller. A number of manufacturers also provide advanced transportation controllers with features similar to the Model 2070s.

CALTRANS does not intend initially to replace the Model 170 controller with the Model 2070, but rather to accommodate more sophisticated control algorithms (as shown in table 7-20), and to permit several simultaneous operations.

The Model 2070 and similar controllers will also accommodate and interface with future ITS applications. The speed and capacity of the new technology will make these controllers flexible for many future applications, and may replace controllers in use today. In this regard, the Model 2070 controller represents an ITS product.

The capability of these devices for programming in high level languages such as C, using a real-time operating system such as OS 9, proves an important feature of ATCs. This feature simplifies the development and maintenance of software. It also makes more practical the development of software for special applications limited to a few sites.

Table 7-19. Key Features of Model 2070 controller.

- Uses Microware OS 9 real-time operating system. Programmable in high-level languages.
- Minimum of 4 MBytes of flash Electrically Erasable Programmable Read Only Memory (EEPROM) organized as 2M 16 bit words
- 1 MByte of Static Random Access Memory (SCRAM) organized as 500K 16 bit words
- Processor executes Motorola CPU 32 instruction set at a minimum clock rate of 16 MHZ
- CPU Module interface with VERSA Module Eurocard (VME) bus back plane
- Three spare VME bus expansion slots provided
- Three serial ports and modem compatible with Bell 202 protocol. More capability may be added in the future. Communications capability may also be obtained through expansion slots.

Table 7-20. Potential Model 2070 functions.

- Freeway/cross street interchange control including:
  - collecting, processing and transmitting detector data from freeway lanes and street approaches
  - controlling the diamond interchange and adjacent on ramps
  - controlling the variable lane use signs at diamond interchanges
- Application of ful-actuated OPAC or MOVA controllers discussed in Chapter 3
- Data processing for video processing detectors
- Traffic signal control plus vehicle emissions monitoring and processing
- Operation of changeable message signs and freeway lane control signals associated with these signs
- Combined use of weigh-in-motion (WIM) and automated vehicle identification (AVI) and automated vehicle classification (AVC) for trucks
- Support of field processing for in-vehicle ATIS applications

The function block concept may facilitate traffic applications software development by allowing (21):

- Selection of preprogrammed blocks from a standard library,
- Configuration of block parameters, and
- Connection of other blocks to the strategy.

Continuous Flow Intersections

Conventional at grade intersections with heavy turn movements experience significant traffic operational problems. Traditional solutions to these problems include:

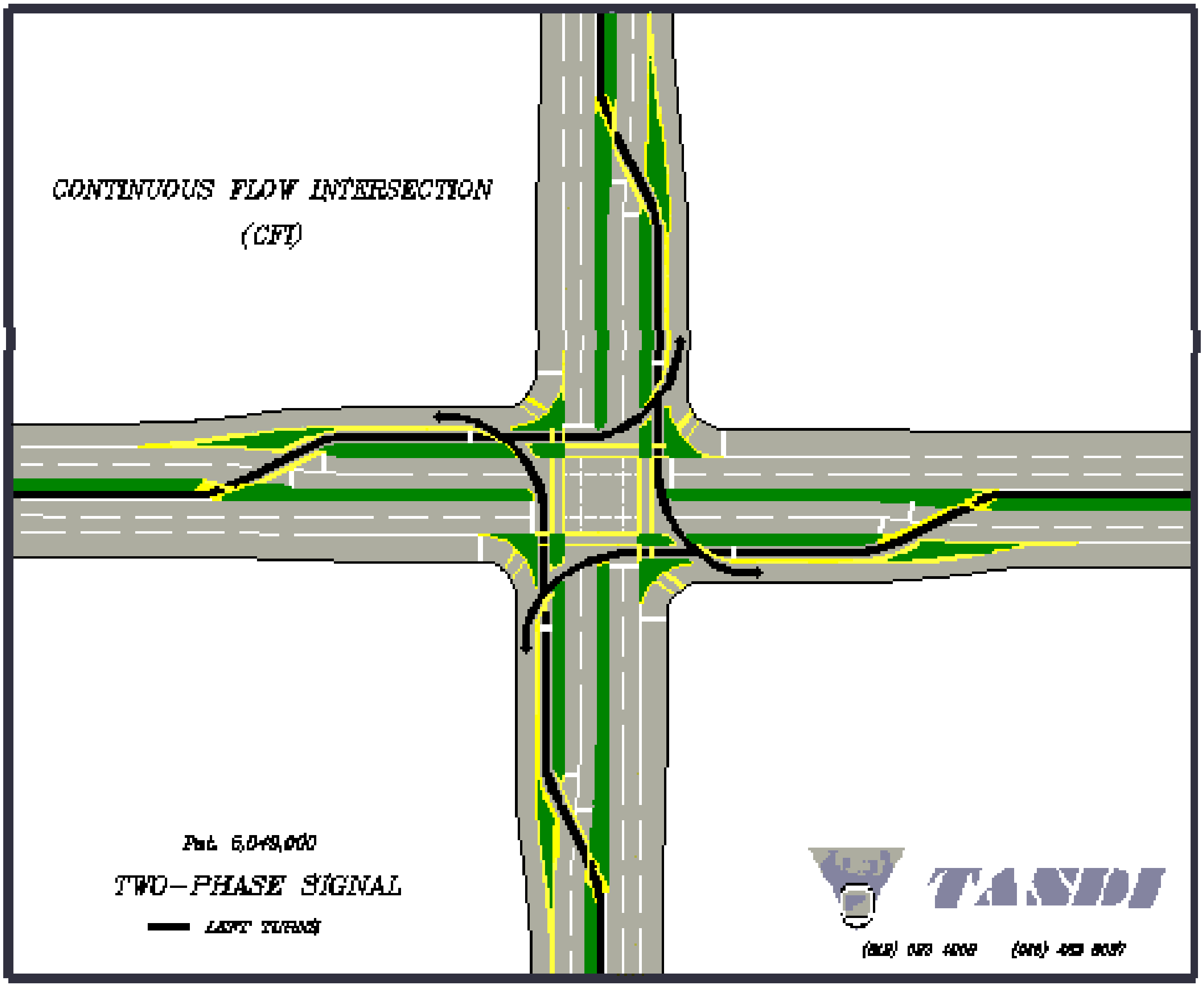
- Assigning protected signal phases to the turning movement,
- Widening the right-of-way, or
- Constructing grade separations.

Major disadvantages of these traditional solutions include the fact that:

- Protected turning signal phases require assigning a portion of the cycle length to turning movements, resulting in less time for through traffic, and
- Grade-separated structures are:
  - Expensive,
  - Disruptive to local traffic operations during construction,
  - Aesthetically unappealing, and
  - Liable to require additional right-of-way.

The *Continuous Flow Intersection (CFI)* can solve traffic operational problems caused by heavy turning movements at conventional intersections (22). The CFI is a patented design (23).

As shown in figure 7-14, CFIs are typically located at grade intersections widened to accommodate left-turning bays. These left-turn bays remove the conflict between left-turns and oncoming through traffic. Access to the left-turn bay is allowed from a mid-block signalized location. The left-turn traffic crosses the roadway into the left-turn bays during the signal phase serving the cross street traffic. This allows the left-turn traffic and the through traffic on the same leg of the intersection to be serviced during the same phase. The result is that only the phases servicing through traffic are required at the intersection to accommodate vehicle flow. Pedestrian



Source: Reference 22, 23

Figure 7-14. Continuous flow intersection.

crossing is allowed during the signal phase, when no vehicles move through the crosswalk. A recent study comparing the performance of traffic operations at a CFI with that of operations at a similar conventional intersection indicated a 60 percent increase in capacity at the CFI.

A recent simulation study comparing the performance of traffic operations at a conventional intersection design controlled by an actuated signal with that of a compatible CFI indicated (22):

- 50 percent increase in capacity,
- Substantial reduction in auto emission pollutants, and
- Significant increase in average speeds.

However, these results occur for intersections with heavy left-turn movements, which approach or exceed the capacity of conventional intersections.

Before considering the installation of a CFI, construction costs associated with additional right-of-way required and coordinated signal controllers should be addressed. Incident management and snow removal techniques must also be considered.

References - Chapter 7

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CHAPTER 8
SYSTEM CONTROL

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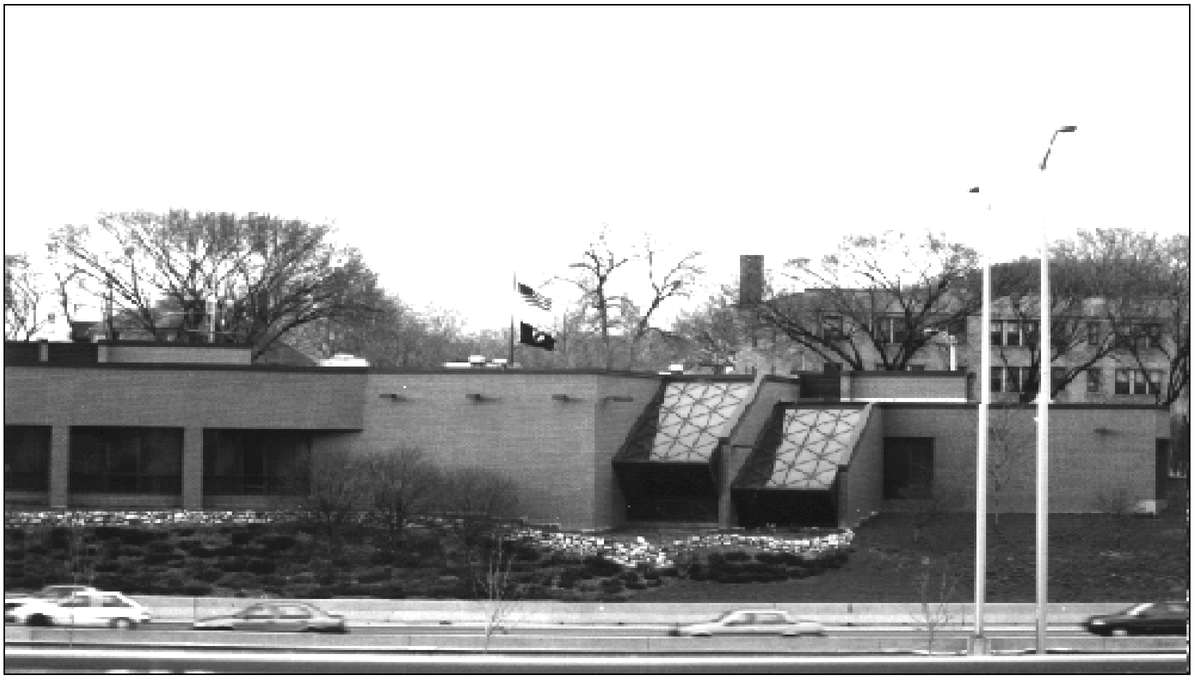


Photo courtesy of Illinois Department of Transportation

Figure 8-1. Traffic operations center.

8.1 Introduction

This chapter deals with concepts and hardware associated with coordinated control of traffic signal systems and control of freeway systems.

The 2 basic types of traffic signal systems are:

- An *arterial* (open network) system in which signals in a linear pattern are supervised to give progressive flow in 1 or both traveled directions.
- A *network* (closed grid pattern) system in which several arterials, forming an interlocking pattern, are supervised to give progressive flow in all traveled directions within the network to the extent practical.

Freeway systems perform a variety of functions including:

- Field data acquisition and processing,
- Command and monitoring of traffic control devices,
- Incident detection and management,
- Control room displays, and
- Information dissemination.

The design of traffic operations centers (TOCs) must address these system control functions.

Table 8-1 shows the organization of this chapter.

8.2 Arterial and Small Network Systems

Arterial and small network systems constitute a majority of United States traffic signal systems. These systems generally find application in smaller cities and counties, and control between 2 to 64 intersections. Agencies also install them in isolated or outlying areas of larger cities (e.g., suburban areas).

An arterial street signal system forms an open network and recognizes that a signal releases platoons which travel to the next signal (see section 3.8). Small network systems, even when closed, may often be treated as open networks.

Coordination of Systems

One central computer can integrate arterial systems in small cities by controlling each arterial as a subsystem. For example, a central computer can

Table 8-1. Chapter 8 organization.

Section Title	Purpose	Topics
Arterial and Small Network Systems	Discusses the application of arterial and small network systems	• Coordination of systems • Open- and closed-loop systems • Supervisory features of closed-loop systems • Traffic-responsive control capability • Commercially available closed-loop systems • Other arterial and small network systems - Advanced traffic management (ATM) system - DARTS
UTCS and Derivative Systems	Describes the functional characteristics and algorithms of UTCS	• Architecture • Earlier UTCS implementation • Later UTCS implementation • Comparison of UTCS systems • Features - typical features of UTCS derivative systems - features provided by certain UTCS derivative systems
Other Network Based Systems	Discusses the principles of SCOOT and SCAT	• SCOOT - benefits - detector requirements - proprietary rights - source code language • SCATS - benefits - detector requirements - proprietary rights - source code language • Integrated traffic management system • Other systems
Time-Base Coordination	Discusses the application of time-base coordination	• NEMA compatibility
Traffic Operations Center	Discusses the concepts of a central management center	• Concepts and functions • Facility requirements • Equipment requirements • Architectures for the operation and control of related traffic systems
A Look to the Future	Describes systems and techniques which will likely see increasing future use	• Traffic signal systems • Freeway corridor and areawide traffic surveillance and control systems

operate each arterial at a different cycle length either in a pretimed or a traffic-responsive mode.

When installed in isolated or outlying areas of larger cities or urbanized regions, or in 2 adjacent cities, traffic signal systems should either be or be made part of a larger *integrated* system. An integrated system supervises coordination of all systems within a region.

Although coordination generally involves interconnection with a central computer, adjacent agencies may network by coordinating traffic operations centers of adjacent systems. For example, adjacent cities may use the same pretimed cycle lengths, except when an accident or other incident requires 1 system or subsystem to operate independently until the incident is resolved.

Open - and Closed -Loop Systems

Many traffic systems designed for arterial and small network applications have been termed *open- and closed-loop*. Both open- and closed-loop systems have applications depending on design requirements and traffic patterns.

Open -Loop Systems

An open-loop system supervises the intersection controller's functions, but does not receive feedback status information. However, open-loop masters may receive information from system detectors for timing plan selection. An open-loop system can include:

- A master controller that controls the cycle length, offset, and split of each traffic signal, or
- A mutually coordinated system of intersections that does not require a master controller.

Closed -Loop Systems

Figure 8-2 shows a block diagram for a typical closed-loop system.

The closed-loop system provides 2-way communication between the intersection signal controller and its master. Most closed-loop systems have a computer (usually PC based) at the control center that communicates with the master controller. This computer enables the system operator or traffic engineer to monitor the system and control its operation (select timing plans, etc.).

The master controller may be located at:

- An intersection, or
- A central location such as a traffic operations center.

In addition to providing traffic control, the master controller receives traffic and/or internal diagnostic information from the intersection controller. The traffic information may relate to:

- Speed,
- Density,
- Volume, and
- Lane occupancy.

The intersection controller receives this information from system detectors and transmits it to the master controller at intervals of 1 second to 1 minute, depending on the type of system. The intersection controller also advises when it is:

- In step with the system (through 1 or more green confirm messages per cycle), and
- In flashing operation due to a malfunction, voltage surge, or intentional changeover from stop and go operation.

In addition, the Type 1 intersection controller manufactured under the NEMA TS2 standard can internally diagnose the outage of signal indications (light bulbs) and detector operation. An external device, available for use with other NEMA and 170 type controllers, monitors signal indications and transmits a signal when a light bulb is out. The closed-loop system master controller can determine proper system detector function by checking detector information with:

- Historical traffic information in its database, or
- A preset algorithm which notes continuous or no detector response over a given time period.
- These diagnostics ensure proper system operation.

The closed-loop *distributed processing* control system concept uses 1 or more on-street, intelligent microcomputer master controller units, each of which is able to:

- Select signal timing plans, and
- Implement plans by supervision of local controllers in its subsystem.

Local controllers may be either pretimed or actuated. Each master can function:

- On a standalone basis, and
- Operate according to a time-of-day or traffic-responsive plan, based on data gathered from the subsystem sensors.

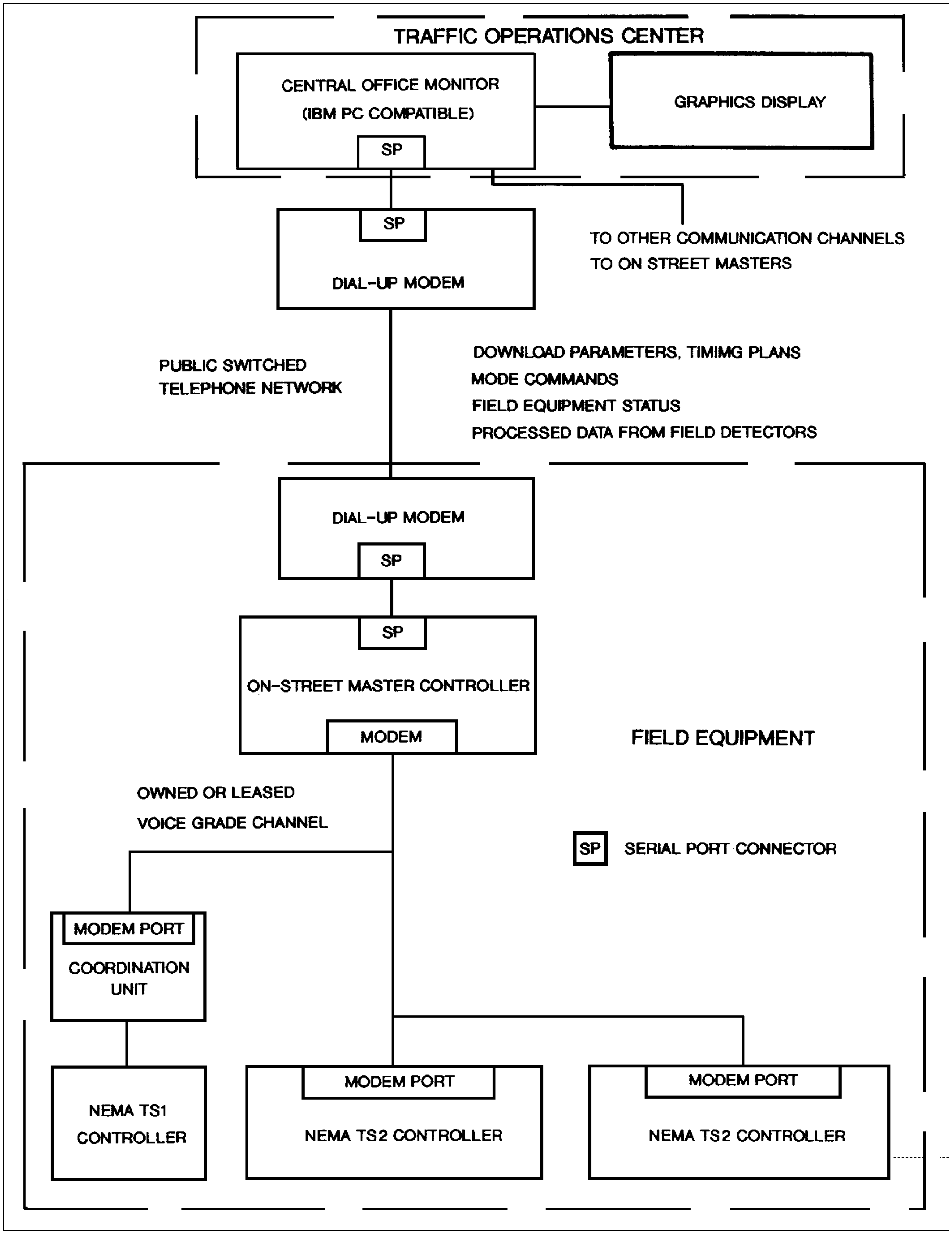


Figure 8-2. Typical closed-loop system.

With many closed-loop systems, the operator can override either the time-of-day or traffic-responsive plan and select another timing plan.

Intersection controllers (or their coordination units) maintain several traffic control plans, which the master controller can select. In solid state systems, the master controller downloads traffic control plans to the intersection controller.

In addition to traffic plan commands, the master controller sends time synchronization signals to the intersection controllers.

The NEMA TS2, certain NEMA TS1, 170, and 179 controllers can store traffic control plans and house communications modems internally within the controller unit. At this writing, the master controller downloads traffic control plans to the intersection controllers. The various systems do not have a standard communications *protocol* (which orders the information transmission sequence). Each system manufacturer and software development firm (software house) uses its own protocol, which for NEMA based systems requires that all controllers be of 1 manufacture. However, adoption of a common protocol, the National Traffic Control/ITS Communications Protocol (NTCIP), is expected shortly and will permit a greater level of equipment interchangeability than is currently possible.

External coordination units developed for NEMA controllers permit the purchase of traffic signal controllers from several NEMA manufacturers. Communications are maintained between the master controller and the coordination unit.

The coordination units command the local controller unit according to the master unit-selected timing plan in effect at any given time. These time-structured commands occur during:

Each cycle, to ensure a guaranteed green interval for the coordinated (non-actuated) phases, and

Selected time slots for the remaining (actuated) phases.

Table 8-2 shows the basic commands sent to the local controller during each (background) cycle.

Table 8-2. Coordination commands.

Name	Function
Force-Off	Issued to begin termination of an actuated phase. Each assigned force-off point is located precisely in the background cycle. It is sent to the controller only if: • Its respective phase is called and serviced, • Calls on the phase continue to (and beyond) the force-off point, or • Calls are present on any of the subsequent scheduled phases. The last (actuated) phase force-off occurs only if the above listed conditions are met. If calls on any of the actuated phases terminate before the scheduled occurrence of the force-off and demand is present on the next phase, the demanding phase will be served earlier than scheduled in the background cycle time frame.
Hold	Issued to guarantee a certain minimum of green time to a phase. Normally used in the coordinated phase to guarantee a window of time in the background cycle for traffic progression on the major street. Thus, the coordination phase is considered non-actuated because its duration is not reliant upon vehicle calls. A hold command can be applied to a phase other than the coordinated phase.
Yield	By de-energizing the Hold command, the resulting yield condition begins the termination of the active phase. The yield condition, no longer recognized by NEMA as a command, is usually associated with the coordinated phase, and in the absence of demand on other (actuated) phases, the controller remains in coordinated phase green. The yield (or permissive) condition may be programmed for a certain duration. If a call subsequently appears on any of the other (actuated) phases during the yield condition, the calling phase would, conditionally, be serviced. The condition for service is that sufficient time remains before the calling phase's scheduled force-off command occurs.

The commands in table 8-2 permit the external coordination unit to provide various phase sequences, such as lead-lag and left-turn phasing. They also permit variations (e.g., holding a minor movement which otherwise would have gapped out) in controller timing from plan to plan.

The intersection controller unit maintains control over the minimum vehicle, yellow change, red clearance, and pedestrian intervals.

Supervisory Features of Closed-Loop Systems

The on-street master controller coordinates field controller operation. The master controller receives signals from the field controller concerning:

- Failure status of field equipment,
- Phase status of the controller, and
- Data from system and local detectors.

While this data is available at the field master controller (and some manufacturers make provision for data extraction at that location), the preferred method communicates this data to the central office monitor. This communication is accomplished either by a continuous data channel (e.g., leased telephone circuit) or by intermittent communications, such as dial-up telephone service.

Although each manufacturer's system has somewhat different features, most manufacturers provide a common core of:

- Data management,
- Display, and
- Supervisory and control features at the supervisory monitor.

Table 8-3 shows this common core.

Traffic-Responsive Control Capability

Currently available *open- and closed-loop* system field master controllers can generally change intersection signal timing based on information from system detectors. The control algorithms most commonly used by these systems are:

- UTCS first generation signature matching algorithm, described in section 3.9.
- Selection of cycle, split, and offset by comparison of detector data to previously established thresholds. This approach is discussed in the description of the Arterial Control System (ACS) in section 3.9.

Table 8-3. Core functions available at closed-loop central office monitor.

- **Data Generation Features**
  - detector data logs
  - event logs (mode status, timing plans in effect, equipment failures)
- **Display Features**
  - text reports of detector data, equipment status and controller timing
  - intersection map displays with real-time phase changes and detector actuations
  - system map displays
- **Supervision and System Control Functions**
  - mode selection
  - timing plan selection for operator control mode
  - control of online, offline equipment, flash commands
  - upload and download of controller database
- **Data Management**
  - software tools to assist in development and management of database
  - comparison of uploaded data with system database files.

Commercially Available Closed-Loop Systems

A number of companies manufacture equipment or provide software for closed-loop systems. Tables 8-4 and 8-5 show the design characteristics of various systems using NEMA and 170 controllers. Table 8-4 shows characteristics that vary by system type, while table 8-5 shows features common to each system.

While the systems prove fundamentally similar, some differences remain. For example, each system provides a designated number of plans, but the methods of developing and applying these differ. For instance, the NEMA based systems shown as having only 1 subsystem in table 8-4 can be divided into subsystems on a time-of-day basis, each subsystem having its own cycle length, split, and offset plan.

Other Arterial and Small Network Systems

The following paragraphs illustrate systems either developed by State DOTs or commercially available.

Table 8-4. Commercial closed-loop systems forarterials and small grid networks.

System Characteristics	Automatic/ Eagle (4)	Econolite (5)	Naztec (3)	Peek/ Transyt (6)	Traffic Control Technologies (7)	BI Tran * (2)	Wapiti * (8)
NAME OF SYSTEM	MARC	Zone Monitor IV	900	Smart Ways	LM System	QuicNet 2	W70SM
SYSTEM CAPACITY							
• Local Traffic Signals/On-Street Master	32**	24**	32**	30**	60**	32**	48**
• No. of Sub-Systems (Zones, Groups, Control Areas per On-Street Master)	2	1***	1***	1***	4	3	1
• System Detectors per On-Street Master	64	32	30/subsystem	48	168	32	32
• No. of Traffic-Responsive:							
– coordination timing plans	16/Subsystem	64	64/Subsystem	124	48	9/Subsystem	18
– cycle length	16/Subsystem	6	16/Subsystem	6	8	****	****
– offsets	3/Subsystem	5	4/Subsystem	5	5*****	3/Subsystem	****
– splits	16/Subsystem	4	****	4	4	****	****
SYSTEM MEASURES OF EFFECTIVENESS							
• Utilization of Green Time	Yes	Yes	Yes	Yes	Yes	Yes	No
• Speed Traps	Yes	Yes	******	Yes	Yes	Yes	No
• Stops	Yes	No	No	No	No	Yes	No
• Delays	Yes	No	No	No	No	Yes	No
TYPE OF LOCAL CONTROLLER	NEMA	NEMA	NEMA	NEMA	NEMA	170	170

* Also provides software for other types of 170 systems

** Sufficient number of on-street masters can be provided with central IBM PC compatible central controller for 250 or more local controllers

*** More subsystems can be controlled during time-of-day and manual operations

**** Included in timing plan

***** 5 individual offsets available for each cycle in each controller

****** Uses 1 detector with estimated vehicle length to measure average speed

Table 8-5. Commercial closed-loop system for arterials and small grid systems.

Characteristics Provided by the Systems Listed in Table 8-4	
Type of system	Distributed – 2 level
Type of central control	IBM PC or IBM PC compatible
Has on-street master	Yes
Can download and upload	Yes
Back-up operator when communication lost with on-street master	Time-of-day through time-base coordinator
Plan selection:	
• Manually by operator	Yes
• Time-of-day	Yes
• Traffic-responsive	Yes
System diagnostics (operations and maintenance)	Yes
System map/graphics	VGA*
System surveillance pattern selection	
• Volume	Yes
• Occupancy	Yes

** Other systems can be provided if specified*
References: 4, 5, 6, 7, 8, 10, 11

Advanced Traffic Management (ATM) System

The ATM system is a microprocessor based traffic- responsive system developed by the Texas Department of Transportation (TxDOT) (see section 3.9). The ATM system represents a microcomputer version of the earlier minicomputer based Flexible Advanced Computer Traffic Signal (FACTS) system that has proven successful on continuous frontage roads and arterials with numerous traffic patterns during the day and week (1).

Table 8-6 shows ATM system features.

For traffic-responsive timing plan changes, the system uses a combination of the 2 most recent 3-minute sampling periods. The system can change cycle length and offset at the end of the 2 most recent sampling periods, and can alter splits each sampling period. TxDOT is developing a 1-1/2 GC version of the ATM system using PASSER IV for use in timing:

- Arterials,
- Frontage roads, and
- Grid networks.

This version will automatically develop traffic plans which can be:

- Compared with existing plans,
- Selected if desirable, and
- Downloaded to controllers for implementation.

The ATM system also has many interrogation and diagnostic features. Via dial-up telephone, maintenance personnel can obtain complete system operation status reports, and can issue some local operational commands. Status reports cover:

- System detector failures,
- Intersection detection failures,
- Intersection on- or offline,
- Local phase problems,
- Computer system status checks, and
- Local conflict flash conditions.

Commands used to correct local operation are:

- Reset conflict monitor (if in conflict flash), or
- Place phase on recall (if detector is malfunctioning).

TxDOT has replaced the FACTS system along NASA 1 in Houston with the ATM system. Once testing is completed, TxDOT plans to replace other existing FACTS installations with ATM systems.

DARTS System (4)

The open-loop Dynamic Artery Responsive Traffic Signal (DARTS) system consists of a series of NEMA-type, full-actuated traffic signals, each with an external logic modular coordination unit (see section 3.9). Although the system has been used for 2 crossing arterials, it normally applies to simple linear-type systems. DARTS was developed by the San Antonio district of TxDOT. Although commercially available from Naztec, Inc. as a packaged system, DARTS remains in the public domain (3).

The system permits each local controller to function in its normal isolated, full-actuated mode until an arterial platoon (queue) arrives at an intersection. The system then achieves platoon coordination on an intersection-to-intersection basis.

DARTS is designed for systems where:

Table 8-6. Features of the ATM system.

- ***Time-of-day/Day-of-week***
  Event schedules by which the operator may schedule TOD/DOW, traffic-responsive, or isolated system operation for designated time periods per respective day
- ***Manual override***
  Traffic plan or system mode, by intersection, if desired
- ***Responsive pattern selection***
  Cycle length, offset levels, and splits selectable independently from a mix of detectors and control parameters
- ***Detector failure monitoring***
  Based on historical volume and occupancy thresholds set by operator with default values triggering TOD plan selection when detectors fail
- ***Local controller failure monitoring***
  Based on response received by the computer from the local controllers (green-confirm per phase)
- ***Subsystem control***
  Locking of adjacent subsystems on same cycle length; reconfiguration, by intersection, operator-selectable
- ***Detector assignment***
  Operator-assigned detector(s) to selected subsystem for selection of traffic-responsive plans
- ***System status***
  Operator-controller output for current system mode, plan(s) in effect, and controller (detector failures)
- ***Variable phase sequence***
  Different plans can have different phase sequences, by intersection, i.e., both the arterial and the cross street may have:
  - LT first
  - directional lead/lag LT
  - through movements first
- ***Local control options***
  On an intersection basis, phase skipping and gap-out operator-selectable per timing plan
- ***Floating background cycle timers***
  Enables system to change plans smoothly and rapidly; transition from one plan to another sets background timer to the offset of the new plan, to the signal that first times out its cycle. Offset implementation begins as other signals reach the end of their respective cycles. A design feature permits coordination with adjacent systems.
- ***Variable plan transition***
  In addition to short way transition, the user has the option to program the break at other than 50 to 51 percent; normally, 30 to 70 percent is used, so that cycle-length decreases or increases can be handled efficiently. The user also has the option to transition some plans more rapidly than others (e.g., a plan designed to handle a sudden surge can be programmed to transition in a single cycle while others can transition more slowly with less traffic disruption) (9).
- ***Controller unit on flash***
  Can either be placed back into system operation or into free operation, by command from the central control point

- High directional traffic volumes occur along a major street,
- Intersections are separated by moderate to long distances,
- Turning movements, pedestrian calls, and cross-street volumes are low, or
- Ratio of cross street to arterial traffic is low.

Each local controller in the system can be a 2-, 3-, 5-, or 8-phase unit (9).

Table 8-7 shows the procedure (see figure 8-3) by which DARTS achieves intersection-to-intersection coordination.

Platoons can be generated at any intersection in the system and progressed through it. However, for a platoon already en route, the start message is withheld until the 2 platoons compress into 1. This feature allows a static platoon, recognized at a downstream intersection, to move forward in proper relation to an oncoming carryover platoon (from an upstream intersection) so that both form a single platoon. This concept handles moderately sized platoons (9).

An example of DARTS can be found on State Highway 218 in University City, north of San Antonio, TX. SH 218 is a 5 lane arterial carrying 23,000 ADT. The DARTS system involves 12 multiphase, full-actuated signals located along a 3.4 mi (5.5 km) section of the roadway.
An evaluation of DARTS showed:

- An increase in average speed for peak and off-peak traffic from 29 to 34 mi/hr (46.7 to 54.7 km/hr), and
- A decrease in the number of stops from an average of 3.9 to 0.8 in each travel direction (10).

8.3 UTCS and Derivative Systems

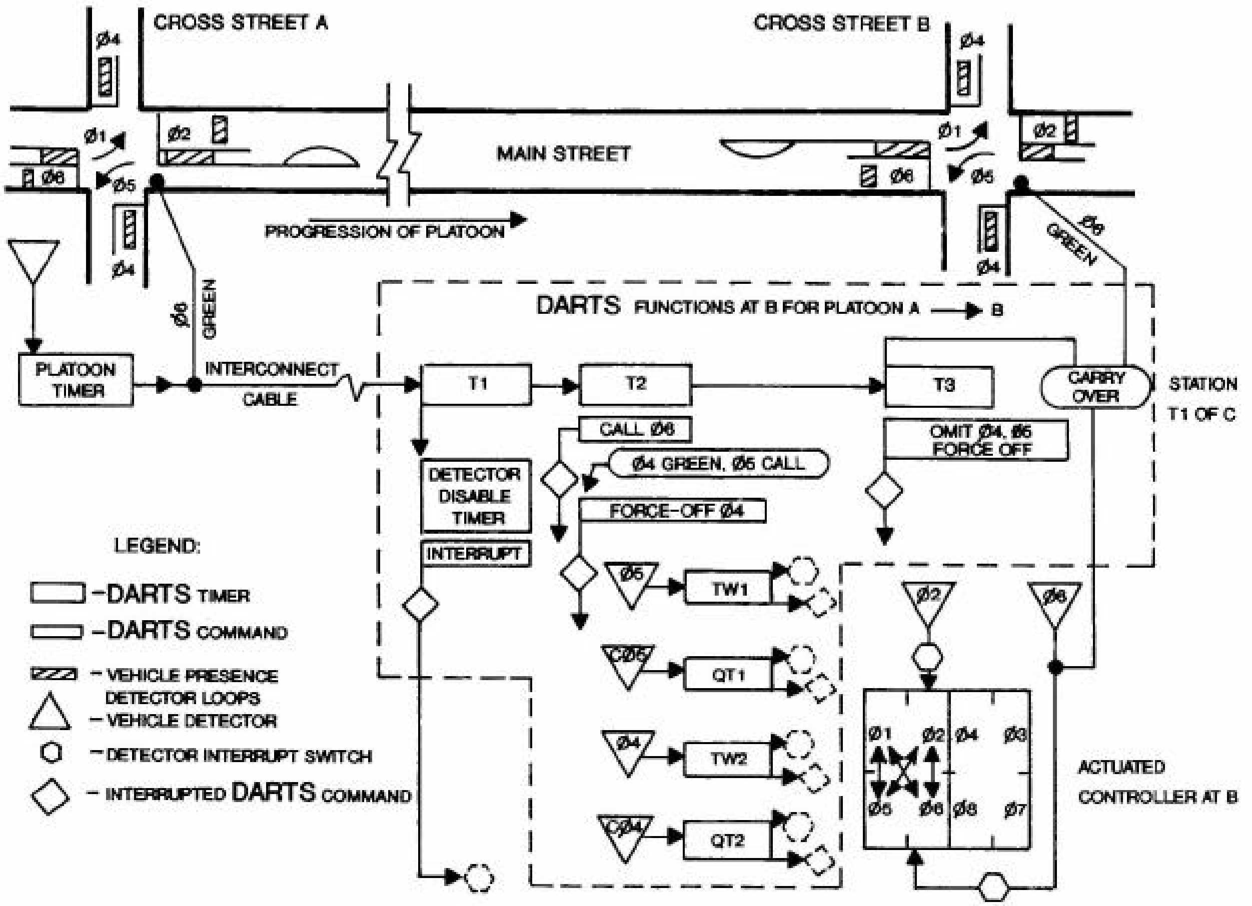
Architecture

Section 3.9 describes the functional characteristics and algorithms of the Urban Traffic Control System (UTCS) family. Implementation of systems which provide these functions started in the 1970s and continues today. However, advances in microprocessor and communications technology have considerably changed the physical implementation of these systems.

Figure 8-4 represents a system architecture that typifies an earlier UTCS, and figure 8-5 shows a later implementation (11). Table 8-8 compares key

Table 8-7. DARTS coordination procedure.

- Recognizes a static platoon during red at Cross Street A as a queue across a detector a specified distance upstream from the stopline (on Phase 6 approach)
- Relays via interconnect, a start message from Cross Street A to B at the precise beginning of Main Street green (at Street A)
- The start message, received at Cross Street B, begins the detector disable timer and T-1 timer (at B). The detector timer disables Phase 2 and 6 detectors, which terminates that phase and permits Cross Street B and Phase 5 left-turns (conflict with soon-to-arrive platoon) movements to occur. When the detector timer times out, Phase 2 and 6 demand is again recognized.
- Interval timer T-1 continues timing. Its total duration represents a portion of the time required for the platoon to travel between intersections at a preselected average speed. It times an interval which begins the clearance timing functions of T-2 at the proper time.
- Interval timer T-2 initiates as T-1 terminates. If Phase 6 is green, it will be maintained because insufficient time remains to serve conflicting phases and return to Phase 6 as the platoon arrives (at B). If Phase 4 is being served and demand appears on Phase 5, it will be served. T-2 assures service of certain phases in a time frame commensurate with the platoon progression.
- Interval timer T-3 begins as T-2 ends. If the controller is in Phase 5 or Phase 4, the coordination unit forces the respective phase to end as its minimum green times out. If Phase 4 is thus terminated, Phase 5 is omitted. The coordination unit also dispatches a start message to the next downstream controller that a *carryover* platoon has started at B, thus initiating timing on detector disable timer and T-1 at that intersection.
- The process repeats for subsequent intersection-to-intersection progression through the balance of the system



NOTES:

1. PHASES 2,4 AND 6 MAY USE PEDESTRIAN INTERVALS.
2. A SECOND SET OF TIMERS FOR T2 AND T3 PRODUCES CHANGES IN SPEED (SCHOOL ZONE).
3. TW IS A TIME-WAITING FUNCTION.
4. QT IS A QUEUE-TIMING FUNCTION.

Figure 8-3. Operational layout for dynamic responsive traffic signal (DARTS) system.

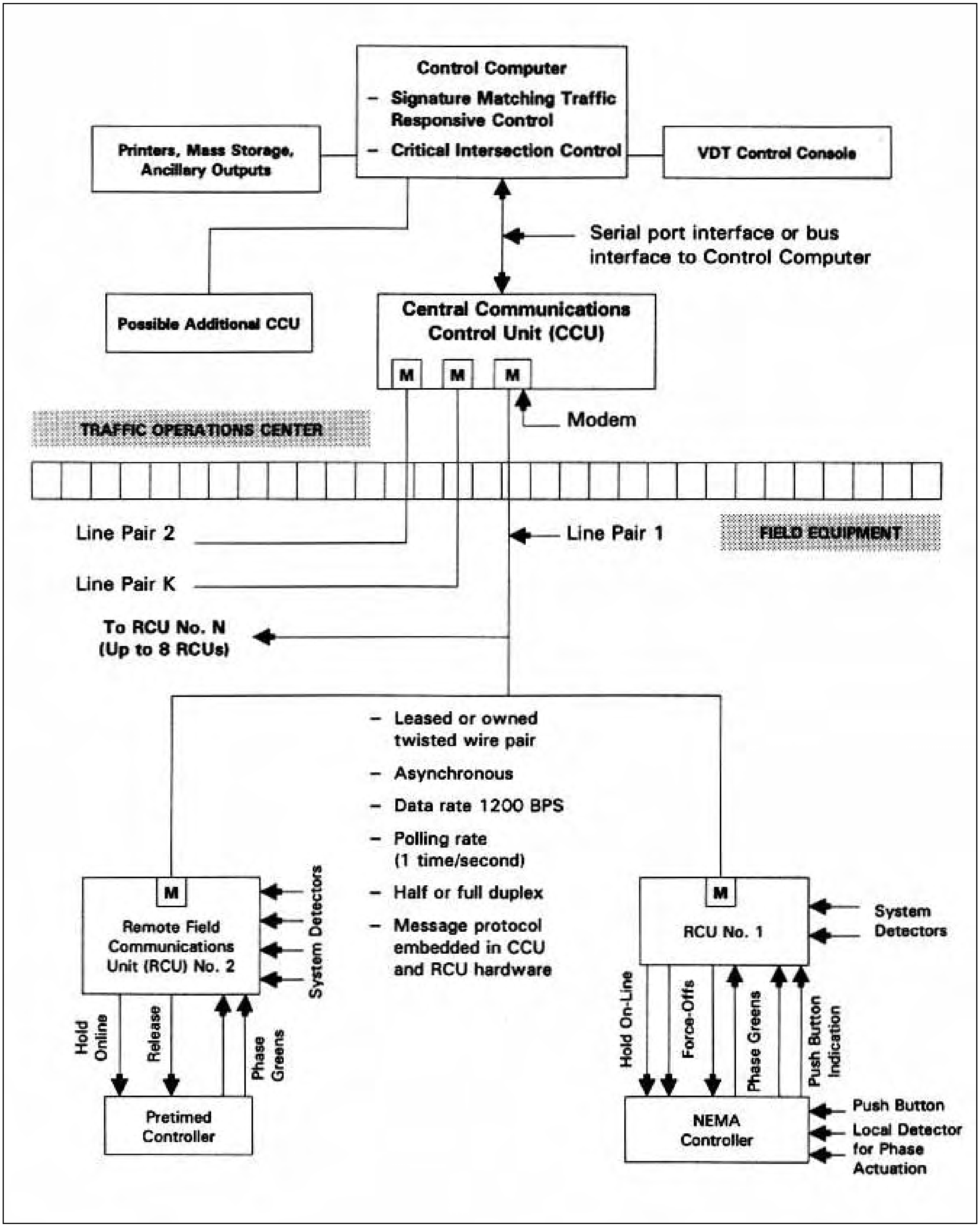


Figure 8-4. Example of earlier UTCS implementation.

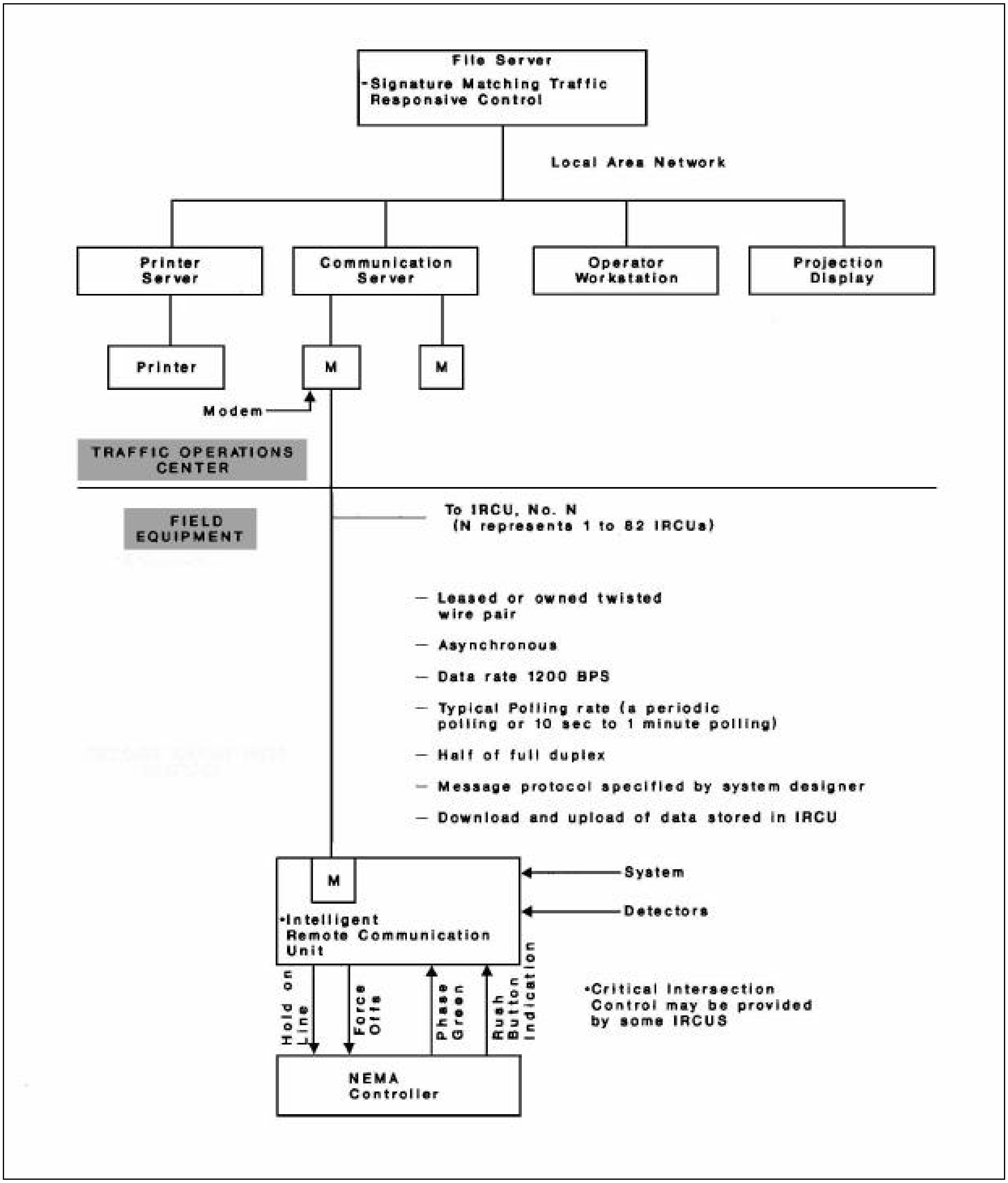


Figure 8-5. Example of later UTCS implementation.

Table 8-8. Comparison of earlier and later UTCS type systems.

Characteristic	Earlier UTCS Implementations	Later UTCS Implementations
Traffic Operations Center Computer	Minicomputer with real-time operating system	Microprocessor based computers with real-time operating system or other operating system. Computers organized into a series of *servers* (file server, communication server).
Traffic Operations Center Architecture	Terminals, printers, displays and central communications unit connected to computer by ports or connected to computer bus	Servers, work stations, displays communicate through a local area network
Storage of Signal Timing Plans	Traffic operations center computer	Field location (field controller or intelligent remote communications unit)
Time Intervals between Communications from Traffic Operations Center and Field Controller	0.5 seconds or 1 second	10 seconds to 1 minute. May be augmented by special communication service requirements. Sometimes short intervals are used to provide detector data for graphic display purposes.

Modern architectures usually feature *local area networks* (LAN) to interconnect the traffic operations center (TOC) components. In modern systems, a field controller or an intelligent remote communications unit (IRCU) usually stores timing plans. To change a plan, the field unit either selects a stored timing plan, or receives the new plan downloaded from the TOC. Usually the central computer also stores timing plans for error checking purposes. In earlier systems, the TOC computer directly controlled each alterable phase or signal control interval, thus requiring a more rapid polling cycle.

The current family of UTCS has been termed UTCS Derivative Systems and includes:

- Computran Modern Traffic Control System (MTCS),
- PB-Farradyne Management Information System for Traffic (MIST),
- F.R. Harris Traffic Management System,
- JHK Series 2000, and
- Sonex Escort.

Features

Table 8-9 describes typical features of UTCS derivative systems.

Table 8-10 describes features of some but not all systems. Table 8-11 describes differences among system features.

Figure 8-6 shows a modern UTCS Derivative System for the City of White Plains, NY (12). The system is controlled by a microprocessor based computer with a real-time operating system. Components in the traffic operations center are interconnected by a LAN. This system supports controllers and remote communication units that were in place prior to its installation, as well as new field equipment.

Figure 8-7 shows the TOC equipment for another manufacturer's system, along with connections to terminals located outside the TOC (13). Many of the TOC components are LAN connected.

System suppliers often provide features not included in their baseline software, but required by an operating agency. The baseline software then is adapted to incorporate this feature.

Table 8-9. Typical features of UTCS derivative systems.

• UTCS Traffic-Responsive Algorithms	• Multi-User, Multi-Terminal
• Automatic Power Failure Recovery	• Security Password Access
• Extensive Report Capability	• On-Line, Interactive Database Management System
• User Customized Reports	• Watchdog Circuitry
• Manipulation of Detector MOE Data by Spreadsheet	• Support of Counting Stations and Speed Traps
• Operational and Failure Logs and Statistics	• Static and Dynamic (Real-Time) Graphics Displays
• Support of Remote Users	• Dissemination of Information to Public
• Support of Alarm-Based Autodialers	• Incorporation of Off-The-Shelf Software Packages
• Importation of CAD Files into Graphics	• Communications Error Checking
• Event Scheduler	• Uploading and Downloading of Controller Timings
• System Sizing for Considerable Field Equipment Expansion	• System Comparison of Central and Field Databases
• Route Preemption	• Special Function Support
• Equipment Failure Monitoring	• Support for Backup Controller Timing
• Intersection Coordination Across Sections	• Support of Electronic Wall or Video Projection Maps
• Failure Log Analysis Software	• Support of Alternate Controller Sequences
• Support of MUTCD Flash	• Support of Controller Phase Omits
• Field Controller Power Outage Recovery	
• Support of Local Preemption	
• Unattended System Operation	

8.4 Other Network Based Systems

Recent years have seen a number of SCOOT and SCATS systems installed in North America. Section 3.9 describes the principles of these systems. This section provides additional information on these systems.

SCOOT (14)

The central computer performs all detector data processing and signal timing computations, and provides signal timing information to the local controller at each phase change.

Benefits

Major trials in 5 cities have assessed the effectiveness of the SCOOT strategy. Table 8-12 summarizes results from these trials (15). Kelman, et al. describe significant improvements in stops and delays in 3 areas in Toronto using SCOOT (16).

Detector Requirements

The detectors used by SCOOT are inductive loops installed at the upstream end of each network link, typically about 49.2 ft (15 m) past the intersection. These may span a maximum of 2 lanes per detector, and generally measure 2 meters in the travel direction. Where there are a significant number of traffic sinks and sources along a link, or other physical anomalies, a detector further downstream may be required.

Table 8-10. Features provided by certain UTCS derivative systems.

- Support of Changeable Message Signs, Reversible Lane Use Control Signals, Incident Detection, Highway advisory Radio and other Advanced ITS Devices or Functions
- Additional Processed Detector MOE Data such as Stops, Delay or Queue
- Support of Signal Maintenance Records and Inventory Control
- Support of UTCS 1.5 Generation Timing Data Functions
- Traffic-Responsive Signature Generation

Table 8-11. Differences in UTCS derivative system features.

Feature	Difference
Critical Intersection Control (CIC)	Implemented in the original Washington, DC UTCS and in earlier UTCS (see section 3.9), CIC requires a signal timing change each traffic cycle. The one second polling periods typical of the early UTCS easily satisfied this requirement but TOC computers in the newer, long polling interval systems cannot. Some of the newer systems provide the CIC algorithm in the IRCU or field controller software.
Commercial Off-The-Shelf (COTS) Central Software	Some system developers use COTS software packages to a great extent for database management, graphics, spreadsheets and other uses. Other system developers have created their own programs for these purposes.
Software Programming Language	The trend is away from the FORTRAN used in the earlier traditional UTCS and toward languages such as C + + and PASCAL
Central and Field Processing Algorithms	Some of the UTCS based algorithms may differ slightly from system to system to accommodate recent enhancements or user defined features
Controller Brand Support	Due to the absence of a standard communication protocol, many systems implemented to date have been developed or installed for a particular controller by: • Developing the system around a controller manufacturer's existing protocol, or • Incorporating the system developer's protocol into the controller The anticipated adoption of the National Traffic Control/ITS Communications Protocol (NTCIP) should remove these restrictions in the future.
Degree of Local Intersection Controller Processing	Manufacturers supply intersection controllers with many local features once handled at the TOC. System developers take advantage of these features by reducing central requirements. Local controllers can: • Log events • Store timing plans • Operate under time-base coordination • Pre-process detector data Intelligent RCUs with these features allow systems to use: • Less sophisticated controllers • Controllers from various manufacturers
Integration of Traffic Control Systems with Freeway Control Systems and Other ITS Applications	Some systems support interfaces for CMS, CCTV, HAR, AVI, lane control signals and other devices
Support of Signal Maintenance Records and Inventory Control	Some systems provide database management for traffic control equipment
Implementation of UTCS 1.5 Generation Signal Timing Data	Some UTCS providers have incorporated UTCS 1.5 Generation automated signal timing plan development (section 3.9) into their systems

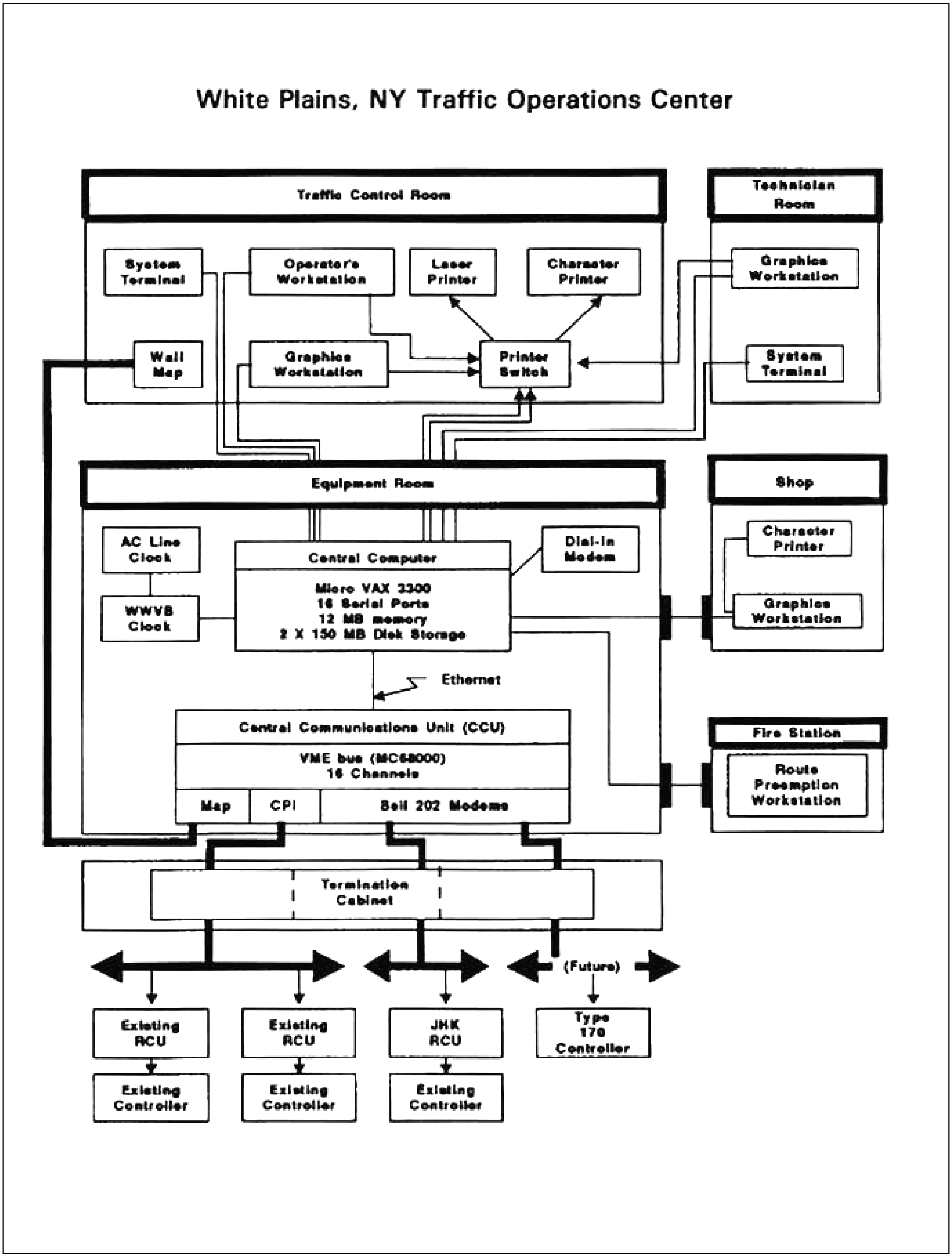


Figure 8-6. JHK System 2000 installation in White Plains, NY.

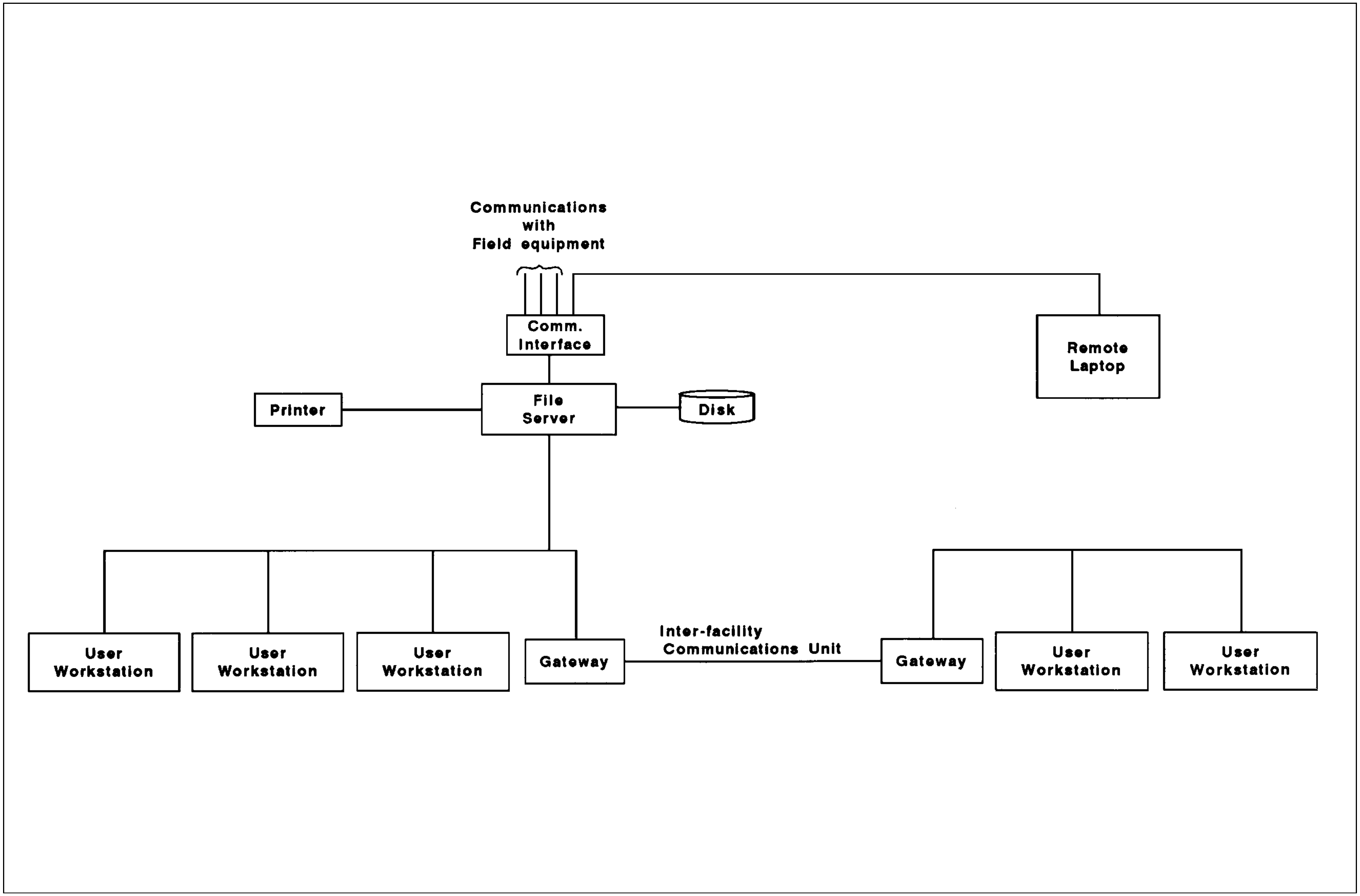


Figure 8-7. Local area network configuration of PB-Farradyne Systems, Inc. MIST system.

Table 8-12. Reduction in delay using SCOOT.

Location	Previous Control	A.M. Peak	Off-Peak	P.M. Peak
Glasgow	Fixed-time	- 2	14*	10*
Coventry-Foleshill Road	N/A	23	33*	22*
Coventry-Spon End	N/A	8	0	4
Worcester	Fixed-time	11	7*	20*
Worcester	Isolated V-A	32*	15*	23*
Southampton	Isolated V-A	39*	1	48*
London	Fixed-time	(Average 8% less travel time)		

*** Results significant at the 95% confidence level***

Proprietary Rights

Proprietary rights to SCOOT are held by the Government of the United Kingdom and 3 UK traffic system companies: GEC Traffic Automation Ltd., Peek Traffic Ltd., and Siemens Plessey Controls Ltd.

Source Code Language

SCOOT developers used CORAL, the most suitable programming language for real-time applications at the time. A version of the SCOOT kernel in C is available.

SCATS (14)

Benefits

A survey in Paramatta in 1981 by the Australian Road Research Board showed no significant reduction in travel times compared with TRANSYT; however, there proved to be a large reduction in the number of stops — 9% in the central area and 25% on arterial roads. Other studies have indicated improvements in travel times, but only in relation to original systems with unknown efficiency.

Detector Requirements

SCATS uses inductive loop detectors, or those that can simulate a loop detector's output. Detectors are located at, or near, the stopline. Traffic engineers identify *strategic* links and install *strategic* detectors, normally 14.8 feet (4.5 meters) long, in all lanes. Occasionally, additional strategic detectors are installed upstream to detect queuing. At the local control level, *tactical* detectors (normally of the same type as strategic detectors) may be located upstream of the stopline.

SCATS requires strategic detectors on all links approaching major intersections and on any links immediately upstream of a major intersection. In general, tactical detectors identify turning movements on minor approaches.

Proprietary Rights

Proprietary rights are held by the Roads and Traffic Authority (RTA), New South Wales, Australia. All users in Australia and New Zealand have access to SCATS, and the Australian signal companies, Philips Traffic Systems and AWA Ltd., have an arrangement with RTA to market SCATS in other countries.

Source Code Language

The SCATS Regional Control computer uses DEC PDP-11 Macro Assembler.

Integrated Traffic Management System

Intersection Development Corporation provides this system (17). It consists of a Master Control Assembly located at the control center, and field controllers. Timing plans are stored at the field site, either in compatible Multisonics controllers or in a Model 170 controller (with a special memory module). A remote interface unit is required for NEMA controllers. The system provides for many of the supervisory, display, and reporting functions common to UTCS derivative systems. Traffic-responsive area control is performed by a control algorithm, which employs user defined functions of detector data to select the appropriate timing plan.

Other Systems

Europe and Japan have developed a number of systems in addition to those described previously. These include PRODYN, UTOPIA, and ACTS, among others. The following briefly describes the PRODYN system.

The French Centre d'Etudes et de Recherches de Toulouse (CERT) developed PRODYN (14, 18). It resembles OPAC (see table 3-17) in its ability to:

- Predict the arrival of vehicles at the stopline,
- Estimate queues, and
- Define no cycle length.

It estimates queues at each intersection for 16 successive time periods of 5 seconds duration each. It optimizes local intersection control over this time period, and the controller implements this optimized control for the next time period. The system transmits the predicted states to controllers immediately downstream to improve their predictions. Only a small network in Toulouse has been implemented to date.

8.5 Time -Base Coordination

Time-base coordination (TBC) permits system operation of pretimed and traffic actuated local controllers without communications links or master control units. TBC also applies to some closed-loop systems for normal traffic control. In these systems, traffic control plans downloaded from the central computer operate through time-base coordination at designated times.

Time-base coordination uses a Time-Base Coordinator function provided by NEMA TS2 and many late model NEMA TS1 controllers. Standalone time- base coordinators are available for early model NEMA TS1 and other controllers. Model 170 controllers achieve TBC through a combination of hardware and application program software.

Time-base coordinators from different NEMA manufacturers are compatible. A system can also mix, for example, NEMA units with Model 170 controllers to provide proper coordination. However, manufacturers do not orient their TBC units to the same zero base point. When units are mixed in a system, the user must ensure a common zero base point throughout.

8.6 Traffic Operations Centers

A *traffic operations center* (TOC), also referred to as a traffic control center or traffic management center, varies with the size of the city or urban area and with the specific functions it performs. For example, where traffic management includes a few closed-loop systems, a section of the traffic engineering offices may prove sufficient for the TOC. As system size grows and the responsibilities of the operating agency increase, the agency will require a larger center with sophisticated computer and communication facilities.

Concepts and Functions

Figure 8-8 shows the general flow of information and operations in a typical modern freeway traffic operations center. Centers may not feature all operations shown, and some may perform additional functions. The numbers in the following discussion reference the appropriate blocks in figure 8-8.

The TOC typically obtains detector traffic data (1), sometimes called *raw* data, from field processors at intervals of between 20 seconds and 1 minute. TOC processors aggregate this data (6) into periods of typically 15 minutes and store it for historical reports and studies. The processors also filter raw data (3) to minimize errors in the deterministic component (section 3.4). Processors input the filtered data to the ramp meter controls (7), graphic displays (8), text data displays (4), and data fusion elements (20).

Incident detection algorithms typically use raw data, (5) and may provide their own filtering processes. These algorithms, with video surveillance (10) and information received from outside the system, serve incident detection, confirmation, and classification functions (8).

- Incident response and monitoring functions (see section 4.5) consist of:
- Notification to the proper agencies responsible for emergency services,
- Provision of information to other agencies responsible for traffic management (13).

Implementation of traffic controls on the freeway and its ramps (12). In some cases, the system design allows the operator to select preplanned responses as a coordinated group that may, for example, consist of ramp meter rates (7), CMS messages (15), lane use signal displays, and variable speed limit sign messa-ges. In other cases, system design requires that the

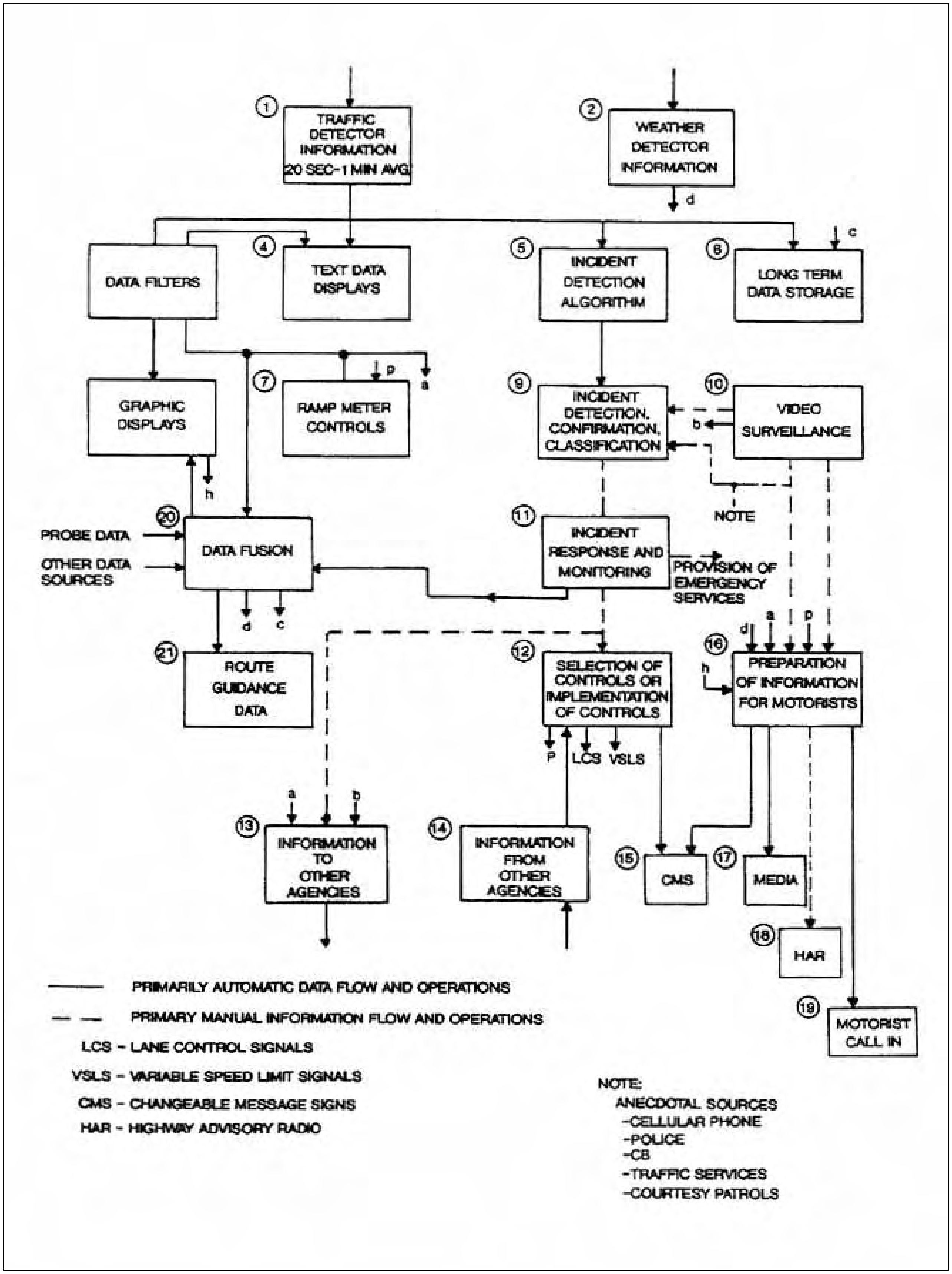


Figure 8-8. General flow of information in freeway operations centers.

operator implement each applicable control separately,

- Provision by the operator of incident information for other motorist information subsystems (16), such as highway advisory radio (18), motorist call-in services (19) and information prepared for delivery by radio and TV stations (17), and
- Termination of incident management plans and motorist information alerts at the appropriate times.

Under conditions of congestion unrelated to incidents, the operator will use traffic condition displays (8) with video surveillance (10) and anecdotal sources to prepare information for delivery to motorists (16).

Some operations centers use data fusion (20) technologies to combine traffic data that may originate from a number of different sources into a best estimate of such quantities as travel time or speed for a route guidance link. The center may supply this data to in-vehicle route guidance systems (21), motorist information systems (16), and the system graphics display (8).

Traffic operations centers may:

- Control and manage traffic signal systems, freeway monitoring and control systems, and corridor control systems,
- Participate in the incident management process,
- Provide motorist aid services,
- Provide traffic condition information to the media, motorists, and other operating agencies and traffic services,
- Provide in-vehicle route guidance information,
- Coordinate traffic controls and motorist information with other operating agencies,
- Coordinate and provide traveler information for all surface transportation modes, and
- Coordinate commercial vehicle ITS services.

Facility Requirements

A traffic operations center may contain some or all of the following facilities:

- Operations room — Serves as the focal point of the facility and can be subdivided to accommodate specific requirements of the agency. The number of workstations will depend on the functional requirements of the systems.
- Computer and communications room — Contains the computers and servers and communications interface equipment and modems. Also provides access for owned communications media and leased or dial-up services. May also be subdivided to accommodate specific operations required by the agency.
- Maintenance room — Required for the technicians maintaining system hardware. Provides storage for necessary tools and spare equipment.
- Conference room,
- Training room,
- Offices,
- Employee facilities,
- HAR taping room,
- Storage room — Stores records and office supplies for daily operations, and
- Reception area.

Equipment Requirements

Figure 8-9 shows a schematic representation of the computer, communication, and display equipment for a typical modern traffic operations center. The schematic shows two computers, one of which is online. The other serves as a back-up, and may perform such offline functions as program development and database updating.

In the system described, each computer features a real-time operating system and disk drive. A process sometimes known as *disk shadowing* transfers changes on the disk currently controlling the system to the standby system.

Major components of the operations center equipment connect through a *local area network* (LAN) capable of data transfer at a rate of 10 Mbps or faster. This LAN architecture facilitates the addition of components to the network. Use of the LAN concept makes modular design easily expandable to:

- Serve more devices in the operations center,
- Interface with additional field devices and controllers, and
- Communicate with additional outside agencies and traffic data users.

The computers shown in Figure 8-9 are often microprocessor based versions of minicomputers. In some cases, functions split among several processors that communicate with each other through the LAN. Alternatively, the processors may be based on IBM PC compatible architectures.

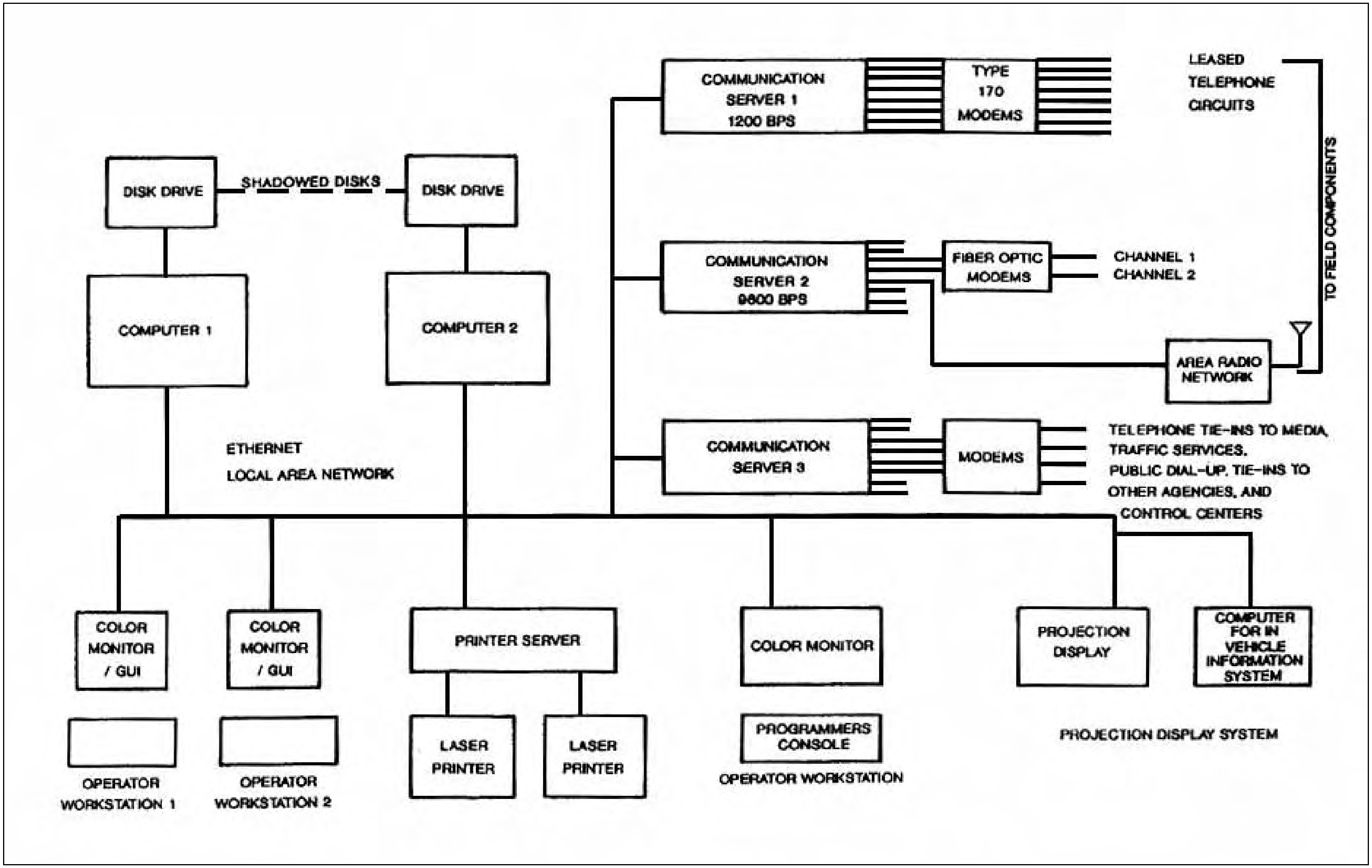


Figure 8-9. Operations center data driven equipment.

The TOC communicates with the field controllers via Communication Servers 1 and 2. These devices accept data from the computer through the LAN, and distribute it to appropriate communication channels. Communication Server 1, for example, divides the computer data into signals for 7 modems and 7 telephone communication channels. These channels typically might service traffic signal controllers, ramp meters, detector stations, and CMSs on freeways remote from the owned fiber optic cable serviced by Communications Server 2. Communication Server 2 also handles data for the area radio network, which may, for example, service CMSs located on surface streets near freeway entry ramps. Communication Server 3 interfaces with the modems that provide a variety of traffic information services to the public, and exchange information with other traffic operations centers and operating agencies.

The operator workstations typically take the form of personal computer based units that contain a LAN interface module. The laser printers shown in figure 8-9 connect to the LAN with a printer server, a device which provides the interface conversions necessary to work with the LAN.

Printers commonly provide:

- Hard copy reports of mode status and equipment failure logs,
- Traffic data summaries,
- Database status summaries,
- Special reports requested by the operator, and
- Logs of system operations.

Graphics typically appear on the operator workstations or on a large screen graphics display. The latter generally has replaced the wall map display found in older operations centers. The display may consist of either a projection video display or a large video screen, or an array of smaller video screens. When new traffic control systems come online, or when the agency adds traffic signals to an existing system, this type of display proves much easier to modify than a wall map. The large graphic display can also show the same information as a workstation, for ease of observation by a number of persons within the control room.

Although a graphics display functions as a public information tool, it also proves useful in:

- System installation,
- Testing,
- Troubleshooting, and
- Maintenance.

When properly designed, the graphics display tells the operator at a glance whether all controllers remain online or whether a group of controller failures appears geographically concentrated, indicating a communications failure.

The video display terminal at a workstation provides the same information shown on the large screen graphics display. The operator can view each traffic control system, subsystem, and intersection. The terminal can show the operation of the traffic signal and detectors at the system, subsystem, and intersection levels. The terminal can also display the approximate geographic layout of the intersection and the traffic signal detector locations and signal phasing.

Intersection oriented graphics displays often depict:

- System status,
- Signal timing in effect,
- System detector data,
- Current phase status,
- Local detector calls, and
- Traffic parameters such as:
  - Volume,
  - Occupancy,
  - Speed,
  - Stops, and
  - Delay.

Displays for freeway operations can show detector information, ramp meter control, changeable message sign operations, and lane control signals. The displays often show speed, occupancy, and level of service in color on a map format.

Freeway TOCs often use CCTV for the following purposes:

- Monitoring of traffic conditions, and
- Detection and confirmation of incidents, and assistance in incident management.

CCTV finds increasing use in traffic signal systems for monitoring of traffic conditions and incident detection and management.

In some systems, operators can use CCTV instead of software algorithms to adjust ramp metering rates and to monitor ramp spillback conditions.

CRT graphics displays can monitor CCTV images as effectively as the graphics display previously mentioned. Through the use of windowing techniques, the workstation can combine the graphics display and CCTV picture, the latter generally located in a corner of the display. This permits the operator to see a live picture of a location concurrently with graphic information.

Within the operations room or in 1 or more adjacent rooms, the TOC may provide workstations for police agency and incident management/motorist aid patrol personnel. Alternatively, the TOC can provide information updates to these organizations, the news media, and other private organizations at their own facilities with additional hotlines to the police and incident management/motorist aid patrol personnel.

Architectures for the Operation and Control of Related Traffic Systems

In many urban areas, a number of agencies become involved in traffic management including freeway operations that involve the State DOT and cities adjacent to the central city, all of which may need integrated operations (see chapter 2). For example, the TOC can house personnel from each agency within an urban area who can use workstations located in the control room. Similarly, the TOC can house and manage all traffic data received from the urban area. In such a system design, the TOC can either:

- House the computer hardware for each agency, or
- House each agency's computer hardware in its own center, with primary traffic control carried out through the workstations at the TOC as shown in figure 8-10.

In the latter case, each agency's center would provide a secondary or back-up control capability.

An alternate design to that shown in figure 8-10 allows personnel from each agency to have workstations located at their own control center, with overall coordination carried out through the TOC. With a design like that pictured in figure 8-10, the TOC may also serve as the database manager.

8.7 A Look to the Future

Future developments may include the following:

Traffic Signal Systems

- Closed-loop systems will undergo continued development. Future field masters may use advanced transportation controllers (see section 7.11).
- Currently available highly traffic-responsive systems, such as SCOOT and SCATS, will see wider application.
- New traffic signal control systems will become available, based on the FHWA RT-TRACS research program (see section 3.13) and other concepts.

Freeway, Corridor, and Areawide Traffic Surveillance and Control Systems

- Advanced transportation controllers (see section 7.11) will see field use. Applications will include those shown in table 8-13.
- Greater use of areawide traffic operations centers (19, 20, 21). These may include operation of both freeway and surface street systems and may prove multi-jurisdictional (see section 8.6).
- Linking of traffic operations centers in major metropolitan areas in network or hierarchical topologies (19, 21).
- Development of areawide ATIS databases to provide seamless flow of traffic condition information among systems of different design and among TOCs.
- Modification of system designs to include the requirements of emerging ITS architectures (22).
- Increases in non-pavement invasive detectors to minimize detector costs related to pavement maintenance.
- Increase in the freeway surveillance system use of technologies such as non-pavement invasive detectors and wireless communications to facilitate surveillance during major reconstruction projects and minimize costs associated with these projects.

Table 8-13. Possible freeway and corridor control applications for advanced transportation controllers.

• **Field Controller Tasks** - remote detector data processing - emergency controls - communications • **Video Data Processing**	• **Special Applications** - traffic *hot-spot* control - freeway and surface street coordination • **Distributed Processing Architectures**

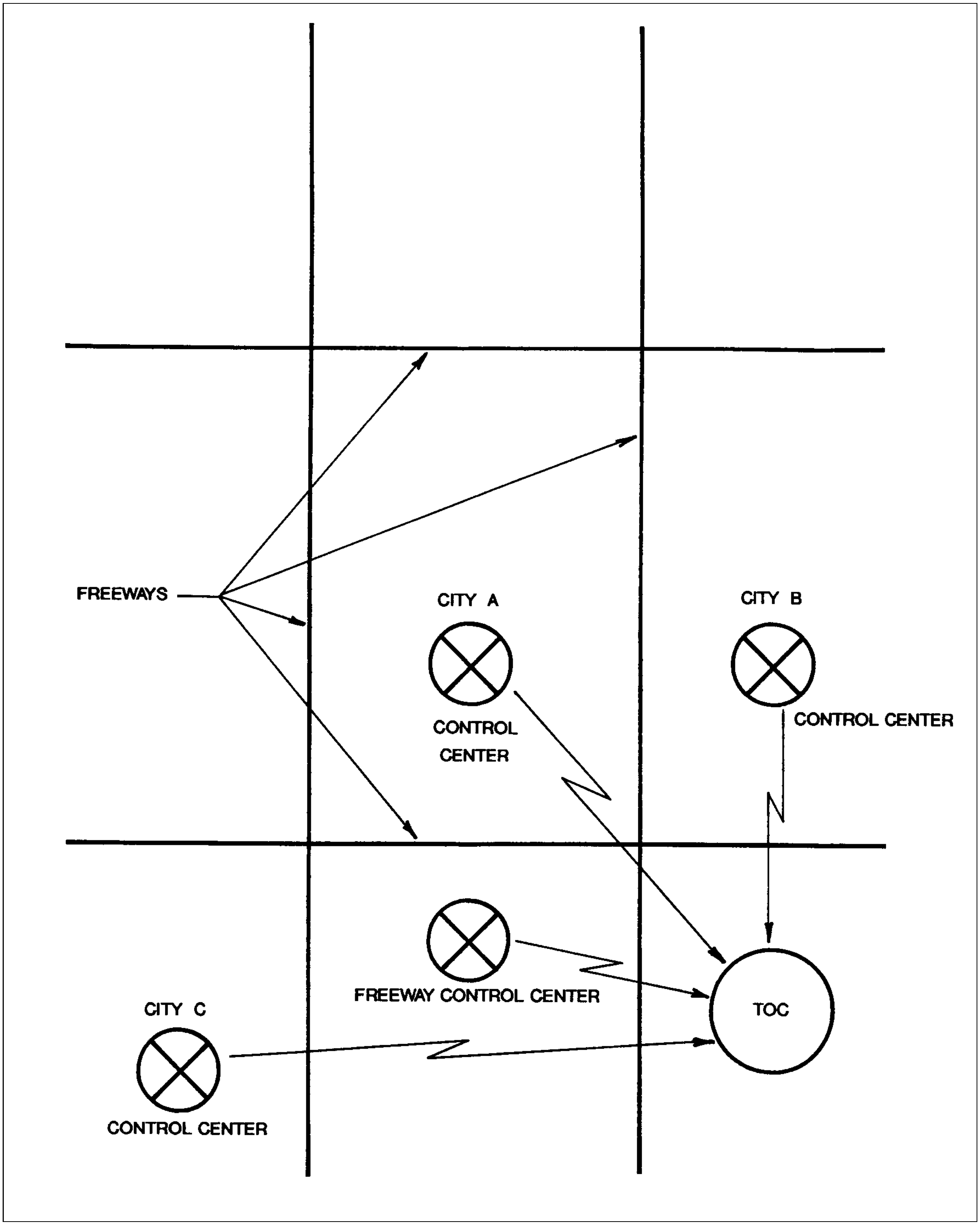


Figure 8-10. Central TOC control of all agency traffic systems within urban area with all computer hardware at agency center.

References - Chapter 8

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CHAPTER 9
COMMUNICATIONS

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CHAPTER 9
COMMUNICATIONS

Figure 9-1. Installing communications cable.

9.1 Introduction

This chapter overviews communications technology, emphasizing its impact on traffic control systems. The chapter describes:

- Basic communication concepts,
- Alternative communication media, and
- Technology.

It also presents an approach to communication system planning. The recently issued FHWA publication Communications Handbook for Traffic Control Systems discusses in more detail many topics in this chapter (1).

This chapter will provide the reader with sufficient knowledge to:

- Understand communications terminology, especially as it applies to traffic control systems,
- Understand concepts of communication system operation,
- Compare different communication media and their operating characteristics,
- Compare and evaluate communication systems specifications and proposals, and
- Understand recommendations or suggestions given by advisors, consultants, or suppliers.

To actually perform a communication system design requires expertise, experience, and information found in other handbooks and sources.

Table 9-1 shows the organization of this chapter.

Communications and Electronics Evolution

It became desirable to interconnect traffic control systems to establish and maintain a reliable timing relationship among intersections. Early small-scale systems used multi-conductor interconnect wire. One of the controllers served as a master control unit to assure synchronized operation of the local units.

Table 9-1. Chapter 9 organization.

Section Title	Purpose	Topics
Basic Concepts	Describes traffic control communications links	• Communication link and signaling techniques - cable - wireless - leased local telephone services - leased CATV cable channels - switched telecommunication services • Bandwidth • Attenuation - types of media • Power budget and dynamic range - characteristics - calculations • Noise and distortion - thermal - radio - human-made - media - error detection methods • Digital data - decimal to binary conversion - switch representation • Parallel versus serial transmission • Interconnection - point-to-point - multidrop • Modulation and demodulation - amplitude - frequency - phase • Data transmission and link control • Modes • Synchronous and asynchronous techniques • Multiplexing - frequency division - time division - code division • Computer and field equipment interface - modems - RCUs - IRCUs - controllers • Digital signal transmission standards - serial port - telecommunication - optical (SONET) • Communication requirements for CCTV - applications - components - full motion video - coded TV (Codec) - freeze frame video

Table 9-1. Chapter 9 organization (continued).

Section Title	Purpose	Topics
Alternative Communication Media and Technologies	Describes communication media and technologies	• Comparative properties of technologies • Twisted wire pairs - owned versus leased - installation considerations • Coaxial cable - cable TV providers • Fiber optics communication - dispersion and modes - attenuation - cable options - light sources and detectors - fiber optic equipment - video transmission - organization of fiber optic communication systems • Radio communication - radio design considerations - multipath fading - power fading - owned radio communication technologies - terrestrial microwave links - spread spectrum radio - commercial wireless network services
Communication System Planning	Describes a methodology for the selection of a communication technology	• Perform screening for institutional issues • Estimate data rate requirements • Perform cost dominant screening for leased services • Complete the technology screening process • Determine potential feasibility of a backbone or trunked system • Determine whether a change in media provides a reasonable candidate(s) • Define technology and multiplexing alternatives for the distribution system • Develop cost estimate for distribution system technology candidates • Determine remaining non-cost related issues • Select communications system based on cost and other factors
A Look to the Future	Describes techniques which will see increasing use in the future	• Public/private cooperative ventures • Availability of wider variety of telecommunication services • Increased use of wireless techniques • Increased use of digitally coded video • Increased use of cellular and digital cellular radio for short term applications

Communication electronics in the early systems used vacuum tube circuits. As electronics advanced, more complex functions were added.

Current technology makes extensive use of large scale integrated (LSI) circuitry and digital computer techniques. These electronic tools implement such modern system and communications techniques as:

- Multiplexing,
- Distributed data processing, and
- Information and data compression.
- For systems communication recent advances include:
- Extensive use of fiber optic techniques, and
- Increasing use of radio techniques.

In addition, interest grows in short range wireless techniques to communicate from a field device (e.g., CCTV camera) to a nearby site that transmits the information to the traffic operations center.

9.2 Basic Concepts

Communication transfers information from one location to another. Effective traffic control requires 2-way transfer of information among widely dispersed system elements. Some examples of traffic control communications links include:

- A distributed traffic control system requires communications between local signal controllers and a master controller, subsystem master unit, or a computer. The computer could be a central - mainframe or a PC depending on the size of the coordination area.
- A freeway monitoring and control system requires communications between field devices such as:
  - Vehicle detectors,
  - Ramp meters,
  - CMS,
  - HAR, and
  - Central computer.

- A traffic video monitoring system requires communications between multiple video cameras and a control center video switcher with a display monitor arrangement. In some instances the command data to the camera for pan, tilt, and zoom (PTZ) uses a communication link independent from the response video communication link.

Communication Link and Signaling Techniques

The path over which information travels is commonly referred to as a link or channel. A link is described by:

- Source to destination path that it interconnects, and
- Information capacity that it possesses.

The physical make-up or the medium of the link affects certain characteristics of the link, including distance capabilities and capacity for carrying information. Media used in traffic control systems include:

- Cable:
  - Twisted-pair,
  - Coaxial, and
  - Fiber optic.

- Wireless:
  - Radio networks at various frequencies,
  - Spread spectrum radio,
  - Point-to-point directional microwave radio, and
  - Air path optics.

- Leased local telephone services:
  - Voice grade lines, and
  - Digital communication services such as T1 lines.

- Leased CATV cable channels
- Switched telecommunication services:
  - Dial-up wireline service, and
  - Cellular telephone service.

Bandwidth

The information-carrying capacity of a link depends on:

- The time that the link is available. Thus, for a shared use type, the capacity available to each user represents a portion of the total channel information-carrying capacity.
- The bandwidth of the link (channel) describes the range in sinusoidal frequencies (referred to in Hertz or cycles per second) that can transmit through the link (channel) without significant attenuation (weakening) or distortion.

The sum of a set of sine waves can represent any signal. Figure 9-2 describes the characteristics of a

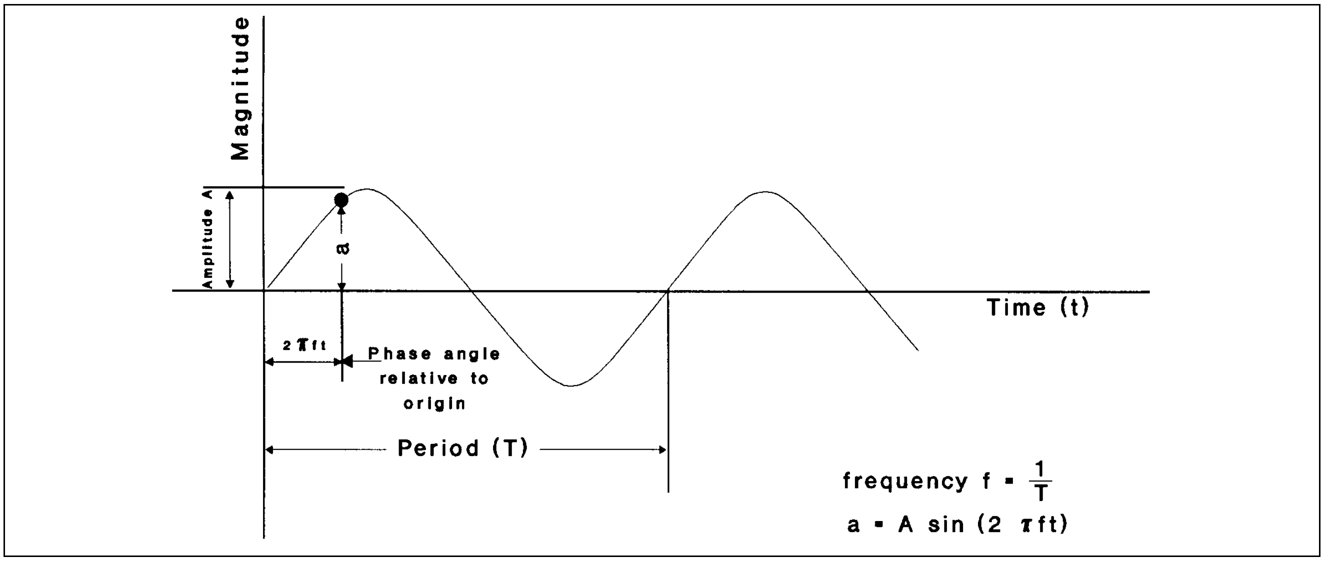


Figure 9-2. Sine wave.

sine wave (1). Generally, a wider channel bandwidth allows more information to pass along the link in a given period of time. A telephone channel can send signals from 300 to 3300 Hz and thus has a bandwidth of 3000 Hz or 3 kilohertz (3 KHz). The term Hertz (Hz) represents 1 cycle per second. A video camera requires a bandwidth of 4 megahertz (4 MHz). A megahertz is 1 million cycles per second. A leased telephone channel, originally designed to carry voice information only, does not have enough bandwidth to carry a full motion video signal. The term bandwidth does not define the frequency of the transmitting signal; it only indicates the range of frequencies which carry the information.

Attenuation

Attenuation represents the decrease in magnitude or power of a signal in transmission between points. The decibel (dB) normally expresses signal strength or power in communications. This logarithmic unit measures a ratio of signal strengths at these points.

If Ptr equals transmitter power and Pr receiver power, then the attenuation in dB is given by:

$$dB = 10 * \log_{10} \frac{(Pr)}{(Ptr)} \qquad (9.1)$$

If the output power at the receiver is 0.001 of the power at the transmitter, attenuation or loss is 30 dB.

The signal strength for wire and fiber optic transmission falls off at a rate proportional to signal strength as it passes down a cable resulting in a constant attenuation per mile or kilometer. In optical fibers, attenuation results from *absorption* and *scattering*. The optical power loss per unit length for optical fibers is expressed in decibels per kilometer (dB/km) at a specific wavelength.

Figure 9-3 shows the relationship between attenuation and frequency for different wireline media and table 9-2 shows attenuation properties for representative media (2, 1).

Radio communication is currently receiving increased emphasis for traffic control system communications. The received power in a radio link falls off inversely as the square of the distance transmitted. Radio transmission is also affected by *fading* (discussed later in the chapter). At microwave frequencies above 10 gigahertz (GHz) or $10x10^9$ Hz, the effect of rain and snow in attenuating the signal becomes increasingly significant.

Power Budget and Dynamic Range

The power budget represents the difference between the electrical or optical power (for fiber optic systems) initially transmitted into the cable at the source and the electrical or light power required for proper operation at the receiver, after passing through:

- Cable,
- Connectors, and
- Various splicing devices.

Figure 9-4 shows an example of a power budget calculation for a fiber optic system (1).

Communications receivers have maximum and minimum acceptable input power levels. The difference between these levels represents the

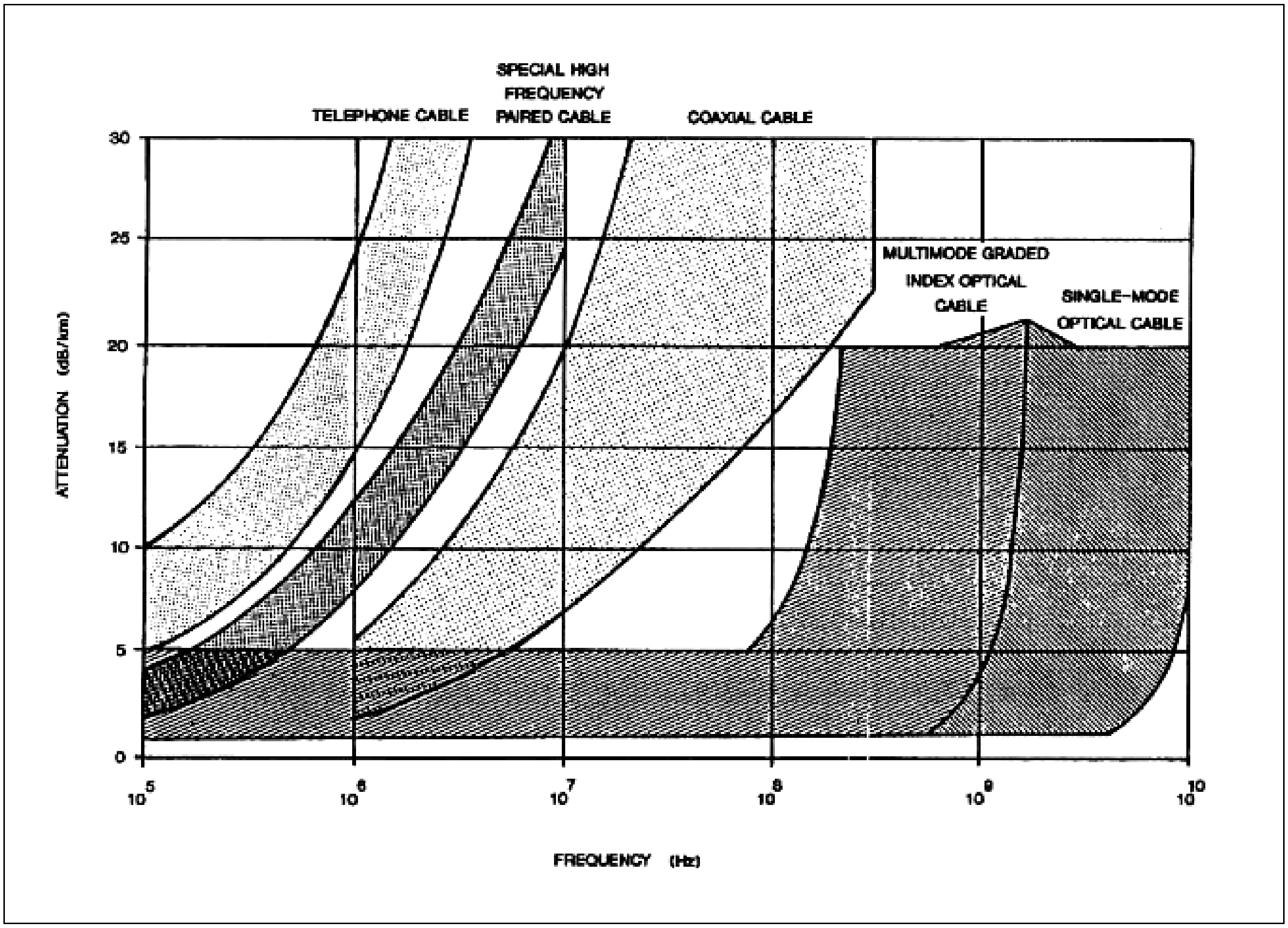


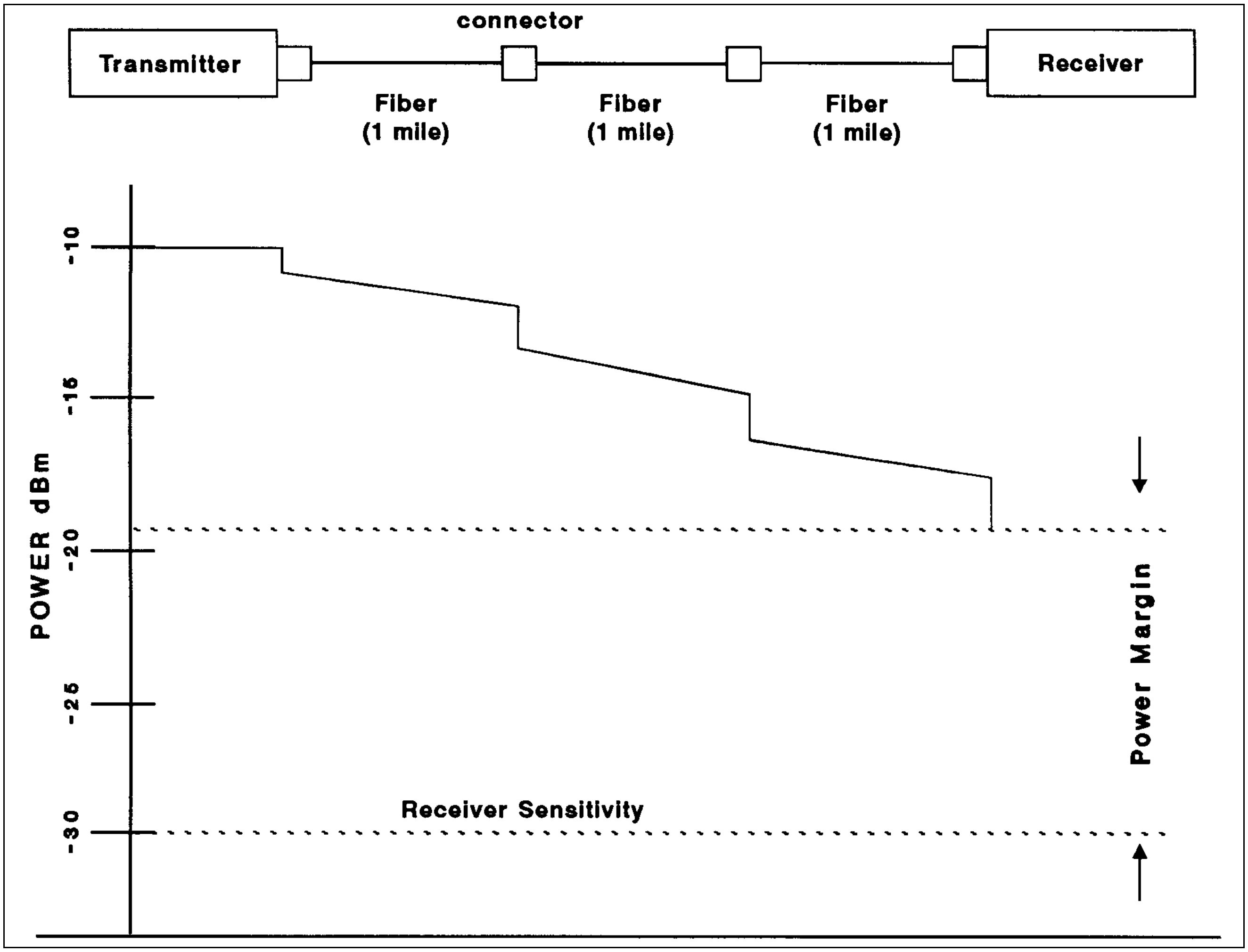
Figure 9-3. Attenuation versus frequency.

Table 9-2. Signal attenuation in channel media.

Type of Medium	Source of Attenuation	Value of Attenuation (db)
LANDLINE		
Copper Cable	Electrical resistance	K1* length
Glass Fiber	Optical scattering and absorption	K2* length
Leased Voice Grade Line	N/A	***See Note 2***
WIRELESS		
Microwave Radio in Free Space	Power reduction due to geometrics	36.58 + 20 log D + 20 log f ***See Note 1*** (Reference 3)
Microwave Radio	Power reduction due to fading	Complex relationships

Definitions and Notes

K1	=	*1.79 db/mi (22 gauge cable at 1000Hz)*
K	=	*.65 db/mi (typical single mode fiber at 1300 nanometers (nm))*
Note 1		*D in mi*
		F in megahertz
Note 2		*Signal controlled to specified limits by local exchange carrier*



Characteristics	
Transmitter Power	-10 dBm (100 microwatts)
Receiver sensitivity	-30 dBm
Fiber attenuation	-1.5 dB/mi
End point connector loss	-1dB each
Midpoint connector loss	-1.5 dB each

Power Budget Calculations	
Transmitter Power	-10 dBm
Receiver sensitivity with bit error rate (BER) = 10^{-12}	-30dBm
Power Budget	20dB
Fiber loss	-4.5 dB
End connector loss	-2.0 dB
Mid link connector	-3.0 dB
Total loss	9.5 dB
Power Margin	10.5dB

Figure 9-4. Power budget for simple fiber optic system.

Table 9-3. Key noise properties.

- Variation in the signal due to extraneous factors
- Causes
  - **Thermal Noise**
    Thermal agitation of electrons in the load resistance of the receiver
  - **Radio Noise**
    Atmospheric – lightning
    Cosmic and Solar
  - **Human-Made Noise**
    Motors, car ignition, power lines, etc.
  - **Noise Peculiar to Media Use**
    e.g., crosstalk in twisted wire pair cable

dynamic range of the receiver. Under certain conditions the power level may require reduction (attenuation) to remain within the dynamic range of the receiver.

Noise and Distortion

Noise results from fluctuations in the signal caused by sources other than the signal. Noise will occur on any communication link. However, engineering the link can reduce this to an acceptable minimum. Noise sources can originate in the communication channel, transmitter or receiver, and include natural and human-made electrical interference.

Table 9-3 summarizes key noise properties (1).

In traffic control systems, errors generally result from *impulse* noise which may cause error bursts (where contiguous bits have many errors). *Interference* and *distortion* can also introduce errors into the link. Error detection techniques include extra signal elements that permit the identification of certain classes of errors in the received data.

An *automatic repeat request* (ARQ) system detects errors and has the data automatically retransmitted. Errors are detected using 1 or more of the techniques described in table 9-4 (1).

Forward error control (FEC) represents an approach that includes error correcting codes with the message to correct a limited number of errors.

Distortion changes the shape of the received waveform from the waveform transmitted. This results because the media changes attenuation or phase characteristics of the transmitted wave by different amounts at different frequencies.

Figure 9-5 shows the effect of delay (or phase) distortion on a wave shape from 2 frequency

Table 9-4. Commonly used error detection techniques.

Technique	Description
Parity - also known as vertical parity	An additional bit is added to each data byte or character. The sum of the 1's in the byte and the additional bit must be an odd or even number as specified. This technique detects an odd number of bit errors in the byte.
Longitudinal Redundancy Check	An additional byte is provided after an entire message or portion of a message (block). A bit in the new byte is computed from the corresponding bit in each data byte in a similar way to the parity check. An odd number of bit errors is again detected. When used in conjunction with parity this is a powerful technique.
Checksum	An additional byte or character is added at the end of the message or block. An algorithm is used which computes the checksum byte as a function of the message bytes. The receiving station performs a similar computation and determines whether the checksum byte is consistent with the received data.
Cyclic Redundancy Code (CRC)	An additional 2 or more bytes are added to the message or block. Algorithms are used to compute these bytes which provide protection, particularly against bursts of errors.
Repeat Transmission	The entire message is repeated. At the receiving station the messages are compared and an error is detected if they are not identical.

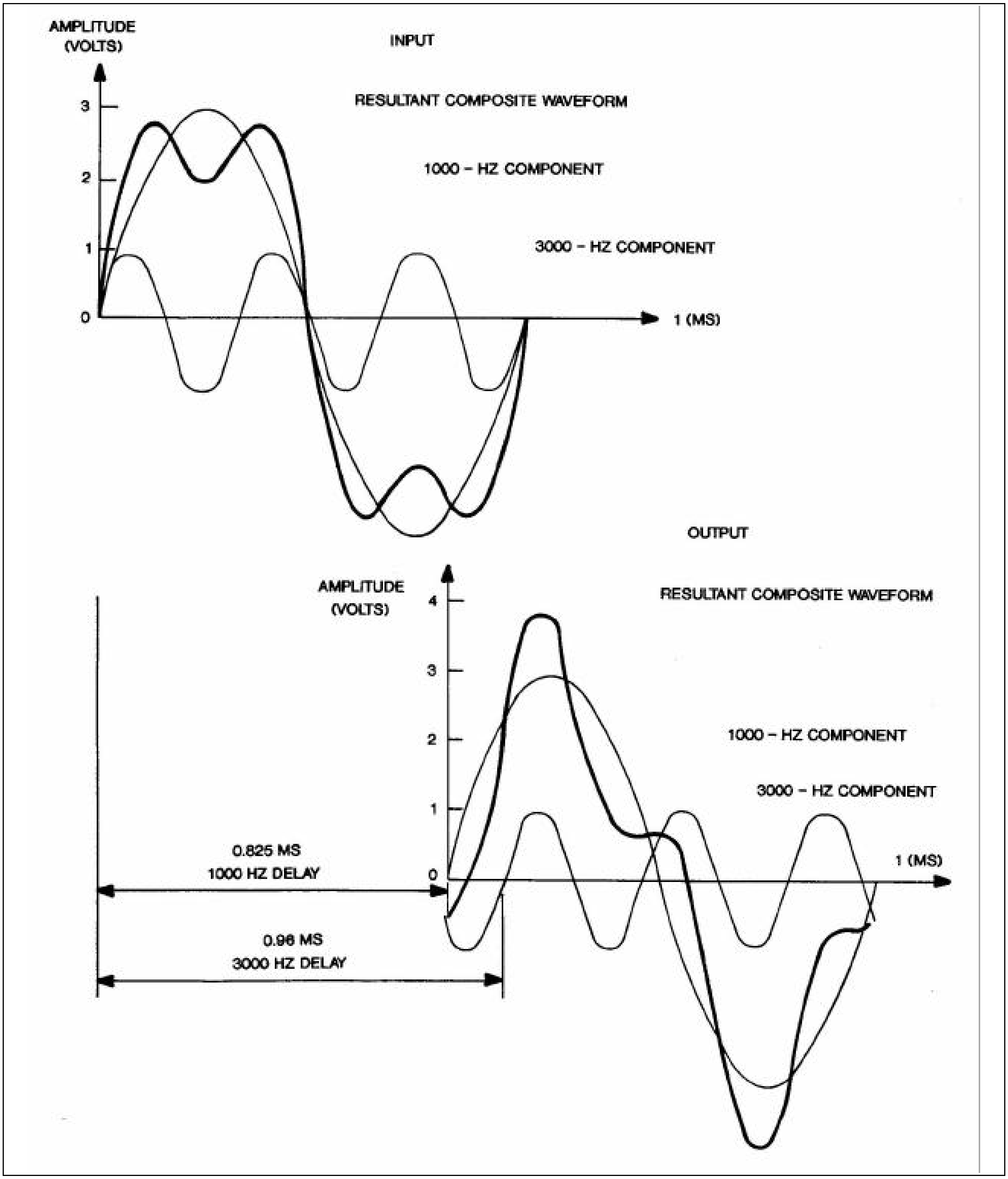


Figure 9-5. Waveforms in and out of 10 mi (16 km) of 22 gauge cable.

BINARY NUMBER

Decimal Number	2^3	2^2	2^1	2^0
1				1
2			1	0
3			1	1
4		1	0	0
5		1	0	1
6		1	1	0
7		1	1	1
8	1	0	0	0
9	1	0	0	1
10	1	0	1	0
11	1	0	1	1

Figure 9-6. Conversion of decimal to binary numbers.

components, 1 KHz and 3 KHz (4). Note that the 3 KHz component experiences more delay and that the resultant waveform significantly changes. Phase distortion may seriously affect data transmission by smearing data bits. Because the receiver cannot distinguish the smeared bits correctly, errors may result.

Digital Data

In many traffic control applications, the information transmitted from the field equipment has 2 values or states. For example:

- Signal lamp is ON or OFF,
- Traffic sensor indicates VEHICLE or NO VEHICLE, or
- Contact closure is OPEN or CLOSED.

Each 2-valued item of information tells the receiver (traffic controller or communications interface unit) about the state of a single YES or NO value. A single 2-valued unit of information is known as a bit (binary digit); values of a bit may be:

- TRUE / FALSE,
- ONE / ZERO, or
- ON / OFF.

Similarly, the digital computer uses a series of electronic switches with only 2 conditions: ON or OFF. In effect a switch is set:

- ON, if a condition exists, and
- OFF, if it does not.

By sensing the status of any switch, the computer can:

- Decide anything reducible to a yes or no, or
- Compute anything reducible to 0s and 1s.

Computers and communication equipment use the binary number system to represent data. This system counts in base 2 just as the decimal system uses base 10.

Figure 9-6 illustrates how decimal numbers convert to binary numbers.

Computers treat the ON or OFF condition of each switch as a binary number (bit). A series of switches may combine to form 1 multi-digit binary number as shown in figure 9-7. When bits group in specific orders, they are called characters, and a group of 8 bits is often called a byte.

Parallel versus Serial Transmission

Transmission of data bytes between traffic controllers and computers can take either parallel or serial form. In parallel transmission, all bits of the byte or

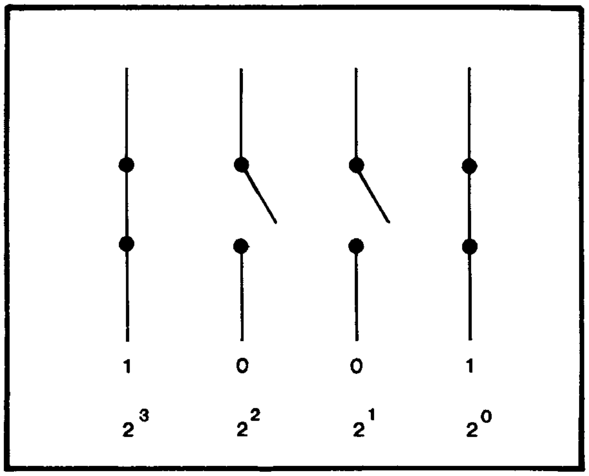


Figure 9-7. Representation of number 9 (in decimal number system) by a combination of switches which provide binary number 1001.

character are transmitted at 1 time. This technique finds extensive application in computer-to-peripheral (e.g., computer-to-printer) transmission where:

- Cable distances are short, and
- Data transfer must occur rapidly.

Because parallel transmission requires 1 data line for each bit, the transfer of an 8-bit character requires a minimum of 8 lines. As a result, this method becomes expensive as the distance between devices increases.

To send data over a single link (line or channel) *serial transmission* proves more economical. In serial transmission, bits are transmitted in sequence over one line. Control signals can be transmitted by additional bits, not additional lines. Thus, serial transmission has become the most widely used method for transmitting data. Figure 9-8 illustrates the differences between *serial* and *parallel* transmission (5).

Interconnection

A communications network design must address the interconnection architecture among data receivers and data sources. The most direct method is point-to-point shown in the simple traffic control system of figure 9-9. Separate links are provided between each receiver and the data source, with the receivers at separate locations. Point-to-point interconnection proves a common technique, since 1 receiver on each line simplifies the control characters and data exchanges between the data source and the receiver. Disadvantages of point-to-point interconnect include:

- Failure of a link totally isolates that receiver from the central facility,
- Increased communication costs, especially in larger systems,
- Unwieldy number of cables returned to central facility in a very large network, and
- Sophisticated communication signal methods cannot be used to share channel capacity between receiver points.

An alternative arrangement used in many systems, especially with owned land lines, is the *multidrop* scheme shown in figure 9-10. If the loop closes back to the central or master facility, the arrangement is also called a *closed-loop* linkage. Closed-loop linkages have the capability of providing communication service to every node if the cable is cut on 1 link. Multidrop interconnection unites 2 or more receivers on the same link (channel), thus reducing system cost by increasing channel utilization. The presence of multiple receivers on the same line requires special control sequences for establishing communication between the data source and the proper receiver. The system accomplishes this through a unique address identifier. Upon receipt of its own address plus additional security checks, the selected receiver stores the command data sent to it from the source. In addition, upon receipt of a valid address, the receiver initiates a response data transmission back to the source.

Figure 9-11 illustrates the multidrop communications link scheme as applied to a typical, areawide, multi-channel traffic signal system.

Modulation and Demodulation

Modulation transforms the signal into a form suitable for the transmission system and media. Transmitting binary data requires at least 2 types of modulated signals. The demodulation process reconstructs the original signal at the receiving end. *Modems* (MOdulator-DEModulator) are devices at each end of the channel that perform these functions and make possible 2-way communication on the channel.

The modulation process alters the characteristics of a sine wave known as a carrier signal (figure 9-12).

The carrier's characteristics which can be altered are:

- Amplitude for amplitude modulation (AM),
- Frequency for frequency modulation (FM), and
- Phase angle for phase modulation (PM).

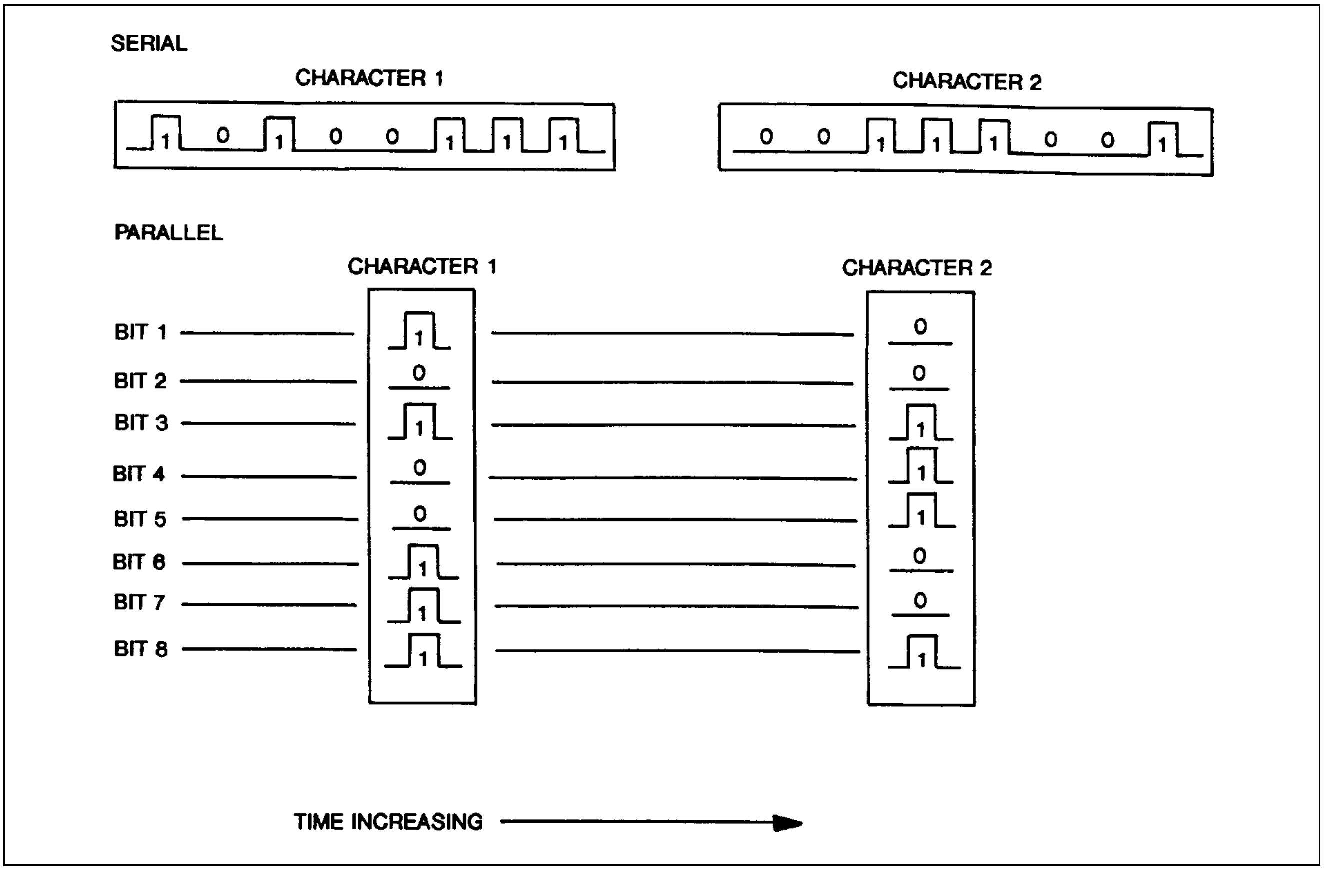


Figure 9-8. Time sequence for serial and parallel transmission.

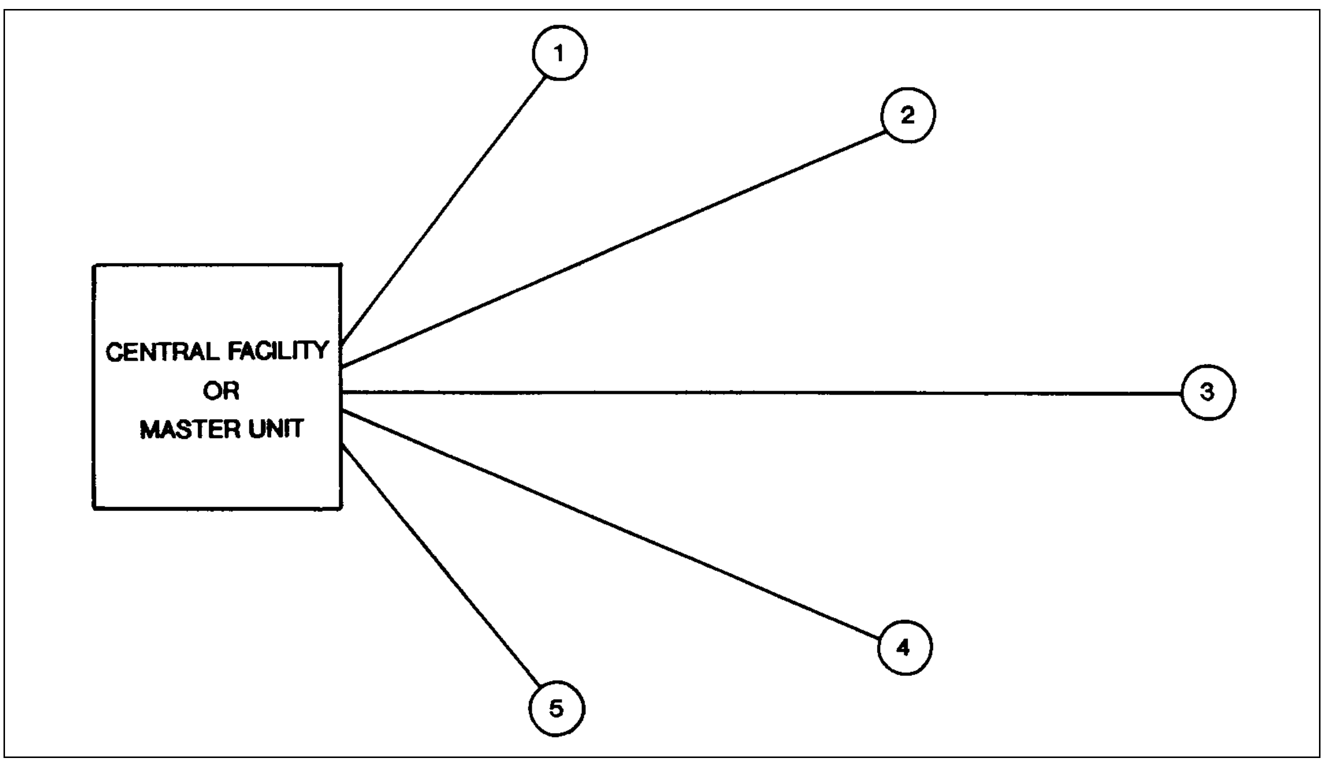


Figure 9-9. Point-to-point interconnection.

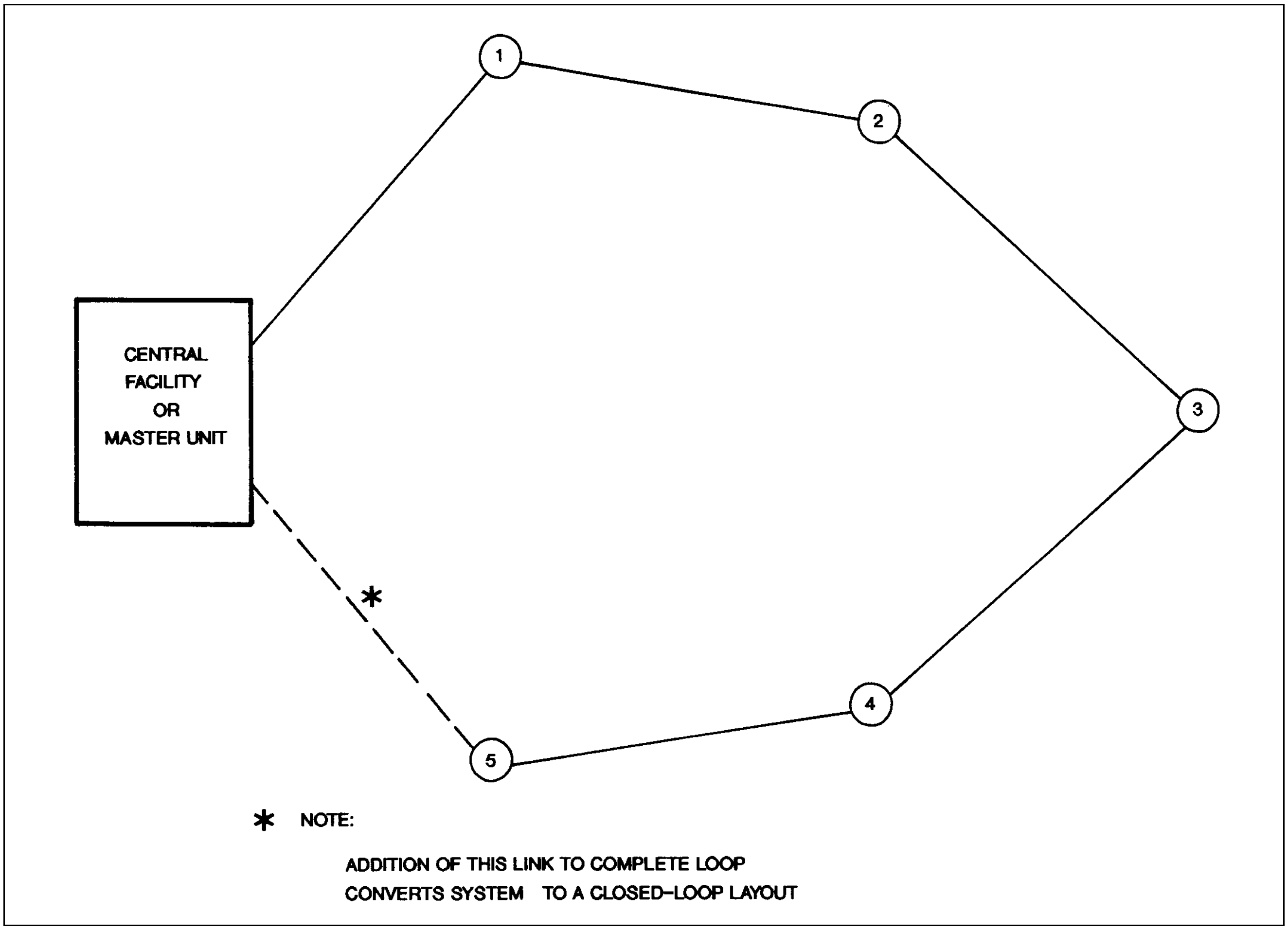


Figure 9-10. Multidrop interconnection.

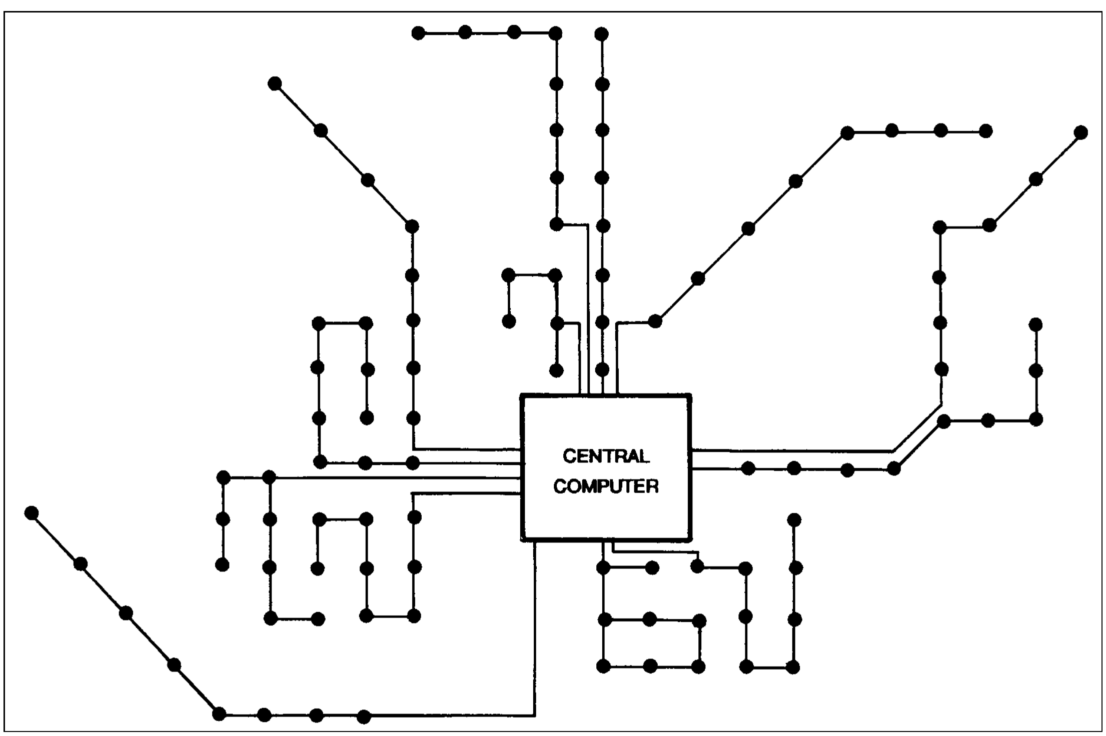


Figure 9-11. Application of multidrop scheme in a large signal network.

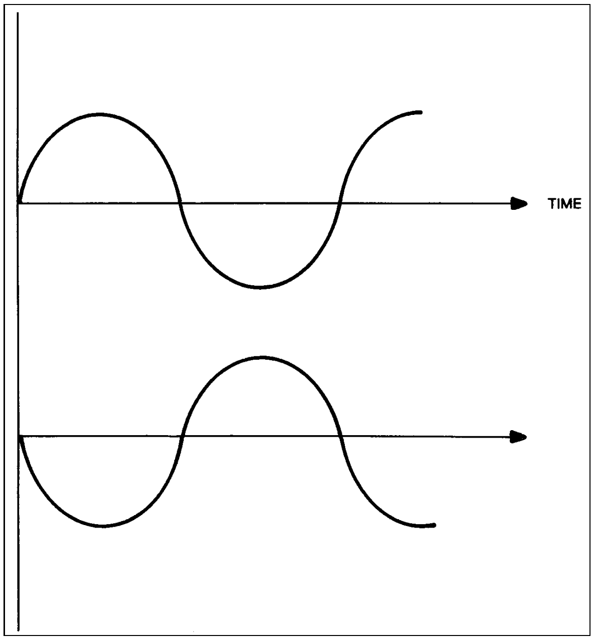


Figure 9-12. Phase modulation.

Amplitude Modulation

Amplitude Modulation (AM) varies the strength of the carrier to represent the digital "1" or "0" level. The simplest AM technique is Amplitude Shift Keying (ASK) where the presence or absence of a carrier represents the binary state as shown in figure 9-13 (1). Because the valid reception of an AM signal depends upon the measurement of the received signal strength, noise on copper twisted wire pairs or leased telephone lines can severely degrade AM reception. For that reason, AM does not see common use in traffic control or other sensitive applications. However, AM is often used with phase modulation in some types of modems.

Amplitude modulation works well for fiber optic systems since few noise sources cause the equivalent of electromagnetic or radio frequency interference.

Frequency Modulation

Frequency modulation (FM) varies the frequency of the transmitted carrier signal to represent differing signal values. FM improves transmission performance in the face of extraneous noise on a communication channel.

In a binary transmission system, FM takes the form of Frequency Shift Keying (FSK) (see figure 9-14). The technique can use either 2 or 3 discrete signaling frequencies. With 2 frequencies (2FS or 2-FSK transmission):

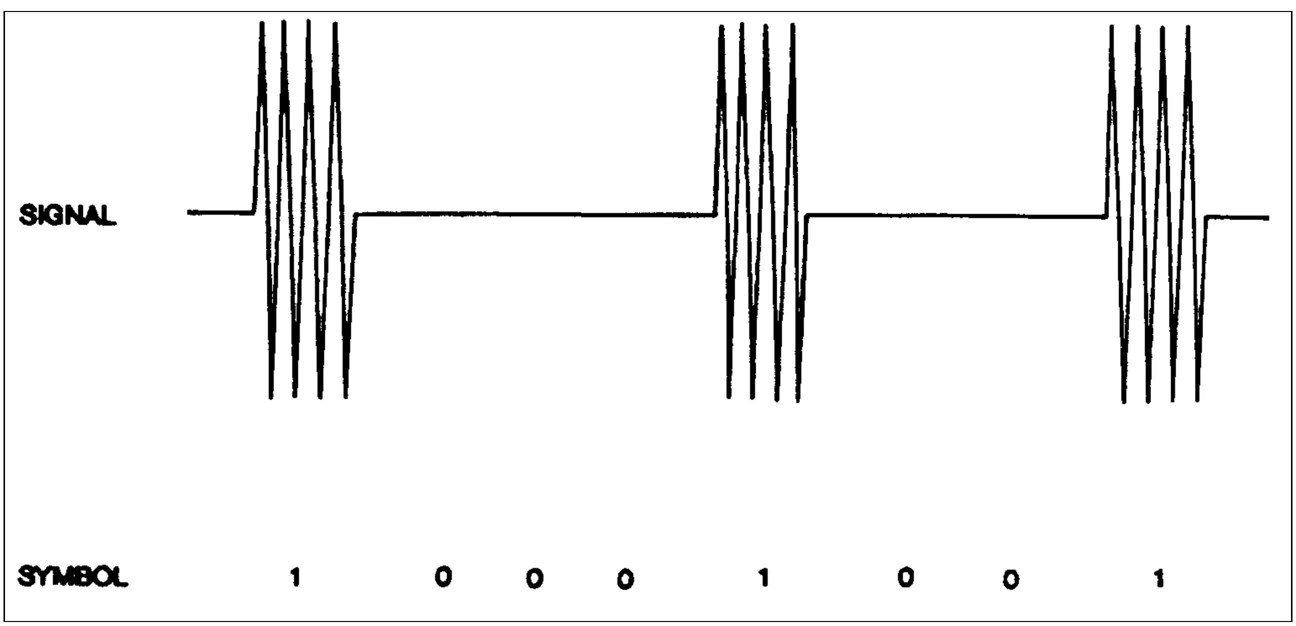


Figure 9-13. Amplitude modulation – amplitude shift keying.

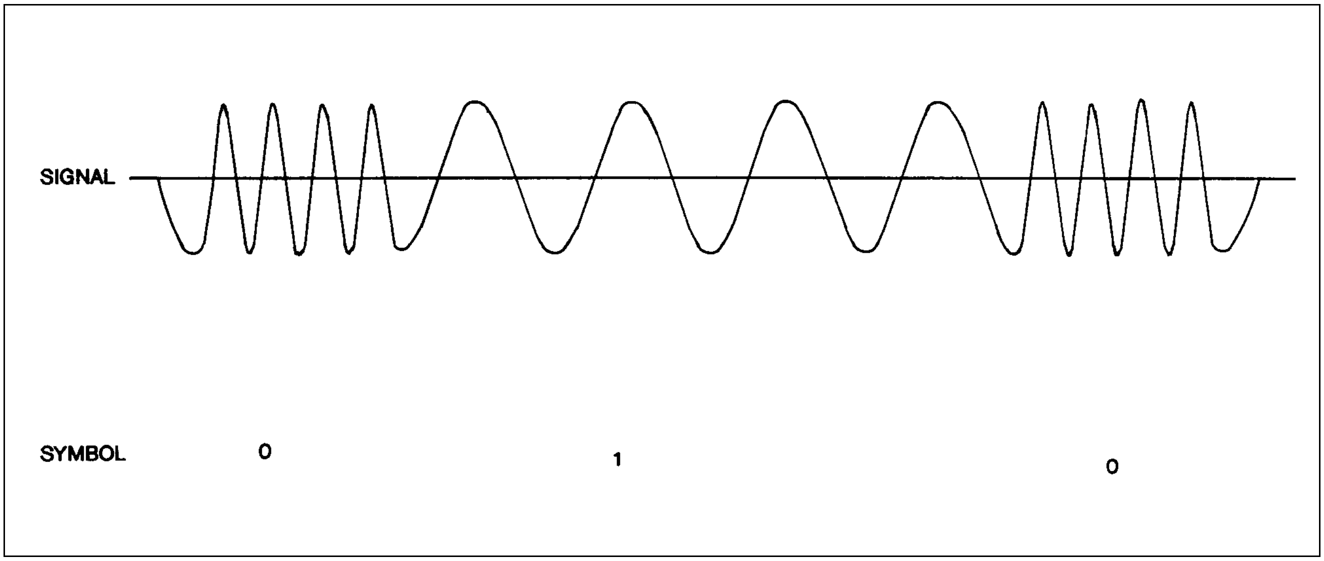


Figure 9-14. Frequency modulation – frequency shift keying.

- One frequency represents the MARK or 1 condition, and
- One frequency represents the SPACE or 0 condition.

With 2FS transmission, the IDLE condition (the absence of any signal) results from turning the modulator off (no signal). Since this condition is equivalent to channel breakdown, channel interruption becomes difficult to detect with 2FS. As a result, 3 frequencies are often used (3FS or 3-FSK transmission) in traffic control communications. Here, a third carrier frequency represents the IDLE condition. This third frequency is generally centered between the MARK and SPACE frequencies.

FM/FSK modulation provides a better quality signal than AM/ASK modulation but requires a wider bandwidth. It sees common use in copper-wire-based communication systems for traffic control.

Phase Modulation

Phase modulation varies the phase of the carrier signal (relative to a constant-phase reference signal) to represent differing signal values, an example of which is shown in figure 9-12. A binary Phase Shift Keying (PSK) system shifts the phase 180^o to represent a MARK, but leaves it unchanged to represent a SPACE. Thus, the MARK/SPACE value is represented by a change in signal, rather than by a signal condition (as in AM or FSK). By using smaller changes in phase to represent more than 2 signal values, more information can be sent through a channel in a given period. Because the receiver must generate a reference phase, PSK becomes somewhat more difficult to demodulate than FSK. The demodulator requires the reference phase to measure signal phase changes. With a low signal-to-noise ratio, PSK offers some improvement in signal recovery.

Commercial modems commonly use phase shifts of less than 180^o, enabling a single symbol to represent more than 2 states. PSK is commonly used with ASK for this purpose. Reference 5 further describes this technique.

Data Transmission and Link Control

Modes

The direction of flow over the channel or transmission mode can take the forms shown in table 9-5 (1).

Traffic control systems usually use the *half* or *full duplex* mode.

Table 9-6 defines terms commonly used with modems.

Synchronous and Asynchronous Techniques

As mentioned previously, serial data transmission has become the preferred method of data transfer between computers and remains the most cost effective

Table 9-5. Transmission mode characteristics.

Mode	Data Flow Detection	Characteristics
Simplex	→ Data flow in one direction only	• Does not provide verification that data were received and acted upon • Does not provide answer-back, status reporting, or validity checking
Half Duplex (HDX)	→ then ← Data flow in either direction, but only in one direction at a time	• Requires modem at each end of the line • Requires control capability to assume proper operation • Uses *latency* time or *turn around* time (the time period required to turn the line around) for the process in which the direction of data transmission is reversed, which can be time consuming
Full Duplex (FDX)	↔ Data flow possible in both directions at the same time	• Acts like 2 simplex channels in opposite directions • Permits independent, 2-way, simultaneous data transmission • May raise cost of channel • Reduces the 1-way capacity if frequency multiplexing is used on a single channel

Table 9-6. Modem definitions.

Term	Definition
Request to Send (RTS)	Electrical signal applied to the modem by the data source notifying the modem that data is ready to be transmitted
Clear to Send (CTS)	Indication by the modem to the data source that the modem is prepared to transmit. A clear-to-send delay, programmed into the modem, allows the receiving modem time to detect and lock to the transmitting modem's carrier before data transmission commences.
Carrier Detect Turn-On Time	Time for a receiving modem to turn-on its signal detector after it detects a carrier from a transmitting modem
Carrier Detect Turn-Off Time	Time for the receiving modem to turn-off its signal detector after detecting loss of carrier or soft carrier
Soft Carrier	Transmission of a specific frequency, below the MARK and SPACE frequencies at the end of a transmission, to avoid spurious signals caused by the sharp transition that would otherwise occur if the carrier were turned off. The receiving modem turns-off its signal detector upon detecting this signal.
Turnaround Time	Time required to reverse the direction on a half-duplex line

Table 9-7. Transmission technique characteristics.

Asynchronous	Synchronous
Each character is prefixed by a start bit and followed by data, parity, and stop bits	Sync characters prefix transmitted data
Idle time (period of inactivity) can exist between transmitted characters	Sync characters are transmitted between blocks of data to maintain line synchronization
Bits within a character are transmitted at prescribed time intervals	No gaps exist between characters, but terminals must have buffers
Timing is established independently in the computer and the remote communications unit (RCU)	Timing is established and maintained by the transmitting and receiving modems, the RCU, or other devices

method for data acquisition and control in traffic control systems. A receiver and transmitter operating with serial data transmission coordinate via a process termed *synchronization*. Bit synchronization enables the receiver to distinguish between successive bits within a string of data.

Two serial data transmission techniques, *asynchronous* and *synchronous*, commonly find use in traffic control systems. Table 9-7 provides a comparison.

In asynchronous transmission the time intervals between transmitted characters may be of unequal length. Start and stop bits are transmitted before and after each character to synchronize the receiver clock. Asynchronous transmission encodes each character into a series of pulses or bits. The transmission begins by a start bit equal in length to a code pulse. Most traffic control systems use asynchronous transmission.

In synchronous transmission, data characters are transmitted at a fixed rate, with the transmitter and receiver synchronized. With no start and stop bits, this technique proves more efficient than asynchronous transmission.

The NEMA TS2 specification includes one RS 485 port that uses the Synchronous Data Link Control (SDLC) protocol. The protocol allows 2 basic types of frames, *control* and *information*. SDLC is a full duplex protocol. Furthermore, SDLC permits the transmission to one remote location while receiving from a different remote location on a multidrop line (1).

Multiplexing

Multiplexing combines the transmission of several signals into 1 channel as shown in figure 9-15 (1).

Traffic control systems use signal multiplexing to efficiently communicate with many different devices over a single channel. The most common multiplexing schemes used in traffic control systems are:

- Frequency-division multiplexing (FDM),
- Time-division multiplexing (TDM), and
- Code-division multiplexing (CDM).

Traffic control systems sometimes use a combination of these schemes.

Frequency Division Multiplexing (FDM)

FDM splits the available transmission frequency range into narrower bands, each constituting a distinct channel. Early centralized computer traffic control systems used twisted wire pairs with FDM; however, current TDM technology has made this form of FDM obsolete for copper-wire, pair-based communication systems.

Traffic control systems using coaxial cable as the transmission medium commonly combine FDM and TDM. Typically the data channels sub-split 6 Megahertz video channels. The sub-split channels can be nominally spaced between 25 KHz to 1 MHz apart, and the modulation method is usually FSK.

Time Division Multiplexing (TDM)

TDM sends a number of signals over a single channel by time-dividing the channel into a number of time slots and assigning each signal its own time slot. The time slot allocation may repeat regularly or be made according to demand.

Many traffic applications use a polled TDM format with the multidrop scheme shown in figure 9-11. The source sends command data characters for each communication channel address concurrently to every

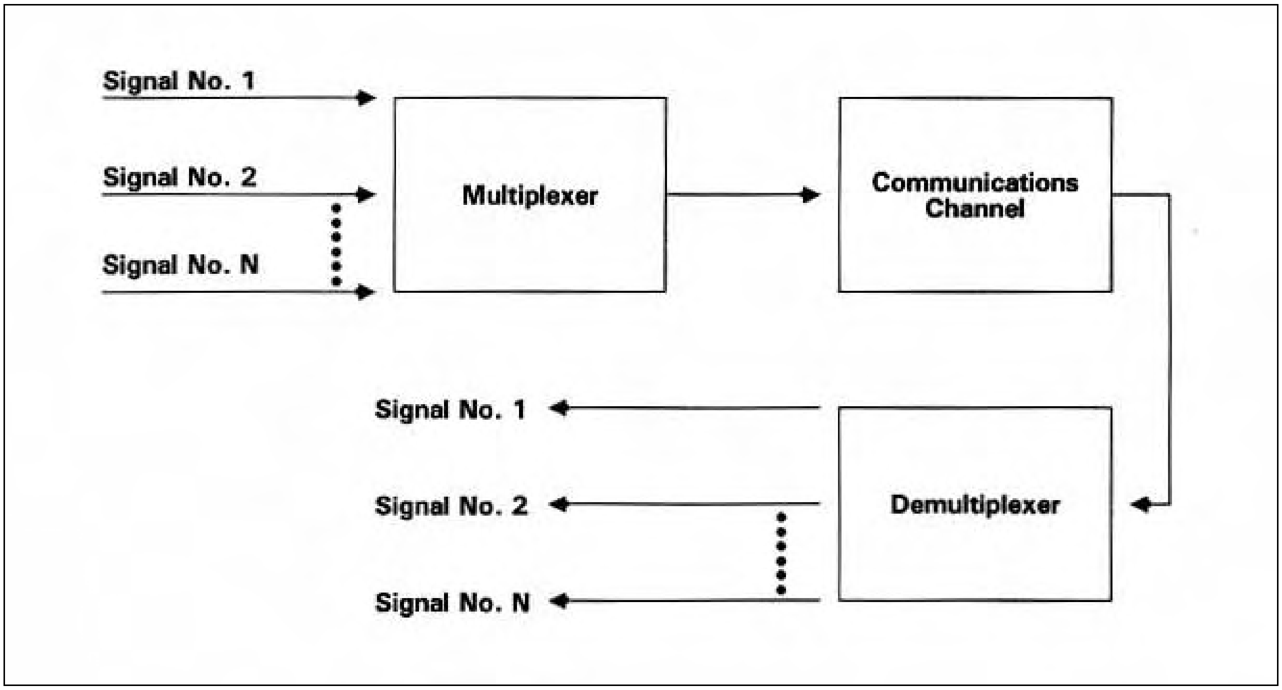


Figure 9-15. Multiplexed signals on a single communication channel.

receiver on the channel. However, only the receiver whose address matches the command data address responds and this response must occur in a predetermined time frame. Figure 9-16 shows how a period of time (polling period) divides to furnish a time interval for each of the 8 local controllers on the channel.

Code Division Multiplexing (CDM)

CDM encodes data by using a specified but different binary sequence for each channel. Many communication channels can share the same frequency channel. Spread spectrum radio systems typically use CDM.

Interface with Computer and Field Equipment

The modem interface with computer and field equipment may be accomplished as follows:

- *Internal Modem* - The modem functions are coupled directly to circuitry compatible with the controller or computer architecture. The modem is physically located in the controller or computer chassis.
- *External Modem* - A physically separate modem interfaces with controllers or computers through serial ports. A serial port is an Electronic Industries Association (EIA) standard physical interface with certain protocols (signal sequences for establishment of communication) and defined performance requirements. The RS 232 (also known as the EIA 232) standard is the most common.
- *Remote Communications Unit* (RCU) or Intelligent Remote Communications Unit (IRCU) - Under some circumstances the prior techniques cannot be used with NEMA controllers. Interface with these controllers is accomplished by separate units known as RCUs or IRCUs. As shown in figure 9-17, the RCU contains a modem section and a section which changes the serial information to discrete signals (inputs and outputs) (1). The discrete signals may connect to NEMA controllers. RCUs also interface with other field devices such as:
  - System detectors,
  - Blankout signs, and
  - Lane control signals.

The intelligent remote communications unit (IRCU) provides additional functions such as:

- Storage of signal timing plans, and
- Preprocessing of detector data.

The National Traffic Control/ITS Communications Protocol (NTCIP), which is expected to be adopted in the near future, will reduce or eliminate the need for these units.

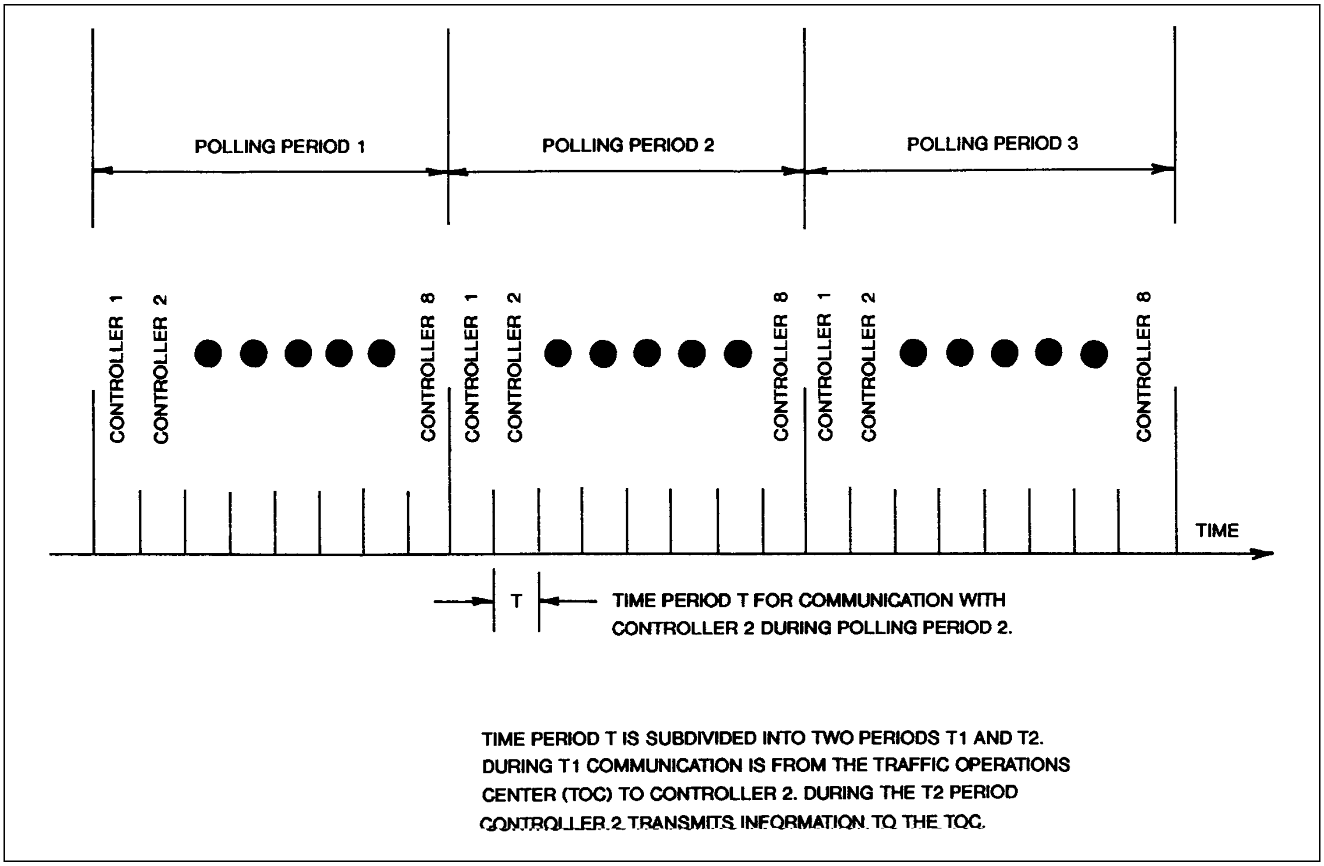


Figure 9-16. Time relationship in time division multiplexing.

Table 9-8 shows the relationship between the interface schemes described above and a number of traffic control system devices.

Digital Signal Transmission Standards

Conformance to key digital standards for data rates and formats:

- Allows the selection of equipment from multiple vendors,
- Ensures compatibility of equipment among vendors, and
- Increases the possibility of obtaining spare equipment at a future time.

The standards important for traffic control system communications include:

Serial Port Standards

As indicated previously, the Electronic Industries Association RS 232 (EIA 232) standard has proved the most common. It provides for data rates up to 19,200 bits/second. The less frequently used standards, RS 422 (EIA 422), RS 423 (EIA 423) and RS 449 (EIA 449) are serial port standards for the transmission of higher data rates at longer distances.

Telecommunication Standards for High Data Rate Channels (1)

The American National Standards Institute (ANSI) T1 standards organization currently defines electrical telecommunications standards for North America. ANSI T1 standards specify:

- Network facility interface points,
- Transmission speeds,
- Signal formats, and
- Standard vendor interconnect specifications.

Table 9-9 provides a condensed view of the North American electrical digital hierarchy, illustrating standard interconnect rates or channels used by telecommunications exchange carriers (1). These specifications form the basis for the majority of North American public and private telecommunications networks.

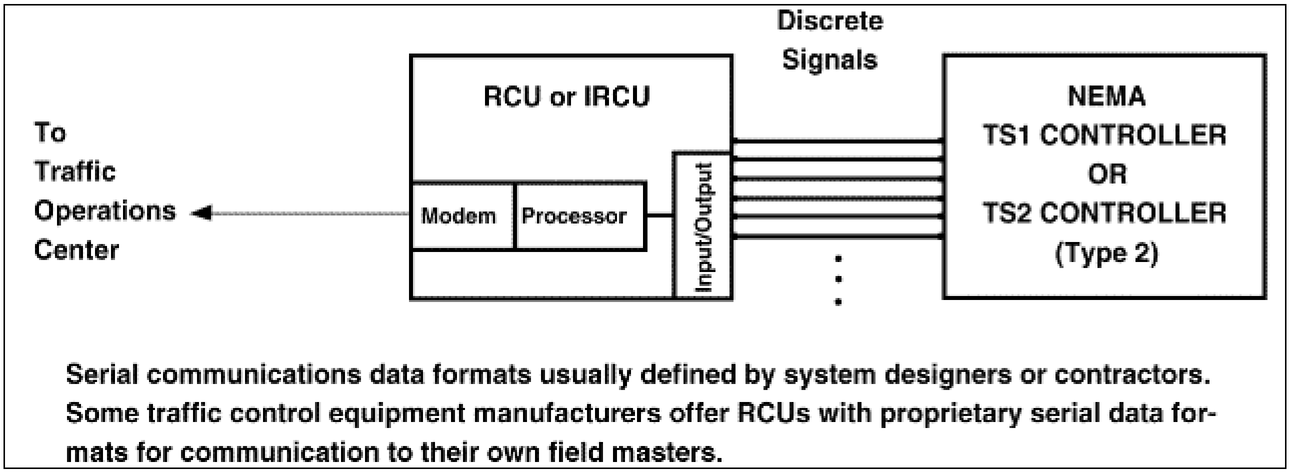


Figure 9-17. Relationship of RCU/IRCU to field controller.

T1 service within the network refers to a Digital Signal Type 1 (DS1) formatted signal and can carry 24 Digital Signal Type 0 (DS0) voice channels, 24 DS0A data channels, or a combination of voice and data.

This standard applies to traffic systems with:

- High levels of data multiplexing, and
- Digital video transmission requirements.

Optical Telecommunication Interface Standards (1)

Beginning in 1988, the ANSI T1 standard body defined optical telecommunications interface standards for North America. All the optical transmission systems installed prior to 1988 were proprietary and commonly referred to as asynchronous lightwave transmission systems. The post-1988 set of domestic optical standards are commonly called Synchronous Optical Network (SONET) in ANSI T1 and Synchronous Digital Hierarchy (SDH) by the Consultative Committee for International Telephone and Telegraph (CCITT), which sets international standards for telecommunications.

The SONET standards define transmission capacity, optical interconnects and internal formatted signals in terms of Optical Carrier type N (OC-N) where N specifies capacity in terms of electrical DS3 equivalents. For example, an OC-3 interconnect specifies a bit rate of 155.52 Mbps and can carry any combination of the same or lower bit rate channels having 3 DS3 equivalent capacity. Therefore, an OC-3 signal can comprise three DS3s, 84 DS1s, 1 DS3 and 56 DS1s, etc. Table 9-10 lists the standard interconnect rates and equivalent channel capacity as defined by ANSI T1 SONET (6).

Communication Requirements For CCTV

Closed Circuit TV (CCTV) already forms an integral part of many traffic control applications, including:

- Roadway monitoring,
- Incident verification, and
- Security.

Components of a CCTV system include:

- Cameras at field locations,
- Camera control accessories,
- Monitors in the traffic operations center,
- Video tape recorders,
- Video switcher, and
- Communications network that links central and field locations.

Since video requires much more bandwidth than the other voice and data functions typically provided by traffic control systems, CCTV frequently becomes the dominant factor in the communications network design.

Full Motion Video Transmission

Video cameras used for most traffic control applications conform to standards defined by the National Television Standards Committee (NTSC),

Table 9-8. Interfaces to central equipment and field equipment.

Equipment	Internal Modem	External Modem	RCU/IRCU
Central Computer	✔	✔	
Field Master Controller	✔	✔	
Model 170 Controller *(Note 5)*	*(Note 4)*	✔	
NEMA Controller *(Note 3)*	✔	✔	*(Note 1)*
Other Field Equipment *(Note 2)*		✔	✔

Note 1: When NEMA controllers are not used with the manufacturer's programmed communication protocols, the controller interface is accomplished with an RCU or IRCU.

Note 2: Simple equipments with discrete inputs/outputs may use an RCU/IRCU or a programmable controller such as the Model 170 as a communications interface.

Note 3: Communication for system detector data or locally actuated detectors may be provided by communications for controller.

Note 4: Model 170 standards provides for internal modem to wire pair media. Non-standard internal modems available for other media.

Note 5: See note 3. 170 controllers can provide communication for other devices with discrete inputs/outputs.

Table 9-9. North American electrical digital hierarchy standards.

Channel	Bit Rate	Composition
DS3	44.736 Mb/s	28 DS1 equivalent capacity
DS2	6.312 Mb/s	4 DS1 equivalent capacity
DS1C	3.152 Mb/s	2 DS1 equivalent capacity
DS1	1.544 Mb/s	24 DS0 equivalent capacity
DS0	64 Kb/s	DS0, DS0A, or DS0B rate only
DS0A*	64 Kb/s	2.4, 4.8, 9.6, 19.2 or 56 Kb/s, or 56 Kb/s carried on a single DS0
DS0B*	64 Kb/s	20 (2.4 Kb/s), 10 (4.8 Kb/s), or 5 (9.6 Kb/s) multiplexed onto a single DS0

* *Transmission for these rates for distances beyond 12,500 ft (3,810 m) normally requires a DS1 or higher multiplexer and a transmission system*

Table 9-10. North American synchronous optical network (SONET) standards.

Channel	Bit Rate	Equivalent Capacity
OC-48	2.48832 Gb/s	48 DS3
OC-36*	1.86624 Gb/s	36 DS3
OC-24	1244.06 Mb/s	24 DS3
OC-18*	933.12 Mb/s	18 DS3
OC-12	622.08 Mb/s	12 DS3
OC-9*	466.56 Mb/s	9 DS3
OC-3	155.52 Mb/s	3 DS3
OC-1*	51.84 Mb/s	1 DS3
STS-N+	N (x) 51.84 Mb/s	N (x) DS3

* *Rarely used North American optical rates and not compatible with CCITT standards*

\+ *This specifies a SONET compatible electrical Synchronous Transport Signal (STS-N) having an equivalent of N DS3 capacity. It can be used as an electrical SONET interconnect within buildings when distances are short or as a means of describing the electrical equivalent of an OC-N formatted signal.*

which has defined the color television standard used in most of North America and Japan.

Table 9-11 summarizes certain key NTSC standards requirements (1). The bandwidth and transmission channel requirements are compatible with fiber optic and coaxial cable communications (described in section 9.3) owned by an operating agency.

In many cases, however, the operating agency does not own these media for the entire distance between the video cameras and the traffic operations center. Leased communications media, or in some cases dial-up, is being used with increasing frequency. Coded TV transmission is the principal technology used with leased high speed data channels. Freeze frame (slow scan) transmission may be used with voice grade channels.

Coded TV Transmission (Codec)

Video compression techniques take advantage of data redundancy and human visual limitations to reduce the transmission bandwidth required to transport video signals. *Interframe coding* techniques eliminate redundancy between successive frames by transmitting only the differences between frames, while *intraframe coding* eliminates redundancy within a video field (7).

Video compression:

- Converts analog video data into digital form, and
- Digitizes the video signal using a video codec (COder DECoder).

Until recently, codec vendors had only implemented proprietary video compression algorithms; i.e., codecs from different vendors could not be used together. However, the Consultative Committee for International Telephone and Telephone (CCITT) H.261 recommendation defines a videotelephony

Table 9-11. NTSC standards.

Characteristic	Value
Bandwidth	4.2 MHz
Transmission Channel	6.0 MHz
Video Resolution	700 pixels (picture elements) x 525 lines
Aspect Ratio	4 : 3
Frame Update	30/second

standard that codec vendors currently implement, thereby providing interoperability. The standard, sometimes called P x 64 (*P by 64*), supports data rates in multiples of 64 Kbps, ranging from 64 Kbps to 2 Mbps (8).

The codec rates and formats are compatible with digital hierarchy standards and therefore can be transmitted by telecommunication service providers such as the local telephone company.

Two factors that influence a viewer's perception of video quality are *resolution* and *frame rate*. Many codecs that transmit video at rates of 384 Kbps or below provide a video resolution of 256 pixels by 240 lines, in comparison to 700 by 525, the NTSC standard video resolution.

Although codec can transmit video at lower data rates, the picture quality may not prove acceptable. Prior to preparing a specification, the user should attend demonstrations provided by the manufacturers to identify an acceptable transmission rate. In addition, appropriate environmental enclosures may be required to use this equipment in the field. Recently, codec equipment with environmental characteristics suitable for traffic system use has become available.

Freeze Frame Video Transmission

In general, freeze frame or slow scan techniques capture a video image (monochrome or color) and code it for transmission over standard voice grade telephone circuits or other narrowband communications media. After transmission, equipment reconverts the coded signal to a still image displayed on a television monitor. Depending on the resolution desired and the use of color, the picture repetition rate may range from several seconds to a few minutes.

Although traffic engineers generally prefer codec techniques, freeze frame transmission may prove useful under certain circumstances.

9.3 Alternative Communication Media and Technologies

This section describes the communication media and technologies most commonly used for traffic control system communication. Table 9-12 summarizes the key properties (1).

Twisted Wire Pairs (TWP)

Manufacturers supply twisted-pair cable in standard numbers of pairs: 6, 12, 18, 25, 50, 75, 100, 150, 200, 300, 400, 600, and 1,200; in wire gauges 19, 22, 24, and 26 AWG. Twisting insulated copper conductors into pairs reduces electrical interference since the conductors produce fields that tend to cancel out. As shown in Figure 9-18, the same current flows in each conductor, but in opposite directions (1). Thus, the current in each conductor produces a magnetic field also in the opposite direction. The 2 induced fields largely cancel each other, thereby minimizing the amount of energy transferred to adjacent pairs.

A binder group consists of a number (i.e., 25) of color coded twisted-pairs stranded together. The amount of twist applied to pairs within a binder group varies to reduce crosstalk, interference due to signal ingress in 1 communication channel caused by signal egress from an adjacent channel. Manufacturers twist multiple binder groups together around a common axis to increase the number of conductors in a cable.

Most wire used for traffic system communications lies between 19 and 26 gauge. Table 9-13 provides representative data for multiconductor cable (1).

Twisted-pair cable for communications may take the form of the private-line voiceband media leased from the local telephone company. Single point or multipoint drops may be used.

Significant features of this medium important to communications system design include:

- Maximum allowable transmitter power level,
- Signal level expected at the receiver, and
- Limitations on number of drops on a multipoint line.

Owned versus Leased

Twisted wire pair cable can be:

- Leased,
- User-owned, or
- A combination of both.

The majority of traffic signal system interconnect currently in service is owned twisted-pair cable. Capital costs for this medium represent a substantial part of overall system cost, especially when the cable is installed underground in new conduit. Table 9-14 compares user-owned and leased, wire-pair cable.

Table 9-12. Summary of properties of communication technologies and media.

Features	Twisted Wire Pair Channels	Leased Voice Grade Channels	Switched Voice Grade Channels	Fiber Optics Channels	CATV (Community Antenna Television) Channels
1. Media	Copper wire	May vary along length but usually copper wire pair at user interface points	May vary along length but usually copper wire pair at user interface points	Glass or plastic fibers	Coaxial Cable
2. Principal Multiplexing/ Modulation Technique Used	Time Division Multiplex (FSK)	Time Division Multiplex (FSK)	Time Division Multiplex (FSK)	Time Division Multiplex	FDM for channels TDM for data on a channel
3. Carrier Frequency Band	300 to 3,000 Hz	300 to 3,000 Hz	300 to 3,000 Hz	850 to 1,550 nanometers	5 to 350 MHz
4. Bandwidth/Channel Bandwidth	Will exceed 2.7 kHz for most systems	2.7 kHz	2.7 kHz	Various	6 MHz/channel. Channels may be further subdivided for data transmission.
5. Data Rates per Channel	1,200 to 3,100 bps. Higher rates possible with different modulation technique.	1,200 bps or higher	1,200 bps or higher	Up to 2.4 Gbps	Up to 7.5 Mbps based on channel subdivision
6. Transmission Range or Repeater Spacing	9 to 15 miles	Service level provided by communications lessor to a standard	Service level provided by communications lessor to a standard	Rarely a limitation when drop/insert units used at communication hubs or drop points	N/A
7. Government Regulation of Channel or Service	None	Tariffs filed with State	Tariffs filed with State	None	None
8. Types of Information Supported	Data, voice, slow scan TV	Data, voice, slow scan TV	Data, voice, slow scan TV	Data, voice, analog TV, Codec	Data, voice, analog TV, Codec
9. Owned or Leased	Owned	Leased	Dial-up lines	Owned	Leased
10. Constraints on Use	N/A	Proximity of telephone service to field controllers	Compatibility with intermittent operation. Proximity to controller.	N/A	Proximity of CATV cable to field controller

Table 9-12. Summary of properties of communication technologies and media (continued).

Features	Leased Digital Channel Services	Area Radio Networks (Owned)	Terrestrial Microwave	Spread Spectrum Radio
1. Media	Various	Atmosphere	Atmosphere	Atmosphere
2. Principal Multiplexing/ Modulation Technique Used	Time Division Multiplex, modulation technique varies	Time Division Multiplex, modulation technique varies	Time Division Multiplex, modulation technique varies	Time Division Multiplex, modulation technique varies
3. Carrier Frequency Band	Baseband and various carrier bands	151 to 174 MHz 405 to 430 MHz 450 to 470 MHz 928 to 960 MHz	928 MHz to 40 GHz	902 to 928 MHz
4. Bandwidth/Channel Bandwidth	Various	25 KHz channels	Varies	Varies
5. Data Rates per Channel	Ranges from 2.4 Kbps to upwards	9.6 Kbps	Up to 7.5 Mbps depending on channel allocation	200 Kbps (typical)
6. Transmission Range or Repeater Spacing	N/A	Several miles	Range varies and may extend to several miles depending on frequency and other variables	0.5 miles to several miles
7. Government Regulation of Channel or Service	Tariffs filed with State	FCC licensing of channels for each network	FCC licensing of channels except for channels in 31 GHz band for each installation	No license in the 902-928 MHz band for the network
8. Types of Information Supported	Data, voice, Codec	Data	Data, voice, analog TV, Codec	Data, Codec
9. Owned or Leased	Leased	Owned	Owned	Owned
10. Constraints on Use	N/A	Channel availability, line of sight in 900 MHz band, multipath sensitivity, geometries	Channel availability, line of sight availability, multipath sensitivity, geometries, weather	Line of sight, geometries, protocol compatibility

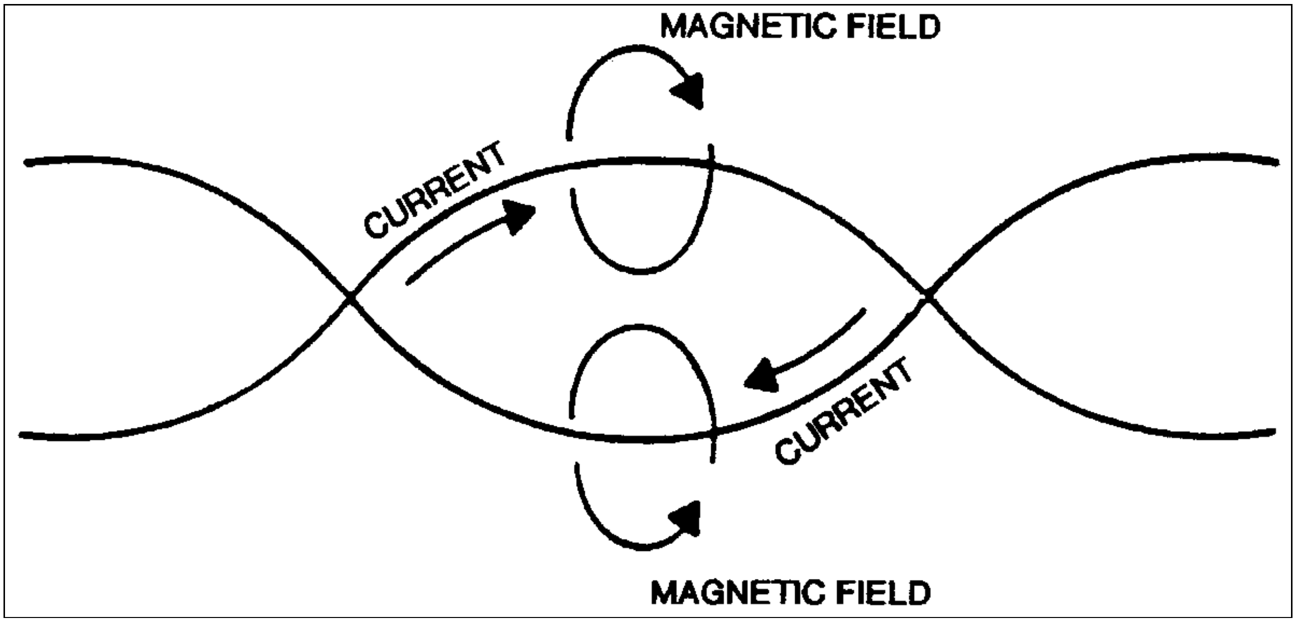


Figure 9-18. Crosstalk reduction by a twisted wire pair.

The local telephone company is sometimes called the local exchange carrier (LEC). In addition to voice grade service, LECs also offer digital private line data service, allowing duplex transmission of digital signals using digital facilities. Synchronous speeds of 2.4, 4.8, 9.6 or 56 Kbps can serve to communicate to field devices or maintenance shops. Additional applications for these services include communications between traffic operation centers.

The LECs also make available higher capacity digital transmission channels such as T1 (i.e., 1.544 Mbps). These facilities can transmit coded video to link traffic operation centers.

Local Exchange Carriers (LECs) now face increasing competition from alternative local communication providers. A recent agreement in New York allows 1 alternative access vendor also to supply circuits to the LEC central office, thereby providing access to local switched services (9). Other vendors are working to obtain similar agreements with LECs.

Most vendors offer high capacity DS1, DS3 circuits; in addition, some vendors supply voice grade, digital data service and fractional T1 circuits.

Traffic control applications may use alternative fiber network vendors in specialized circumstances. For instance, a metropolitan traffic control application requiring high-capacity leased links between traffic operation centers might benefit by using an alternative access provider, assuming the network serves the desired locations. On the other hand, an alternative access vendor may not provide service for low capacity data links to scattered locations as required for many traffic control applications.

Installation Considerations

Twisted-pair cable can be installed by one of the following methods or some combination:

- Underground, in conduit,
- Underground, by direct burial,
- Aerial, using existing/new utility poles, and
- Support of cable or conduit by bridges, overpasses, and elevated highway and rail structures.

These methods are also used to install other types of cable.

Coaxial Cable

Coaxial cable communications is a broadband technology with the capability of carrying many communication channels to transmit either data or video.

The operating agency may own the coaxial cable system or obtain it from the community antenna television (CATV) provider. In some cases the CATV supplier must provide services to satisfy franchise requirements.

Table 9-13. Copper cable dimension and cost data.

Number of Pairs	Cable Diameter in (mm)	Cable Weight per Foot lb/ft (kg/m)	Year 1992 Unit Cost* ft (m)
6	0.51 (12.95)	0.11 (0.16)	$ 0.32 (1.06)
25	0.78 (19.81)	0.28 (0.42)	$ 0.75 (2.47)
50	1.00 (25.40)	0.48 (0.72)	$ 1.29 (4.24)

* *Cost is for a 22 gauge PE 39 cable with solid insulated conductors and a core that is filled with FLEXGEL filling compound for moisture protection*

Table 9-14. User-owned versus leased wire-pair cable.

Feature	User-Owned	Leased
Capital Cost	High - especially when installed underground in new conduit	Reasonable - involves connection from access points to cabinets and from central facility to manhole(s) or other cable access
Ongoing (Maintenance) Cost	Reasonable - owner has full maintenance responsibility	High - lease costs almost always tied to general service rate increases. Agency must maintain connection described above
Response to Maintenance Requirements	May be better or worse than leased line service depending on jurisdiction's capability	In some cases can be specified
Maintenance Responsibility	Clearcut - always borne by the owner	Sometimes difficult to determine whether problems are the responsibility of lessor or lessee
Control of Communication Network	Excellent - owner is user and can fully control	Less control - communication traffic requirements and limitations on leased channel may impede use
Design of Communication Network	Completely flexible since designer/owner starts from scratch	Constrained by telephone company cable network. In most cases it is generally compatible with signal system requirements.
System Expansion	Cost determined by location of expansion	Accessibility to expansion site usually available
Reliability	Excellent - with proper maintenance procedures	Good to poor - depends upon lease contract terms and level of owner's maintenance function

The 1970s and early and middle 1980s saw the installation of a number of owned coaxial cable systems. The use of coaxial cable for freeway monitoring systems proved common during this period. Towards the latter 1980s, fiber optics (see subsequent description) increasingly supplanted owned coaxial cable. Communication services provided by community antenna television (CATV) operators continue to be used.

Coaxial cable (*coax*) consists of a single inner conductor and an outer annular conductor (shield), whose center is coaxial with the center of the inner conductor. The annular space between the conductors is filled with a dielectric material selected for its:

- Electrical properties:
  - Insulation resistance,
  - Dielectric value, and
  - Dielectric strength.
- Mechanical properties:
  - Strength,
  - Lightness, and
  - Water absorption characteristics.

The cable's design provides:

- Minimum signal losses,
- Large signal information capacity,
- Low signal interference susceptibility, and
- Low signal leakage (4).

Figure 9-19 shows a schematic of coax cable construction (1). Traffic control applications commonly use a 0.75 in (19.05 mm) semi-rigid coax for trunk lines, with smaller diameters for connections between the trunk and field drops.

A traffic control communications system using coaxial cable consists of coaxial cable and repeater amplifiers arranged as a tree network connecting a traffic operations center communications unit with transceivers at each intersection. The cable and amplifiers have a wide radio-frequency bandwidth (5 MHz to 400 MHz), which can handle the communication requirements of any traffic control system, and accommodate many television channels. The cable has moderate signal attenuation losses, while the repeater amplifiers have low noise levels and excellent signal linearity over a wide range of output levels. The repeater amplifiers are placed along the cable network at points where the signal has attenuated to the minimum permissible level. By using appropriate filters and amplifiers at the repeater positions, the cable can carry signals in both directions simultaneously. This is done by dividing the total bandwidth into 2 parts, 1 for signals toward intersections, and 1 for signals from intersections (a form of FDM) (4).

A coaxial cable system uses frequency-division multiplexing (FDM) and time-division multiplexing (TDM) to accommodate all traffic control signals on a single conductor. TDM techniques transfer information between the central unit and the intersections.

Cable TV Providers

CATV may prove a reasonable option if:

- Franchise agreements allow government use of the CATV system,
- CATV company offers communication channels at favorable rates, and
- Technical requirements prove satisfactory.

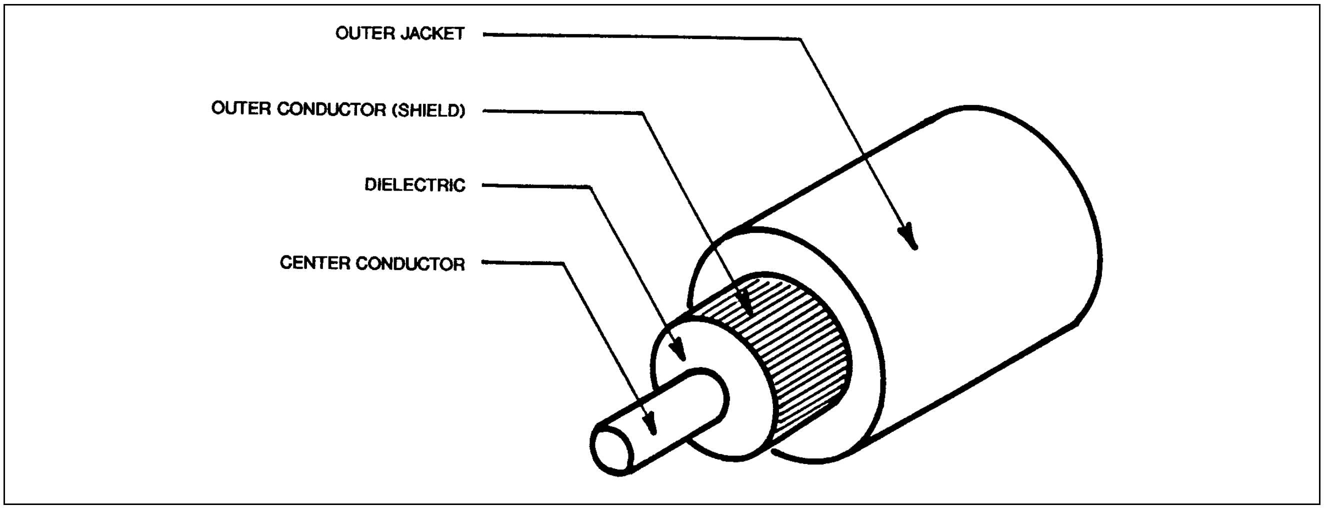


Figure 9-19. Coaxial cable construction.

Table 9-15 summarizes the advantages and disadvantages of CATV for traffic control applications (1).

Agencies have successfully implemented traffic control systems using CATV. Overland Park, KS, has operated such a system for many years. Similarly, systems have been successfully implemented in Paterson, NJ, and Dallas and Richardson, TX.

Fiber optic transmission technology is currently available to CATV providers and some have plans to convert their networks. CATV technology generally proves compatible with traffic control system requirements; however, the feasibility of using this technology must be studied for each system.

Fiber Optics Communication

This section summarizes fiber optic techniques applied to traffic systems. See the Communications Handbook for Traffic Control Systems for a more detailed description (1).

Starting with the 1980s, the telecommunications industry deployed fiber optic communication systems to provide high-volume, cost-effective trunks for voice and data. As the cost of deploying fiber decreased and the construction process matured, fiber optic communications became increasingly used for owned wireline traffic communication systems. Fiber optics technology provides the capability to carry high data rate signals or video signals over long distances (low attenuation) and with virtual immunity to electromagnetic interference.

An optical fiber consists of:

- Core region,
- Cladding, and
- Jacket.

The core of an optical fiber guides light by total internal reflection off the boundary of the cladding that surrounds it. A protective jacket surrounds the cladding. Figure 9-20 shows a schematic of fiber optic cable.

Figure 9-21 depicts light entering at the left and propagating through the fiber (1). Light rays entering the core at less than the critical angle (an angle determined by the optical properties of the core and cladding) refract into the not highly transparent cladding and attenuate. Light rays entering at greater than the critical angle reflect and continue to propagate in the core.

Dispersion and Modes

The spreading or dispersion of light pulses determines the information carrying capacity, or

Table 9-15. Advantages and disadvantages of CATV.

Advantages
• Single 6 MHz channel adequate for data transmission
• Network already in place
• Design effort and initial installation cost much lower than a dedicated coax system
• Franchise agreement may provide for government use of CATV cable and bandwidth at reduced rates or free, reducing recurring costs
• Second separate coax institutional network (I-net) may exist for the express purpose of providing bi-directional services to commercial subscribers
• I-nets generally provide good levels of service to subscribers
Disadvantages
• Most CATV networks designed and installed with emphasis on downstream transmission of video signals to cable subscribers
• Video channels take up most available bandwidth
• Bandwidth available to traffic control may be very narrow, ranging from a single 6 MHz channel to 4 or 5 channels
• Single 6 MHz channel does not support full motion video transmission in addition to data communications
• Frequencies of available channels often least desirable in susceptibility to noise and interference
• Quality of video signal required for CATV considerably less than required for data. (Noise that does not adversely affect video (e.g., lines on a TV picture) may interfere with data transmission.)
• CATV subscriber facilities sometimes concentrated in residential areas
• Service to the CBD and industrial areas sparse or nonexistent
• Area of coverage and network layout may not coincide with traffic signal locations
• Traffic control system may have to compete with other public section I-net users for more desirable channels

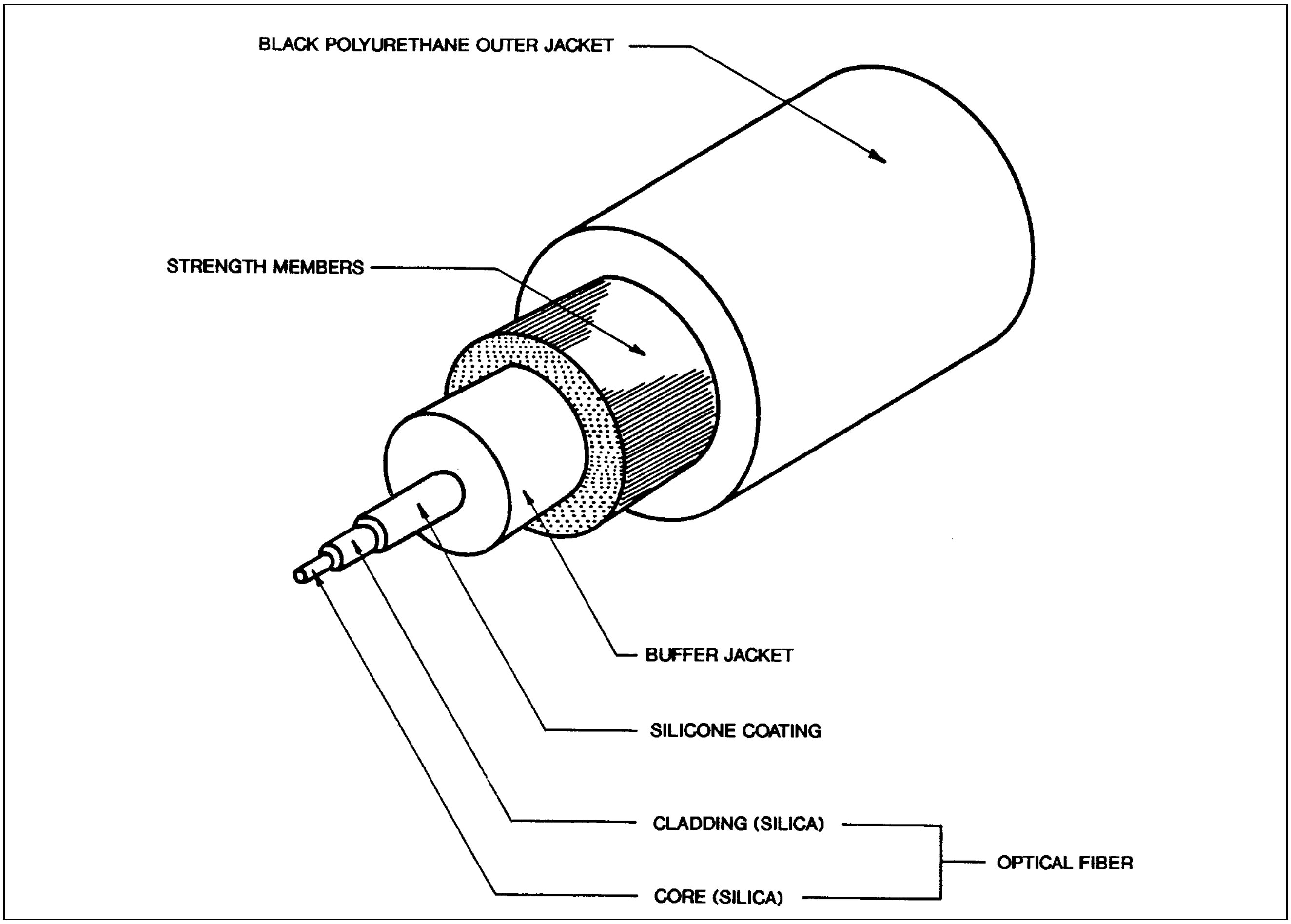


Figure 9-20. Fiber optic cable.

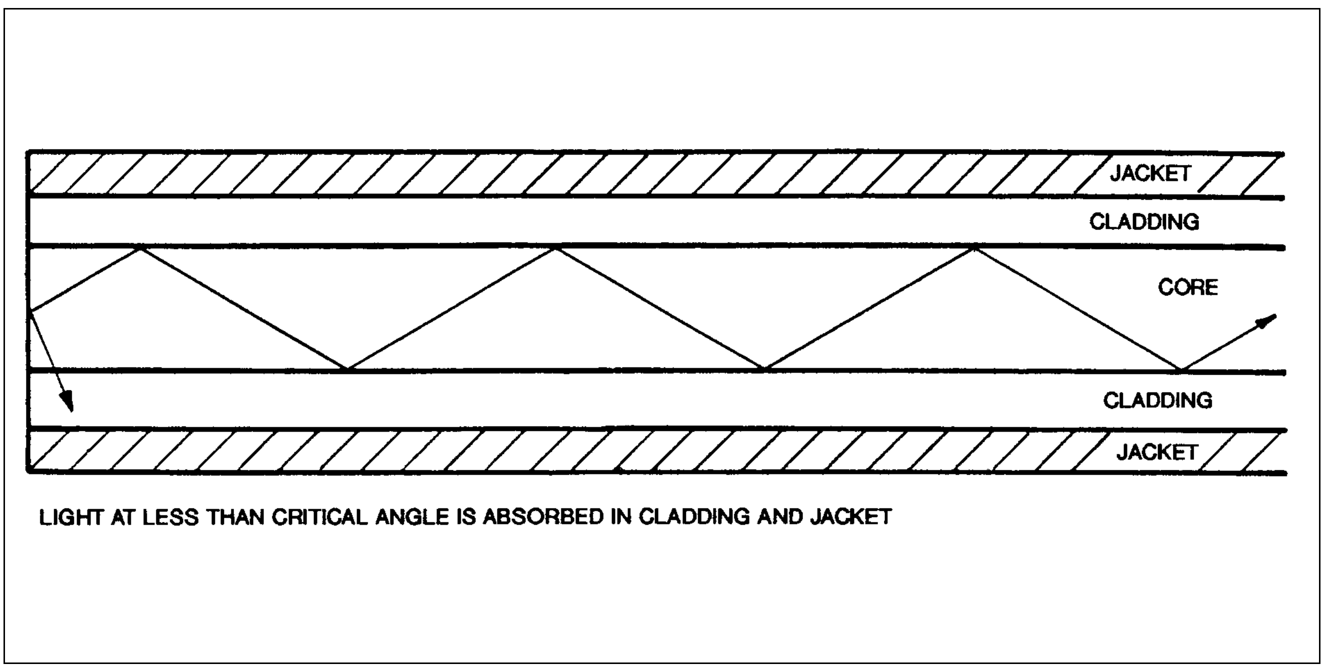


Figure 9-21. Light propagation in optical fiber.

bandwidth, of fiber. Rays entering the fiber at different angles travel different distances through the same length of fiber. This causes a pulse of light to broaden as it travels along a fiber.

As the pulses spread, they overlap and may interfere with each other. Dispersion limits the data transmission speed. It increases with distance; thus the maximum transmission rate decreases with distance.

Maxwell's equations govern the propagation of electromagnetic waves. When a guide such as an optical fiber confines electromagnetic waves, the solution to these equations leads to modes. In essence, a mode represents a path that a light ray can follow as it travels along a fiber. The number of modes or paths supported by a fiber relates to the core diameter; the larger the diameter, the greater the number of modes that propagate along the waveguide (fiber). *Multimode fibers* refer to optical waveguides that support many different modes of propagation. Optical fibers sufficiently thin and with the appropriate refractive indices support only a single mode of propagation in the core and are called *single mode* fibers. Dispersion is much smaller and attenuation much lower in fibers that carry light in only one mode. Dispersion (pulse spreading effect) increases as the number of modes increases, as shown in Figure 9-22 (1).

To compensate for modal dispersion, graded-index fiber may be used. Graded-index multimode fiber reduces dispersion by having a variable index of refraction highest on the fiber axis and lowest at the core-cladding interface. Since light travels more slowly in an optically dense medium (higher index of refraction) than in a less dense one, the light from each angle arrives essentially together, thus greatly reducing pulse spreading.

Attenuation

Attenuation (loss of light energy) may result from:

- *Absorption*, where propagating light interacts with impurities in the silica glass,
- *Scattering*, where geometric imperfections in the fiber cause redirection of light out of the fiber, or

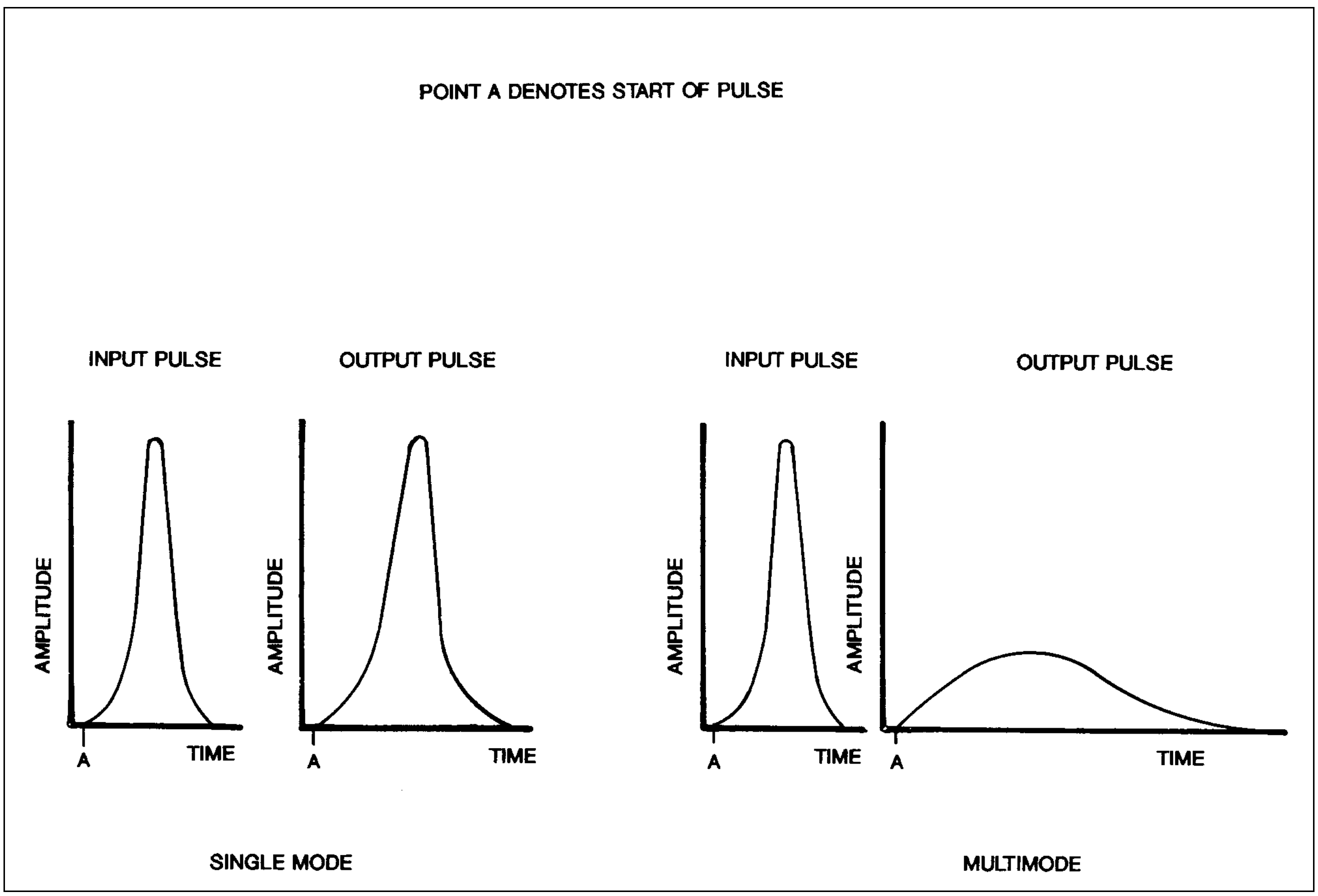


Figure 9-22. Response of single mode and multimode fibers to input pulses.

Table 9-16. Example of fiber properties.

Property	Single Mode Fiber	Multimode Fiber
Core Diameter	8.3 microns	62.5 microns
Maximum Attenuation • At 850 nm (160 MHz-km) • At 1300 nm (500 MHz-km) • At 1310 nm • At 1550 nm	 N/A N/A 0.35 dB/km 0.23 dB/km	 3.75 dB/km 1.00 dB/km N/A N/A
Cladding Diameter	125 +/- 2 microns	125 +/- 2 microns
Outer Coating Diameter	250 microns	250 microns

- *Microbends*, which may occur during fiber or cable manufacture, and macrobends, which can result from improper installation practice (e.g., exceeding the minimum bending radius).

In general, single mode fiber has lower attenuation than multimode fiber.

Cable Options

A wide variety of cable options, including fiber count, exists to meet specific requirements. Dimensions of the fiber cable depend on the selected options, but the cable diameter will generally prove less than 0.69 in (17.53 mm).

Single mode fiber is strongly recommended for any communications link that serves as, or could evolve into, part of a backbone network. For non-backbone data links with significant equipment costs, equipment compatible with both multimode and single mode fiber should be considered. Table 9-16 provides an example of key properties typically found in single-mode and multimode fiber.

Light Sources and Detectors

The light emitting diode (LED) and the injection laser diode (ILD) are the 2 most common fiber optic light sources (10). These devices are mounted in a package that enables an optical fiber to be placed very close to the light emitting region. This couples as much light as possible into the fiber. ILDs operate much more efficiently than LEDs in percentage of optical energy coupled into the core of the fiber, while LEDs cost much less. ILDs produce light in a way that results in higher output powers and more directional beams. The higher drive currents and optical power levels make laser lifetimes shorter than LEDs. Both LEDs and ILDs operate in the infra-red portion of the optical spectrum. The operating wavelengths are chosen for compatibility with the best transmission wavelengths of glass fibers and sensitivity ranges of photo diodes. The most common wavelengths today are: 820 to 850 nanometers, 1300 nanometers, and 1550 nanometers.

Efficient coupling requires a light source similar in size to the fiber core. For small core single mode fibers, the best match is a semiconductor diode laser, which emits light from a region a fraction of a micrometer high and a few micrometers wide. Light emitting diodes (LEDs) with larger emitting areas work well with larger core multimode fiber.

Two types of optical detectors have become the most commonly used in receivers, P-n junction photodiode (PIN) and avalanche photo diode (APD). In general, the PIN costs less but provides a slower response time than the APD.

Detectors operate best over a limited dynamic range. Optical receivers must be used for the fiber size for which they were designed.

Fiber Splices

A splice permanently joins 2 optical fibers. In uncontrolled environments, installers encase splices in a closure designed to offer environmental protection and mechanical support. Field splicing methods for optical fibers group into 2 major categories:

- Fusion, and
- Mechanical.

The fusion splice proves the lower loss approach but takes longer to accomplish.

Connectors of various designs typically have losses ranging from 0.35 db to 0.7 db.

In controlled environments, relatively inexpensive interconnection cabinets (patch panels) terminate distribution (drop) cable. These cabinets can accommodate small fiber counts, terminating, splicing and storing 12 to 48 fibers. Front panel connectors facilitate the connection to the fiber optic modems and other equipment. Flexible jumper cables with factory installed connectors may be used between the cabinet and fiber optic equipment. Larger distributing frames are used at hub points or the operations center, where a single shelf may terminate up to 144 fibers.

An alternative distribution system used in traffic applications is a breakout box and cable assembly. These assemblies have factory installed jumper cables on one end and distribution cable on the other. These cables are pulled from the equipment cabinet (e.g., traffic controller) to a pull box and can provide connections for up to 24 fibers.

Fiber Optic Equipment

Fiber optic modems provide a function analogous to that of electronic modems. An electrical connector for a standard serial port such as RS 232C and a pair of fiber optic connectors are provided.

Some manufacturers produce a dual fiber optic repeater with an electrical port that can easily interface with both TS2 NEMA and Model 170 type controllers. When configured in a daisy chain topology, the controllers can communicate with the same polled protocol used in wired TDM multipoint communications systems in both centralized computer and closed-loop traffic control applications. These units are sometimes called drop/insert units. Figure 9-23 shows how a typical drop/insert unit may be connected in daisy chain fashion. Drop/insert units perform the following functions:

- Detect the optical signal,
- Provide the signal in electrical form for use by the traffic controller or other field devices,
- Inject a response, if necessary, from the traffic controller, and
- Convert the electrical signal back to an optical signal, and transmit at a higher power level than the original detected signal (regeneration).

In a daisy-chain configuration any failure of a drop/insert unit results in the loss of every drop

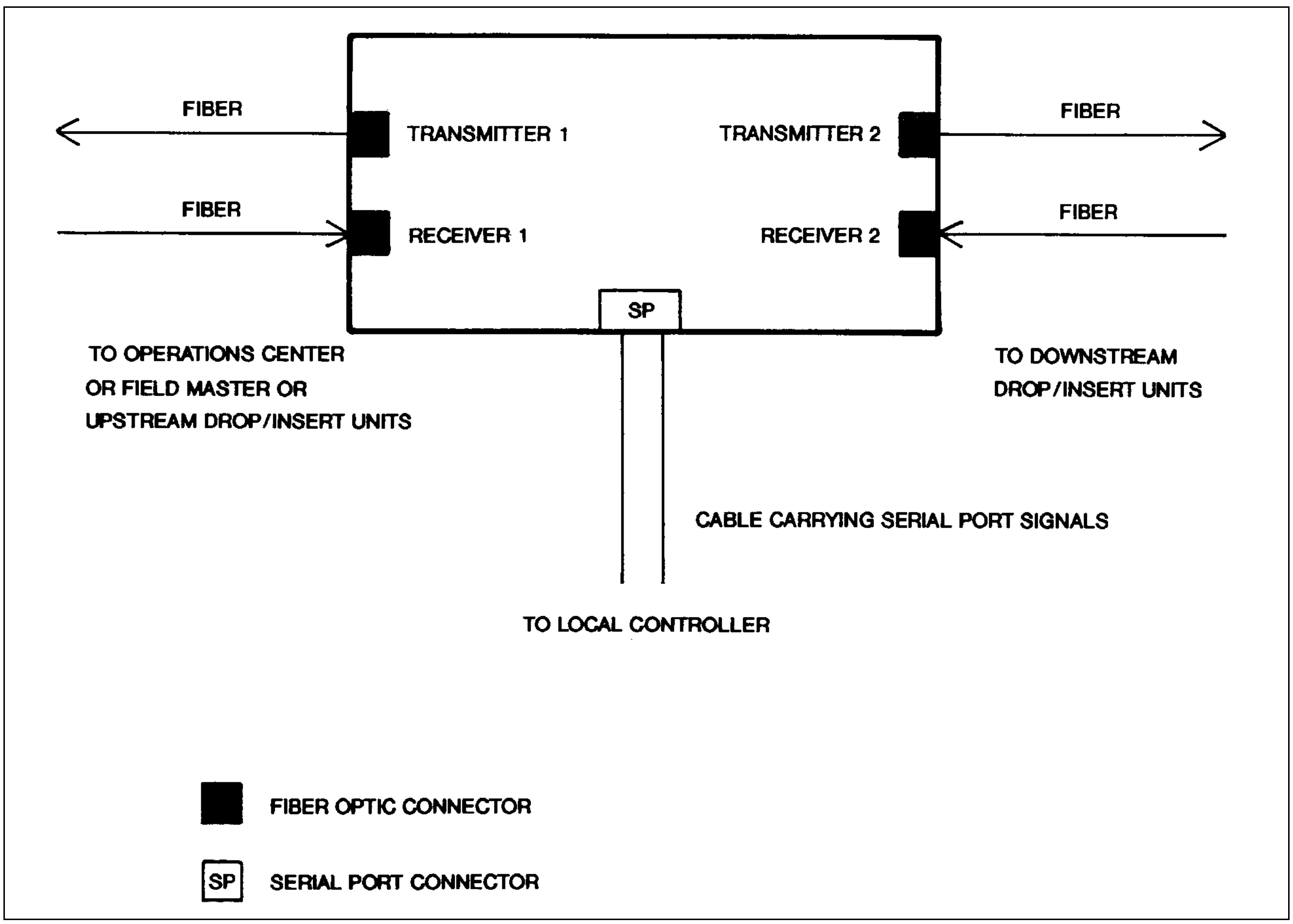


Figure 9-23. Connections for drop/insert unit.

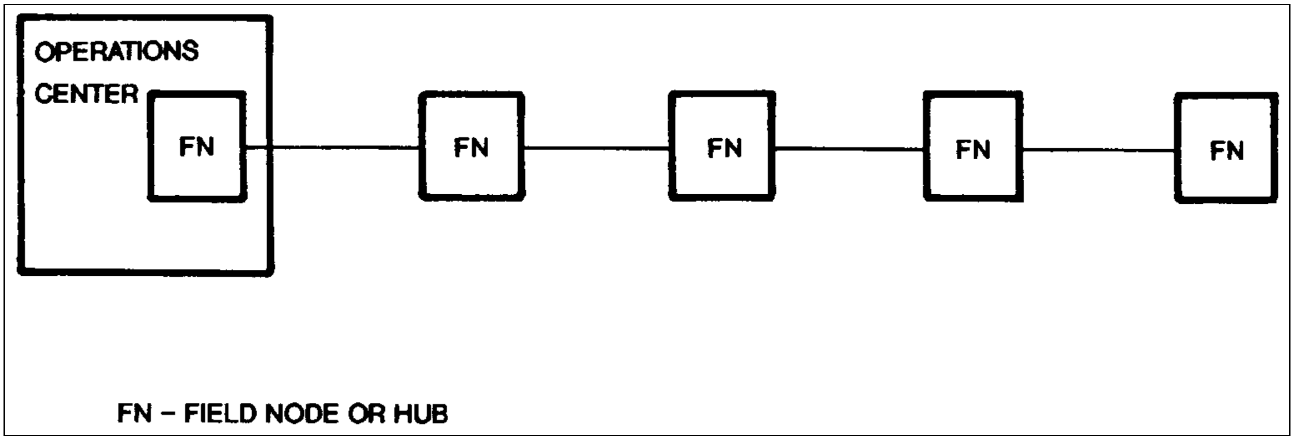


Figure 9-24. Backbone communications layout.

beyond the unit. However, units that contain a passive transfer feature can be used to avoid this type of failure. A separate battery backup for the drop/insert unit provides continued communication to the downstream units in the event of electrical power failure in the controller.

For fiber optic systems, multiplexers are classified into 2 types: electronic and optical. Electronic multiplexers combine signals electronically. This combined electrical signal drives a fiber optic transmitter. A technique called wavelength-division multiplexing (WDM) sends multiple signals down a single fiber optic channel at different wavelengths. For traffic systems, WDM does not prove cost effective for local distribution; however, it may be used for long distance backbone and trunk links.

Video Transmission

Video signals may be transmitted using fiber optics in the following ways:

- Baseband - Transmits unmodulated video signals,
- Modulated - Extends the transmission range using amplitude modulation or frequency modulation, and
- Multiplexed - Enables transmission of a number of video signals on the same fiber.

Organization of Fiber Optic Communication Systems

Figures 9-10 and 9-11 show the types of networks for small or moderate size traffic control systems. The networks can use either single mode or multimode fiber as appropriate (see previous discussion). They commonly use time-division multiplex (TDM) techniques as described in section 9.2.

Large scale traffic signal and freeway control systems frequently use an architecture comprising a backbone and distribution system. Figures 9-24 and 9-25 show a typical conceptual design. It uses a number of field nodes or hubs typically spaced at distances of several miles and connected by single mode fiber. A distribution system is associated with each node. An access multiplexer in the field node services data from the distribution system drop/insert. In some cases the distribution system servicing the field controllers uses twisted wire pair cable. The field node multiplexes the distribution channels using a higher data rate TDM channel. This information combines with signals servicing the other field nodes onto a single backbone fiber channel.

Signals from a number of video cameras are brought to the multiplexer by multimode fiber (in some cases via coaxial cable). Analog multiplexing combines these signals onto a single mode fiber. This fiber then becomes part of the backbone fiber cable system. Not shown in figure 9-25 are any ancillary channels required for camera control purposes.

An alternative technique converts video signals to digital format. It is likely that this technique will become more prevalent in the future. It is also compatible with video compression technology (Codec) previously described.

The backbone configuration depicted may use the SONET standard described in section 9.2.

Backbone systems of the type shown schematically in figure 9-26 lend themselves to a protected ring

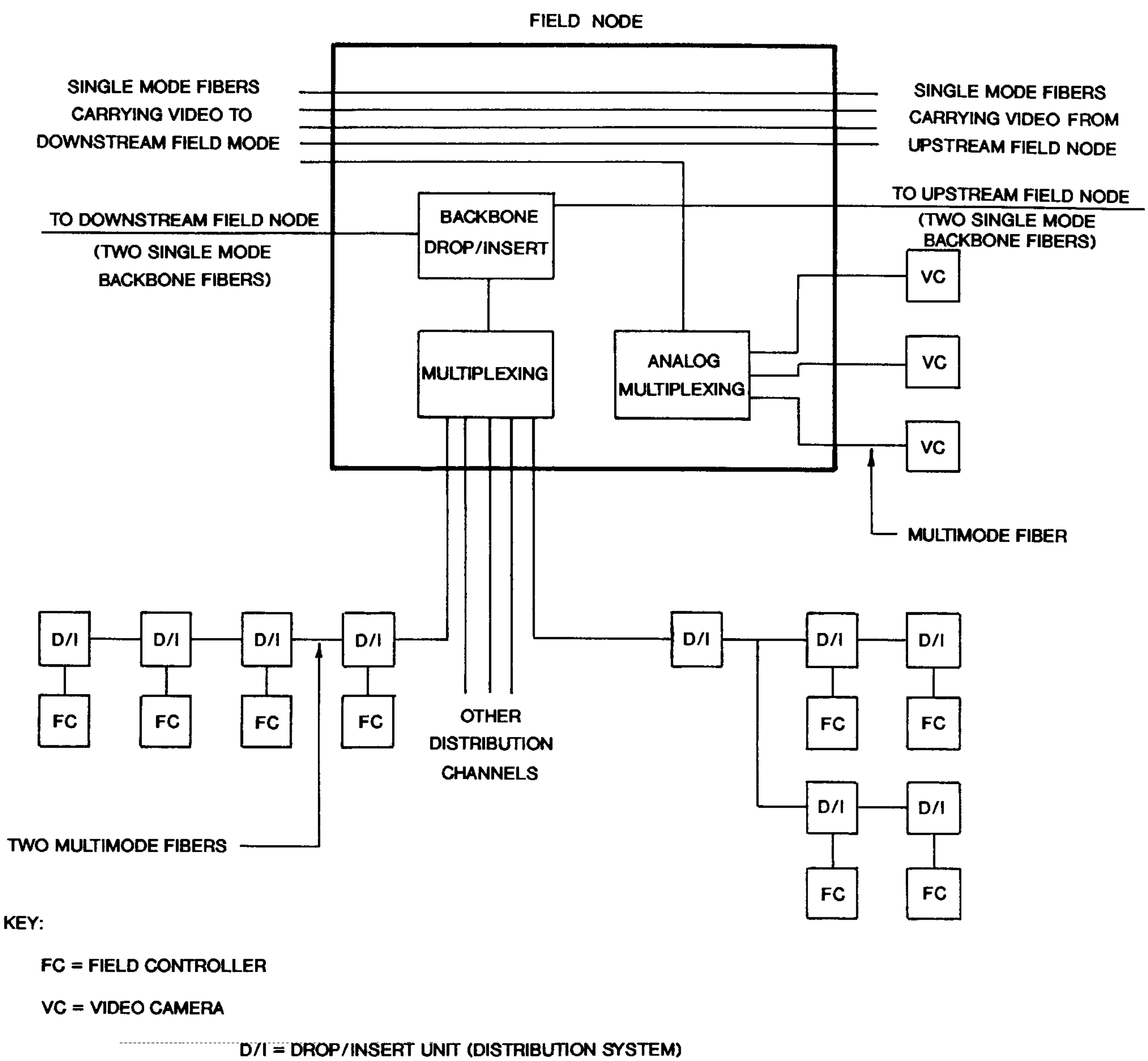


Figure 9-25. Field node and distribution system.

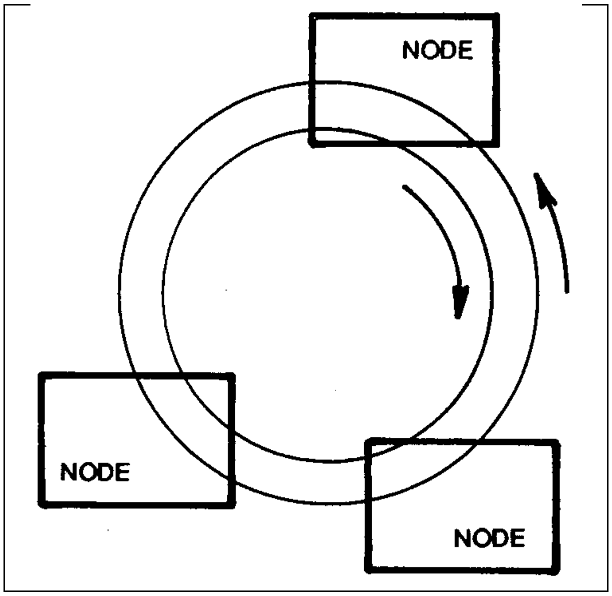


Figure 9-26. Protected ring configuration.

architecture. The same signal is transmitted in opposite directions over 2 different fiber sets. Loss of a node will therefore only affect distribution systems at that node. If separate cables are used for each ring, a cable cut will not result in signal loss at a node.

Radio Communication

Although land line communications have predominated in traffic control systems, the high capital or leasing cost make radio communications increasingly attractive, where applicable.

In addition to traditional radio media, traffic system designers now look to:

- Cellular networks,
- Satellite transmission,
- Packet radio,
- Spread spectrum radio, and
- Other data communications options.

Radio Design Considerations

Traffic system applications generally use radio frequency bands above 100 MHz. In addition to the general communication system design requirements described in the preceding sections, radio communication system designs must address the following:

- FCC regulations often limit the maximum radiated power and elevation of antennas, thus limiting range. Repeater stations may compensate for this.
- Some radio technologies require FCC licensing of the transmitter station. The scarcity of available channels limits the use of some radio technologies in many urban areas.
- Some radio technologies require line-of-sight paths between communicating sites. This may not be feasible in some cases.

Radio systems are subject to special propagation characteristics. The designer can calculate the attenuation in the signal path of a wireline system with good precision based on the medium's loss properties. In radio systems, however, attenuation properties of the medium may prove quite variable. The design must account for fading, the term for these variations. Two types of fading predominate:

- Multipath, and
- Power.

Multipath Fading

This type results from interference between a direct wave and another wave, usually a reflected wave. Multipath fading may display fades in excess of 30 dB for periods of seconds or minutes (3).

Figure 9-27 shows how changes in the phase of the reflected path signal can either add to or subtract from the direct path signal (11). The case of the subtracted signal (destructive addition) causes multipath fading.

Power Fading

Absorption by precipitation or water vapor causes an increase in loss through the atmosphere that appears at the receiver as a reduced signal. This loss becomes severe at frequencies above 11 GHz. The impact on traffic system communication depends on:

- Frequency band selected,
- Geographical location of the site, and
- Permissible amount of time with loss of communication.

Certain radio based communication equipment may have *turnaround times* that become significant fractions of the communication time period during a polling cycle. The designer should verify compatibility with the polling protocol when selecting equipment. If the manufacturer must modify its product for traffic applications, the designer should prepare a system specification rather than an equipment specification.

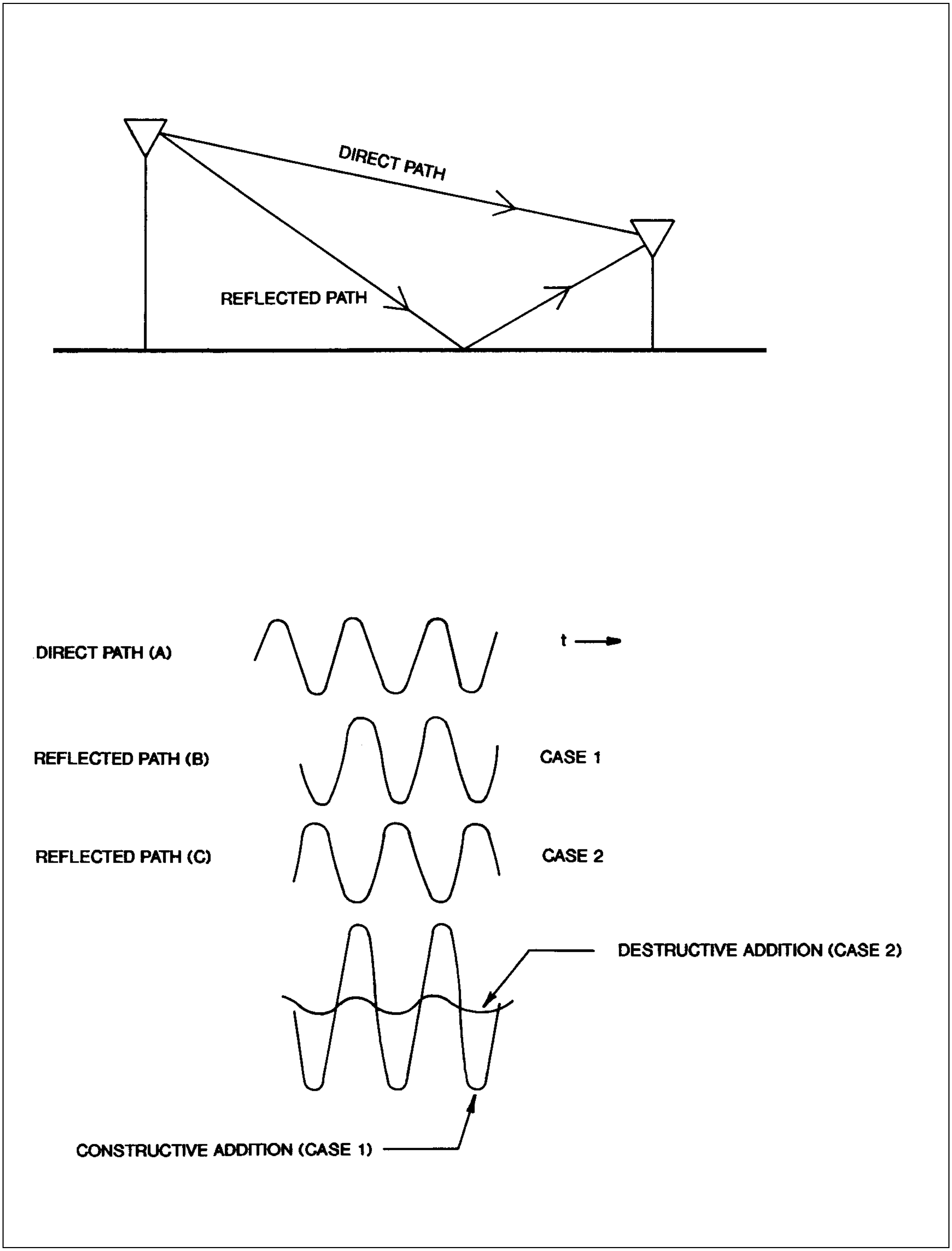


Figure 9-27. Nature of multipath fading.

Table 9-17. Owned radio communications.

Owned Radio Communications	Characteristics
Area Radio Networks (ARN)	• Operates in 150 MHz to 960 MHz bands • Requires FCC license
Terrestrial Microwave Link	• Operates in 928 MHz to 40 GHz bands • Requires FCC license • Can transmit data, voice, video, between 2 points
Spread Spectrum Radio	• Does not require FCC license in 902 MHz to 928 MHz band • Can transmit data and compressed video

Owned Radio Communications Technologies

Existing and planned traffic control systems use the following types of owned radio communications technologies:

- Area Radio Networks (ARN),
- Terrestrial Microwave Links, and
- Spread Spectrum Radio.

Table 9-17 summarizes the major characteristics of these technologies and table 9-18 presents advantages and disadvantages of radio communications (1).

Area Radio Networks (1)

Area radio networks (ARN), sometimes called packet radio, broadcast signals to an area rather than a specific location (not point-to-point or daisy-chain). ARN can operate traffic controllers and provide mobile voice communications with highway maintenance vehicles.

Area radio signals radiate in all directions, depending on antenna directivity. Unlike point-to-point microwave or spread spectrum radio, as the signal propagates it may:

- *Bend* slightly over changes in the ground surface,
- *Reflect* off buildings or other obstacles, or
- *Penetrate* into buildings.

Scattering and reflection allow the signal to propagate into built up areas although these effects reduce signal strength. Terrain barriers may limit feasibility of this technology.

One frequency usually serves all transmitters and another channel all receivers on the network.

Table 9-19 shows some properties of area radio networks.

Table 9-18. Advantages and disadvantages of radio communications systems.

Advantages
• No need for physical medium since signal propagates through atmosphere
• No cost of major landline installations and maintenance
• Used to span natural barriers or provide communications link between points where rights-of-way are not available
• Flexible implementation
• Commercial off-the-shelf equipment available
• Used in a number of traffic control systems
Disadvantages
• Relatively complex design (compared to landline communications systems) since the local operating environment (e.g., terrain, potential sources of interference, available frequencies, etc.) must be investigated and taken into account as part of design process. (However, a variety of theoretical models can be used to predict radio wave propagation for a given set of conditions.)
• Limited choices of operating frequencies based on regulatory issues
• Path line of sight constraints (e.g., in the microwave region of 900 MHz and above, line of sight to the receiving antenna(s) generally required). Propagation relationships govern the actual clearance required of obstacles and adjacent structures.
• Fading considerations
• Turnaround time considerations
• Limited bandwidth
• Requires external antennas and cable
• May require repeaters

Table 9-19. Key properties of area radio networks.

• **Commonly used bands:** 450 to 470 MHz; 928 to 960 MHz
• **12.5 KHz channels of for data, not video**
• **Point-to-multipoint service**
• **Repeaters sometimes used**
• **Turnaround times may prove too long for certain applications**

Terrestrial Microwave Links (1)

Traffic control applications have used terrestrial microwave links primarily as a communications trunk between offices and/or remote work centers (e.g., maintenance building) carrying voice and data. In some cases, microwave links communicate with signal controllers or transmit video information. Table 9-20 presents some properties of terrestrial microwave links.

Microwave signals radiate through the atmosphere along a *line-of-sight* path between transmitting and receiving antennas. Both technical and frequency utilization requirements dictate highly directional microwave frequency antennas. Since operating frequency may significantly impact microwave system design and performance, the designer should investigate frequency availability before selecting microwave radio as the communications medium for a particular traffic control application.

Spread Spectrum Radio (1)

The military initially developed *spread spectrum radio* (SSR) techniques during World War II to resist enemy radio interception and jamming. Since it was developed, SSR has been used for high-security applications that require jamming resistance, low detectability, and low interference to other systems operating in the same band. In 1985 the FCC opened several frequency bands for spread spectrum radio use without user licenses required.

Spread spectrum refers to a communications technology that spreads a signal over a wide range of frequencies at the transmitter, then compresses the signal to the original frequency range at the receiver. For example, the transmitter spreads a 1 watt 100 Khz bandwidth signal over a 100 MHz band using a technique that the receiver knows in advance, thereby allowing the receiver to collect the original signal.

Table 9-20. Key properties of terrestrial microwave links.

• Data and TV capability
• Line-of-sight
• Point-to-point transmission
• Usually use highly directional antennas. Antenna installation feasibility and cost may be key factors at lower frequencies.
• Power fading limitations above 10 GHz
• Can daisy chain for traffic signal control but path availability problem is compounded
• FCC has allotted spectrum for many bands above 928 MHz. Some bands require site licensing; others do not.
• Easiest bands to obtain are above 6 GHz. These are less costly but subject to power fading limitations.

This is an application of code division multiplexing (CDM). An important advantage with SSR and CDM is that separate channels do not require unique transmitter and receiver modules.

Figure 9-28 illustrates the difference between a conventional radio and a spread spectrum signal (12). The receiver can successfully decode a spread spectrum signal even if the noise level exceeds the signal level. The bandwidth of a spread spectrum signal (which carries the same data rate as a conventional signal) exceeds by many times a conventional signal's bandwidth.

Since each network works with a different code, different networks in the same location can use the same band.

Table 9-21 summarizes some of the key features of SSR as applied to traffic control systems.

Commercial Wireless Network Services

Commercial wireless network services may find application under certain circumstances such as temporary installations. This class of services is currently experiencing rapid expansion. It includes the following alternatives:

- Cellular radio service (cellular telephone) - Costs for these services include monthly minimums and air time charges.
- Packet radio service - Costs for these services include monthly minimums and packet use charges.

Reference 1 provides additional information.

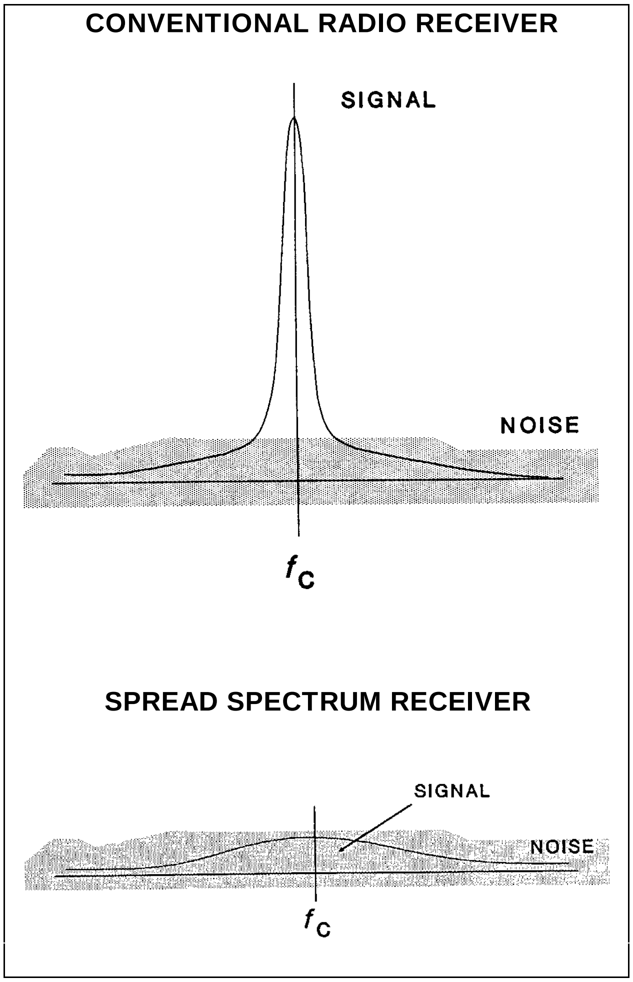


Figure 9-28. Conventional radio versus spread spectrum signal.

9.4 Communication System Planning

Previous sections have described communication fundamentals and technologies.

The *Communications Handbook for Traffic Control Systems* shows how to identify candidate technologies and make a selection based on life cycle cost and other factors (1).

The following paragraphs summarize the methodology.

The Handbook describes several traffic communications system architectures in a general format. It then defines generic data communication links to connect the elements of the architecture.

Figure 9-29 shows an example of an architecture with its generic links.

The Handbook provides a table that relates communication technologies with applicable generic communication links for both data and video. This relationship, together with certain physical constraints, screens out non-applicable technologies.

Additional steps comprise the selection process:

- *Perform Screening for Institutional Issues* - Institutional issues in selecting a communication system design may place constraints on the candidate alternatives.
- *Estimate Data Rate Requirements* - The Handbook provides information to assist in the estimation.
- *Perform Cost Dominant Screening for Leased Services* - A number of alternative communication services may be available for the communication level required. This step eliminates those that are not cost competitive.
- *Complete the Technology Screening Process* - Additional issues not covered previously are now considered. These include ensuring the availability of equipment that can:
  - Satisfy functional requirements,
  - Interface with field equipment (e.g., controllers), and
  - Satisfy environmental requirements directly or with suitable enclosures.

- *Determine Potential Feasibility of a Backbone or Trunked System* -- This step screens and possibly eliminates backbone or trunking communication architectures for certain traffic system types.
- *Determine Whether a Change in Media Provides a Reasonable Candidate(s)* -- Systems that change media while preserving the same channel capacity may prove useful in certain geometric or physical situations.
- *Define Technology and Multiplexing Alternatives for the Distribution System Technology* -- For each link type in the remaining set of candidate architectures, define the best multiplexing alternative for each remaining technology option. Consider the no multiplexing alternative.

  Many of the alternatives have been eliminated in the prior series of steps, leaving relatively few candidates for more detailed consideration.
- *Develop Cost Estimate for Distribution System Technology Candidates*

Table 9-21. Key features of spread spectrum radio.

- Power is transmitted over a very wide frequency spectrum at low power densities
- Unlicensed frequency bands:
- 902 to 928 MHz
  2.4 to 2.4835 GHz
  5.725 to 5.85 GHz
- SSR technology *sees* through interference by use of wide bandwidth and coding schemes. There is, however, some minimum noise floor.
- Basically lin-of-sight limited, SSR is insensitive to multipath interference. Can adapt to many obstacles in a traffic system environment.
- Data rates for present digital communications equipment range from 200 Kbps tp 300 Kbps. OK for traffic data use and low end Codec TV.
- Generally point-to-point repeaters may be used

Determine Remaining Non-Cost Related Issues - This step identifies issues that may be relevant such as risk of escalating future leased channel costs, service reliability differences and ease of maintenance.

- *Select Communications System Based on Cost and Other Factors* -- Because communications represents only 1 component of the traffic control system, evaluation techniques such as benefit/cost and utility/cost analysis may not adequately differentiate among competing communication system alternatives. The designer should use these factors, together with engineering judgement, to make a selection.

9.5 A Look to the Future

The following future trends are anticipated:

- *Increased public/private cooperative ventures* -- These will most likely include increased use of public rights-of-way for private wireline facilities not currently covered by franchise agreements. In return, communication cable, communication channels or communication services will be made available for government use.

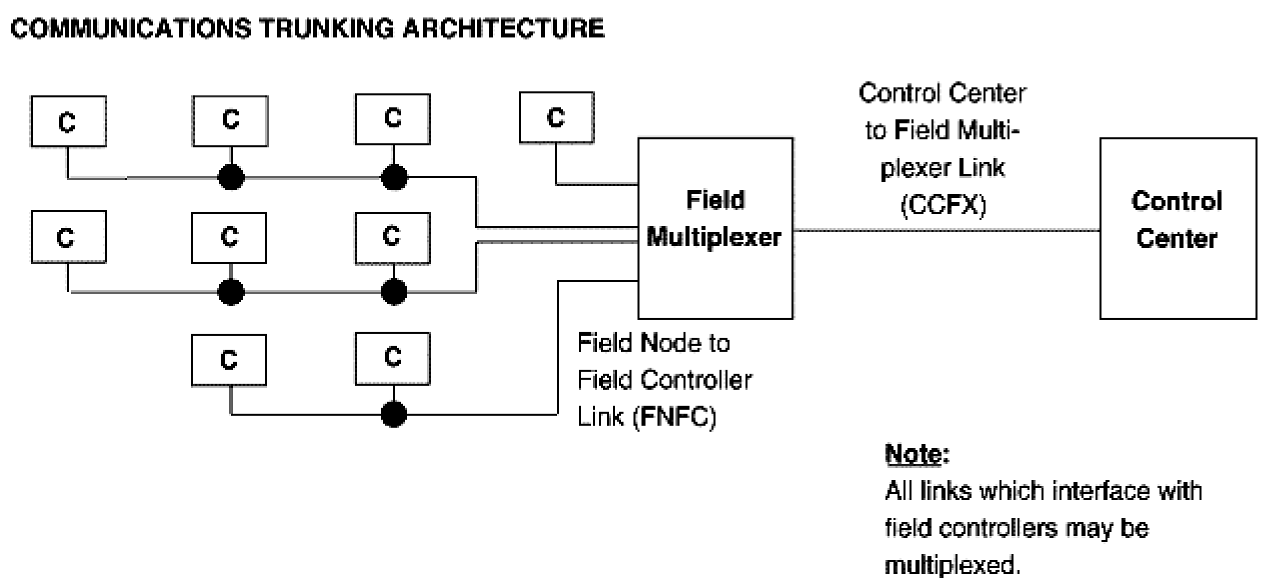


Figure 9-29. Example of communications system architecture and generic links.

- *Wider variety of telecommunication services, particularly data transmission services* - Leased channel services are being provided in increased numbers by a variety of wireline, microwave, and packet radio based service providers, thus offering traffic system operators a greater variety of options than previously available.
- *Increased use of wireless techniques to provide communications for surveillance systems* - Likely where cable run will be impacted by future highway construction or where a surveillance system can assist in traffic management during construction.
- *Increased use of short range wireless techniques* - This method avoids the costs of cable for runs facilities or other media for long range between detector sites and traffic controller or between TV cameras and ties to owned cable transmission of the video signal to the traffic operations center.
- *Increased use of digitally coded video data* - Transmission to traffic operation centers is conducted over:
  - Leased digital channels (or in some cases switched channels), and
  - Owned high capacity fiber optic facilities using standards such as SONET.
- Increased use of cellular and digital cellular radio
  - For temporary or portable facilities such as CMS.

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CHAPTER 10
TRAVELER INFORMATION SYSTEMS

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CHAPTER 10
TRAVELER INFORMATION SYSTEMS

Figure 10-1. Traveler information kiosk.

10.1 Introduction

The highway transportation system involves 3 major elements:

- Vehicle,
- Roadway, and
- Driver.

Of these, the driver is often the most complex element and the one most prone to failure. A majority of these failures are the result of errors in perception or processing of information that is:

- Inappropriate,
- Insufficient, or
- Overlooked.

Traveler information is essential for the roadway system to operate efficiently and safely. In mainline control, traveler information systems (TIS) advise motorists of freeway conditions so that the driver can take appropriate action, thus enhancing the efficiency and safety of traffic operations. Traveler information allows the driver to make informed decisions and act accordingly; i.e., continue on a planned route or divert to an alternate to avoid delays.

Chapters 3 and 4 discuss *functions* of traveler information systems on urban streets and freeways. This chapter summarizes TIS functions, but focuses on the hardware required to implement those functions.

The major visual techniques for conveying driver information include:

- External:
  - Signals,
  - Static signs,
  - Changeable message signs (CMS),
  - Portable signs,
  - Pavement markings, and
  - Lane-use control.

- Internal:
  - In-vehicle information, navigation, and route guidance (future).

Major audio techniques include:

- External:
  - Warning signals,
  - Public-address systems,
  - Telephones, and
  - Solar-powered telephones.

- Internal:
  - Commercial radio,
  - Radio broadcast data system (RBDS),
  - Cellular telephones,
  - Citizen band (CB) radio,
  - Highway advisory radio (HAR), and
  - Audio delivery of information from in-vehicle navigation systems.

This chapter identifies typical hardware associated with the various audio and visual techniques.

Table 10-1 shows the organization of this chapter.

10.2 Static Signs

Static signs convey only 1 message. Single-message displays are most useful in recurrent situations where the engineer desires the same driver response each time. Therefore, the engineer should position static signs in locations where the message always proves meaningful.

The Manual on Uniform Control Devices (MUTCD) remains the principal source of standards for static signs (1). The MUTCD also provides the traffic engineer with guidance on signs relative to:

- Use,
- Design,
- Application,
- Placement, and
- Maintenance.

The Traffic Engineering Handbook further clarifies some terms and procedures identified in the MUTCD (2). The Handbook discusses practical implementation and refers to other State and Federal documents that fill in details purposely left open by the MUTCD. Many states have standards that define their implementation of the MUTCD.

Static signs are classified into 3 basic types:

- *Regulatory* signs that inform roadway users of:
  - Traffic laws or regulations, and
  - The applicability of legal requirements otherwise not readily apparent.

- Warning signs inform roadway users of potential or existing hazardous conditions on or adjacent to a highway or street.

- *Guide* signs inform roadway users of:
  - Directions to common destinations,
  - Roadway identification via route markers, and
  - Other valuable information.

State laws allow for enforcement of these signs by police and other local authorities.
Table 10-2 provides examples of the intended use of each basic sign type.

Though normally considered passive, static signs can be transformed into *active* signs by adding flashing beacon signals. An active sign's message is valid only when the signals flash. Examples include:

- "Ramp Metering in Effect When Flashing," and
- "School Speed Limit XX MPH When Flashing."

Figure 10-2 depicts an active sign. Note the solar panels that power the flashing beacons. This display type compares favorably to changeable message signs in terms of both cost and the agencies' capability to fabricate it.

Active signs typically see use in traffic management functions and provide a lower cost solution than blank out signs (a form of changeable message sign). Section 10.3 further describes blank out signs. A time-clock switch closure or a communication signal can readily activate the flashing beacons associated with active signs.

Traffic engineers also add extinguishable blank out text to static signs, thus creating a hybrid. The blank out text activates when applicable and supplements the static sign message. Figure 10-3 shows blank out sign text added to a static guide sign.

The MUTCD also recommends the use of *diagrammatic* guide signs along freeways to:

- Graphically depict the exit arrangement in relationship to the main highway. Such guide signs have proven superior to conventional guide signs for some interchange types (1).

Table 10-1. Chapter 10 organization.

Section Title	Purpose	Topics
Static Signs	Describes basic functions of static signs	• Regulatory • Warning • Guide
Changeable Message Signs (CMS)	Describes applications of changeable message signs	• Standards • Applications • Credibility • Comprehensibility • Conspicuity and legibility • Display Types - light reflecting - light emitting - hybrid • Controllers • Installation, maintenance, and operation • Design and selection
Portable Signs	Describes the functions of portable signs	• Types of portable signs • Applications
Highway Advisory Radio (HAR)	Describes applications and uses of the highway advisory radio system	• Applications • Users • Messages • Vertical antenna HAR systems • Induction cable antenna HAR systems • Technical standards
Motorist Aid Systems	Describes the classification and uses of motorist aid systems	• Call box and emergency telephone system • Cellular telephone system - obtaining in-vehicle traffic information • Citizen band (CB) radio • CCTV monitoring system
Commercial Radio	Describes the use and importance of commercial radio	• Disadvantages of commercial radio • Sources of information
A Look to the Future	Describes concepts being introduced at the current time or in the future	• Automatic highway advisory radio • Radio broadcast data system (RBDS) • ITS in-vehicle information navigation and route guidance systems • In-vehicle signing

Table 10-2. Static sign use.

Static Sign Type	Purpose	Typical Uses
Regulatory	To inform motorists of traffic laws and regulations	• Intersection control • Definition of right-of-way • Speed limits • Turning movement control • Pedestrian control • Exclusions and prohibitions • Parking control and limits • Regulations associated with roadway maintenance and construction • Preferential vehicle (e.g., HOV) lane use • School zone restrictions • Railroad - highway at-grade crossing control
Warning	To warn motorists of unusual existing or potentially hazardous condition(s) on or adjacent to a street or highway	• Roadway width and horizontal and vertical alignment changes • School areas • Crossings and entrances to streets, highways, and freeways • Impending intersection controls • Road construction and maintenance • Roadway alterations • Advisory speeds • Unexpected crossing areas • Railroad-highway at-grade crossings
Guide	To provide destination and directional information	• Route markings and milemarkers • Destinations and directional arrows • Distances to destinations • General motorist services • Tourist, recreational and cultural interests • Roadway construction and maintenance detours • Exit numbering • Emergency evacuation routes

- Use at advance guide sign locations where:
  - Splits have off-route movements to the left,
  - Optional lane splits exist, and
  - Exits where route discontinuity and left-exit-lane drops exist (1).

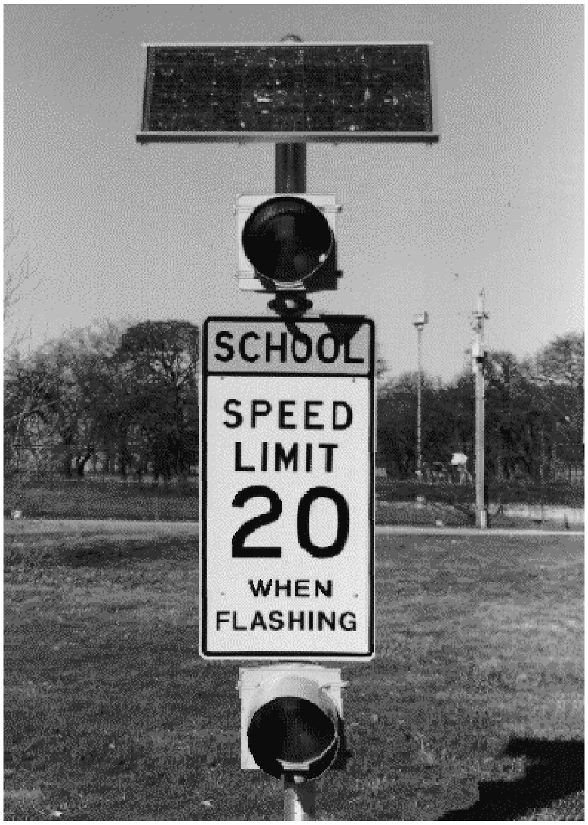
The MUTCD also includes standards for:

- Sign background,
- Letter color, and
- Shape and size.

Many signs for roadway maintenance and construction areas largely duplicate normal regulatory warning and guide signs. To identify their temporary character, all roadway maintenance and construction signs use an orange background.

The MUTCD also addresses signs for HOV and bicycle facilities, and provides information on the use of guidance devices such as:

- Object markers,



Courtesy of RTC Manufacturing, Inc.

Figure 10-2. Active sign.

- Pavement markings, and
- Roadway delineators.

Recent developments in static signs include:

- Solar-powered light emitting diodes (LEDs) to further self-illuminate static sign messages, and
- The addition of yellow or red LEDs to diagrammatic guide signs to indicate congested road sections.

Figure 10-4 depicts a static yield sign with LEDs incorporated to further distinguish the sign and draw attention to it.

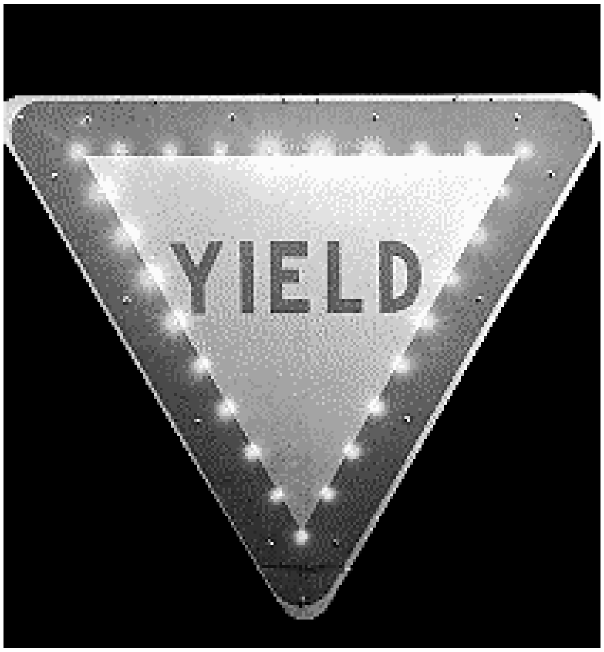
Figure 10-5 shows another method of internally illuminating static signs. The enclosure contains fluorescent lamps behind the sign panel that improve the sign's visibility.

10.3 Changeable Message Signs

Changeable (variable) message signs (CMS) electronically or mechanically vary the visual word, number, or symbolic display as traffic conditions

Courtesy of Electrofiberoptics Corporation

Figure 10-3. Static sign hybrid.



Courtesy of Interplex Solar, Inc.

Figure 10-4. LED illuminated static yield sign.

warrant. CMS have seen increasing use as an efficient means of conveying traffic information. This type of sign has emerged as a valuable tool that enables the traffic engineer to effectively communicate with the driver. While static signs convey a message about static situations, efficient roadway operation requires dynamic displays to advise travelers of changing conditions.

Standards

The MUTCD indicates that it *has not specified detailed standards for variable message signs* (1). Understanding that rapid technological advancements in CMS continue, it has instead chosen to:

- Encourage highway and transportation organizations to develop and experiment with CMS,
- Carefully evaluate installations so that a body of research and knowledge becomes available for future standards, and
- Inform future users of successes to emulate and pitfalls to avoid. Understanding that the technological and economic limitations associated with CMS often preclude conformance with the exact sign shapes, colors, and dimensions specified in the MUTCD, it nevertheless urges that CMS *ascribe to the principles established and to the extent practicable with the design and applications prescribed* (1).

No widely-accepted standard currently exists that addresses most aspects of changeable message signing. However, there does exist a large body of information and guidelines published mainly by Conrad L. Dudek and the Texas Transportation Institute (TTI) (3-9).

In addition, some State authorities have arrived at their own specifications and guidelines (10 -12).

Applications

CMS displays can address a wide range of traffic management functions. Changeable message signs usefully inform drivers of varying traffic, roadway, or environmental conditions. In addition to advising or requiring different types of driver action/reaction, multiple-message displays can also provide more specific information relative to locations, delays, and roadway conditions (3, 4, 12-17). CMS systems can perform a critical role on high speed highways by providing drivers with real-time information on current roadway conditions, such as:

- Incidents,
- Work zones,
- Weather, and
- Special events.

There exists little North American data or research that quantifies the benefits of CMS. However, in European Freeway Surveillance and Control Systems (FSCS), the combined use of CMS, lane control signals, and variable speed limit signs have significantly reduced the number of primary and secondary accidents. These systems warn motorists of:

Courtesy of American Signal Company

Figure 10-5. Illuminated fluorescent sign.

- Downstream lane or roadway blockages,
- Fog or reduced speeds, and
- Other perturbations to normal traffic flow (18, 19).

CMS systems have become increasingly important in improving the safety and operation of existing highway and urban facilities. For example, CMS represent the primary source of real-time motorist information in the Information for Motorists System (INFORM) in the Northern Long Island, N.Y. corridor and elsewhere (20, 21). These signs, placed at key locations along major roadways, indicate prevailing traffic and roadway conditions, and provide alternate routing information where applicable. Table 10-3 lists applications of various types of driver information displays.

Credibility

To operate an effective motorist information system, the operating agency must cultivate and maintain driver credibility.

To retain driver credibility, a CMS system must supply information that remains:

- Timely,
- Accurate, and
- Reliable.

Once the driver loses confidence, even the most elaborate and costly system can quickly lose its effectiveness. The transportation agency that operates the CMS system must devote time and resources to:

- Assure display of the proper messages at the proper time,
- Continually monitor the signs' operation for effectiveness and appropriateness, and
- Remove a message as soon as it becomes inappropriate (22).

Dudek has researched and conducted interviews with operations personnel to compile a list of ways in which drivers can lose confidence in CMS (i.e., pitfalls to avoid). Table 10-4 lists ways to prevent loss of CMS credibility.

Comprehensibility

For an effective CMS display, the driver must comprehend the message. *The comprehensibility of a sign is a measure of how readily an observer can understand the message intended to be conveyed by the sign* (7).

Table 10-3. Applications of changeable message signs and other types of real-time displays.

- **Traffic Management and diversion**
  - freeway traffic advisory and incident management
  - freeway-to-freeway diversion
  - special events
  - adverse road and weather conditions
  - speed control
  - overheight and overweight vehicles
- **Warning of adverse conditions**
  - adverse weather and environmental conditions (fog, smog, snow, ice, rain, dust, wind)
  - adverse road conditions (ice, snow, slippery pavement, high water)
  - truck load spills
- **Control at crossings**
  - bridge
  - tunnel
  - mountain passes
  - weigh station
  - toll station
- **Control during construction and maintenance**
  - warnings
  - speed control
  - path control
- **Special-use lane and roadway control**
  - reversible lanes
  - exclusive lanes
  - contraflow
  - restricted roadways

Source: Reference 4

Message design issues include:

- Element content,
- Information load in terms of units of information,
- Length of overall message,
- Presentation of message on CMS, and
- Redundancy of key words.

In composing messages for display on a particular CMS, the designer should:

Table 10-4. Ways to prevent loss of CMS credibility.

• Don't display inaccurate or unreliable information • Don't display information too late for drivers to make appropriate responses (untimely information) • Don't display messages that drivers don't understand • Don't display messages that are too long fro drivers to read at prevailing highway speeds • Don't tell drivers something they already know • Don't display information unrelated to: - environment - roadway - traffic condition - routing • Don't display garbled messages • Don't divert motorists to a route that does not offer a significant improvement

Source: Reference 7

- Assess how long it takes for a motorist to read a message of that length, and
- Determine the motorist's exposure time to the message.

Exposure time represents the length of time that the message remains legible to the driver. To read the entire message, exposure time must exceed reading time. Exposure time relates directly to the distance that the message remains legible at predominant driving speeds. Reading time depends on:

- The complexity of the concurrent driving task, and
- Various attributes of the message.

Table 10-5 presents a number of design guidelines and considerations for:

- Message length,
- Exposure time, and
- Display format (7).

Table 10-5. Message length, exposure time and display format design guidelines and considerations.

• Maximum message length is dictated by available or design exposure time • Maximum message lengths of 3 to 4 units of information push the limits of driver retention • Maximum of 2 units of information per sign line • Compact and chuck extended formats are recommended display formats for most freeway applications (see figure 10-6) • A run-on continuous train display of text moving across a CMS is not suitable for typical freeway speeds • Maximum message length of either 4 to 8 character words approaches the processing limits of drivers • Minimum exposure time of 1 second per 4 to 8 character word of 2 seconds per 12 to 16 character line CMS • For sequenced messages, additional exposure time is necessary or, conversely, shorter message lengths are necessary

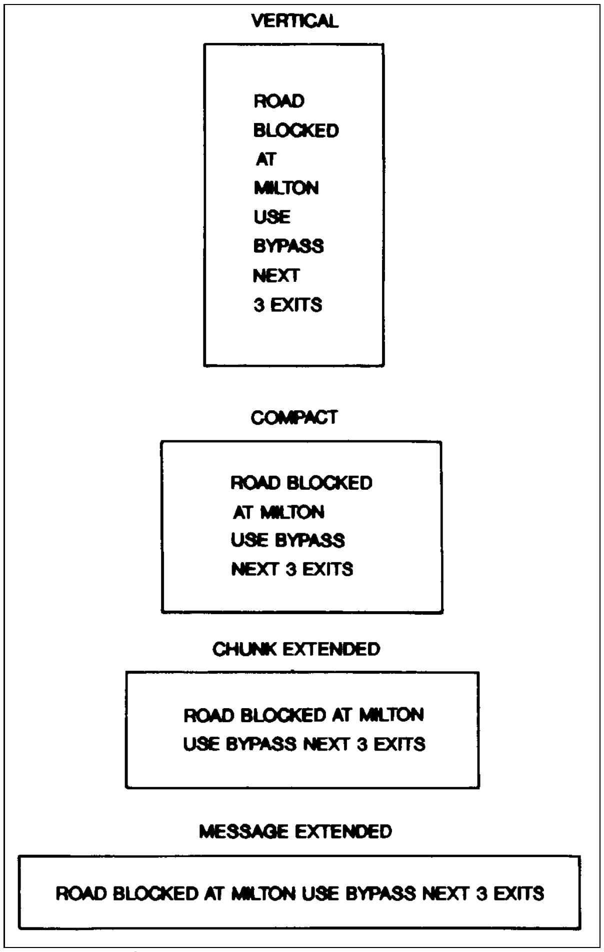
Conspicuity and Legibility

Two other functional requirements for CMS, *conspicuity* (target value) and *legibility* lead to the physical aspects of CMS technology. Conspicuity describes how noticeable a sign is - whether the motorist can pick it out of surrounding clutter and recognize its importance. Legibility refers to the readability of the sign legend. Together, conspicuity and legibility form the basis for the general criteria of visibility. Table 10-6 presents these factors (7).

The following section provides the traffic engineer with a working knowledge of the different types, features, uses, and effectiveness of CMS display technologies (4, 7, 9, 16, 17).

Display Types

A highway agency has access to a variety of CMS types, each with its own unique characteristics. A number of references describe the various types of CMS available today (7, 9).



Source: Reference 10

Figure 10-6. Discrete static message format types.

CMS fall into 3 basic categories:

- Light reflecting,
- Light emitting, and
- Hybrid.

Light reflecting CMS incorporate message characters made from materials that reflect light back to the motorist from an external source, such as the sun or vehicle headlights.

Light emitting CMS incorporate message characters that emit light generated within the CMS itself directly to the motorist.

Hybrid CMS incorporate message characters that both reflect light from external sources and emit their own generated light.

Each of these categories can be used in *matrix* CMS.

Matrix CMS enjoy widespread use, as transportation authorities take advantage of their enhanced capabilities. Matrix CMS allow complete variability as to message text, whereas other CMS may only allow a set of fixed messages.

A number of recent studies indicate the need for light emitting technology to compensate for a multitude of environmental and roadway conditions (23, 24). However, studies have not overwhelmingly favored one light emitting technology over another (23 -25).

Recent CMS installations have favored the purely light emitting and hybrid technologies while moving away from purely reflective technologies.

Table 10-7 provides the key aspects of various CMS technologies.

Light Reflecting

These displays use electromechanical principles to:

- Select among sets of fixed messages (each employing static sign type reflective legends), or

Table 10-6. Factors affecting conspicuity and legibility.

- Contrast of CMS and roadside environment
- Contrast of sign legend and sign background
- For light emitting displays at night, a legend too bright against the background may blur
- Position of the sun behind the CMS (the backlight condition) causes a blinding glare that reduces sign legibility
- Position of the sun directly facing a light emitting CMS will reflect off the light emitters and glass sign face, reducing the contrast between sign legend and sign background, which reduces sign legibility
- For matrix CMS, which form characters by pixel combinations, pixels must be spaced close enough to recognize a character but sufficiently far to distinguish the separate characters of a message
- Character height – an Ontario Ministry of Transportation study indicates that freeway CMS should have character heights at least 18 in (457 mm) (23). These characters approach the 50 ft/in (0.6 m/mm) legibility distance rule-of-thumb.
- Character width, font style and stroke width
- Character spacing
- Size of sign border

Table 10-7. Changeable message sign technologies.

Category	Type	Display Technology	Message Selection	Appearance
Light Reflecting	Foldout	Exposed mechanical mechanisms; sign panel flaps are in open or closed position	Non-matrix - typically limited to 2 messages	Sign displays conform to MUTCD standards for static signs
	Scroll	Enclosed mechanical mechanism; multiple sign faces are imposed on a continuous film and scrolled into place	Non-matrix - typically limited to 12 messages	Sign displays conform to MUTCD standards for static signs
	Rotating Drum	Enclosed mechanical mechanism; each line of display contains a drum with up to 6 message faces	Non-matrix - strategic selection of message faces on each drum	Sign displays conform to MUTCD standards for static signs
	Electromagnetic Flip Disk	Enclosed electromagnetic mechanism. Electronic signals cause small disks to rotate into position. Magnetic forces hold them in place.	Matrix - virtually unlimited selection of messages	Messages are formed from colored reflective pixels (typically yellow) against a black background (pixel color variable through coating on reflective surface)
Light Emitting	Neon	Non-mechanical, light source - glass tubes filled with neon are energized by electrical signals	Non-matrix - limited by sign surface area; multiple characters cannot be interwoven into same neon space	Typically, red neon messages form against a black background
	Fixed Grid Fiber Optic	Non-mechanical, light source - light energy (typically supplied by a halogen bulb) is guided through fiber optic bundles and emitted from pixel openings in the sign face	Non-matrix - multiple characters can be interwoven in same sign space. Total messages limited by sign surface area.	Messages are formed from lighted pixels (typically colored yellow with a filter) against a black background. Wide choice of pixel colors available through filter selection.
	Fixed Grid Light Emitting Diode	Non-mechanical, light source - each pixel is comprised of a number of light emitting diodes (LEDs) which emit light when an electrical signal is applied	Non-matrix -multiple characters can be interwoven in same sign space. Total messages limited by sign surface area.	Messages are formed from lighted pixels (typically colored yellow through multiple individual yellow LEDs or a combination of red and green LEDs)

Table 10-7. Changeable message sign technologies (continued).

Category	Type	Display Technology	Message Selection	Appearance
Light Emitting (continued)	Lamp Matrix	Non-mechanical, light source - (typically incandescent bulbs) formed into a matrix of pixels. Each pixel (lamp) is activated electrically.	Matrix - virtually unlimited message selection	Bulbs that emit white light offer best operational performance. Characters formed against black background.
	Light Emitting Diode	Non-mechanical, light source - each pixel is comprised of a number of LEDs	Matrix- virtually unlimited message selection	Messages are formed from lighted pixels (typically colored yellow through individual yellow LEDs or a combination of red and green LEDs) against a black background
	Shuttered Fiber Optic	Enclosed electro-mechanical shutter controls emission of light from pixels. Light energy (typically from a halogen bulb) is guided through fiber optic bundles controlled by shuttered pixel openings in the sign face.	Matrix - virtually unlimited message selection	Messages are formed from lighted pixels (typically colored yellow with a filter against a black background). Wide choice of pixel colors available through filter selection.
Hybrid	Fiber-Optic Flip Disk	Enclosed electromagnetic mechanism. Electronic signals cause small disks to rotate into position and are held by magnetic forces. Light energy, typically from a halogen bulb, is guided through fiber optic bundles and through an opening in or adjacent to the disk.	Matrix - virtually unlimited message selection	Messages are formed through the combination of colored reflective pixel disks (typically yellow in color) and the emission of fiber optically guided light (usually also colored yellow with a filter) against a black background
	LED - Flip Disk	Enclosed electromagnetic mechanism. Electronic signals cause small disks to rotate into position and are held by magnetic forces. Visibility of the reflective disk surface is enhanced by the incorporation of light emitted by LEDs.	Matrix - virtually unlimited message selection	Messages are formed through the combination of colored reflective disks (typically yellow in color) and the typically yellowish light emitted from LEDs against a black background

- Control the appropriate reflective disks in a matrix to form characters.

Several light reflecting sign technologies exist.

Foldout

The *foldout* sign serves as a relatively simple and effective 2 message sign, using a small motor to swing 2 hinged panels across the face of a standard sheet metal sign. This sign type can display:

- Two separate messages, or
- One message with the panels open (blank with the panels folded). The motor rotates these panels 180 degrees to change the display.

This sign type's ability to conform with MUTCD standards pertaining to sign legends, background and colors proves an important feature.

Since foldout signs are relatively inexpensive, they have seen wide use in the U.S. for a variety of situations:

- School zone control,
- Lane control,
- Turn movements,
- High-water warning, and
- Weigh stations.

The major problems with these signs result from the highway environment and mechanical failures, such as panels jamming due to severe ice or snow conditions. Figure 10-7 (a-c) illustrates the operation of a foldout sign.

Scroll

A *scroll* sign contains a tape or film rotated to properly position a desired message in the display window. The sign contains several stored messages, formed as a continuous belt of flexible material (plastic film), mounted on rollers at the sign's ends. The belt can rotate either vertically or horizontally.

As with foldout signs, scroll signs can conform to MUTCD standards pertaining to sign legends, background, and colors.

The enclosure's environmental sealing and protection is a desirable feature of this sign. Furthermore, some models have a standby power source and are manufactured for transportable operation. Unfavorable characteristics include:

- Limited number of messages (typically 8 to 12), and
- Length of time required to change messages which, if excessive, may cause driver confusion.

Figure 10-8 illustrates a scroll sign.

Rotating Drum

Rotating drum signs generally contain 1 to 4 multifaced rotating drums, each containing 2 to 6 message faces. Each face of a drum has 1 line of a fixed message formed to the panel. Drums pivot on the ends and rotate with a mechanical assembly to change the display. Figure 10-9 illustrates this type of CMS.

The drum sign's favorable characteristics include:

- Simple operation,
- Ability to operate from a 12-volt power source or hand crank,
- Low probability of garbled message, and
- Capability to conform to the MUTCD.

Since message faces are constructed similarly to static signs, they offer similar visibility characteristics. Compared to other non-matrix type CMSs, each fixed message display face panel may be easily removed and replaced by a different message display face panel. Sign legends and backgrounds may use any color combination and comply with MUTCD sign standards.

Unfavorable characteristics include:

- Lack of environmental sealing,
- Limited character size, and
- Limited number of faces on a drum.

Limitations on the number of displayable fixed messages makes these signs less flexible than Matrix CMSs. However, a 3-line, 6-face drum rotary display recently installed in Minneapolis, MN can display 150 usable messages.

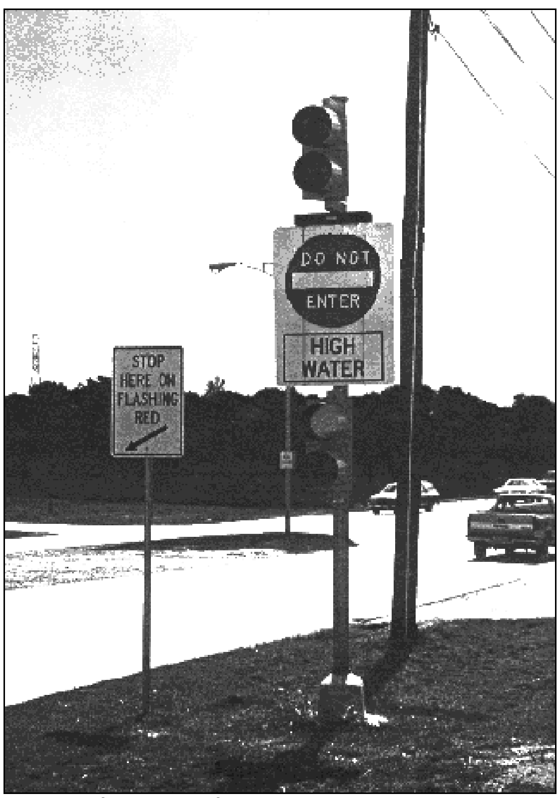
In the process of drum rotation, undesired messages may become visible to the motorist for short periods (e.g., 1 or 2 sec). In addition, mechanical failures can cause the drums to misregister when the limit switches become defective, which sometimes results in misleading information. Recently manufactured drum signs, however, have resolved the environmental problem by enclosing the face with a polycarbonate sheet. Anti-reflective coatings on the face reduce glare due to illumination by external light sources such as luminaires or vehicle headlights.

Courtesy of RTC Manufacturing, Inc.

(a). Foldout signs.

Courtesy of RTC Manufacturing, Inc.

(b). Foldout signs.



Courtesy of RTC Manufacturing, Inc.

(c). Foldout signs.

Figure 10-7. Operation of a foldout sign.

Electromagnetic Reflective Disk Matrix

A *grid* of disks forms these signs. Each disk represents 1 *pixel* of a typical 5 by 7 array of pixels reserved for each character.

Each disk has 2 sides:

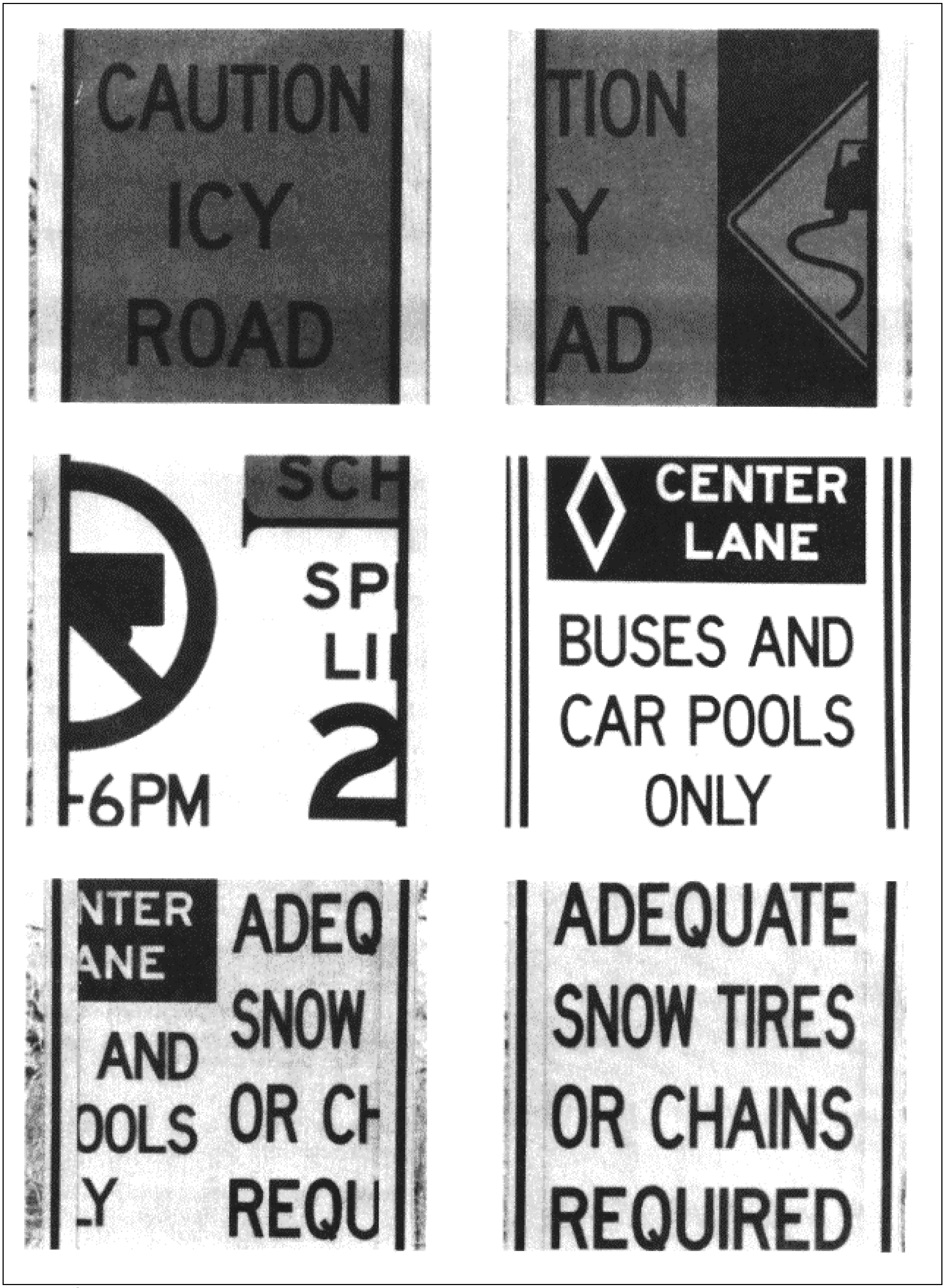
- One side is reflective yellow or white in appearance, and
- The other side is matte black.

A character forms by switching the appropriate subset of pixels to display their reflective yellow side. As with other CMSs, message lines may consist of any number of characters but usually do not exceed 24 characters per line.

Signs vary with regard to the construction of various pixel characteristics, such as:

- Reflective disk coating material,
- Reflective disk shape, and
- Disk rotational element.

In the simpler version, solid panels separate the 5 by 7 pixel arrays to dictate character spacing. Alternatively, a sign can contain a full matrix or continuous grid of disks across the entire display.



Courtesy of Skyline Products, Inc.

Figure 10-8. Scroll signs.

ROTARY DISPLAY USING STANDARD HIGHWAY REFLECTIVE BACKGROUND AND COPY

Courtesy of Skyline Products, Inc.

Figure 10-9. Rotating drum signs.

The sign achieves character spacing by leaving columns of disks with their matte black surface facing motorists.

Typically, full matrix grids include more pixels and cost more. Full matrix grids:

- Better suit graphic displays (often not used for traffic control applications),
- Allow for more accurate:
  - Spacing between characters,
  - Positioning and centering of words on a line, and
- Allow more flexibility of letter heights and line messages. For example, these signs can alternately display 3-line 18 in (45.7 cm) high messages and 2-line 24 in (61 cm) high messages.

The reflective disk matrix offers:

- Total message or display flexibility,
- Wider angle of legibility than LED or fiber optic displays, and
- Low power consumption.

Low power consumption results from:

- Use of magnetic principles to retain disk position in its last commanded state, and
- Low power needed to:
  - *Flip* disks,
  - Change messages (re-orient disks as appropriate), and
  - Provide face illumination only when needed.

Intrusion of excessive dirt and moisture can cause disks to stick or fail prematurely, which a suitably sealed enclosure can mitigate. At least one manufacturer cites disk reliability of 100,000,000 operations.

Some agencies have reported visibility problems, i.e., lower target values than for static signs of comparable size. This mainly results from the larger reflective surface area of static signs compared with only the reflective legends of the disk matrix CMS. Illumination becomes necessary during low ambient light or sun backlight conditions to increase the contrast ratio of the sign and make it more visible to the motorist. Problems of glare and blurring have resulted from external light sources reflecting off the sign face or from internal sources. Dirt and moisture collecting on the disk over time may reduce legibility. Various techniques can minimize these effects.

Figure 10-10 depicts an electromagnetic flip disk CMS.

Light Emitting

This technology formulates messages by lighted pixels or characters against a dark or black background. To remove messages, the sign

Courtesy of TELE-SPOT Systems

Figure 10-10. Electromagnetic flip disk CMS.

extinguishes all light sources and motorists only observe a solid dark or black background.

Message change times for light emitting CMS prove virtually instantaneous compared to the mechanical counterparts previously described, and the technology reduces maintenance due to mechanical moving parts.

Light emitting signs must incorporate a method of controlling light output levels in response to varying ambient lighting conditions. The sign must achieve maximum light output under bright sunny conditions, especially with the sun shining directly on the sign face. Unless controlled and reduced, the same light output at night proves irritating to motorists. Manufacturers of light emitting signs offer several steps of light output via photocell control of the light source power supply. The following light emitting technologies offer this feature:

- Fixed Grid Fiber Optic,
- Fiber Optic Matrix,
- Lamp Matrix,
- Fixed Grid Light Emitting Diode (LED),
- LED Matrix, and
- Hybrid.

Manufacturers supply various types of light emitting sign technologies in both non-matrix and matrix formats.

Light Emitting -- Non-Matrix

Signs of this type, often described as blank-out signs (BOS), offer a fixed selection of messages. The sign selects messages by activating the appropriate light source and extinguishing all others. If no message display is desired, the sign extinguishes or blanks out all lamp sources.

Neon

The *neon* or *inert gas* sign uses neon tubing to form legend characters. The sign display area limits the number of allowable messages. Designs can:

- Stack the neon tubing for each message, or
- Separate each message on the sign face.

A large number of messages requires numerous layers of tubing. This causes the emitted light to transmit through the outermost tubes, thus reducing message legibility. Alternatively, an enlarged surface display area will accommodate more messages.

The New Jersey Turnpike Authority has had considerable success with red neon during all types of weather conditions, and still procures red neon speed warning/speed limit signs for new installations. Two neon tubes per message provide redundancy. Experience shows that green neon does not prove acceptable for the highway environment.

Currently, neon signs do not incorporate light dimming and need customization for each application.

Fixed Grid Fiber Optic

A *fiber optic* display disperses light energy from a point light source through fiber bundles that form messages on the sign's face. Character pixels can interleave more readily than neon characters, and hence, a similar size sign space can incorporate more messages. European manufacturers have developed signs capable of displaying up to 14 messages. Figure 10-11 depicts a fixed grid, fiber optics sign used in an overheight vehicle detection system.

Although this type of display has seen use predominantly for lane and pedestrian control, some fiber-optic displays have been developed for:

- Variable speed limits,
- Weigh stations,
- Inclement weather,
- Alternate routing applications, and
- Dynamic lane assignments (26).

Figure 10-12 depicts a fixed grid fiber optic BOS used in a dynamic lane assignment application.

Dual color signal indications for left-turn lane control provide another example of fiber optics in traffic control. Dallas, TX has over 100 intersections using fiber optics for this application. This allows a vertical stack of four 12 in (305 mm) signal heads for overhead installations, with the bottom section providing both a green and yellow arrow during the change interval. Displays of this type are only acceptable if they meet the light output and color requirements of the MUTCD (1).

Fixed grid fiber optic signs offer acceptable light emission and low power usage but remain limited in message selection, especially compared to their matrix counterparts.

Fixed Grid, Light Emitting Diode

A light emitting diode (LED) is a semiconductor device that emits light when electrical current passes through it. A broad range of colors are available with the high output red, green, or yellow LEDs finding the most widespread use in the highway environment. A subsequent paragraph describes the construction of LED pixels and LED operational characteristics.

Courtesy of Fiber Optic Display Systems, Inc.

Figure 10-11. Fixed grid fiber optics BOS.

Like other varieties of non-matrix light emitting signs, this sign can be classified as a blank-out type. Manufacturers arrange LEDs in fixed formats to represent characters and messages. Multiple messages, comparable in number to the fixed grid, fiber optic type, can be arranged in the same sign face. Message and usage applications resemble those described for fixed grid fiber optic signs. Figure 10-13 depicts an example of a fixed grid LED, BOS type.

Light Emitting -- Matrix

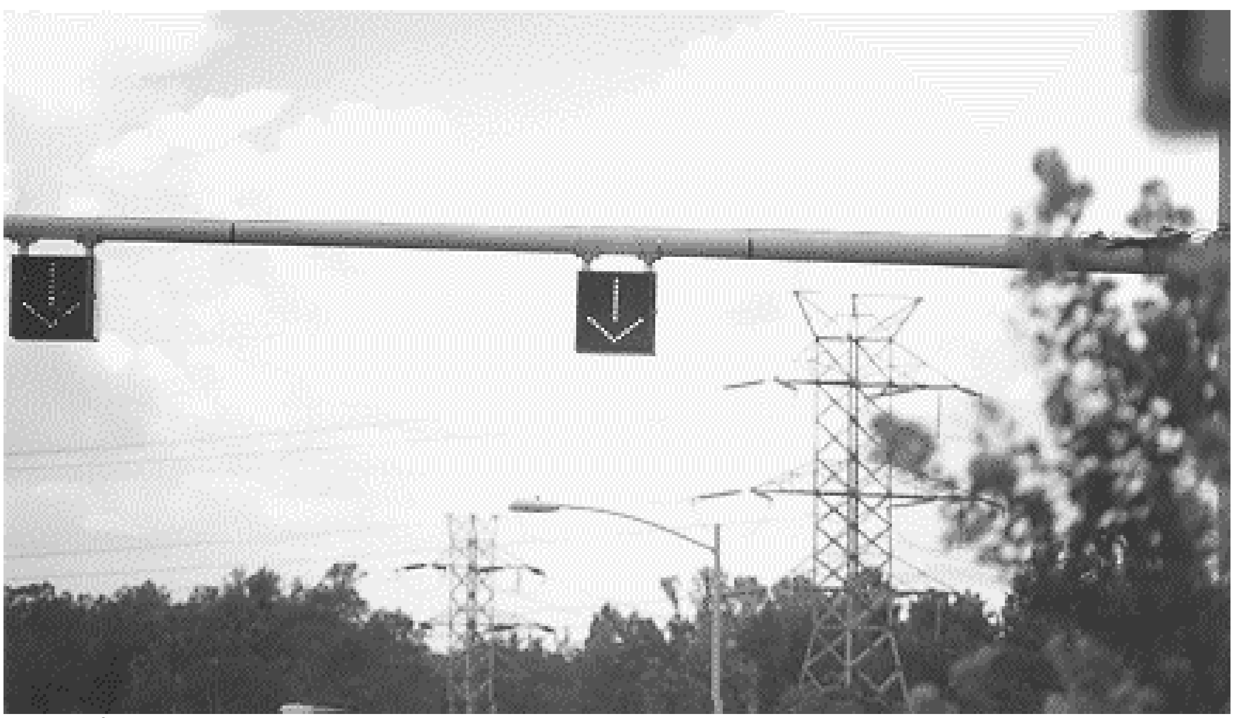
Signs of this type use matrices of pixels, each pixel representing an individual light source. Characters and messages form by activating the appropriate pixel/light source.

The matrix format allows for a much wider variety of message selection and total message flexibility. This sign usually carries increased complexity and higher cost compared with the non-matrix type.

Light emitting-matrix signs include the incandescent lamp, LED matrix, and shuttered fiber optic signs described in the following paragraphs.

Lamp Matrix

An array of incandescent lamps for each message line forms the face of a lamp matrix display. Selectively illuminating the lamps in a character module permits the display of various characters that form a message.



Courtesy of C.J. Hood Company, Inc.

Figure 10-12. Fixed grid fiber optic dynamic lane assignment.

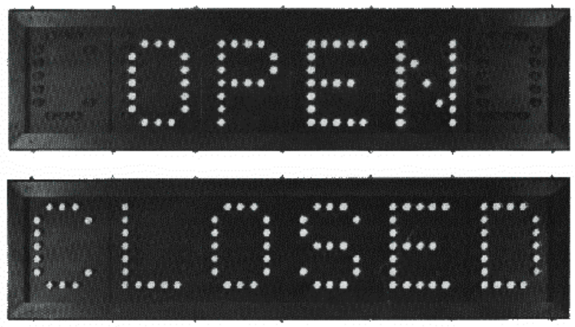


Figure 10-13. Fixed grid.

This type of CMS has the advantages of:

- A relatively simple operating principle,
- High target value,
- Message flexibility, and
- Proven operation in many environmental conditions.

Its disadvantages include:

- Requirement for continuous power to the lamps, and
- High operating and maintenance costs resulting from high energy and bulb replacement requirements (7, 27).

The California Department of Transportation (CALTRANS) continues to use lamp matrix signs as its CMS standard (Model 500). The Model 170 controller serves as the CMS controller, interpreting commands received from a control system and in turn applying electrical signals to appropriate controller outputs to formulate the desired message.

CALTRANS uses its own software to control and monitor CMS. The agency calls the central or laptop portion SIGNVIEW and designates the corresponding model 170 CMS field controller software SV170. SIGNVIEW offers many of the features incorporated into recent matrix sign controllers, described elsewhere in this section. The SV170 software permits limited access by users through the Model 170 keypad. Two of these features include:

- Stored message display control, and
- Monitoring status.

CALTRANS periodically evaluates other light emitting technologies, but currently believes that some have not sufficiently matured to become a long term replacement, and that none offer comparable visibility. CALTRANS is currently considering a more formal study of available technologies.

Light Emitting Diode Matrix

LED signs offer the promise of low power consumption and low maintenance but to date have not realized their potential.

LED signs can be constructed in a *clustered* or *discrete* format. The clustered format consists of a number of LEDs encapsulated closely together to form a removable pixel fixture. The discrete format mounts individual LEDs to a sign face, groups of them mounted more closely together to form pixels. To date, most LED signs manufactured for the roadway environment have been of the clustered variety to:

- Provide sufficient light output, and
- Obtain the desired amber message display color.

Early LED sign clusters comprised many individual LEDs, most green and some red. Green LEDs could not match red LEDs in light intensity and hence more proved necessary to match the output of the red LEDs. The combination of red and green LEDs provided the amber look desired by many highway authorities.

However, the red/green combination LED signs have not proven adequate for message appearance. LED output tends to decrease over time and vary due to temperature. Over time, LED sign pixel colors would change both on an absolute basis and with respect to one another. Continuously activated messages causes the uneven degradation of certain LEDs, giving the appearance of burned-in messages and uneven light output. Replacement clusters, installed to repair failed clusters, had a higher light output than their neighbors. The signs required extra power to:

- Remove heat build-up caused by the LED clusters, and
- Maintain a relatively cool environment to preserve LED life and operating characteristics.

Recent developments have led to the creation of a high-output, yellow LED. The Pennsylvania Department of Transportation has recently installed in the Philadelphia region one of the first overhead yellow LED matrix signs. Yellow LEDs are used in a clustered format. The number of LEDs has been considerably reduced, thereby decreasing power and ventilation requirements. To date, sufficient experience does not exist to determine the sign's performance over time, in terms of LED life, degradation and uniformity of appearance.

A study by a manufacturer offers promise for long term LED performance (28). The study indicates that in the older GaAsP (gallium-arsenide-phosphide) technology, light output degradation occurred as a function of drive current and operating temperature. The manufacturer states that the newer AlInGaP (aluminum-indium-gallium-phosphide) technology:

- Requires much less drive current,
- Produces more light output, and
- Proves less affected by equivalent operating temperatures.

At lower operating life (up to 1000 hours), light output degradation proves virtually non-existent. However, specific data for longer operating life for this newer technology is not yet available.

At least 1 manufacturer offers the overhead ITE yellow LED matrix manufactured in a discrete format. These promise a cooler operating environment for the LEDs, resulting in:

- Reduced ventilation requirements,
- Slower LED degradation, and
- Extended LED life.

Figure 10-14 depicts an all-amber, LED-cluster CMS.

Shuttered Fiber Optic

Like their fixed-grid, fiber optic sign counterparts, fiber optic cable bundles guide light energy from a point source to pixels on the shuttered fiber optic sign face. The sign has pixels arranged in matrix form and the light sources remain continuously on. Pixel shutters mounted behind the sign face control the emission of light from each pixel. The sign forms characters by shuttering some pixels to block and some to permit light emission.

The sign can have pixels arranged in:

- Character modular form, where blank panels separate groups of pixels, or
- Full grid matrix form, suited for graphics displays but carrying added cost and complexity.

The shuttered fiber optic sign permits substantially improved message flexibility, compared to its fixed grid counterpart, but introduces a mechanical component. However, shutter manufacturers and various users have reported extremely low failure rates. Figure 10-15 depicts a shuttered fiber optic CMS. The signs require periodic bulb replacement.

The shuttered fiber optic sign has enjoyed successful installations in many parts of North America.

Courtesy of LEDSTAR, Inc.

Figure 10-14. Amber LED cluster matrix CMS.

Courtesy of Fiber Optic Display Systems

Figure 10-15. Shuttered fiber optic CMS.

Hybrid

Fiber Optic/Flip Disk

These signs stem from the electromagnetic reflective disk matrix type. The disk surface, with a typically reflective fluorescent yellow appearance, has an opening to pass light emitted from the end of a fiber or fiber bundle. The fiber optic cable terminates just behind the disk. The flat black disk surface completely blocks the light emission when the sign positions the disk in the off state.

The fiber optically directed light provides an additional visibility boost to the reflective disk pixels. During times that do not require the additional light emission, e.g., when bright sunlight shines on the face, the sign extinguishes fiber optic light sources to conserve energy. The fiber optically guided light becomes particularly valuable under nighttime conditions. It eliminates the need for external light sources, which can cause glare problems, to illuminate the disks.

Some agencies are retrofitting their purely reflective electromagnetic flip disk signs with the more recent fiber-optic/flip disk technology.

Figure 10-16 depicts a fiber optic/flip disk hybrid CMS.

LED/Flip Disk

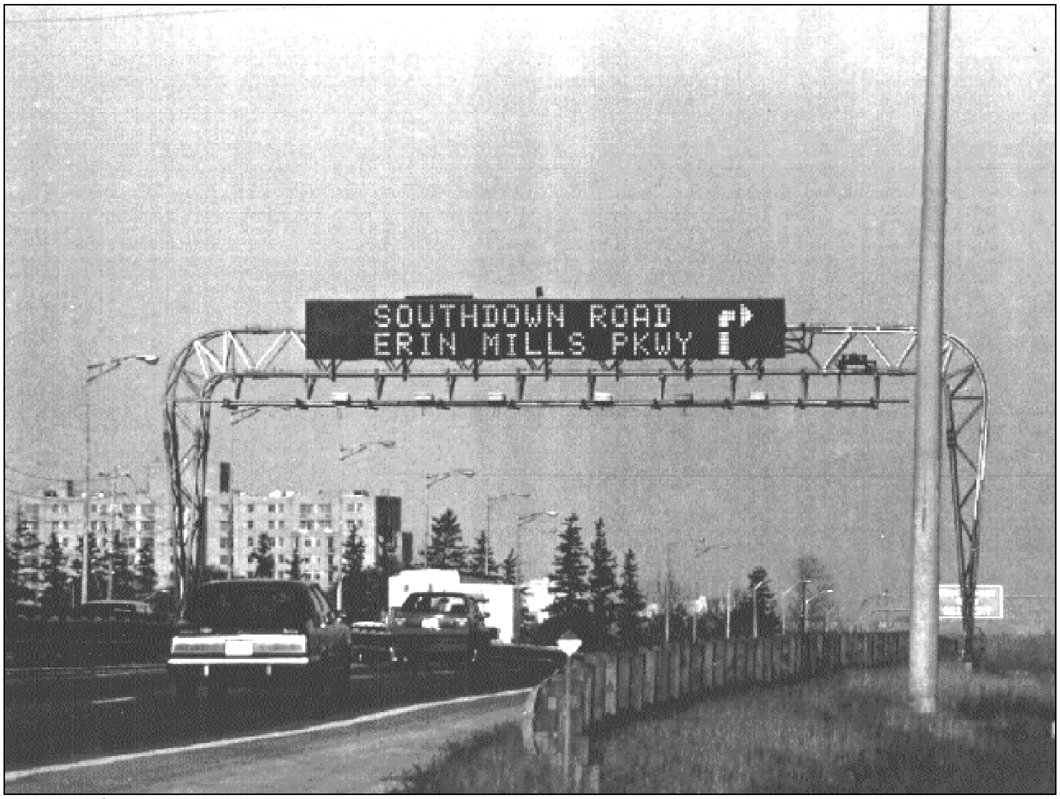
Like the fiber optic/flip disk signs, the combination LED/flip disk signs also stem from electromagnetic reflective disk matrix signs. In this case an LED, rather than a fiber optically guided light source, emits light through an opening in the reflective fluorescent yellow disk surface. The solid flat black disk surface blocks the light emission when the sign positions the disk to the off state.

When initially installed, visibility of these signs compares favorably to the fiber optic/flip disks. However, only a few installations of the LED/flip disk sign exist and their reliability and appearance consistency have not yet been evaluated over time.

At least 1 manufacturer offers an alternative design wherein the LED is adjacent to the flip disk. The LED and flip disc operate concurrently, but the LED light emission remains independent of the mechanical flip disk.

Controllers

Most of the CMS display types described use an electronic microprocessor based sign controller to control and monitor the sign display elements. CALTRANS, and at least 1 other manufacturer, use Model 170 Traffic Signal Controllers as sign controllers. Other signal manufacturers use their own



Courtesy of TELE-SPOT Systems

Figure 10-16. Fiber optic / flip disk CMS.

proprietary designs. Programmers develop software for these controllers in various languages from assemblers to higher order languages like C or Pascal.

Regardless of sign controller construction or software, some basic features, shown in table 10-8, prove common to many of the sign technologies. Various manufacturers supply other functions and features, as well.

CMS systems range from fixed time, on-site control to remote automatic control. Controls can take the form of simple on-off switches located on site for blank-out sign control or can include a microprocessor based controller (previously described) for local or remote control. Table 10-9 describes some sign control and operation techniques available.

Installation, Maintenance, and Operation

Agencies must consider installation, maintenance, and operation when selecting a sign technology for specific applications. Criteria include:

- Attachment to mounting structure,

Table 10-8. CMS controller typical features.

- Light level control and monitoring
- Font selection
- Multiple message storage
- Event scheduler
- Diagnostics
- Password/Security protection
- Event logger
- Power failure recovery
- Dial-up polled communications interfaces
- Multiple media communications interfaces (dial-up or leased telephone lines, cellular, coaxial cable, fiber-optic cable)
- Robust communications protocol including error detection and recovery procedures
- Rapid message writing techniques
- Subset of manual controls when control center or laptop computer is unavailable
- Fail-safe operation/automatic blanking
- Flashing messages

Table 10-9. Sign control operation techniques.

Type Of CMS Operation	Description	Possible Applications
Remote automatic control	Sign messages are displayed and changed automatically by a remote control system when varying environmental, roadway or traffic conditions are sensed by detectors. Manual override capability is normally provided.	(a)
On-site automatic control	Sign messages are displayed and changed automatically by an on-site control system when varying environmental, roadway or traffic conditions are sensed by detectors.	(b)
Remote manual control	Sign messages, based on varying environmental, roadway or traffic conditions, are displayed and changed by sign operators from remote central office locations.	(c)
On-site manual control	Sign messages, based on varying environmental, roadway or traffic conditions, are displayed and changed by an operator using a control panel located at the sign site; in the case of a manually operated foldout sign, the sign is opened to display a message. In both cases, personnel must travel to the sign site after the need for a message has been determined.	(d)
Fixed-time automatic control	Sign messages are displayed and changed automatically at preselected times of the day.	(e)
Fixed-time, remote manual control	Sign messages are displayed and changed at preselected times by operators from a remote location.	(e)
Fixed-time, on-site manual control	Sign messages are displayed and changed at preselected times by operators at the sign site.	(e)

(a) Traffic management and diversion (traffic advisory and incident management, diversion messages on freeways and surface streets special events, adverse road and weather conditions, speed control); warning of adverse conditions (weather, environmental, road); control at crossings (bridge, tunnel, mountain pass); special roadway control (restricted roadways)

(b) Traffic advisory (warning of slow traffic, speed control); warning of adverse conditions (weather, environmental, road, overheight trucks); control at crossings (bridge, tunnel, mountainpass); control during construction and maintenance; special roadway control (restricted roadways)

(c) Same as for remote automatic contol; also, control at weigh stations and toll stations; control during construction and maintenance

(d) Same as for remote control; because of the delay in traveling to the CMS site(s), messages generally are not as timely in comparison with remote control operation

(e) Special-use lane roadway control (reversible, exclusive, and contraflow lanes and restricted roadways)

Source: Reference 4

- Frequency of maintenance:
  - Mechanical parts, and
  - Light element replacement,

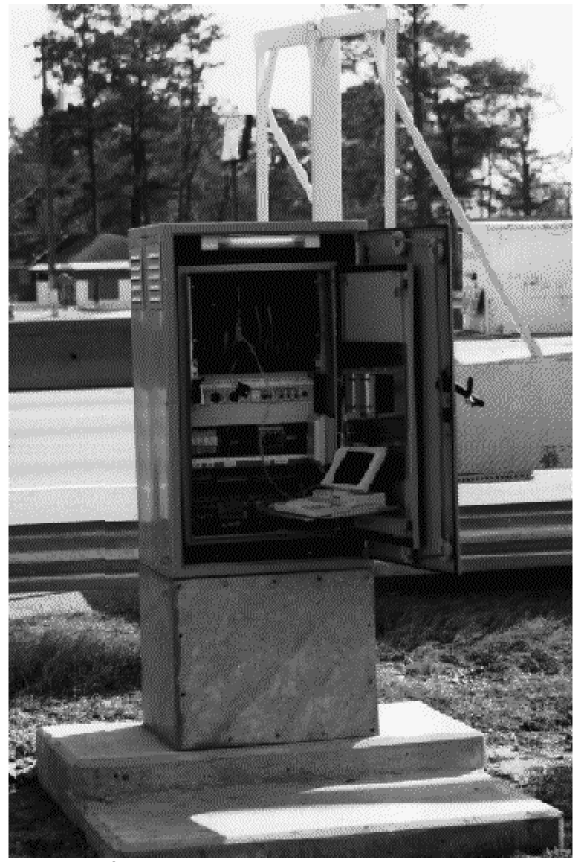
- Sign maintenance safety features:
  - Front or rear catwalks, and
  - Walk-in enclosures,

- Power usage,
- Location of controller and driver electronics (ground mounted cabinet or overhead in sign) (see figure 10-17, which depicts a ground mounted CMS controller),
- Site specific operation and installation criteria, and
- Regional environmental conditions.

Maintenance of CMS proved a major concern in a recent Arizona DOT solicitation (29). ADOT procured CMS based on the total life-cycle equipment costs including costs for:

- Initial installation,
- Annual electrical operation, and
- Annual maintenance over a 5-year life cycle.

The contract also required annual legibility tests to demonstrate continued acceptable performance.



Courtesy of Fiber Optic Display Systems, Inc.

Figure 10-17. Ground mounted CMS controller.

Design and Selection

The wide range of available CMS technologies and the multiple and differing functions and features offered by the various manufacturers make selection and procurement a challenge. Dudek presents guidance for the selection process as shown in table 10-10 (7).

Table 10-10. CMS selection process.

- Clearly establish the objectives of the CMS
- Prepare the messages necessary to accomplish the objectives
- Determine legibility distance required to allow motorists ample time to read and comprehend the messages
- Determine locations of the CMS that allow motorists ample distance to read, comprehend, and react to the messages
- Identify type and extent of localized constraints that might affect the legibility of the CMS
- Determine the target value and legibility of candidate CMS(s)
- Determine costs of candidate CMS(S)
- Select the CMS that allows the selected messages to be read under all environmental conditions within the cost constraints of the agency

10.4 Portable Signs

In some situations, when a highway does not have permanent CMSs, a portable CMS can display real-time information. Portable capability allows the highway agency to:

- Move the CMS into place prior to predictable events (e.g., special events), or
- Manage traffic when unpredictable major incidents occur.

In the latter case, considerable delay in deploying the CMS may occur because of service personnel's travel time to the site.

A portable CMS can warn motorists of lane closures on freeways and surface streets and can:

- Prepare motorists for lane-changing,
- Reduce speed at the beginning of the taper, and
- Reduce last minute lane changes when exiting to avoid congestion (11, 30).

CALTRANS criteria stress using portable CMS to *enhance*, not replace advance warning signs (including arrow boards) in planned lane closures. Arrow boards more effectively provide drivers with positive guidance (11).

Because of mobility, portable CMSs have proven superior to fixed CMS locations for *end of queue* management (31).

Portable signs include:

- Truck- or trailer-mounted signs;
- Pickup signs (leg-supported signs that can be placed in a truck or trailer, hauled to a site, and set out on the roadside); and
- Ground-mounted, with removable, transportable message panels.

Manufacturers supply portable signs in most, if not all the sign display technologies described in section 10.3. Solar panels with backup diesel generators can power the more energy efficient technologies such as electromagnetic flip disk or hybrid LED/flip disk. Sign power distribution systems of this type can extend refueling trips to 90 days or more depending on the amount of sunlight available. The popularity and availability of cellular phone technology makes remote operation of these signs feasible. Virtually all the control and operation techniques described in table 10-9 are also available to portable signs.

Figure 10-18 shows an example of truck-mounted signs used by major incident response units. These portable CMS range from simple manual message generation technologies to the more sophisticated full matrix electronically controlled CMS. The manual message generation technologies include:

- Message panel inserts,
- Velcro-backed characters, and
- Magnetic characters.

Characters, text, or message panels attach to or insert into a rigid-frame support. Each truck stores a library of message inserts or characters and displays messages in various combinations as required.

Portable CMSs offer the advantage of flexible sign location but response time may not prove acceptable in all situations. Portables are also usually smaller than overhead, permanent, fixed-position CMSs.

Figure 10-18. Major incident response units with portable CMS.

10.5
Highway Advisory Radio

Highway information radio systems provide travel or roadway information to motorists via their automobile radios set to the AM band. The Federal Communications Commission (FCC) calls the licensed systems Travelers' Information Stations (TIS) while the Federal Highway Administration (FHWA) calls them Highway Advisory Radio (HAR) (32). Table 10-11 shows typical users and applications of TIS/HAR systems (33).

HAR comes in 2 forms:

- Stationary, and
- Portable.

Stationary systems are permanently installed at fixed locations, while portable systems mount on trucks and travel to different locations to broadcast on a need basis (34).

HAR can play an important role in the Advanced Traveler Information Systems of ITS. It has seen successful applications such as:

- Warning of roadway incidents or congestion,
- Warning of adverse environmental conditions (fog, ice, etc.),
- Notification of highway construction or maintenance,
- Alternate route information,
- Advisories within and regarding transportation terminals (airport airline - terminal information),

Table 10-11. Typical TIS / HAR applications.

Users	Applications									
	Parking / Traffic Conditions	Emergencies and Evacuations	Local Public Advisories	Schedule / Hours of Operation	Fees and Ticket Information	Events Listing	Safety Information	Weather	Road Conditions / Detours	Rules and Regulations
Departments of Transportation	□	□					□	□	□	□
Turnpike Authorities	□	□			□		□	□	□	□
Chambers of Commerce / Tourism			□	□	□	□		□		
Airports	□		□	□	□		□			□
Universities	□	□	□	□	□	□	□		□	□
Nuclear Power Plants		□	□				□	□	□	□
Industrial / Chemical Plants		□	□				□	□	□	□
Military Bases	□	□					□	□	□	□
Government Agencies	□	□		□	□	□	□	□	□	□
Special Events / Fairs / Arenas	□	□		□	□	□	□		□	□
Amusement Parks / Campgrounds	□			□	□	□	□			□
Police / Emergency Units	□	□	□				□	□	□	
Municipalities	□	□	□	□		□	□			

- Disseminating public park, historical site, and other tourist information, and
- Warning of roadway incidents or congestion (35).

HAR messages are typically short so they can repeat at least once in the narrow coverage area allowed. The agency should calculate the maximum message length by using the true broadcast time divided by 2. This allows those who drive into the broadcast area after the message has begun to hear the message again in its entirety.

HAR messages must be non-commercial. On allocated frequencies, the FCC disallows broadcasting of:

- Advertising,
- Commercials, or
- Entertainment.

Typical messages should have 3 parts:

- Salutation,
- Incident related information, and
- Closing.

The salutation should greet and welcome the listeners. Although briefly stated, *this sets a positive tone for the message*.

The bulk of the message will contain detailed incident information to inform the motorists as to:

- Incident type (car/truck accident, emergency road repairs),
- Result (left and center lanes closed for 2 hours), and
- Effect (backups for 2 mi (3.2 km)).

Whenever possible, the message should provide diversionary information. However, legal issues or agency policy may preclude this. The message must reflect up to the minute conditions; otherwise the agency will jeopardize credibility of the service.

A closing or post-incident message can simply state that:

- There was an accident,
- It is now cleared, and
- The emergency traffic radio will soon leave the air (34).

The FCC regulates the use of HAR and dictates requirements so that HAR systems do not interfere with other neighboring licensed radio stations.

Installation of an HAR system requires an FCC licensure application procedure that includes studies that the proposed system and site location will not interfere with other AM licensed broadcast stations. The FCC also requires a number of post-licensing and post-installation activities to retain the license and seek license renewal. These include:

- Developing an actual field strength contour map, and
- Maintaining reasonably continuous operation.

The Federal Aviation Administration (FAA) may also become involved with proposed installations near airports.

The FCC recently made significant changes in the AM frequency band assignment of TIS. Prior to 1992, TIS were limited to 530 KHz or 1610 KHz. The FCC Code of Federal Regulations states that TIS will be authorized on a secondary basis to stations authorized on a primary basis in the bands 510 to 535 KHz and 1605 to 1715 KHz (36).

HAR systems typically comprise a:

- Broadcast antenna (vertically polarized monopole or buried radiating coaxial cable),
- Grounding system,
- Low power roadside transmitter,
- Communications link to a control center,
- Recorder,
- Message development facility, and
- Beacon equipped static signs providing notification of traffic messages. Figures 10-19 and 10-20 show conceptual examples of HAR deployments.

Vertical Antenna HAR Systems

The system may use a single vertical antenna or several vertical antennas forming an electronically interconnected array. A single vertical antenna provides a circular transmission zone while a directional array can transform the transmission pattern to a non-circular shape. Table 10-12 shows advantages and disadvantages of the vertical antenna.

Induction Cable Antenna HAR Systems

The second method of broadcast uses a roadside cable instead of conventional vertical antennas. Directional induction radio transmission continues the radio signals to the width of a multilaned highway.

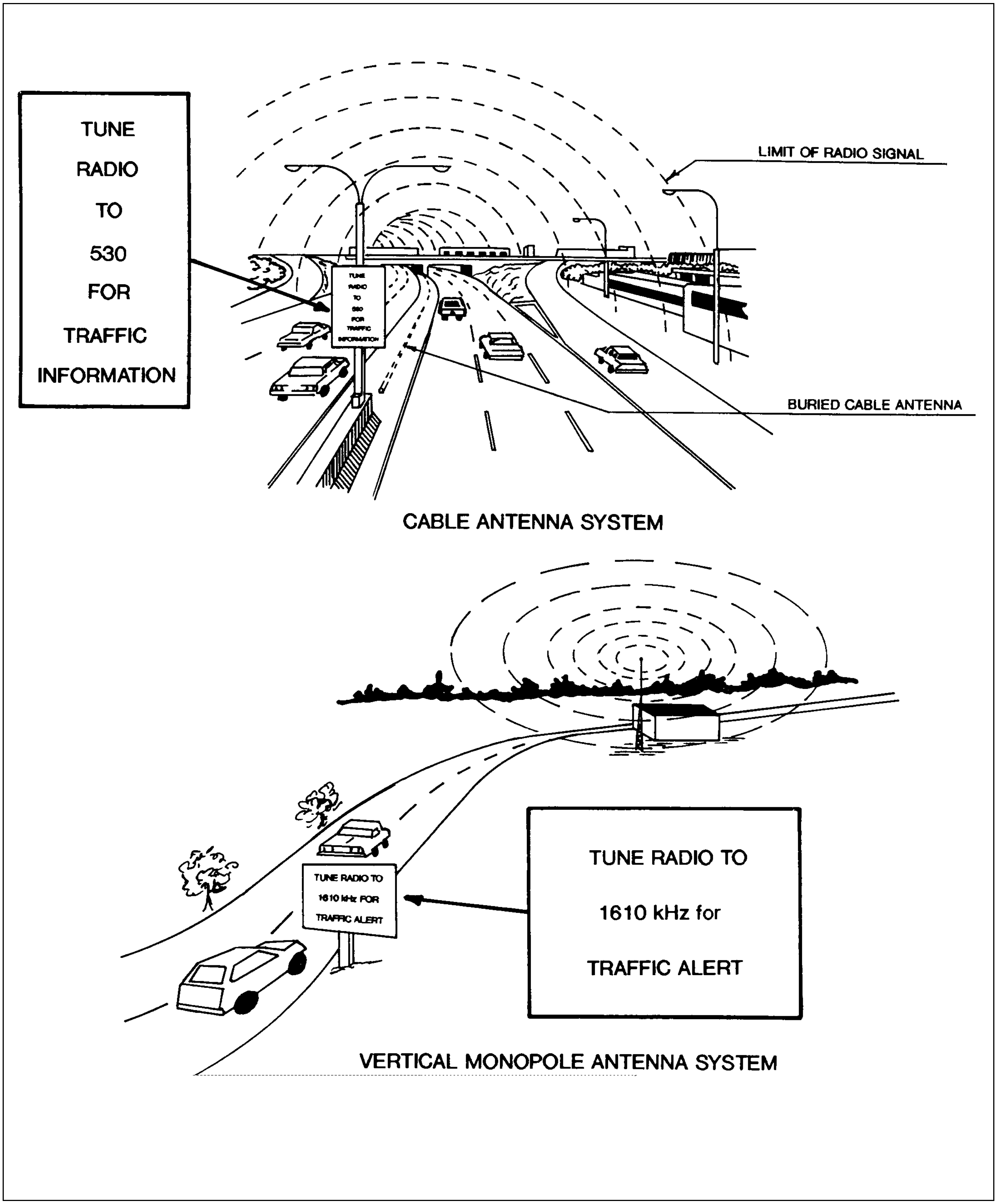


Figure 10-19. Typical highway advisory radio (HAR) system.

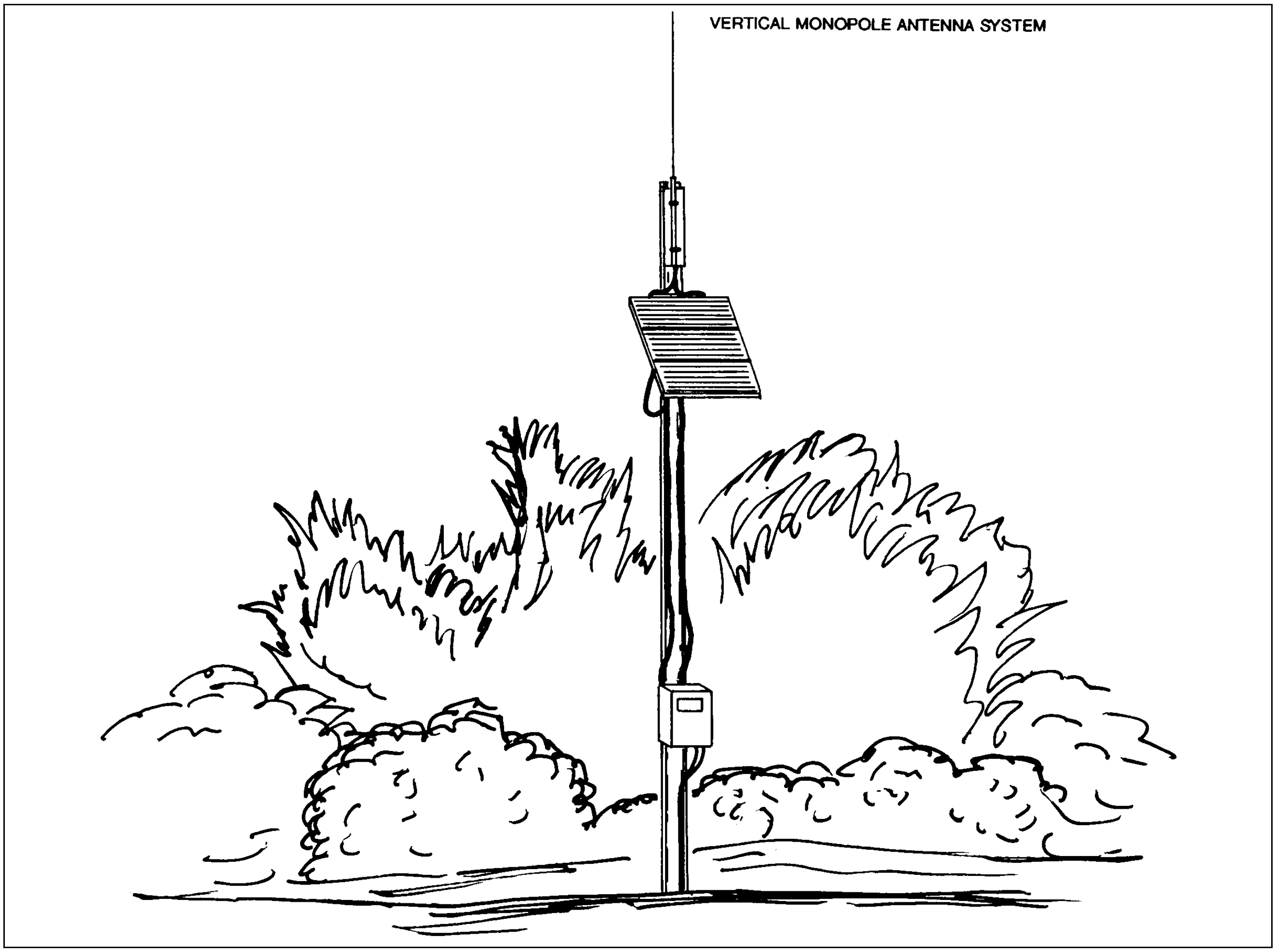


Figure 10-20. Typical highway advisory radio (HAR) antenna.

The cable antenna produces a strong, but highly localized induction-type radio signal within a short lateral distance of 100 to 150 ft (30.5 to 45.7 m) from the cable. This proves sufficient to produce a good signal for the width of a multilane highway while restricting the field. At a distance of several hundred ft (greater than 60 m) from the cable, the field falls below the effective response value of typical automobile receivers. This results in a relatively high degree of efficiency in the use of radio spectrum for roadway communications, as several highways in 1 area may use the same carrier frequency without interference. Another feature allows the system to broadcast different messages over 2 separate frequencies on the same cable. Thus, the system can individualize messages by direction of travel.

Table 10-13 shows advantages and disadvantages relative to the use of cable antennas.

Tunnel roadway applications, such as the Third Harbor Tunnel in Boston, MA, have combined AM/FM Radio Rebroadcast with HAR to share some of the same radiating cables, as appropriate. In addition, the Third Harbor Tunnel and other Tunnel AM/FM Rebroadcast Systems have complete channel override for transmitting HAR type messages (37).

The advance of solid-state message recorders revolutionized the HAR industry. The mechanical audio cartridges that preceded them proved subject to a number of problems since eliminated:

- Tape transport failures,
- Tape record/playback headwear,
- Recording tape wear, and
- Tape breakage.

Periodic maintenance, alignment, and cleaning has also been greatly reduced if not eliminated.

Solid-state message recorders provide a number of other advantages (38-40):

Table 10-12. Advantages and disadvantages of vertical antenna.

Advantages	• Physically small and can be installed in a relatively small space • Usually placed within several hundred ft (100 m) of the highway • May be used to alert motorists to a freeway incident prior to freeway entry and where alternative routes are available • Usually less costly to purchase and install than a cable antenna
Disadvantages	• Usually visible, but can be partially camouflaged • Subject to damage by weather, accident, or vandalism • Single antenna provides a circular zone of coverage that may interfere with other coverage zones on adjacent highways

Table 10-13. Advantages and disadvantages of cable antennas.

Advantages	• Can provide continuous coverage through tunnels, in buildings, under overpasses • May be placed above or below ground • If installed below ground, not subject to damage by weather or vandalism
Disadvantages	• Must physically extend the full length of the coverage zone • Installation is relatively expensive compared to vertical antenna systems • Must use either 2 pair of leased lines (1 to modulate the transmitter and the other to monitor the broadcast), or a sensitive receiver to monitor the roadway's broadcast • Requires sufficient roadway traffic monitoring to ensure that timely and credible information is being broadcast

- Easily variable message lengths,
- Multi-channel capability so different messages can be provided to different transmitters,
- Multiple message storage,
- Remote programming and recording (such as via cellular telephone or standard touchtone telephone),
- Preset Time-of-Day or Day-of-Week message scheduling,
- Other audio source play thru, and
- Computer data inputs via RS-232-C type ports.

Manufacturers now offer reliable, portable, trailer-mounted HAR transmitter and antenna equipment (see figure 10-21). This equipment finds widespread use among state agencies for rapid deployment during:

- Emergencies,
- Construction, or
- Other random incident occurrences (39).

For example, CALTRANS deployed a Portable HAR at the Oakland Bridge following the October 1989 earthquake (41).

Recent advances in the telephone and data communications field have also broadened HAR system capabilities. Cellular telephone enables an authority to call a recorder or transmitter and switch pre-recorded messages or record new messages from off-site (39). One central station recorder can link multiple transmitters together using TV Separate Audio Program (SAP) and FM Radio Subsidiary Communications Authorization

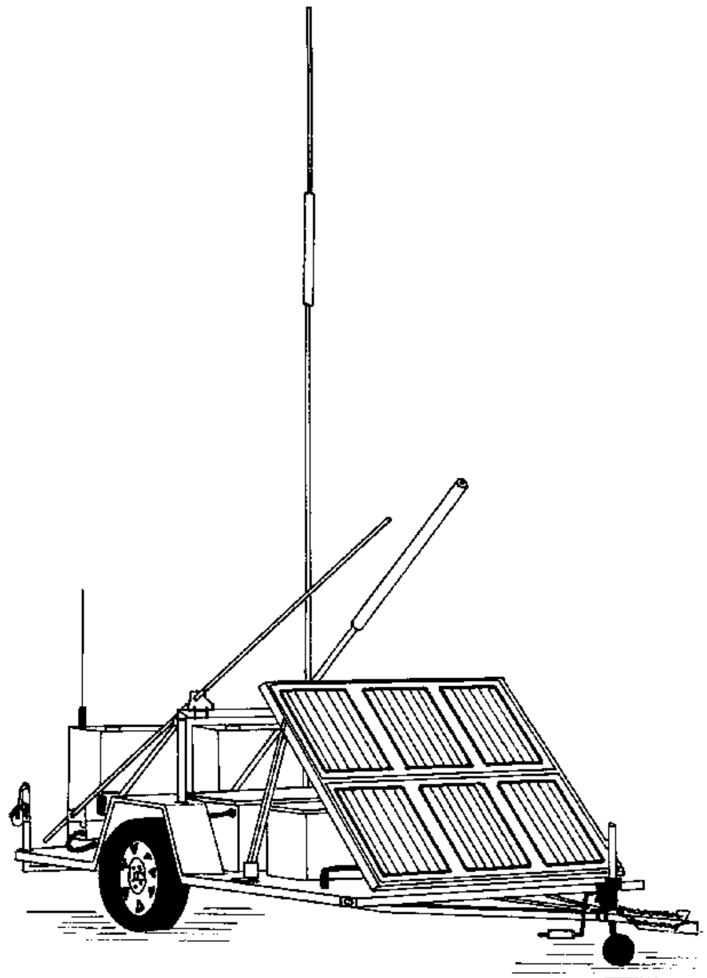


Figure 10-21. Typical portable highway advisory radio.

(SCA) sub-carriers. Depending on the extent of area coverage required and number of transmitters interfaced, other communication media may also become feasible.

HAR trends appear toward areawide coverage such as the Minneapolis-St. Paul and Chicago area systems. Efforts are underway to interconnect and synchronize adjacent HAR 530 KHz systems at the Tappan Zee Bridge and Spring Valley Toll Plaza on the New York State Thruway. The Boston Central Artery/Tunnel Project roadway divides into 5 zones, each with its own transmitter. All are controlled together from 1 central solid-state recorder with the capability for direct central computer input.

Technical Standards

Table 10-14 lists technical standards concerning HAR communications (36).

10.6 Motorist Aid Systems

A motorist aid system:

- Assists the detection of stranded motorists,
- Offers means to communicate their needs, and
- Provides the appropriate aid response.

These systems are classified as follows:

- Call box and emergency telephones,
- Cellular telephone,
- Citizen band (CB) radio, and
- CCTV monitoring systems.

Table 10-15 identifies various motorist aid systems used in a sample of urban areas.

Table 10-14. HAR technical standards.

- Frequency tolerance of 100 Hz shall be maintained
- For a station employing a cable antenna, the following restrictions apply:
  - length of cable shall not exceed 3.0 km (1.9 mi)
  - transmitter RF output power shall not exceed 50 watts and shall be adjustable downward to enable the user to comply with the specified field strength limit
  - the field strength of the emission on the operating frequency shall not exceed 2mV/m when measured with a standard field strength meter at a distance of 60 m (197 ft) from any part of the station
- For a station employing a conventional radiating antenna(s) (i.e., vertical monopole, directional array), the following restrictions apply:
  - the antenna height above ground shall not exceed 15 m (49.2 ft)
  - only vertical polarization of antennas shall be permitted
  - transmitter RF output power shall not exceed 10 watts to enable the user to comply with the specified field strength limit
  - the field strength of the emission on the operating frequency shall not exceed 2mV/m when measured with a standard field strength meter at a distance of 1.5 km (0.9 mi) from the transmitting antenna system
- For co-channel stations operating under different licenses, the following minimum separation distances shall apply:
  - 0.50 km (0.3 mi) for the case when both stations are using cable antennas
  - 7.5 km (4.7 mi) for the case when one station is using a conventional antenna and the other is using a cable antenna
  - 15.0 km (9.3 mi) for the case when both stations are using conventional antennas

Table 10-15. Examples of motorists aid system deployment.

	Anaheim	Chicago	Cincinnati	Detroit	El Paso	Fort Worth	Houston	Los Angeles	Miami	Minneapolis	N. Virginia	Orlando	Portland	San Diego	San Francisco	Seattle	Toronto	Tampa Bay
Motorist Aid Call Box Telephone	✓			✓			✓	✓	✓	✓		✓		✓	✓	✓		
Cellular Telephone		✓		✓			✓	✓		✓						✓		
CB Radio		✓	✓	✓			✓	✓		✓	✓					✓		
Video and CCTV	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓		✓	✓	✓	✓	✓	✓

Source: Reference 42

Call Box and Emergency Telephone Systems

Motorist call boxes or emergency telephones served as one of the earliest incident detection systems. A motorist aid *call box* consists of a switch or toggle that signals the operating agency via phone line that an incident has occurred. The box allows no direct communication from the person reporting the incident. A motorist aid *telephone system* includes a handset that allows the person reporting to relay additional information. Telephones have proven preferable because voice communication allows the motorist to explain the needed services exactly. However, a call box with coded message buttons proves less costly than a telephone requiring voice transmission. Recent technological advances have reduced the price difference by permitting the development of solar-powered, cellular-radio-based telephones. Figure 10-22 illustrates a solar-powered, cellular telephone (43).

Major advantages of a motorist call box or emergency telephone system include (42):

- Motorists can report incidents 24 hours a day,
- Motorists can report directly to a response agency dispatch office, and
- Motorist acceptance is high.

Major disadvantages include (42):

- Relatively high start-up costs,
- Potential for vandalism and false alarms, and
- Safety problems engendered by requiring the motorist to leave vehicle for call box locations in the median or on highways without shoulders.

Vandalism and high operating maintenance costs, and the increasing presence of cellular phones in vehicles have lessened the attractiveness of call box and emergency telephone systems. Recent development of a rugged, weatherproof unit constructed of Lexan polycarbonate has reduced the theft of call boxes for scrap value.

Cellular Telephone System

Cellular telephone systems have 2 important functions with regard to roadway incidents:

- Reporting, and
- Verification.

Motorists with cellular telephones can call a dispatch office to report incidents directly from their vehicles. In many urban areas, motorists can report a freeway incident by simply dialing 911 as for any other emergency. A typical system implemented in 1989 in Chicago allows motorists on the expressway system to contact the Illinois Department of Transportation (IDOT) by dialing 999. An IDOT dispatcher then contacts the appropriate service agency. The motorist does not get charged for the cellular call. This service handles several thousand calls per month; most calls request service for another motorist (2).

Of course, the motorist may use cellular systems to directly call for emergency roadside service.

Advantages of cellular telephone systems include the following (42):

- Existing staff can generally monitor calls,
- Little training on equipment use required,
- Respondents can obtain complete and comprehensive information on the incident before departing for scene, and
- Cooperative reporting compensates for limited cellular telephone ownership.

Disadvantages of cellular telephone systems include the following (42):

- Ownership of cellular phones is limited (although growing rapidly), and
- Roadside signs are required to remind drivers of the dedicated cellular telephone number.

The cellular telephone system uses a dialed connection between mobile units and the national telephone network to provide a full-service telephone within the vehicle. Service areas consist of an array of small cells with a radius from 1 to several miles (1.6 to several km). Each cell serves a limited number of users on the assigned frequency. By using low-power equipment, the small cell design allows reuse of the same radio frequency in different cells within the same city, provided calls remain far enough apart to avoid interference. As the number of users and calls increase, the service provider splits cells into smaller cells to increase system capacity. The system operates in the 800 MHz spectrum.

A mobile switching office provides the switching and control function. The mobile switching offices process and coordinate calls almost instantly, automatically switching individual calls from 1 cell to the next (*handoff*) as the caller drives across service areas.

Obtaining In-Vehicle Traffic Information

Some public agencies such as IDOT provide a telephone number to report traffic conditions from

Courtesy of GTE Government Information Services, Inc.

Figure 10-22. Cellular telephone system.

cellular phones. Some private agencies also provide a similar service.

Cellular telephone service provides one medium for the transmission of digital traffic information to the vehicle. This information would be further processed in the vehicle for display of congestion locations and route guidance information to the motorist.

Citizen Band (CB) Radio

Citizen band (CB) radio can serve as an in-vehicle, 2-way motorist aid system. This system allows motorists to remain in their vehicles and contact the appropriate agency to render aid.

Requests for assistance are typically broadcast over Channel 9 (27.065 MHz), designed as an official emergency channel by the FCC in 1970. Since then, several states have developed programs such as:

- Ohio REACT,
- Detroit KUY,
- Michigan MEP, and
- Missouri SHP (44).

The National Highway Traffic Safety Administration (NHTSA) sponsors the National Emergency Aid Radio (NEAR) to develop CB system improvements and promote the use of CB radio in emergencies. This national organization has over 30 States actively participating in the NEAR program. The evaluation of this program clearly indicates the:

- Value of a 2-way, in-vehicle radio; and
- Need for a fully organized, well-structured communication system for this method of motorist aid to prove successful.

States and private organizations provide the systems, while the NEAR program provides the required structure.

Some systems make use of CB base station transceivers at unattended remote locations. This allows an operations center to receive Channel 9 alarms throughout an entire urban area. The operator can then dial-up the CB transceiver near the alarm site and talk to the caller. Such a system requires the use of a dial phone network and CB units placed at strategic locations to provide major road coverage. This type of system can also confirm and verify the nature of incidents detected by an electronic monitoring system (44).

The advantages and disadvantages of CB resemble those described for cellular telephone.

Modern communication technology such as the cellular telephone has diminished the need for CB radio. Today major users of CB radio include:

- Bus drivers,
- Service patrol operators,
- Truckers, and
- Delivery operators.

CCTV Monitoring Systems

Advanced traffic management systems with continuous CCTV coverage can serve as motorist aid systems. Operators at TOCs can observe stopped motorists and dispatch aid as required. Section 4.5 describes CCTV monitoring systems.

10.7 Commercial Radio

Commercial radio proves an important element of a traveler information system. It has wide-area coverage and reaches a large segment of the traveling public. Many commercial stations schedule traffic information broadcasts at periodic intervals, typically 10 minutes.

Disadvantages of commercial radio include:

- Late or obsolete information, and
- Incomplete information, particularly in large metropolitan areas. This results from the time and resource limitations of radio stations.

Sources of traffic condition information used by commercial radio stations include:

- Personnel in traffic operations centers (TOCs) who develop broadcast text or broadcast directly from the TOC,
- TOCs providing information to the media by fax or digital data links. Information may be provided manually or by automatic message generation techniques in the TOC,
- Airborne and ground observers, and
- Subscription to private traffic information services such as the SHADOW Network, Inc., which services several large metropolitan areas.

10.8 A Look to the Future

In the future, travelers information systems will provide new methods of communication with travelers in vehicles and external to vehicles. Architecture concepts for many of these methods are being developed under the National ITS Architecture Development Program (45).

This section describes several examples of emerging traveler information systems in various stages of development and deployment.

Automatic Highway Advisory Radio

Automatic highway advisory radio (AHAR) finds itself at or near prototype stage. AHAR would operate on a set of frequencies, nationwide. Any AHAR message would automatically transfer a motorist's compatible radio to a designated station, eliminating the need for advance signing and manual tuning. AHAR operates at 45.80 MHz (FM).

Figure 10-23 illustrates the AHAR concept. Figure 10-23 (a) shows the basic system's components while Figure 10-23 (b) illustrates their arrangement along a highway (17). A vehicle moving right to left enters the enable receive zone and hears a continuously transmitted enable code consisting of a single dual-tone multiple-frequency (DTMF) digit. The scan zone represents a time allowance for a scanning receiver to locate the frequency. The enable receive zone must have sufficient width for the receiver, after locking on, to receive the enabling code. Once enabled, the vehicular receiver stops scanning and waits for the message. The vehicle receives the message after entering the message receive zone. The message receive zone should have about 3 mi (4.8 km) of width for the real-time analog approach. This permits a vehicle moving at 60 mi/hr (96.5 km/hr) to receive an uninterrupted 60 second message at least twice from beginning to end (46).

New York and California have used a new system, called ARI-2, but it has not yet developed into widespread use. An ARI system with Actual Measurement (ARIAM) uses automatic incident detection equipment for generating messages.

Europe has begun implementing another traffic information broadcasting system called the Radio Data System (RDS) Traffic Message Channel (TMC). RDS provides for the transmission of a silent data channel on existing FM radio stations. It identifies radio data broadcasters and allows self-tuning receivers to automatically select the strongest signal carrying any particular program (47).

In Detroit, MI, an HAR system exists as part of the Information Dissemination Program. In 1995, the State will revamp and upgrade this program to an AHAR system under the DIRECT Project.

The European Radio Data System (RDS) operates on an FM radio subcarrier and is being implemented in Western Europe and the U.K. Traffic messages are encoded on RDS. Britain has used the RDS to implement an ARI type system (47).

Radio Broadcast Data System

The Electronics Industry Association (EIA) and National Association of Broadcasters (NAB) have recently adopted a commercial standard (Radio Broadcast Data System (RBDS)) to implement an RDS in the United States. The National Radio Systems Committee formally released the United States RBDS Standard on January 8, 1993 (47).

Using RBDS, FM stations can transmit data to *smart* receivers. The smart receivers can perform a host of automatic functions as shown in table 10-16.

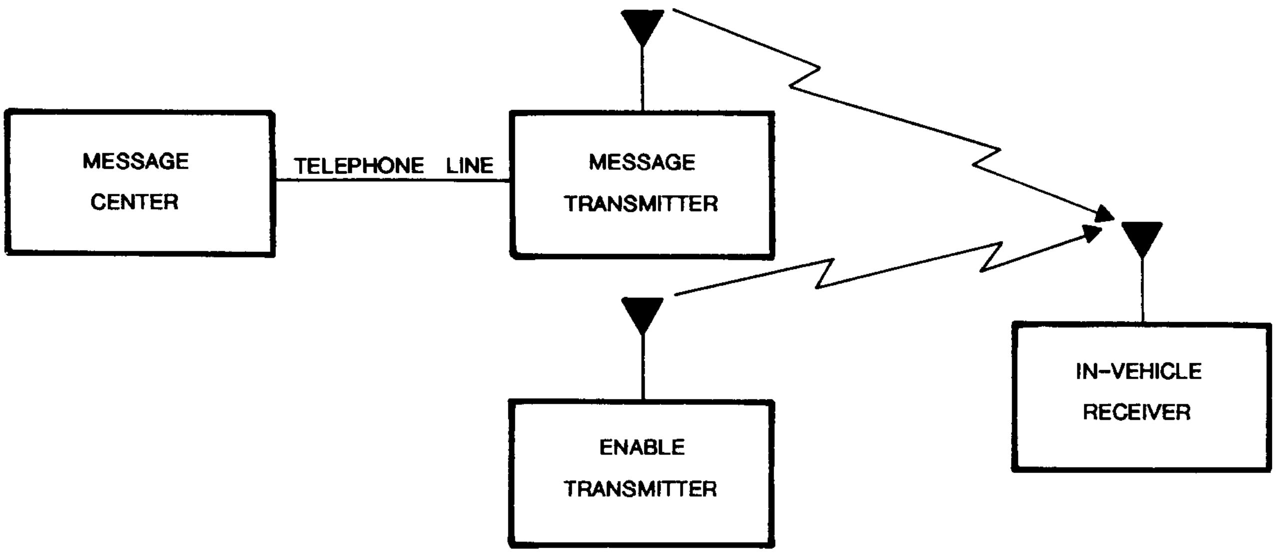


Figure 10-23 (a)

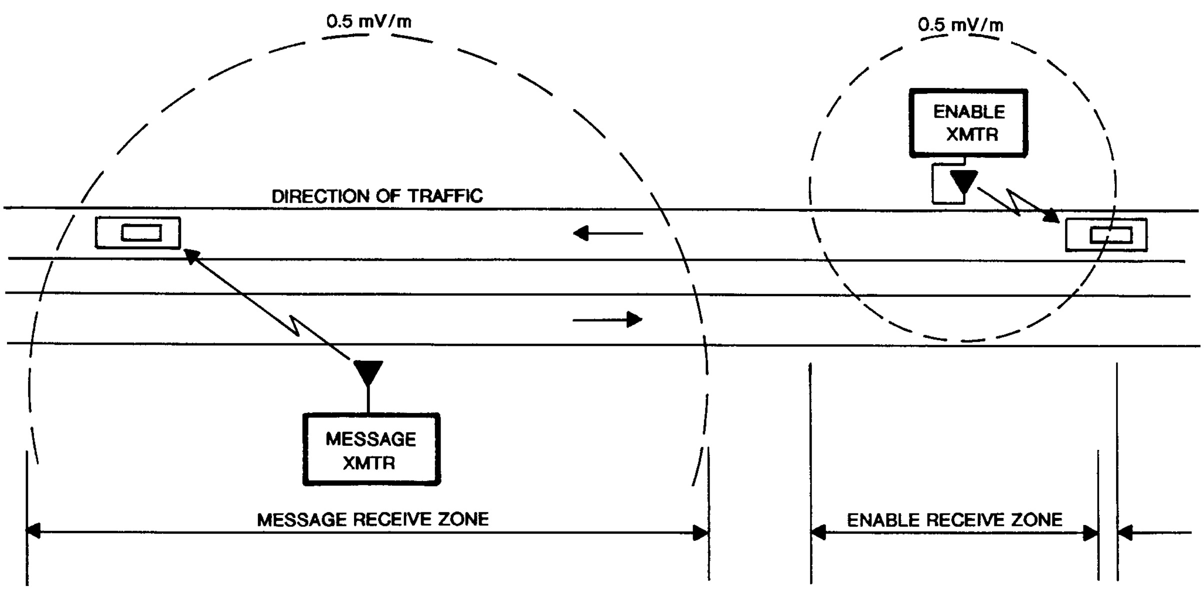


Figure 10-23 (b)

Figure 10-23. Automatic highway advisory radio (AHAR).

Table 10-16. RBDS features and functions.

Features

Displays station call letters as a means of recognition. Allows for:

- Automatic receiver tuning
- Traffic or emergency messages to awaken radios that may be off or playing a cassette/CD

Functions

The RBDS format consists of a number of codes used to implement functions in RBDS receivers

Clock Time and Date Code (CT) allows for continuous update of:

- Clock time
- Date display in the radio

Program Identification Code (PI) performs a variety of functions:

- Allows the radio to know what area of the country it is in
- Carries information relating to individual stations and programs
- Allows alternate frequency searches

The function of alternative frequency searching allows for a *cellular* type of environment, thus allowing listeners to stay tuned to their present frequency or freely change to another. More importantly, as travelers move from one location to another, the receiver switches inaudibly between frequencies.

Traffic Program Code (TP) allows broadcasters to identify their station as one providing traffic information

Traffic Announcement Code (TA) is identical to the old ARI system. A transmitting station causes the receiver to:

- Switch automatically from an audio mode to traffic announcements
- Switch on traffic announcements automatically when in a reception mode and signal is muted

Program Service Code (PS) allows for the station's call letters to be displayed, i.e., WDRE

Radio Text Code (RT) is primarily for home receivers. The RT code allows for text to be transmitted and displayed on printers and computer type monitors.

Program Type Code (PTY) can format a program station, and alert the radio for an emergency

Applications

RBDS has the following potential applications:

- Sends information to display signs located in:
  - Hotels,
  - Restaurants, and
  - Malls.
- Uploads computer programs to home and business computer systems;
- Transmits data to in-vehicle navigation systems, with updates on traffic problems and road closures; and
- Pages -- every station can operate its own digital paging service.

The RBDS Technical Subgroup serves as a subcommittee of the National Radio Systems Committee that studies the functions and uses of RBDS codes.

Due to the establishment of the RBDS Standard, there exist at present many opportunities such as:

- Coupon information transmitted by broadcasters directly to listeners,
- Correction data for Global Positioning System (GPS), and
- Data updates in appliances using RBDS decoders.

ITS In -Vehicle Information, Navigation, and Route Guidance Systems

In-vehicle information, navigation, and route guidance systems constitute a major subset of Advanced Traveler Information Systems (ATIS). In-vehicle systems must link to Traffic Operation Centers (TOCs) by mobile data communications for maximum effectiveness.

Technology Requirements

Fundamentally, these systems require in-vehicle means for identifying vehicle location with sufficient accuracy to know precisely:

- On which street the vehicle is traveling, and
- Which intersection the vehicle is approaching.

They also require:

- Means for accepting driver input such as:
  - Mode of operation,
  - Destination, and
  - Criteria for route selection (e.g., fastest, shortest, scenic).
- Digital road map databases and software for computing *best* routes and generating route guidance instructions, and
- Means for presenting:
  - Map displays,
  - Route guidance instructions, and
  - Other output information to the driver.

Technology Approaches

For maximum effectiveness, these systems require a communication link to receive traffic data (often in the form of link travel times) from a TOC or other centralized source of real-time or near-real-time traffic information. This traffic information may be:

- Automatically taken into account by in-vehicle routing software,
- Presented to the driver in alphanumeric form,
- Shown symbolically on a map display, or
- Presented orally to the driver.

In some approaches (e.g., Ali-Scout), the TOC determines best routes under current traffic conditions and downloads them to the in-vehicle equipment via a roadside based computer and communication system.

The most sophisticated concepts require 2-way communication links. In addition to the 1-way functions described above, 2-way links support the use of ATIS equipped vehicles as *traffic probes*. To augment other measures of traffic conditions, these probes relay to the TOC actual travel times experienced along route segments. Other potential uses of the vehicle-to-infrastructure link include reporting individual vehicle destinations for use in predicting traffic conditions, and sending Mayday messages.

Current practice for determining vehicle location centers depends strongly on *dead reckoning* in combination with *map matching* using digital road maps stored on CD-ROM. GPS augmentation proves commonplace. In some cases, proximity beacons update vehicle location and may also communicate traffic or other information to in-vehicle equipment. Table 10-17 defines these location technologies.

Table 10-17. Vehicle location technologies.

Technology	Description
Dead Reckoning	Process of calculating a vehicle's relative location by using on-board sensors to measure distances and directions traveled from an earlier location
GPS (Global Positioning System)	U.S. Department of Defense system consisting of 24 satellites spaced in orbits such that a receiver can determine its position by simultaneously analyzing the travel time of signals from at least 4 satellites. Although capable of high accuracy, GPS alone is inadequate for automobile navigation because signal reception on roadways is sometimes blocked by buildings, foliage, etc.
Map Matching	Software process for eliminating dead reckoning and GPS location errors by recognizing the measured pattern of a vehicle's path and correlating it with the road patterns of a digital map
Digital Map	Road details (coordinates of intersections and turns, street names, classifications, address ranges, etc.) digitally encoded in a computer file. Map databases may also include locations of gas stations, garages, parking, public buildings, hotels, restaurants, attractions, and other facilities commonly used by motorists.
Proximity Beacon	Roadside device capable of communicating its location and/or other information to equipment in passing vehicles via short-range radio, microwave, or infrared signals. See chapter 9 for a more detailed discussion of radio communication.

Figure 10-24 illustrates the block diagram of a typical system incorporating the technologies listed in table 10-17. Systems that use dead reckoning and map matching alone occasionally must be manually reset to a known position, a drawback that a location sensor can eliminate. A GPS receiver or proximity beacon receiver typically serves as a location sensor.

Proximity beacons may also serve as communication links with in-vehicle systems. However, the selection of one or more standard communication links is currently still in process. Table 10-18 lists candidate mobile data communication technologies for linking TOCs and in-vehicle equipment along with their principal characteristics.

Navigation systems have potential for enhancing traffic safety by enabling drivers to confidently proceed without:

- Hesitating at decision points, or
- Making abrupt last-moment maneuvers to stay on the proper route.

However, controls and displays must be carefully designed and positioned considering human factors to avoid distractions that could negatively affect safety.

Table 10-19 lists technologies that currently accept driver input (e.g., mode of operation, destination, criteria for route selection) and convey map, route guidance instruction, and other information to drivers.

Future Trends

Multi-purpose Personal, Portable Advanced Traveler Information Systems (PPATIS) represents an emerging trend which will influence future directions for these systems. These hand-held devices assist travelers with planning and execution of all modes of ground transportation.

In addition to database and communications-based functions, future PPATIS could include location and real-time navigation functions using embedded GPS or other radio positioning receivers along with micro-accelerometers and rate sensors (i.e., integrated

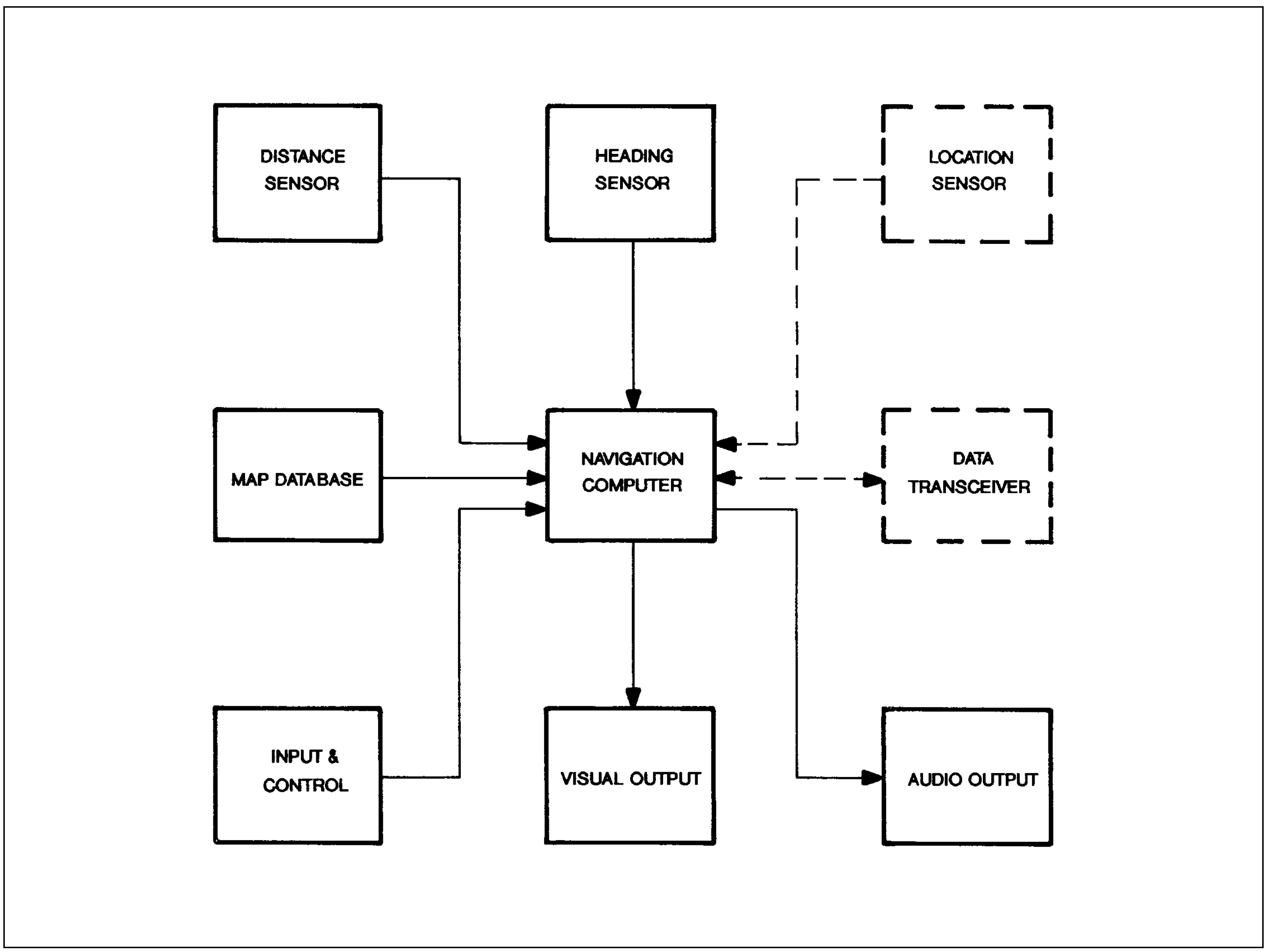


Figure 10-24. Typical ATIS block diagram.

Table 10-18. Mobile data communication technologies.

Technology	Characteristics
FM Subcarrier (e.g., RBDS)	• 1-way • Voice or data • Low data rates • Extended area coverage
Proximity Beacon	• 1-way or 2-way • Data only • High data rates • Spot area coverage
Inductive Loop	• 1-way or 2-way • Data only • Spot area coverage
Land Mobile Radio	• 2-way • Voice and data • Local area coverage
Specialized Radio Service (SMR)	• 2-way • Voice and data • Local/extended area coverage
Cellular Radio	• 2-way • Voice and data
Mobile Satellite	• 1-way or 2-way • Voice or data • Wide-area coverage

circuit chip devices). Automobile drivers, transit riders, cyclists, and pedestrians could eventually use the same portable system, somewhat like cellular telephones today.

Examples

The TravTek and Ali-Scout in-vehicle information, navigation and route guidance systems represent state-of-the-art examples of systems with vastly different architectures. Table 10-20 compares their main features.

Figure 10-25 illustrates the overall TravTek architecture (48). The in-vehicle system represents a functional prototype that includes virtually all features and functions. It has comprehensive navigation and route guidance features. It also includes extensive on-board databases that enable a choice of navigation assistance (i.e., digital map display showing current location and selected destination) or route guidance. The driver may select route guidance in the form of:

- A highlighted route on the map display;
- Real-time, turn-by-turn instructions via symbolic display (see figure 10-26); and/or
- Synthesized voice.

TravTek's self-contained features are enhanced by real-time traffic data received via SMR radio from a TOC for:

- Symbolic display on the map screen (see figure 10-27), or
- Computing best routes under current traffic conditions.

An integrated cellular phone can:

- Automatically dial hotels, restaurants, etc. selected from the on-board database; or
- Automatically dial an AAA Information & Services Center for other information and services including emergency road service.

An operational field trial in 1992-1993 tested TravTek extensively in Orlando, FL with 100 equipped vehicles used mostly as rental cars. Results of an extensive evaluation indicate that test subjects rated TravTek highly (5.29 out of 6.0 for helping find the way) (49). Even local drivers used the route guidance features on approximately one-half their trips (50).

Table 10-19. Input, control, and output technologies.

Input and Control	Output and Display
Dedicated Push Buttons	Monochromatic or Color CRT or LCD
Software-Defined Buttons	Map Display
Keyboard Devices	Alphanumeric Information
Remote Control Devices	Symbolic Route Guidance
Touch Screen Selection from Displayed Menus	Synthesized Voice

Table 10-20. TravTek and Ali-Scout.

TravTek	Ali-Scout
• Dead reckoning with GPS and map matching • Color CRT map display • Graphical and voice route guidance • 2-way radio provides traffic data to vehicle and returns probe data • Traffic-dependent routes calculated by on-board software • On-board map database includes tourist info	• Dead reckoning with map matching • Monochromatic LCD for displaying route guidance in graphical and alphanumeric form • Includes voice route guidance • Route guidance for main arteries only • 2-way infrared beacons provide reference location and traffic-dependent route maps and return probe data

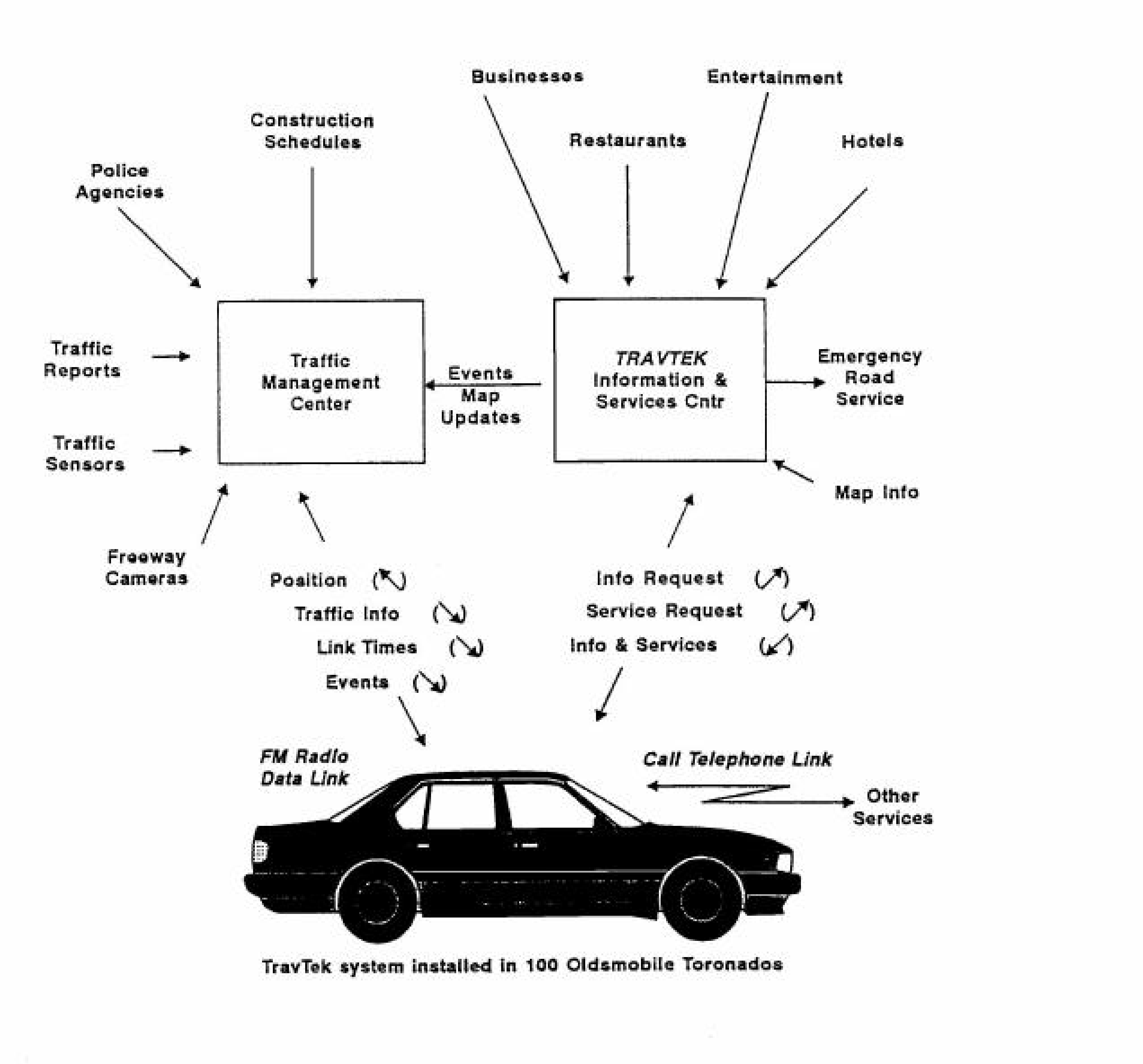


Figure 10-25. TravTek system architecture.

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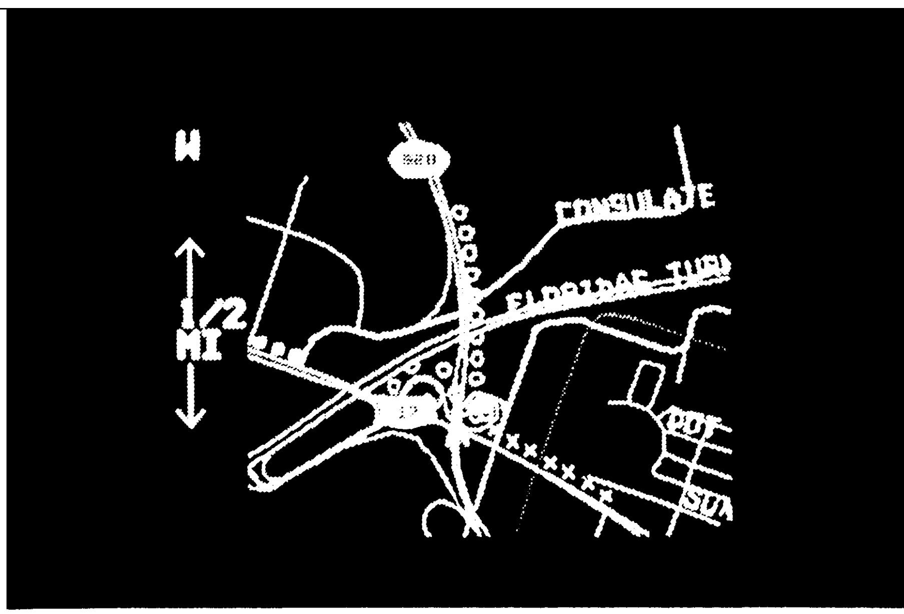
Figure 10-26. TravTek CRT display and steering wheel controls.



LEGEND:

INCIDENTS = (STARS)

AREAS OF CONGESTION = (OPEN CIRCLES – MODERATE CONGESTION,
FILLED CIRCLES – HEAVY CONGESTION)

CLOSED ROADS = (X's)

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Figure 10-27. TravTek traffic information map display.

Figure 10-28 shows the overall architecture of Ali-Scout incorporated in the FAST-TRAC operational field trial underway in Oakland County, MI (51, 52). A 1988-1991 operational field trial in Berlin, Germany tested an earlier version of Ali-Scout extensively in some 700 vehicles. Eighty-three percent of the test subjects rated Ali-Scout good or very good in finding the way to destinations and 49 percent perceived savings in travel time (52).

In contrast with TravTek's autonomous capabilities, Ali-Scout depends totally on infrastructure support via a network of strategically located communication beacons. A traffic-dependent route tree to all destination zones from a given beacon location is downloaded to equipped vehicles as they pass the beacons. Based on the driver specified destination, the in-vehicle equipment:

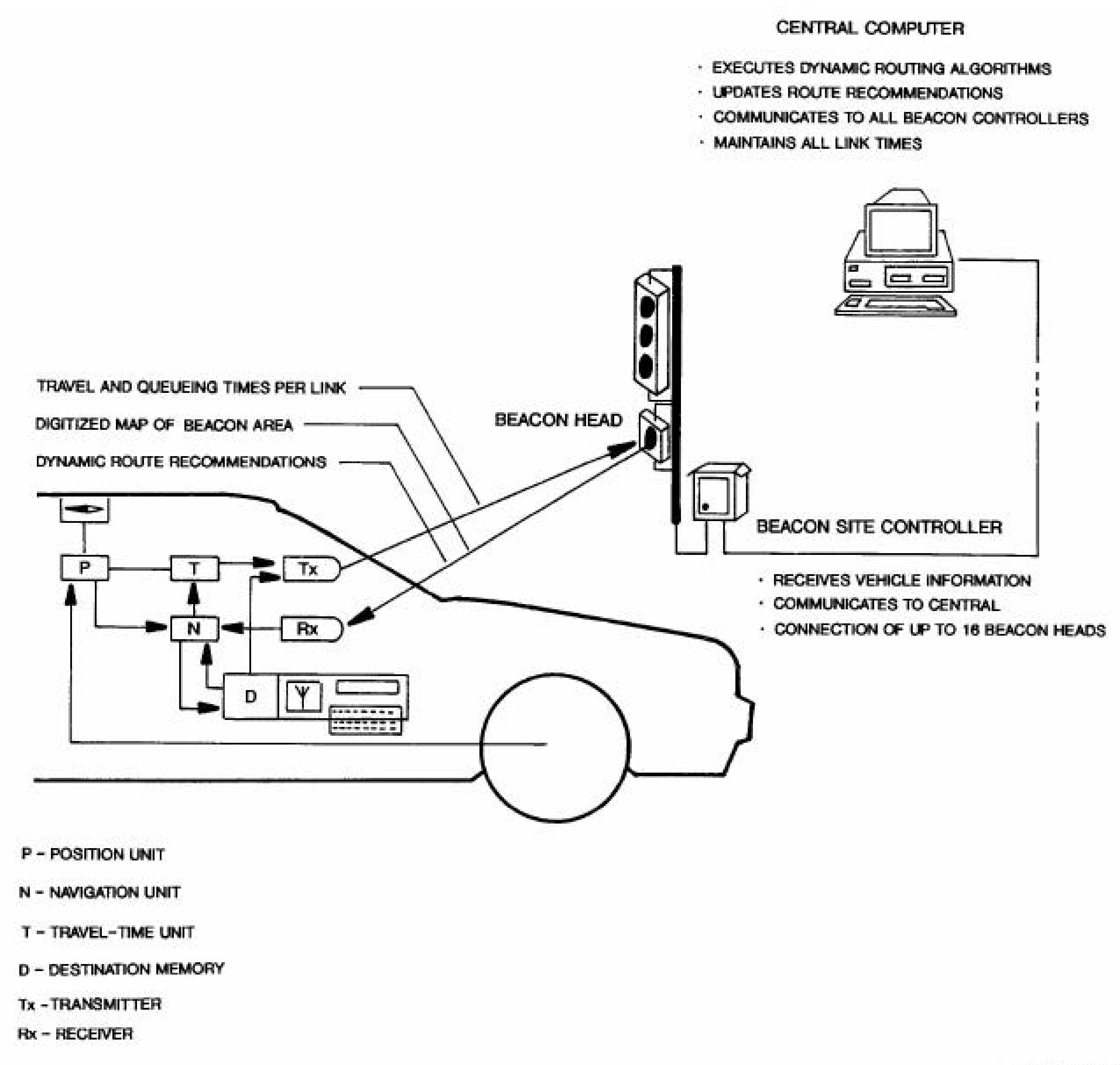

Figure 10-28. Ali-Scout system architecture.

- Selects the appropriate route from the tree, and
- Provides turn-by-turn guidance via symbolic display (see figure 10-29) and synthesized voice.

Route guidance is thus limited to highways and streets equipped with beacons.

In-Vehicle Signing

In-Vehicle Signing (IVS) refers to the display of information found on roadway signs and other traffic control devices inside the vehicle (53). The visual aspect of IVS involves displaying the information on the dashboard or windshield of the vehicle. However, IVS not only replicates existing information, it enhances the information quality, usefulness, and meaning without interfering with the driving task. At present, the scope of IVS is not clearly defined. At one end of the spectrum, IVS may be regarded as a component of en route driver information. At the other extreme, IVS can be viewed as encompassing all or part of several user services including en route driver information, route guidance, and traveler services information. Potential benefits of IVS follow:

- Enhance sign recognition at night and in adverse weather conditions,
- Provide for the individual needs of drivers with impairments,
- Inform the driver of an upcoming roadway hazard,
- Provide the posted speed limit continuously to the driver to encourage compliance, and
- Provide selective route guidance information tailored to the driver's specific needs.

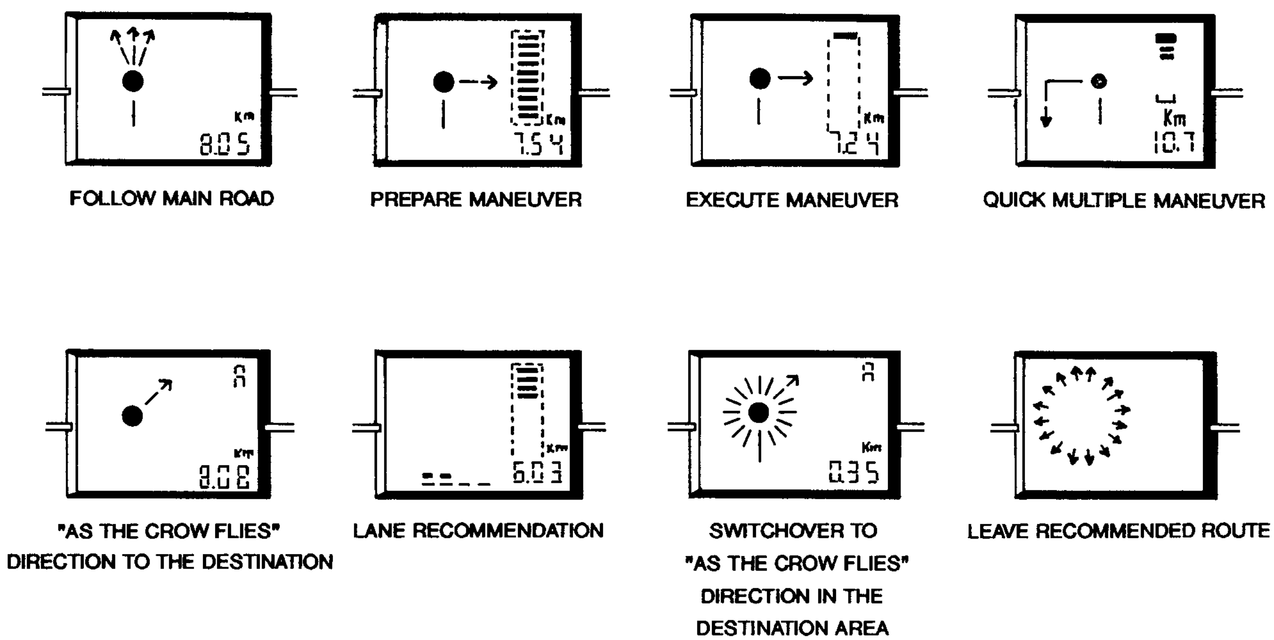

Figure 10-29. Ali-Scout in-vehicle graphic displays.

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CHAPTER 11
SELECTION OF A SYSTEM

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CHAPTER 11
SELECTION OF A SYSTEM

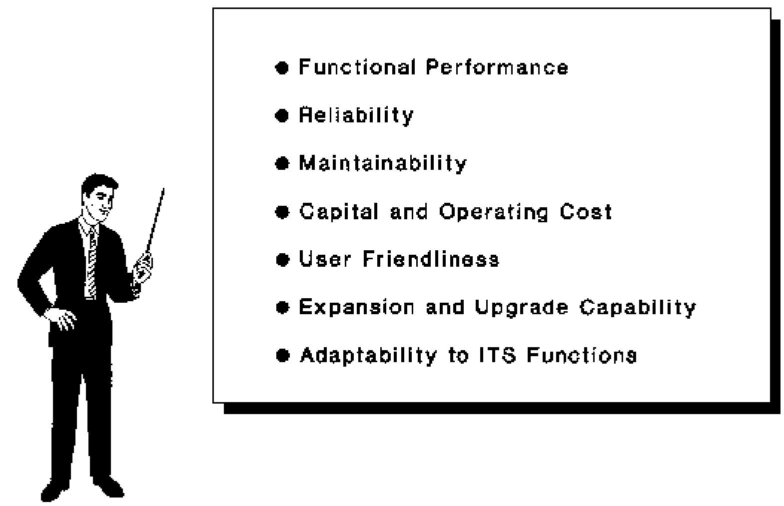

Figure 11-1. Selection of a system.

11.1 Introduction

Traffic control systems technology has made significant advances during the past decade. The demonstrated effectiveness and reliability of advanced traffic control systems has encouraged their widespread acceptance. As a result of new techniques, agencies considering traffic control system improvements have available a wide range of choices with respect to hardware and operational features. Making an appropriate selection from these available alternatives proves important - because of the expenditure of public funds - and because the choice will impact system users on a daily basis for an extended period of time.

A system selection process encourages the objective consideration of alternatives in a structured, rather than subjective, manner. Further, the structured decision approach can generate a sense of commitment to the choice among system stakeholders including:

- Participating agencies,
- Traffic system engineers, and
- The driving public.

The following material describes a system selection process that:

- Focuses on recently developed Federal-aid requirements, and
- Relates these requirements to a process that has application regardless of funding source.

The reader should also see 333 references covering the selection of control at individual intersections, urban street systems, and freeways (1, 2, 3).

Table 11-1 shows the organization of this chapter.

11.2 Federal-Aid Requirements

The Federal Highway Administration (FHWA) has accumulated significant experience on system success and failure by its active role in funding and observing the planning, design, implementation, and operation of traffic control systems. CFR Section 655.409 of the FHWA Federal-Aid Policy Guide, specifies the requirements for the implementation of a system. Appendix A provides this section.

Table 11-1. Chapter 11 organization.

Section Title	Purpose	Topics
Federal-Aid Requirements	Describes federal requirements and predesign analysis	• Policy and eligibility • Traffic engineering analysis - preliminary - alternative systems - procurement and system startup - special features - analysis of laws and ordinances - implementation plan - documentation
System Selection Process	Describes the process of selecting a control system	• Define system requirements • Identify alternative systems • Evaluate alternative systems - utility-cost analysis - benefit-cost analysis • Consider expansion and upgrade requirements

These requirements are based on control systems experience regardless of funding source. In other words, the requirements equally apply to planning, design and implementation of control systems using either local or Federal-aid funds. The following material describes the specific elements of these requirements and the selection process that they support.

Policy and Eligibility

FHWA recognizes traffic monitoring and control projects as an integral part of Federal-aid highway construction, and considers all phases of such projects eligible for appropriate Federal-aid highway funding. This statement of policy proves important; it provides credibility for the relative importance of control system elements relative to other highway construction. Further, the policy defines the critical area of system startup eligible for Federal-aid.

The policy addresses another critical factor under eligibility -- the ability to *operate* and *maintain* the system. Experience shows that an early *commitment* to adequate personnel and budget resources for operations and maintenance becomes key to operational success. The Operations Plan includes an operation and maintenance analysis and the local agency must remain aware of this requirement and commit to its implementation.

Traffic Engineering Analysis

Planning for traffic monitoring and control system improvements generally includes a feasibility study that analyzes multiple predesign elements. The type and scope of the project under consideration determines the study's level of detail. For example, *predesign* studies for a system of 6 isolated traffic-responsive ramp meters differ from those needed for an areawide freeway monitoring and control system. The traffic engineering analysis should contain the following basic elements:

Preliminary Analysis. The preliminary traffic engineering analysis examines the present situation and identifies the problem along with currently available resources. Specific factors include:

- Controlled area - A control system may be planned for staged implementation. What are current and long-term needs? Questions concerning integration of systems also require consideration.
- Operating characteristics - Portions of an area may require adaptive control while others may only need traffic-responsive or pretimed control. What are current and long-term needs?
- Transportation characteristics - The analysis may require traffic flow data to determine characteristics of the system to be controlled. Significant factors could include: volumes, turning movements, speeds, number of buses, actuated versus pretimed control, topographic factors (i.e., grades), and proposed new roadway facilities.
- Existing systems resources - Certain elements of an existing system may suit continued use. The analysis should evaluate such items as: controllers, detectors, interconnect cables and conduit systems. Pay particular attention to

staff (number and capability), equipment and facilities, and budgetary commitment to operations and maintenance. The study should also evaluate the ability of these resources to accommodate changes in system requirements.

- Objectives of the system - Based on the current situation, the study should identify problems to be solved, leading to a specific definition of what the system must do. In this way, the analysis defines specific system goals so later phases can measure alternative systems against these goals.

The preliminary analysis phase simply accumulates meaningful data for future analysis and decision-making.

Alternative Systems Analysis. As indicated in chapter 2, there exists a wide range of control system options ranging from basic to sophisticated. Further, systems are available in a number of forms, including:

- Manufacturer-packaged,
- User-tailored, and
- Custom-built.

Choosing from these available alternatives requires a critical examination of perceived system needs along with an in-depth consideration of life-cycle costs and performance issues. Some specific analysis criteria follow:

- Performance ability - Matching a control system's capabilities to a set of identified agency requirements becomes the most crucial element in system selection. Performance ability is frequently expressed in terms of:
  - Traffic operations requirements,
  - Equipment reliability and adaptability,
  - Ease of implementation, and
  - Ease of hardware and software maintenance and parts availability.

- Personnel and budget implications -- The capabilities of existing staff, maintenance facilities, and willingness to commit to ongoing budget requirements definitely impact control system decisions. Total replacement of pretimed with traffic actuated controllers, for example, would require additional training and maintenance.

- System costs - While initial system cost will prove a major decision factor, the analysis must account for full system life cycle costs over an assumed period of use. In this way, recurring maintenance and operation costs and special training costs can be considered along with initial system cost. Also determine incremental costs associated with adding to the control system special ITS features.

- System benefits - System improvements are expected to reduce delay, travel time, accidents, fuel consumption, emissions and other factors. Most of these benefits can be quantified and expressed in monetary terms. Others prove less quantifiable and must be expressed by a surrogate that approximates their value or benefit. A later section in this chapter describes a specific utility-cost approach.

Procurement and System Startup Analysis. Chapter 12 describes procurement options available for consideration. These include:

- Traditional engineer/contractor approach,
- Systems manager approach, and
- Design/build approach.

All of these have resulted in successful implementations.

System startup concerns the planning necessary to smoothly transition from old to new control, including:

- Traffic management during construction,
- Timing plan and database preparation, and
- Acceptance testing.

Chapter 12 discusses each of these items, important elements in the predesign system planning process. Note that flexibility exists in Federal-aid requirements to accommodate the special needs of systems procurement. State and local agencies inexperienced in such procurements generally impose more restrictive requirements.

Special Features Analysis. Each agency with responsibility for traffic control systems represents a unique entity with possibly some unique requirement(s). These may represent either truly new requirements or infrequently encountered situations with limited prior application. Including these features should be determined by need and a favorable benefit/cost analysis.

Analysis of Laws and Ordinances. Effective system operation may depend in part on motorist compliance and enforcement to ensure compliance. Thus an agency may need to revise local laws and ordinances for unconventional traffic control devices or use of existing devices. For example, many local traffic codes may not address high occupancy vehicle (HOV) lanes on freeways. A detailed analysis of laws and ordinances thus becomes a legitimate element of predesign studies.

Implementation Plan. An implementation plan becomes the foundation of agreement for:

- System design,
- Funding,
- Procurement,
- Construction management,
- System startup, and
- Operations and maintenance.

The authorization of Federal-aid highway funds requires commitment to the operations plan. Even if not required, this commitment proves necessary for successful system performance.

Documentation. The final step documents the methodology and decisions reached in the traffic engineering analysis.

11.3 System Selection Process

This section describes the analysis *structure* that leads to a *consensus* agreement for a control system approach. The structure includes the following steps:

- Define system requirements,
- Identify alternative systems,
- Evaluate alternative systems, and
- Select desired approach.

Define System Requirements

The need to install or upgrade traffic control systems can focus on two conditions:

- Traffic growth or changes in traffic characteristics that impose control requirements beyond the capability of the existing system, or
- Mechanical/physical obsolescence of equipment that results in degraded or inefficient operation, or equipment that requires excessive maintenance.

In any case, the control system must fill specific, clearly identified needs.

A structured approach involving all interested agencies can identify these needs. To guide the project from concept to reality, this approach uses a project team representing:

- Management,
- Planning,
- Design,
- Operations, and
- Maintenance.

Include multiple agencies as appropriate to enhance *jurisdictional* cooperation during planning, design, implementation and operation. Working in a common forum, this project team can develop specific system requirements that:

- Reflect each individual group's need, and
- Resolve any conflicting objectives.

The system *must* meet certain requirements, e.g., control a certain number of intersections. Other requirements may prove desirable but not absolutely needed; they can be met to varying degrees. A requirement for equipment interchangeability might fit this category. The project team should identify and prioritize these requirements. These priorities, reached by consensus, constitute the basis for system design and evaluation.

Identify Alternative Systems

A wide range of traffic control system alternatives exists. Marketplace dynamics show constant change in available systems and capabilities because:

- Manufacturers continually develop system capabilities,
- Users experiment and develop unique approaches, and
- Research produces technological advances.

Because of these changes, identifying alternative systems requires continued interface with:

- Manufacturers,
- Users,
- Systems houses,
- Consultants,
- Researchers, and
- Interested individuals.

Equipment manufacturers or system suppliers generally develop one or more types of traffic signal systems as classified in table 11-2.

The engineer must obtain information on the functional and design features and specifications of these systems from the manufacturers and system suppliers. In some cases, designers can specify additions or modifications to the baseline system, although this can prove costly. Discuss cost and other practical implications with suppliers of the type system under consideration.

The communications required for system interconnection has many technology alternatives and usually proves a key cost component. The Communications Handbook for Traffic Control Systems describes a communication selection methodology, summarized in section 9.4 (4).

Unlike traffic signal systems, freeway monitoring and control systems are generally not available from a manufacturer's product line or a system supplier's typical design. As a result, performance and cost are generally determined by the specific features required. Key cost and performance features are strongly influenced by the following:

- Extent of CCTV coverage,
- Spacing frequency for mainline detector stations,
- Number of CMS/HAR,
- Number of ramp meters, and
- Type of communications.

Evaluate Alternative Systems

System evaluation and selection includes the following steps:

- Initially screen the broad spectrum of possible systems,
- Evaluate and compare in detail the remaining alternatives, and
- Make final selection based on system requirements, costs and benefits.

The detailed evaluation typically includes these steps:

- Estimate benefits or utilities for each alternative,
- Estimate costs of each alternative,
- Perform comparative analysis, and
- Select the system offering the most potential.

A wide variety of techniques exists for the comparison of costs and benefits of alternative systems. Among these, 2 analysis techniques have gained widespread use in the traffic control field:

Table 11-2. Types of signal systems.

- Time-base coordination
- Field masters coordinating local controllers
- Closed-loop systems
- UTCS first generation derivative systems (including 1.5 GC)
- Advanced traffic adaptive systems such as SCOOT and SCATS

- Utility-cost, and
- Benefit-cost.

Utility-Cost Analysis

In this commonly applied technique, a utility measure becomes a proxy for a system benefit (5). The sum of system utilities divided by total system cost represents the utility-cost factor for a particular system.

An earlier paragraph discussed the ranking of system requirements. Each requirement receives a relative weight reflecting its importance to this jurisdiction, forming the basic scale for measurement of alternative systems. The utilities and their weights should be determined as a project team effort.

Figure 11-2 illustrates the computational procedure that rates each alternative against specified requirements (2). The ability of each alternative system to meet each requirement is rated 0 to 10. Zero indicates that the system does not satisfy the requirement at all while 10 indicates total satisfaction. This internal rating scale simply measures how well an alternative system satisfies a requirement. Combining the individual rating with the relative weight measures the utility value for that requirement. The sum of all individual utility values gives an overall utility rating for each alternative system. Table 11-3 shows example weighted system requirements (6).

In some cases, the project team may initially express needs in the form of goals and subgoals, as shown in the example of table 11-4 (3). These goals must then be converted to design requirements with appropriate weighing factors.

Cost, the other factor in the utility-cost analysis, reflects estimates of both one-time and recurring costs over some identified time period. Since fund

Requirement	Relative Importance of Each Requirement Sum = 100	Ability of Alternative Systems to Meet Each Requirement Rating (0 to 10): Alternative System 1		Alternative System 2		Alternative System 3	
1. Intensity of CCTV coverage	25	4	100	7	175	10	250
2. Spacing of mainline monitoring station	25	2	(50)	6	150	8	200
3.	8	(5)	40	4	32	7	56
4.	(4)	10	40	6	24	6	24
5.	16	10	160	7	112	7	112
	etc.						
	100		390		493		642

Relative weight scale
How important is this requirement in this jurisdiction? The total of these values must equal 100.

Internal rating scale
How well does this alternative system satisfy this requirement? The range of this value is between 0 and 10 where 0 means the system cannot accomplish this function, and 10 means the requirement is totally satisfied.

Utility value
Obtained by multiplying the internal rating scale by the relative weight of each requirement. These values are summed to determine the total utility of each alternative.

Figure 11-2. Example of utility calculations.

Table 11-3. Example of utility measures and weights.

Utility Measures	Range of Weights by Team Members	Normalized Average of Team Member Weights	Weight Rating X Normalized Average
Adaptability (Rating 16.0)			
Incorporation of new control logic	10-60	28.4	4.6
Accommodation of traffic pattern shifts	10-50	32.8	5.2
Adjustment to physical changes	20-40	28.3	4.5
Incorporation of non-traffic control functions	10-15	10.5	1.7
		100.0	16.0
Areawide Traffic Management (Rating 14.9)			
Special traffic functions	15-30	24.5	3.6
Special events	10-40	22.8	3.4
Coordinated control of all signals	40-70	52.7	7.9
		100.0	14.9
Implementation Characteristics (Rating 14.4)			
Implementation in phases on priority basis	25-40	36.7	5.3
Minimal degree of implementation complexity	10-25	19.5	2.8
Minimal impact on traffic	10-30	18.3	2.6
Use of existing equipment	10-40	25.5	3.7
		100.0	14.4
Performance Monitoring and Operator Interface (Rating 14.1)			
Dynamic display map	25-50	33.1	4.7
Operator console	20-45	32.6	4.6
Data logging and MOE analysis	20-50	34.3	4.8
		100.0	14.1
Reliability (Rating 19.5)			
Failsafe and backup capability	10-45	26.1	5.1
Hardware failure monitoring and reporting	20-30	22.2	4.3
Software reliability	10-50	24.5	4.8
Ease of maintenance	15-50	27.2	5.3
		100.0	19.5
Traffic Operation (Rating 21.1)			
Adequate number of timing plans with multiple zones	10-25	16.1	3.4
Isolated, arterial, and network control	10-30	17.2	3.6
Coordination of adjacent zones	10-40	18.4	3.9
Local intersection optimization	15-35	25.0	5.3
Selection of timing patterns by manual, time-of-day (TOD) or traffic-responsive (TRSP)	10-35	23.3	4.9
		100.0	21.1
TOTAL			100.0

Source: Reference 6 (Supplemented)

Table 11-4. Example freeway goals and subtotals.

Goals and Subgoals	Weight of Subgoal (0-100)	Percentage of Goal Attributed to Subgoal
1. Traffic Operations (34 percent)		$\left(\frac{70}{160} x\ 100 = 44\right)$
Reduce freeway delay to the motorist	70	44
Maintain level of Service D	50	31
Reduce stop-and-go congestion	40	25
	160	100
2. Safety (4 percent)		
Reduce freeway accidents	100	57
Reduce ramp merging accidents	75	43
	175	100
3. Implementation (2 percent)		
Disruption of traffic during construction	60	46
Time frame of installation	30	23
Training of operational personnel	40	31
	130	100
4. Operating Factors (14 percent)		
Equipment simplicity	60	38
Level of equipment maintenance	100	62
	160	100
5. Freeway Management (23 percent)		
Provide management mechanism	50	10
Accommodate future demands (expansion capability of equipment)	80	16
Redistribute delay/demand	30	6
Defer capital improvement	35	7
Provide traffic operations surveillance	60	12
Improve accident/incident response	40	8
Facilitate data collection	80	17
Provide driver information	40	8
Coordinate with corridor signal systems	75	16
	490	100
6. Operation Efficiency (23 percent)		
Responsiveness to flow instability	60	16
Responsiveness to incidents	50	14
Variation of peak start/end times	50	14
Responsiveness to fluctuating demand	30	8
Adjustment of metering rates	100	27
Responsiveness to traffic pattern changes	75	21
	365	100

Source: Reference 3 (Supplemented)

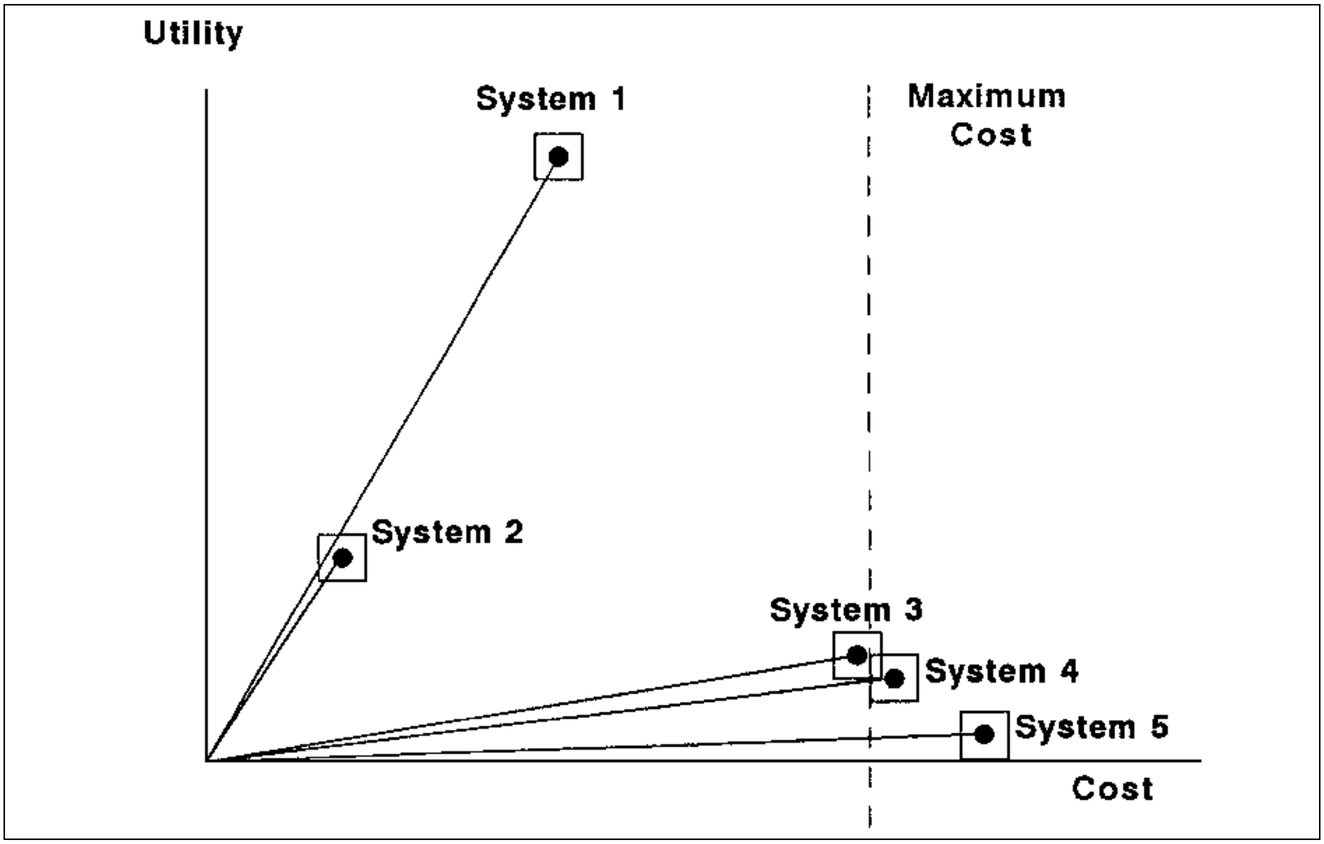

Figure 11-3. Utility-cost comparison of alternative systems.

disbursements occur at different times over the analysis period, a present worth analysis converts all costs to a present value. In this way, alternative system costs can be compared.

The utility-cost ratio of each alternative system becomes the total utility divided by total cost. One can reach the conclusion that the best system has the greatest utility-cost ratio. However, this conclusion may prove faulty because a simple, inexpensive system with low utility and low cost may have the same ratio as a sophisticated, affordable system with high utility satisfying all defined requirements.

To avoid this conclusion, plot the results of the utility-cost analysis as in figure 11-3. The slope of the line indicates the utility-cost ratio, and the endpoint represents individual values of utility and cost for each alternative. In this manner, systems with nearly equivalent utility-cost ratios, such as Systems 1 and 2, can be readily compared. Notice also that the rectangle at each point represents the range of uncertainty associated with costs and utilities. Further, notice that Systems 4 and 5 can be excluded from further consideration because they exceed acceptable cost, and provide less utility than the lower cost System 3.

Benefit-Cost Analysis

Benefit-cost analysis offers a second technique for:

- Comparing alternative systems, or
- Justifying the installation of a new system.

This technique compares benefits and costs in much the same way utility-cost analysis compares utilities and costs. However, benefit-cost analysis expresses benefits in absolute terms (i.e., dollars) rather than as a utility rating. A cost-effective system has a benefit-cost ratio greater than unity over the life of the system. In both methods, it proves important to consider life-cycle costs.

This method proves advantageous because it expresses system benefits as monetary savings to the user and possibly to the operating agency, thus providing an *absolute* rather than *relative* measure of potential savings. The public and officials with funding authority more readily understand this approach. The disadvantage is that some benefits may prove difficult to estimate, and others difficult to quantify.

The usual approach in benefit-cost analysis compares annual benefits with annual costs. This section describes how to determine annual costs and benefits, and how benefit-cost analysis can compare and evaluate system performance.

Determining Costs

Annual costs have 2 components:

- Equivalent annual cost of the initial capital outlay, and
- Annually incurred costs for operations and maintenance.

Table 11-5 outlines the steps to determine the total annual cost (annualized life-cycle costs) from the initial capital cost of the system. The table shows a simple formula useful for estimating the total annual cost of a system over a typical 15-year lifetime at 7% interest (7). Table 11-6 gives the relationship for other lifetimes and interest rates. The example assumes annual O & M costs approximate 10% of the system's capital cost and no salvage value exists.

Determining Benefits

The analysis must measure the benefit of a new or improved system relative to the existing system. To do this, the analysis compares existing conditions with those anticipated from the improvements.

Table 11-7 lists the total cost of congestion and its various components. Table 11-8 provides possible sources for estimates of improvements. Values for the cost coefficients can be found in the literature.

Congestion delay results from recurrent congestion that proves more or less predictable from day-to-day and week-to-week. It represents the total delay on all links relative to congestion-free conditions. At this writing, commonly used values for delay range from $12 to $15 per vehicle hour.

The cost due to incidents sums the cost of:

- Collision-caused incidents (property damage and personal injury accidents), and
- Non-collision-caused incidents (delay from weather, breakdowns, etc.).
- Estimate the cost of collision-caused incidents from statistical data on the:
- Average delay per collision,
- Average number of collisions per year, and
- Average cost per collision.

Section 3.11 provides accident cost data.

Fuel consumption approximates a linear function of average vehicle delay and average number of stops and starts, and can be estimated from average fuel consumption data and average fuel cost (3, 6). Section 3.11 provides fuel consumption rates.

Although not easily quantifiable in terms of dollar benefits, the effect of a new traffic control system on vehicle emissions is a key issue. Improved traffic control systems provide the potential for emission reduction. Section 3.11 discusses models for estimating emissions. An analysis of emission effects represents an important element in system evaluation.

System Evaluation

Viable traffic control systems will have a benefit-cost ratio greater than unity and comply with the Clean Air Act of 1990. While systems with high benefit-cost ratios are generally preferred, a benefit versus cost diagram similar to the utility versus cost comparison of figure 11-3 may prove useful. Thus, systems with a lower benefit-cost ratio but a higher level of net benefits (benefit minus cost) may be preferred.

Consider Expansion and Upgrade Requirements

Within limits, the provision of capability to expand and upgrade the system is usually cost effective in that it avoids system replacement or significant modification resulting from:

- Inability to satisfy physical expansion requirements,
- Inability to satisfy additional functional requirements, and
- Inability to procure spare parts or maintenance services.

Although the requirements for future expansion may not be fully known during initial system design, in many cases the jurisdiction's geography, coupled with a knowledge of anticipated functionality improvements allows planning for system expansion and upgrade.

Table 11-9 describes the relationship of the expansion or upgrade of functional characteristics to a number of system design characteristics. The *Communications Handbook for Traffic Control Systems* provides further detail on expansion of communications capability (4).

Table 11-5. Determining total annual cost.

Total Annual Cost = Equivalent Annual Capital Cost + Annual Costs

Or, $C = C_{cap} + C_a$

Where: $C_{cap} = CRF(i,n)\ (I - S) - i\ S$

CRF = Capital Recovery Factor = $i(1+i)^n / \{(1+i)^n - 1\}$

I = Initial Capital Cost   i = Annual Interest Rate

S = Salvage Value   n = Life of System (years)

$C_a = C_{operations} + C_{maintenance}$

Example

i = 7%   n = 15 years   S = 0   CRF = 0.110

Usually, C_a = 10% of Capital Cost = 0.1 x I /year

Then, C = CRF x I + 0.1 x I

and **C = 0.210 x I**

Table 11-6. Typical annualized cost per dollar of capital cost.

Interest Rate	4	5	6	7	8	9	10
10 Year Life	0.223	0.230	0.236	0.242	0.249	0.256	0.263
15 Year Life	0.190	0.196	0.203	0.210	0.217	0.224	0.232
Assuming annual O & M costs = 10% of capital cost; salvage value = 0							

Table 11-7. The cost of congestion.

TOTAL COST OF CONGESTION

$$C_C = C_D + C_{IC} + C_{INC} + C_F + C_P$$

Where:

- C_D = Congestion delay costs
- C_{IC} = Incident costs (collision-caused)
- C_{INC} = Incident costs (non-collision-caused)
- C_F = Fuel wastage costs
- C_P = Air pollution costs

COST OF CONGESTION DELAY

$$C_D = D_C \times O_V \times O_P$$

Where:

- D_C = Average delay due to congestion - veh-hrs/year
- O_V = Average vehicle occupancy (persons/vehicle)
- O_P = Personal cost of delay ($/person-hour)

COST OF COLLISION-CAUSED INCIDENTS

$$C_{IC} = (D_{IC} \times O_V \times O_P + C_C) \times N_{IC}$$

Where:

- D_{IC} = Average delay/collision-caused incident (veh-hrs/incident)
- N_{IC} = Average number of collision-caused incidents/year
- C_C = Average cost per collision (property damage + personal injury)

COST OF NON-COLLISION-CAUSED INCIDENTS

$$C_{INC} = D_{INC} \times O_V \times O_P \times N_{INC}$$

Where:

- D_{INC} = Average delay/non-collision-caused incident (veh-hrs/incident)
- N_{INC} = Average number of non-collision-caused incidents/year

COST OF WASTED FUEL

$$C_F = (fc \times D + fs \times N_S) \times c_f$$

Where:

- D = Total delay = $D_C + D_{IC} + D_{INC}$
- fc = Fuel consumption (gallons/veh-hr)
- fs = Fuel consumption per stop/start(gallons/stop)
- N_S = Number of stops
- c_f = Cost of fuel ($/gallon)

Table 11-8. Possible sources for estimates of improvement.

- Estimates for improvements provided in previous chapters
- Simulation
- Estimates of improvements described in the literature for similar candidate systems or techniques
- Estimates of improvements from a pilot system

Table 11-9. Relationship of expansion or upgrade of functional characteristics to system design characteristics.

System Functional Characteristics That may be Expanded / System Design Characteristics Affected by Modifications	Communication capability (Reference 4)	Computational power	Program dimensions and database	Other computer equipment in Traffic Operations Center (e.g., servers, workstations, local area networks)	Functional modularity of software	Standards and protocols which support open architecture	Size of Traffic Operations Center
Physical expansion (e.g., number of intersections, miles of freeway under surveillance)	Yes	Yes	Yes	Yes	No	Yes	Yes
Addition or enhancement of ATMS and ATIS functions (e.g., corridor control, automatic messaging to media and motorists calling in)	Yes	Yes	Yes	Yes	Yes	Yes	Possibly
Addition of other ITS functions	Yes	Yes	Possibly	Yes	Possibly	Possibly	Yes
Upgrades to new equipment	No	Possibly	Possibly	Possibly	No	Yes	No

References - Chapter 11

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CHAPTER 12
DESIGN AND IMPLEMENTATION

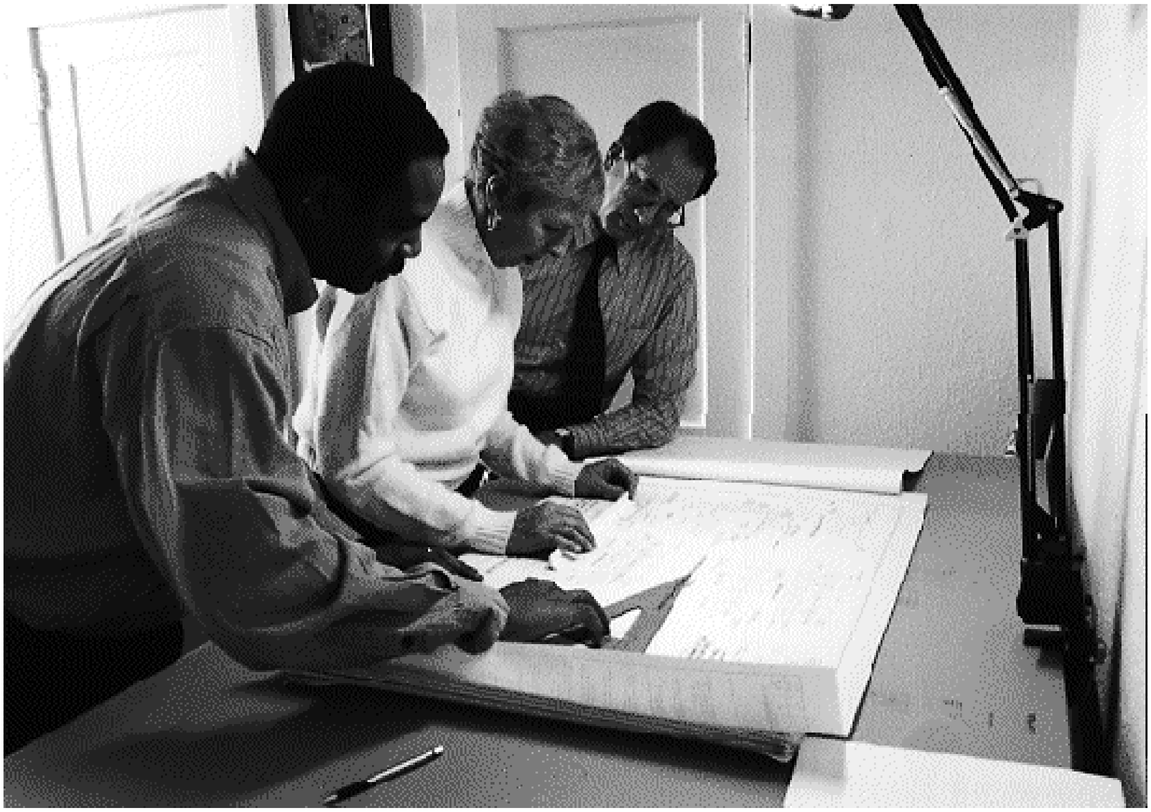


Figure 12-1. Plan preparation for traffic control system.

12.1 Introduction

The material in this chapter:

- Places the system design, procurement, and installation tasks in perspective with respect to total system planning and implementation;
- Describes alternative approaches to the procurement of systems, including contractor selection;
- Describes the various elements of the design process, with particular emphasis on the contents of bid documents; and
- Describes elements of a system installation and project management approach.

This chapter applies to traffic control systems of virtually any size or complexity. Table 12-1 shows the organization of this chapter.

12.2 System Implementation

System implementation includes the following major elements:

- System Feasibility Study,
- Design Plans, Specifications, and Cost Estimates (P, S & E), and
- System Installation.

Appendix A provides the section of the Federal-Aid Policy Guide that addresses these elements.

System Feasibility Study

It often becomes necessary to determine the most appropriate alternative(s) in selecting a traffic control system addressing both short and long range needs. This activity typically takes the form of a *feasibility* study, concept design, or preliminary design. Recommended elements of this study include:

Table 12-1. Chapter 12 organization.

Section Title	Purpose	Topics
System Implementation	Describes the process of implementing a traffic control system	• System feasibility study • Design plans, specifications, and cost estimates (PS&E) • System installation - construction - training, debugging, documentation, evaluation and turnover
Procurement Approach	Describes the basic approaches of acquiring a traffic control system	• Engineer (Consultant)/Contractor approach • Systems manager approach • Two-step procurement • Design/Build approach • Comparison of approaches
Design Plans and Specifications	Describes the quality and types of workmanship and materials as well as the construction and installation process of the components	• Design plans • Specifications - sources of specifications - closed versus open specifications - functional versus material specifications - standard specifications • Contract documents - invitation to bid - instructions to bidders - bid proposal - bonds - agreement - conditions - contractor qualifications - pre-bid conference - precedence • Technical specifications - definition of terms - installation of traffic signals - specifications for materials and equipment • Software, database, performance and system test
Deliverable Services	Describes the responsibilities of the contractor for providing items or services to the contract	• Systems management • Documentation • Training • Startup assistance • Warranties/guarantees • Maintenance • System acceptance tests - equipment checkout tests - system electrical tests - computer software tests - systems operations tests
Project Management	Describes methods for attaining overall system goals within budget and timeframe	• Contract administration • Scheduling - critical path method (CPM) - bar charts - Gantt charts

Table 12-1. Chapter 12 organization (continued).

Section Title	Purpose	Topics
Implementation Pitfalls	Describes unexpected difficulties and how to avoid them	• Inexperienced contractors • Construction management • Timing coordination during construction • Database development • Insufficient staff for operations and maintenance • Utility coordination • Planned use of untested facilities or techniques • Alienation of maintenance staff • Privatization of operations and maintenance

- Identify needs and goals,
- Inventory existing traffic signal equipment and communication system,
- Identify system performance requirements,
- Identify alternative systems (hardware and software),
- Identify communication requirements and methodologies,
- Recommend design approach,
- Identify benefits and make preliminary cost estimates,
- Study procurement alternatives and select an approach, and
- Develop plans for an implementation program.

The feasibility study should establish the framework for design and specifications addressing both system and communication concept. It should address capital, maintenance and operating costs and staffing requirements.

Design Plans, Specifications and Cost Estimates (P, S & E)

This phase of the process transforms the feasibility study into design documents and specifications suitable for competitive bids. Software specifications should sufficiently detail functional operation characteristics such as:

- Surveillance and control algorithms,
- Mode structures,
- Graphics,
- Operator controls and displays, and
- Interfaces with other systems.

The completion of the P, S & E marks the beginning of the project management process, which carries the project through the following steps:

- Procurement of the system components, including review of the proposed components relative to the specifications;
- Construction of the system, including inspection and subsystem testing;
- System training, debugging, and documentation; system acceptance testing and other deliverable services;
- Startup; and
- Turning the operating system over to the user.

System Installation

Construction

This phase includes design (if required), manufacture, and installation of system components. Construction also involves the inspection, testing, and approval/disapproval of various components designed for the project. Testing may be performed on major components and subsystems. Unless properly managed, long construction delays may occur that can prove costly to the client and the systems manager or contractor.

Training, Debugging, Documentation, Evaluation, and Turnover

This marks the final phase of system implementation and also prepares for final turnover to the client. In this phase, the contractor performs:

- System debugging and support,

- Training of operational and maintenance personnel, and
- Documenting system hardware and software.

The contractor performs system acceptance testing and the operating agency or its consultant evaluates the tests. Under the systems manager approach, the systems manager may in part perform some of these tasks.

System operation and maintenance training should begin at the early stages of the project and involve appropriate parties throughout as illustrated in figures 12-2 and 12-3. This concept allows for training of:

- Administrative,
- Engineering,
- Operating, and
- Maintenance staff.

Various levels of training should take place for appropriate audiences. Effective training and subsequent system operation require appropriate documentation.

Construction contracts often include provisions for system support and maintenance for a period of time after system acceptance.

12.3 Procurement Approach

The feasibility study selects a preliminary design as the most appropriate to satisfy traffic control system goals. The agency should establish the procurement approach and contracting procedures as part of or subsequent to the feasibility study. The following sections describe 3 possible approaches:

- Engineer (consultant)/contractor,
- Systems manager, and
- Design/build.

The first two approaches must satisfy the following principles:

- An organization separate from that supplying the hardware, bidding on the project, or installing the system must develop the specifications; and
- The procurement of all hardware and software items must follow competitive bid requirements.

Engineer (Consultant)/Contractor Approach

The engineer (consultant)/contractor approach represents the traditional procedure for contracting within the highway agency community. Agencies have procured the majority of traffic control systems using this approach. On the basis of feasibility studies and system selection, the engineer (consultant) prepares the design plans, specifications, and estimates (PS&E) for the proposed system. Either an agency employee or a consultant can serve as the engineer. The agency then issues the completed PS&E to the contractor community, and receives bids in accordance with roadway/highway established practice. Established procedures have evolved through years of use within each agency on other than traffic control system projects. These procedures, not necessarily optimum for high technology traffic control systems, usually still apply.

In this approach, the contractor bids on a single set of plans and specifications and agrees to provide a complete system, comprising hardware and software, procured, installed, and integrated by the contractor's organization. Hardware items may be manufactured by the contractor's firm or subcontracted within the conditions imposed by the contract. The contractor also has responsibility for all systems integration tasks, documentation, and training. He may also have responsibility for system startup assistance and the development and implementation of timing plans and other database elements.

The engineer's (consultant) activities continue during system installation and include:

- Monitoring the contractor's progress,
- Reviewing the contractor's submittals,
- Interpreting or clarifying plans and specifications,
- Inspecting the installation,
- Processing the contractor's technical submittals and payment requests, and
- Coordinating activities with other agencies such as:
  - Utility companies, or
  - Control center architect.

The engineer or consultant holds responsibility for the witnessing and acceptance of components, witnessing tests at all levels and accepting the entire system. The agency or its selected consultant can perform all or part of the engineer's duties.

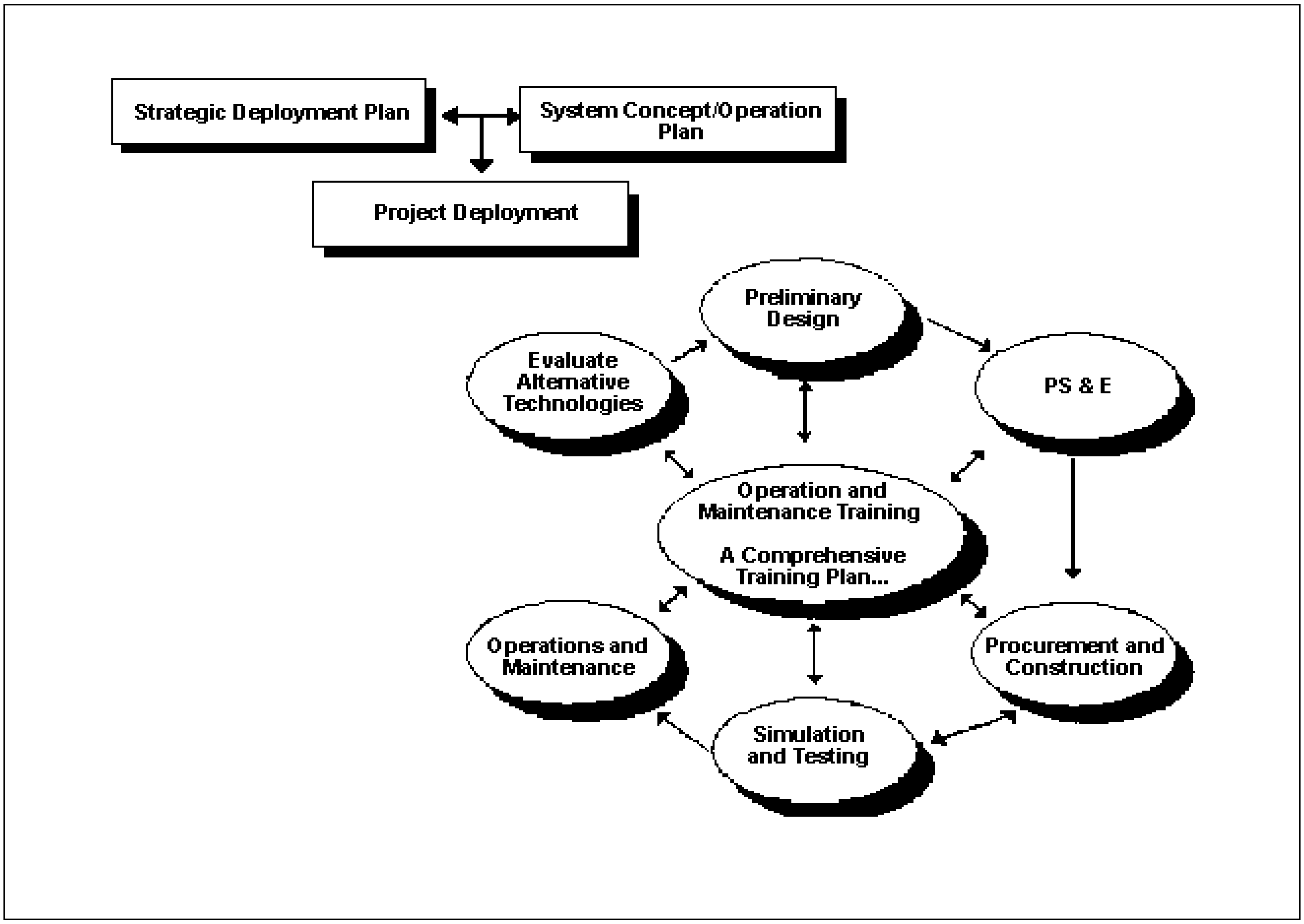


Figure 12-2. Operation and maintenance training concept.

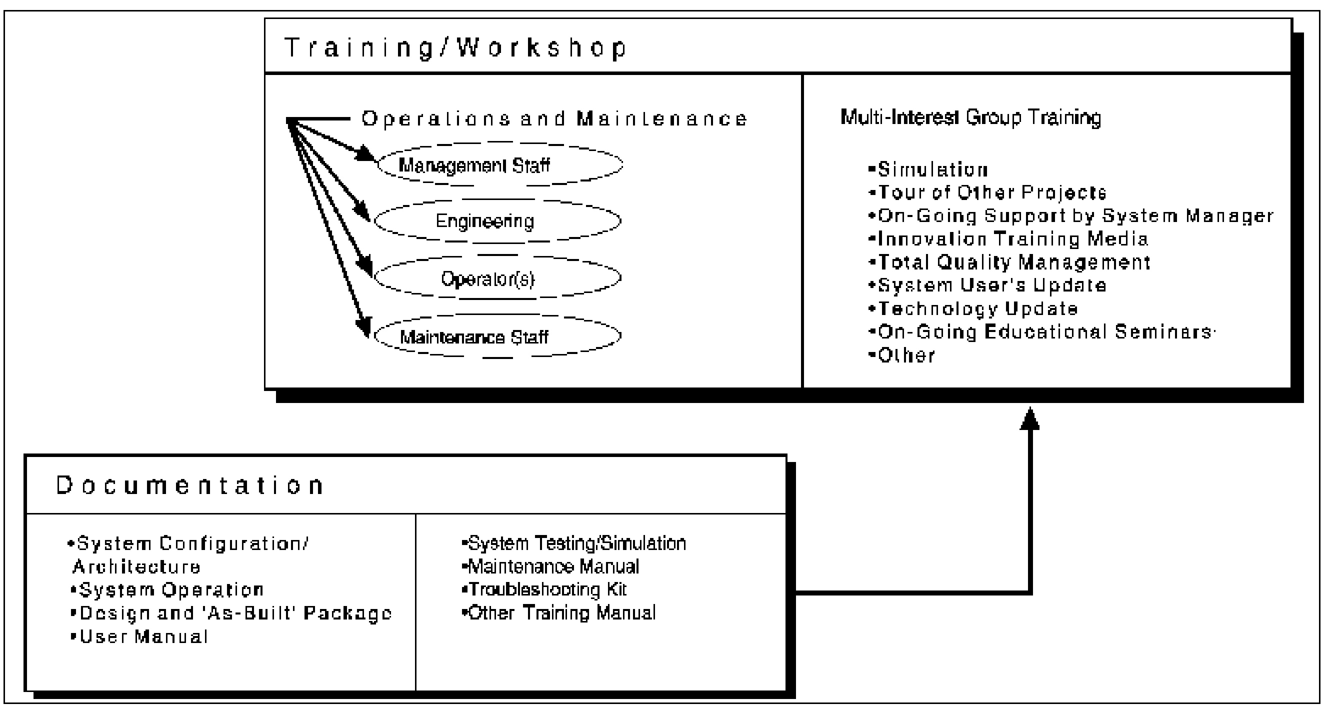


Figure 12-3. Training / workshop activities and documentation.

Systems Manager Approach

The systems manager approach requires the selection of a single firm or consulting team (as systems manager) to become responsible, under an engineering services contract, for:

- System design,
- PS&E preparation,
- Systems integration,
- Documentation,
- Training,
- Management of testing, and
- Startup.

Selecting a systems manager generally follows the typical procedures for selection of an engineering consultant with negotiated cost-plus-fixed-fee contracts frequently used.

To avoid conflict of interest, the systems manager usually accepts a hardware exclusion clause that prohibits his/her organization from supplying any of the hardware components of the system.

However, some systems managers provide software. In cities such as Los Angeles and New York, the systems manager provided software, whereas in others, a separate contractor supplied system software.

The systems manager prepares the PS&E. The agency's normal bidding processes then procure the individual subsystems or services, and the systems manager subsequently oversees testing and installation of the equipment. The systems manager may also provide the integration of all hardware and software to provide a total operating system.

Two-Step Procurement

In the early days of computer-based traffic control system implementation, several problems arose because of designer and contractor inexperience. This resulted from their unfamiliarity with computers, software, and digital data communications, and the complexity of such large systems. In some cases, inexperienced contractors, chosen through the low-bid process, attempted control system projects without a clear understanding of the requirements or risks. That period saw initiation of the 2-step procurement procedure that modifies the typical low-bid process to include contractor prequalification (1). Agencies may use this approach if procurement regulations permit.

The *first* step distributes the system PS&E (typically functional specifications) to all interested contractors, who are invited to submit a technical design proposal. In this response, prospective contractors respond to the specification by:

- Identifying their technical experience and capabilities to perform work of this nature,
- Providing staff capability data,
- Describing their approach to performing project requirements including its software,
- Describing major hardware elements,
- Providing estimates of level-of-effort on project tasks and software, and
- Commenting on schedule requirements.

This submission specifically excludes cost data. However, it requires sufficient information to justify contractor prequalification or rejection based on the provisions and requirements of the specifications.

The *second* step issues a formal request for bid, perhaps with addenda to clarify issues or inconsistencies revealed during the first step. This bid goes to only prequalified contractors. The second step becomes the typical advertise, bid, evaluate and award process of the engineer (consultant)/contractor approach.

Design/Build Approach

The design/build approach selects a single responsible entity to perform all work associated with the deployment of the traffic control system. The public agency monitors the activity of the design/builder. The design/builder:

- Performs all design work,
- Contracts and/or constructs system elements, and
- Commissions the system and turns it over to the operating agency (2).

A feasibility study or detailed set of requirements usually forms the basis for the design build.

The design/build contract may take the form of a negotiated or cost competitive contract.

The design/build concept may not prove consistent with the procurement regulations (or the interpretation of these regulations) of the procuring agency.

After negotiation of the agreement, the designer/builder completes all aspects of the project in conformance with the preliminary design. The agency and designer/builder generally negotiate changes.

The design/build approach has the key attribute of complete assumption of responsibility by the designer/builder. This generally allows more rapid completion because of streamlined procurement procedures and quicker resolution of problems. Also, the designer/builder has an incentive to reduce its costs and risks by completing all work quickly and turning the system over to the agency. Assuming a qualified design/build team, all skills rest within the team, leading to closer coordination and cooperation.

The approach does place a burden of supervision on the agency to maintain quality. The designer/builder moves at full speed and may prove reluctant to change direction if required due to technology changes. It also may force the agency into making quick decisions.

Michigan DOT procured both the original SCANDI freeway surveillance and control system in Detroit and its subsequent expansion under this approach. Recently, several State departments of transportation have considered the design/build approach for both roadway and freeway/traffic control projects. Examples include:

- Florida DOT (bridge, roadway, and toll road facilities) (3), and
- Washington DOT (areawide, multi-jurisdictional advanced traffic management system) in the Seattle metropolitan region (4).

In addition, some local agencies such as Salem, OR have used this approach for the design and implementation of computerized signal system projects (5).

Comparison of Approaches

All these approaches and variations can result in successful implementations. Table 12-2 summarizes the primary differences between them.

Choice of the procurement approach impacts the preparation of plans and specifications. Specifications developed under the engineer (consultant)/contractor approach generally emphasize the functional characteristics of the equipment and impose operational design, and environmental constraints. They will describe what the system must do but leave to the contractor, within constraints, how it must be done.

By contrast, the systems manager or designer/builder must develop detailed specifications that describe interface requirements, voltage levels, data rates, connector types, etc., to ensure their proper

Table 12-2. Features of procurement approaches.

Approach	Feature
Engineer (Consultant) Contractor	• Costs less than systems manager approach because of competitive bidding for total installation • May result in lower design cost because less detail required for certain elements • Minimizes potential conflicts of interest
Systems Manager	• Provides greater expertise in contract monitoring, equipment acceptance and testing than many agencies can provide • Can easily modify functional requirements and provide additional features during implementation • Has greatest value for very large systems or systems having unique characteristics
Design/Build	• Assures project cost limit prior to starting detailed design • Eliminates time between project phases thus leading to more rapid project completion • Requires sufficient level of technical definition prior to award to assure satisfaction of all functional requirements, operating features and quality standards

integration into a total system. In certain cases, it may also become necessary to procure major subsystems sequentially to ensure compatibility.

The system manager and engineer/contractor approach can and have been combined and mixed. In one application, a local agency:

- Purchased new local controllers,
- Installed them using their own maintenance staff,
- Contracted for installation of underground conduit using the PS&E developed by a consultant, and
- Selected a systems manager to implement a computer-based control system in space prepared by a separate department's architect and building contractor.

Without regard to the procurement approach selected, the success of a traffic control system ultimately depends on people. As clearly stated by O'Malley, *It cannot be overemphasized that regardless of the sophistication of the tools that we have to do the job, it is still people, whether it be individuals, private firms, or government agencies, that ultimately must work together to achieve success* (6). Observation has shown that the most successful operational systems have a knowledgeable agency staff that participated in all phases of the predesign, design, and implementation.

12.4 Design Plans and Specifications

Construction contract documents represent tools for communication between the owner (purchaser, local government) and contractor (supplier). Properly prepared, they prevent disagreements and facilitate project completion by clearly communicating what the owner wants done and when.

The two principal elements of contract documents are plans (drawings) and specifications (7). Plans define the physical relationships of materials procured by the contract, while specifications define the *quality* and *types* of workmanship and materials. Understanding the unique role of each of these documents will produce clarity, brevity, and consistency, and avoid redundancy. Ideally, a change in requirements will not lead to inconsistencies and misinterpretations because of the failure to modify both documents.

The following sections describe typical contents of plans, specifications, and contract documents.

Design Plans

The design plans show how components of a traffic control system are constructed and installed. Table 12-3 shows the types of plans generally included.

The items in table 12-3 provide information for the contractor and equipment supplier to prepare a project bid. The plans also serve to control the project's construction.

For details of the elements shown in table 12-3, see the *Manual of Traffic Signal Design* prepared through the Institute of Transportation Engineers (ITE) (8).

Specifications

Specifications spell out the minimum acceptable requirements for the traffic control system's equipment and materials and how the contractor should install the system. Deficient specifications can often lead to inferior equipment and materials. When defining the minimum acceptable requirements, remember that a construction contractor will, when possible, provide the lowest cost equipment meeting these requirements.

Sources of Specifications

Specifications should reflect the system's functional requirements and equipment and, as appropriate, physical requirements and constraints.

To ensure conformance with available products, agencies often adopt existing specifications proven to result in acceptable equipment and materials. Agencies often use existing specifications in their entirety or modify them to fit their particular needs. Several good sources for equipment and materials specifications include:

- Federal Highway Administration (FHWA),
- Institute of Transportation Engineers (ITE),
- International Municipal Signal Association (IMSA),
- National Electrical Manufacturers Association (NEMA),
- Other cities, and
- State highway or transportation departments.

Closed versus Open Specifications

Specifications should result in high quality equipment and materials. However, specifications should not be written around a particular manufacturer's equipment or material, thus precluding competitive bids. *Closed* specifications, those that specify a particular

Table 12-3. Types of design plans.

- **Title Sheet**
  Shows name, location and scope of project
- **Summary of Quantities**
  Shows material and equipment quantities
- **General Notes**
  Frequently call special attention to critical requirements to assure they are not overlooked; must avoid conflicts with specifications
- **Intersection Layout**
  Shows pole, signal, and conduit locations and other pertinent intersection information
- **Conduit, Cable and Signal Head Tables**
  Indicate:
  - number designation of the run
  - size of conduit
  - size and number of cable or cables in the conduit
  - approximate length of conduit

  Signal head tables outline:
  - type of signal head
  - size and type of signal lenses
  - type and size of pole on which type are mounted
- **Intersection Phasing Diagram**
  Indicates phasing of each intersection and includes vehicle and pedestrian intervals
- **Wiring Diagram**
  Indicates color coding of wiring from local controller cabinet to signal heads and from master controller to local controllers; wiring diagrams can serve as a permanent record for maintenance purposes
- **Intersection and System Timing Plans**
  Illustrates interval timing, offsets, and other intersection timing for backup timing plans
- **Construction Design Drawings**
  Shows minimum requirements for construction dimensions and materials for foundations
- **Traffic Control Plan**
  Indicates handling of traffic during construction, particularly addressing the need for continuous interconnected operation of existing signals
- **Details of Barricades, Detour Layouts, and Signing**
  Illustrates the construction phase of the project
- **Diagram of Underground Utilities**
  Shows details of location
- **Standard Plans**
  Possessed by each agency, generally provide numerous standard drawings of frequently encountered details already approved for use in situations applicable to the project

manufacturer's equipment, may not meet the intent of Federal, State, or most local procurement laws, and more than likely will lead to high, non-competitive bids. *Open* specifications allow a number of competitive bidders on equipment and materials, usually resulting in lower bids.

Functional versus Material Specifications

Functional specifications describe what the system must do, whereas *material* specifications describe in detail the individual features or capabilities of each component or subsystem. As previously indicated, the procurement approach selected influences the preferred type of specification. Under the systems manager approach, for example, items such as voltage levels, communications modulation techniques, or connector pin assignments, must be specified in detail to ensure the ability to integrate the components into a total system.

By contrast, the engineer/contractor approach prepares specifications more functionally oriented, ideally specifying *end result* requirements and placing the responsibility on the contractor to provide an *integrated system*. The specifications may also include certain physical requirements such as environmental requirements and standard interfaces and protocols. When external facilities such as city-installed cable, leased telephone, or shared use coax cable form part of the system, the specifications should thoroughly specify integration requirements through acceptance test criteria.

The often preferred approach contains a blend of functional and material specifications. Clear and concise specification language should pay adequate attention to minimizing conflicts among sections often achieved by not covering an item in more than 1 section.

Standard Specifications

Standard specifications, invoked by name, number, and date become a legal part of the contract.

Examples include:

- Specifications previously adopted by the city or State,
- Wire specifications available from the International Municipal Signal Association (IMSA),
- Communications cable specifications from the Rural Electrification Administration (REA), interface specifications available from the Institute of Electrical and Electronic Engineers (IEEE), Electronic Industries Association (EIA), American National Standards Institute (ANSI), National Television Standards Committee (NTSC), International Consultative Committee for Telegraphy and Telephony (CCITT), International Telecommunications Union (ITU),
- Standard specifications for materials testing available from the American Society for Testing Materials (ASTM), and
- Military specifications (MIL specs) available from the U.S. Department of Defense.

The design engineer should become familiar with standard specifications and invoke them, as appropriate.

Contract Documents

Together with design plans and specifications, contract documents form the complete legal package to which the contractor must conform. Contract documents typically contain:

- Invitation to bid,
- Instructions to bidders,
- Bid proposal,
- Bonds,
- Agreement,
- Conditions of contract, and
- Qualifications.

Invitation to Bid

An invitation to bid generally takes the form of a 1 page document containing a brief project summary along with bidding and construction procedures. It simply advises prospective bidders about the existence of the project and enables them to decide whether it lies within their area of capability and interest. It further directs interested contractors to the source of bid documents.

Instructions to Bidders

Instructions to bidders tell each bidder how to prepare a bid so that all bids received have equivalent format for comparison and evaluation. This document systematizes bid forms, and its contents should confine themselves to that purpose. The document deals with the issue of exclusions and substitutions by a bidder to ensure comparability of bids.

Bid Proposal

A bid proposal provides a uniform format to facilitate comparison and equal consideration for contract award. The instructions tell bidders what they must do. On the bid proposal form, they respond and quote their proposed price for doing it. Bid proposals, addressed to the agency, include general statements which commit the bidder to:

- Having read the documents thoroughly, and
- Being familiar with the site and the problems associated with supplying the system as designed.

The bidder should acknowledge receipt of all issued addenda, and individuals authorized to bind the bidder must sign where indicated.

Bonds

A bond serves as a legal document that binds another party into a formal contract as security that the bidder (or contractor) will perform as agreed. The following 3 types of bonds see common usage:

- Bid bond **--** Posted by the bidder to ensure he/she will sign the contract if awarded; frequently amounts to about 10 percent of the base bid;
- Performance bond **--** Posted by the successful bidder to guarantee that he/she will complete the project and not default. This bond typically amounts to the full contract price; and
- Labor and materials payment bond **--** Posted by the successful bidder to guarantee that he/she will pay for all materials and labor and not leave the agency liable for liens against the completed system; this bond generally amounts to the full contract price.

Agreement

The agreement provides the following 5 elements:

- Identification of the parties (who),

- Statement (perhaps by reference to another document) of the work to be performed (what),
- Statement of the consideration (how much),
- Time of performance (when), and
- Binding signatures of parties.

The agreement is often mistakenly called the contract. Actually, the contract consists of all the contract documents, while the agreement represents only one of those documents.

Conditions

The general conditions document serves as the *fine print* defining contractual relationships and procedures relative to the project. Most city and State agencies have established general conditions that apply to all their construction documents. The National Society of Professional Engineers (NSPE) also publishes applicable general conditions (9). Agencies normally print general conditions in large quantities and issue them as standard documents. Since general conditions apply to typical construction projects, traffic systems usually require modifications called supplementary conditions. For example, an agency may require access to computer equipment during installation for database development.

Contractor Qualifications

Agencies typically require contractors to prequalify to receive project bid documents. This prequalification typically takes the form of a general review of submitted financial and experience data.

Traffic control systems represent specialized projects and require a level of expertise and experience not widespread within the contractor community. Therefore, some local and State agencies permit specification of required contractor technical experience. (Also, see Two-Step Procurement previously discussed.) This section of the contract documents should advise contractors on the minimum experience and qualifications necessary to submit a bid, and instruct them how to submit special qualification data for review. Many local and State agencies include a variety of pre-qualification requirements, such as:

- Conformance with the Equal Opportunity Act,
- Involvement as a percentage of the overall contract of:
    - Women Business Enterprise (WBE),
    - Disadvantaged Business Enterprise (DBE), and
    - Minority Business Enterprise (MBE).

These requirements prove common in most local and State agencies. Certain agencies also require that the contractor have a local office.

Pre-Bid Conference

For moderate or large-scale projects, a pre-bid conference often becomes advisable. The pre-bid conference reviews the instructions to bidders and elements of the specifications. The conference may identify special or unusual features of the project. The pre-bid conference usually provides prospective contractors with the opportunity to ask questions or raise pertinent issues.

Precedence

A specific hierarchy of precedence defines and clearly establishes which document governs in case of conflict within the documents. An example hierarchy (in decreasing order of control) follows:

- Agreement,
- Plans,
- Special provisions (technical specifications),
- Standard specifications,
- Supplementary conditions, and
- General conditions.

Technical Specifications

Technical specifications outline the specific requirements for materials, equipment, installation and operation. These specifications, an integral part of the contract documents, should include individual specifications for major items of material and equipment and methods of construction and installation. They should also include items such as operating manuals, training, and software.

Technical specifications should include the following three major categories:

Definition of Terms

The lead section should define words used frequently throughout the technical specifications. These definitions serve as a glossary for terms peculiar to the design plans, specifications, and other contract documents. Examples include:

- ITE - Institute of Transportation Engineers;
- Traffic signal - Any power-operated traffic control device, except a sign or flasher, that warns or directs traffic to take some specific action; and

- Signal system - 2 or more signal installations operating in coordination.

Installation of Traffic Signals

The specification for the installation of traffic signals sets forth detailed requirements for installation of various material and equipment items.

Other standard specifications (e.g., drilled shaft foundations, reinforcing steel), adopted and published by the local governing authority, may cover certain items associated with the installation of traffic signals. Standard specifications for roadway construction can normally be obtained from public works departments of cities or State highway departments. A reference, noting the name of the publication and the effective date, usually covers specifications for parts of the signal system not pertaining directly to the traffic signal installation.

Table 12-4 shows the items that the traffic signal installation technical specification should include (10).

The specification for installation of traffic signals can also include other items that fit particular site-specific needs.

Table 12-4. Items in traffic signal installation specification.

Name	Description
General	The items covered by the specifications, the requirement for furnishing new stock, and the procedure for the substitution of materials and equipment
Materials furnished by contractor	Details of what materials and equipment the contractor must furnish and what materials and equipment others must furnish
Power connection	Method for furnishing power from source to controller and specifications for power line
Conduit	Methods for installing conduit, to include conduit approved by Underwriters Laboratories, methods for joining conduit, and methods for testing the usefulness of an installed conduit
Wiring	Methods for wiring controller cabinet, signal heads, and pole bases
Grounding and bonding	Requirements for grounding and bonding signal housing, controller housing, signal common, and power service common
Sealing	Requirements for sealing conduit to provide continuously sealed electrical circuit
Concrete	Standard specifications for concrete and reinforcing steel
Concrete foundation for controller cabinet and signal posts	Methods and requirements for digging, placing, finishing, and backfilling concrete foundations
Paint and painting	Items to be painted, type of paint, number of coats, and method of painting (e.g., baked-on or sprayed)
Preservation of sod, shrubbery, and trees	Requirements for the replacement of damaged sod, and the protection of shrubbery and trees
Removal and replacement of curbs and walks	Procedure for obtaining approval to cut curbs and/or sidewalks, and the method for their replacement
Controller cabinet keys	Where delivered and number of each required

Specifications for Materials and Equipment

The number and types of technical specifications required for materials and equipment depend on the control system planned. For example, a control system may consist only of the installation of a master computer along with interface (adapter) units at the local intersections. In this case, the technical specifications would include those for the master computer, the interface unit, and the installation of those items. Other control systems might consist of the installation of a master controller, intersection controllers, and conduit.

Many new systems include elements of Advanced Traffic Management Systems (ATMS) and Advanced Traveler Information Systems (ATIS), and such elements as wide-area communications networks (WAN), local area networks (LAN), closed circuit television (CCTV), changeable message signs (CMS), and highway advisory radio (HAR). In addition, systems may involve more than one agency, which requires attention to specification of communication link functions and protocols.

Table 12-5 provides guidelines for representative portions of material and equipment specifications required by traffic signal control systems and freeway traffic management systems.

Software, Database, Performance, and System Test

Advanced Traffic Management Systems (ATMS) offer many features, functions, and alternatives not previously available. For example, systems containing a central computer and either intelligent remote communications units or Type 170 controllers (see figure 8-5) allow significant processing and decision-making to take place at the local controller while allowing system monitoring and control from a central location. Systems of this type achieve this through the *upload/download* of various parameters.

Some available system software provides a comprehensive database that may include:

- Traffic engineering data such as intersection layout (CAD) drawings, or
- Maintenance files of system components and equipment.

Performance of this software varies greatly. For example, some systems allow certain of these functions to operate in real-time. The degree of integration of CCTV images with the system can vary.

Table 12-6 lists a number of representative elements. To ensure accurate and reliable performance, prepare detailed system test procedures and performance requirements.

It usually proves important that the contractor develop detailed system test procedures for system software and database handling. The agency should review these procedures prior to performance tests to ensure inclusion of appropriate types of tests and duration. Examples include the following tests:

- Communications,
- Upload/download,
- Algorithm performance,
- Software acceptance, and
- System acceptance.

Many of these tests can be performed in the agency's traffic operations center with *demonstration* controllers purchased as part of the project prior to live tests with traffic signals in the field.

In some cases, the traffic system implementation plan assigns development of the entire system database to the contractor, including signal timing plans and the various coefficients and parameters required for system operation. In other cases, the agency or its consultant provides this data to the contractor for entry into the system. The specifications should clearly assign these responsibilities.

The ability of the agency or its consultants to support the software (correct errors or add new features) after the construction phase depends on how well the software is *structured* and *documented*. Experienced personnel should specify requirements for program structure and documentation.

12.5 Deliverable Services

With a continuing growth in the traffic control application of computers, local area networks, and sophisticated electronic components, a need has developed to add a *deliverable services* section to the specifications. This section defines the contractor's responsibilities to provide:

- System management,
- Documentation,
- Training,
- Startup assistance,
- Warranties/guarantees, and
- Maintenance.

Table 12-5. Guidelines for representative sections of specifications.

Specification	Guidelines
System master	Include both field-located arterial master and central computer
Intersection controller	Typically Type 170 or NEMA TS2; Type 170 controllers may require software specifications
Mast-arm pole assembly	Include mast-arm pole, base, and anchor bolts with bolt circle requirement
Pedestal pole assembly	Include pole, base, and anchor bolts
Strain pole	Used for span-wire mounted signal heads. Include pole, base and anchor bolts.
Signal heads	Include housing, doors, lenses, lamps, wiring, terminal blocks, terminal compartment, and mounting attachments, but with separate specifications for pedestrian signals
Signal conductor	Include covering, color coding, and physical characteristics
Signal cable	Include insulation, physical properties, electrical properties, color coding, and fillers
Detectors	Include physical properties, electrical properties, environmental conditions under which equipment must operate, controls, and methods of operation. Can include traditional detection and/or image processing detectors. May use NEMA TS2 or Type 170 specifications.
Communication cable	Include insulation, color coding, physical properties, and electrical properties
Field communication or controller interface equipment	Include interface standards, data rates, physical and electrical properties
Color graphics display	Specify parameters and methods of display
Printer	Type, speed, and quality
Video terminals	Specify sample operator screens and controls, screen size, refresh rate, and colors
Computer software	Provide functional specifications for control software, compilers, assemblers, utilities, and diagnostic programs
Television (TV) monitoring	Specify monitors, cameras, and interface protocols
Changeable Message Signs (CMS)	Specify type, dimensions, method of operation, and interface protocols
Communications equipment	Specify data modems and interface devices
Utility Coordination	Include names of utilities, contractor requirements for avoidance of utility disruptions, utility services (e.g., power or telephone line tie-ins) to be accessed, and method for tie-in

Table 12-5. Guidelines for representative sections of specifications (continued).

Specification	Guidelines
Testing	Include testing levels desired (component, subsystem, system), organizations responsible for preparation and approval of test specifications, conduct of tests and acceptance of results
Intellectual Property Rights	Include the desired status of rights to software (computer source code ownership, rights in use)

This section should also identify those database preparation tasks assigned to the contractor (section 12.4).

The following briefly describes deliverable services:

Systems Management

Systems management includes responsibility for all project-related tasks in the following areas:

- Design,
- Manufacture,
- Procurement,
- Assembly,
- Testing,
- Installation,
- Inspection (may be shared with the using or procuring agency),
- Training,
- Initial operation, and
- Initial maintenance.

The systems manager or contractor should direct, coordinate, review, monitor, and control the project to maintain a schedule for timely and adequate completion.

The specification should require submission and frequent updating of a detailed project implementation schedule.

Documentation

System documentation proves an absolute necessity for successful system operation. The specification should require documentation in sufficient detail to:

- Reflect as-built conditions, and
- Fully describe the methods of operation, maintenance, modification, and expansion of the system or any of its individual components.

Where manufacturer-supplied documentation covers these requirements, it should be used in lieu of specially prepared material. Table 12-7 lists typical hardware documentation requirements.

The agency/consultant should require the right to review all documentation prior to project acceptance.

Software documentation and rights generally prove more difficult to specify and obtain. For many hardware elements, suppliers consider unique software provided in memory proprietary. Such software, sometimes called *firmware*, provides all specified operational features and supports flexible operation through a wide array of user input-output options. In such cases, the user may never need access to those programs for modifications and thus not need detailed software documentation. NEMA controllers and field masters typify such components.

In larger computer-based systems, the user may need to modify or expand the system, thus requiring access to the software. In such cases, it becomes necessary to access *source* programs. Further, a full complement of executive, utility, and basic library programs for the computer system must be specified, along with the system programmer and user manuals.

Generally speaking, the following 3 levels of software rights exist:

- Proprietary-The purchaser has no rights to proprietary software other than provided by license or use agreement.
- Semiproprietary-The user (or purchaser) has no rights to semiproprietary software unless needed assistance proves not available from the supplier.

Table 12-6. Representative system software elements.

- Traffic system control algorithm requirements
- Graphics features for areawide map, subsystem and intersections
- Upload/download requirements, magnitude of parameters
- *Real-time* functions, definition of real-time (within 1 or more seconds)
- Integration functions with CCTV, CMS, HAR
- Modes of operation such as manual, traffic-responsive, time-of-day, day-of-week
- Special functions such as railroad preemption, emergency vehicle preemption
- Backup capabilities
- Operating systems
- Documentation including agency right to ownership, use and modifications, negotiation on system upgrades
- Communication requirements
- Field equipment diagnostic functions
- Database support including:
  - system features and functions, including:
    - types of data to store
    - format of files
    - types and functions of support software
    - graphics
    - printing
    - historical data files
- Features desired for traffic engineering applications such as:
  - maintenance files
  - level of service calculation files
  - signal timing files
  - intersection layout drawings
- Test procedures and requirements

Table 12-7. Typical hardware documentation requirements.

Requirement	Description
General description	General descriptions of all components comprising the system
Theory of operation	Detailed description of system operation, including schematics, logic, and data flow diagrams
Normal operating procedure	Description of the system's routine operating procedures
Maintenance	Copies of manufacturers' recommended procedures; preventive maintenance procedures; troubleshooting data necessary for isolation and repair of failures or malfunctions (corrective maintenance); and detailed instructions where failure to follow special procedures would result in damage to equipment or danger to operating or maintenance personnel
Installation	Detailed description of physical and electrical properties of the system and other pertinent information necessary for the installation and use of the equipment
Parts list	Listing and identification of various parts of system
Schematic diagrams	Complete and accurate schematics to supplement text material
Maps or drawings	Drawings of conduit layouts, cable diagrams, wiring lists, cabinet layouts, wiring diagrams, and schematics of all elements of the communication system

- Full rights--Rights to use, modify, and transfer software are conveyed and restricted only as defined by specific agreement.

Control system specifications should specify the required level of purchaser rights so that all bidders can reflect these requirements in their proposal or bid.

With regard to when the contractor should provide documentation, typical requirements follow:

- Soon after the selection of a specific computer system and peripherals, programmer and user manuals for that system should become available for agency staff;
- Equipment manuals available for technicians' study prior to maintenance training should become available concurrently with the on-site delivery or storage of hardware elements;
- To facilitate maintenance, cable routing details and wiring diagrams reflecting as-built conditions should become available after installation and prior to use of those components;
- Application software documentation, along with a draft system user manual, should become available on-site prior to conducting operations training and placing any intersection under system control. Revisions of these manuals may be required to reflect changes made prior to system acceptance;
- The final payment for system installation should be withheld until delivery of acceptable final documentation, and
- Where a period of operational support is provided (see subsequent discussion), updates to final documentation should be required.

It is imperative that complete documentation be obtained. All submitted material should be closely studied and applied during initial system implementation to ensure that all needed documentation exists and is complete and clear to the operator.

Documentation becomes more valuable over time because, as the system ages, it experiences maintenance and modification. Personnel changes also occur. Therefore, the agency must take responsibility for management and preservation of the provided documentation. Furthermore, the agency should develop a *troubleshooting* document(s) and tailor it for appropriate personnel such as operations and maintenance staff. Documentation may take the form of conventional manuals or reside on computer.

Training

In traditional traffic control systems, training is typically provided in the principal areas of operation and maintenance. Further, such training specifically addresses the needs of each staff level:

- Management/supervisor,
- System operators, and
- Maintenance technicians.

Training should provide those technical skills needed to effectively use and maintain all system features and components. In this respect, the training specified and provided should reflect the actual needs of agency personnel.

If, for example, maintenance personnel already routinely maintain microprocessor-based controller units, training should cover familiarization with the actual unit. In contrast, an agency converting from twisted wire pair to fiber optic communications should specify extensive training, perhaps even including the operation and use of test equipment.

A secondary purpose of training fosters acceptance of the new system among agency personnel. It can provide opportunities for involvement that remove those natural barriers to system acceptance.

Training may be provided at 3 times:

- Preinstallation,
- During installation (before use), and
- During operation.

Preinstallation training offers an early opportunity to gain skills in a non-pressured environment on subjects such as:

- Equipment configuration,
- System capabilities and features,
- Systems operation,
- Logistic support requirements,
- Programming concepts, and
- Database needs and preparation.

During system installation, other opportunities for training become available. Here, maintenance personnel can be given detailed training in:

- Operation,
- Preventive maintenance, and
- Corrective maintenance (troubleshooting).

Actual hardware should remain available during this time for hands-on training.

After system acceptance and during the period of contractor operation, training may be directed toward:

- Refresher training for operations/maintenance personnel,
- Training for new personnel, or
- Additional hands-on training under operational conditions.

Regardless of when or how much system training is specified, system contractors/suppliers benefit if the user becomes knowledgeable and proficient with the system. However, formal training proves expensive--both to the contractor and user. Because of this, numerous users of successfully operating systems confirm that the *best training is gained by an active, aggressive involvement with the contractor during the system's installation, checkout, and initial operation.*

Startup Assistance

The period of initial system operation typically becomes a time of intense activity. Expect maintenance problems as a result of the full exercise of hardware coupled with any remaining unfamiliarity with the system. Software bugs may surface and timing plans and database may need refinement. In addition, operator skills and routines develop day by day. During this time, the continued support of the systems manager or contractor can enhance successful operation of the system.

This continued support beyond system acceptance has been termed *startup assistance* and FHWA considers it an eligible item for funding. Startup assistance can include the following tasks (11):

- Provide systems engineer to assist agency operators/engineers in adapting the system to local traffic environment;
- Define and correct hardware and software deficiencies discovered through sustained operation;
- Assist in maintaining, repairing, and replacing failed system components;
- Provide on-the-job training as an extension of formal training provided earlier; and
- Prepare and provide updates to system documentation.

Warranties/Guarantees

The specification should define the period of time after system acceptance during which the contractor guarantees work and materials. For hardware, a manufacturer may warrant the product for 1 year or more *from the date of delivery.* Problems arise when the contractor stores such items or does not use them in the system until later in the project. To avoid ambiguities, the specification should clearly require the contractor to guarantee all hardware items for some time beyond final system acceptance. Further, any remaining equipment warranties by individual hardware manufacturers should transfer to the agency.

Maintenance

The specifications should clearly spell out maintenance responsibility for hardware items. Common practice obligates the contractor to maintain equipment until system acceptance in accordance with the contract. Except for startup assistance, FHWA policy clearly defines maintenance beyond system acceptance *ineligible* for Federal funding. However, some agencies include a separate non-participating bid item for maintenance during an initial period of operation (possibly 1 year) to:

- Ensure a source of maintenance during a critical time of system operation;
- Determine anticipated maintenance costs at system completion; and
- Place responsibility for maintenance on the contractor, encouraging quality construction and the choice of more reliable hardware.

Provision of spare parts and/or subsystems also proves important. Considered maintenance items, they cannot be purchased with Federal funds. However, the contract can include spare parts as non-participating bid items. This becomes particularly appropriate when the system requires custom-made subsystems such as RCUs. For certain components, it may prove desirable to permit future purchase at an established price within a specified time period.

System Acceptance Tests

Testing of the installed control system should precede system acceptance by the engineer. Testing proves essential when a third party installs a subsystem. The specifications should spell out methods for testing and test documentation. In general, acceptance testing consists of:

- Equipment Checkout Tests

  Each major system component should be tested on an individual basis to verify its operation. This should include diagnostic testing of each functional feature of items such as controller units and detector electronics. Environmental testing of components and subsystems can be done on a sampling basis. Any of the following can provide facilities for environmental testing:

  - Systems manager or contractor,
  - Agency,
  - State highway department, or
  - Independent testing laboratory.

  For large and/or expensive items (such as CMS or system software), it may prove appropriate to perform a level of testing (witnessed by the procuring agency or its consultant) prior to the items leaving the manufacturer's or system integrator's facility.

- System Electrical Tests

  The specifications should require tests to determine electrical continuity. Tests should cover each conductor, including spares.

  Electrical cables, wires, and connections should be tested per local and the National Electrical Codes. As a minimum, DC resistance tests of each conductor and the insulation-resistance tests between conductors and between conductors and ground should be performed.

  Typical test instruments include volt-ohm-milliammeters (VOMs) and megohmmeters (meggers).

  Communications cable plant should be DC tested with respect to open circuits, short circuits, resistance, capacitance, resistance and capacitance unbalance, crosses, and insulation resistance. In addition, signaling tests should be conducted and the tests should include measurements of loss or gain at 1 or more frequencies, noise, crosstalk, delay distortion, and return loss. Typical test instruments include VOMs, meggers, signal and/or sweep frequency generators, signal level meters and/or spectrum analyzers, time domain reflectometers, and voltage standing wave ratio (VSWR) meters.

  Fiber optic cable and splices should be tested per ANSI/EIA standards with respect to signal levels and attenuations at various nodes and terminations. Typical test instruments include optical signal generators, optical signal level meters, and optical time domain reflectometers, all calibrated to the applicable wavelengths.

- Computer Software Tests

  The contractor should test and demonstrate each feature of the control system software.

- Systems Operations Tests

  The installed system should be tested to determine the total system's reliability and performance.

  In advanced traffic management and traveler information systems (ATMS/ATIS) involving several integrated components, specifications should include standalone tests for each subsystem such as:

  - Field controller and cabinet equipment complement,
  - CCTV,
  - CMS, and
  - HAR.

  Traffic operations center tests for hardware/software and databases should be performed. Functional system tests should be performed for various modes of operation:

  - Manual,
  - Traffic-responsive,
  - Time-of-day, and
  - Adaptive.

  Several iterations (10 or more) should be performed, documented appropriately, and focused on both function and reliability/integrity. Many of the system tests can be performed via simulation at the operations center prior to actual implementation. The communications system should be tested separately and certain communications tests should be performed for longer periods of time (3 or more days) to ensure acceptable failure rates.

  Testing individual components when delivered and/or installed detects problems early and corrects them immediately. Simply testing the final system may allow small problems to create more serious ones affecting total system integrity. In either event, a final systems acceptance test is considered mandatory. Figure 12-4 shows a sample specification for such a test (12).

  The systems acceptance test should test each function of each mode. Field-device states

2.8.3.4 System Acceptance Test

After installation and debugging of all central control equipment, local controllers, detectors, communications, and other system hardware and software elements, the system shall be required to satisfactorily complete a 30-day period of acceptable operation. The intent of this System Acceptance Test is to demonstrate that the total system of hardware, software, materials, and construction is properly installed; free from identified problems; complies with the specifications; and has exhibited the stable, reliable performance level required for the control of traffic. The System Acceptance Test shall fully and successfully demonstrate all system functions using live detector data and controlling all system-controller intersections.

2.8.3.4.1 Action in Event of Hardware Failure

Failure in any hardware item during the test period, with the exception of expendable items such as bulbs and fuses, shall necessitate restarting the 30-day test period for its full 30-day duration for that item after its repair.

2.8.3.4.2 Action in Event of Software Failure

Any failure of system software or discovery of a software deficiency that causes a system malfunction or discovery of software operation that is not in compliance with the specifications shall cause the 30-day test to be halted and repeated in its entirety after correction of the software problem. If no problems are discovered, and if no software problems are introduced as a result of correcting the initial deficiency, the Engineer may reduce the restart 30-day test period for software to not less than 15 days. In no case shall the total test period be reduced under 30 days.

2.8.3.4.3 Uncertain Causes of Failure

In the event a problem is discovered for which it is uncertain whether the cause is hardware or software related, the 30-day test restart and repeat shall follow the procedure defined in 2.8.3.4.2 for software.

2.8.3.4.4 Persistent Intermittent Failures

No intermittent hardware, software, communications, or control operation or other malfunctions not related to a specific hardware or software malfunction shall be permitted to persist during the test period. If such problems are encountered, the test shall be suspended until the problems are corrected.

2.8.3.4.5 System Shutdown for Testing/Correction

While it is the intent that the system by fully operational during the entire System Acceptance Test, the possibility for system shutdown for purposes of testing and correcting identified deficiencies is acknowledges. During any period that the system operation is restricted or limited in any way as a result of testing, the 30-day System Acceptance Test shall be halted and shall not continue until a period of 72 to 168 hours of successful performance, as determined by the Engineer, has proved that any corrections or modifications made are valid, the problem is corrected, and no new system problem or deficiency has been created as a result of the change. Diagnostic testing that does not result in changes to system hardware or software shall result only in loss of acceptable test time.

2.8.3.4.6 Maximum Downtime

Total system downtime in excess of 72 hours during the 30-day test period shall cause the System Acceptance Test to be restarted. System downtime is defined as a condition which, due to central control hardware, software, or communications equipment malfunctions, causes the system to operate in standby mode, causes the central system to cease operation, or causes any subsystem to revert to its locally generated standby timing program.

2.8.3.4.7 Documentation Updating

All system documentation having errors, omissions, or changes that may have been detected or occurred as a result of system modifications or other reasons during the 30-day test period shall be corrected and resubmitted before final system approval is granted.

2.8.3.4.8 Acceptable Performance

Final system acceptance shall not be granted until the level of performance for each hardware item and for system software as defined in this section and in all other sections of the specifications has been reached, and all other contractual elements (excluding Operational Support and Maintenance) have been met to the satisfaction of the Engineer.

Source: Reference 12

Figure 12-4. Sample specification – system acceptance.

should be monitored to verify that they assume commanded states (CCTV is useful where available to simplify field verification). Traffic data collected by the system should be verified by field observation.

12.6 Project Management

Project management transforms a need into a reality in a controlled way. It primarily aims to attain the overall system goals within the project budget and timeframe. Project management techniques include:

- Providing visibility of the actions within the project,
- Establishing orderly procedures for attaining ultimate goals, and
- Centralizing responsibility and accountability.
- These techniques manage and control (13):
- Diverse technologies,
- Involvement of numerous agencies,
- Diverse interfaces,
- Scheduled interrelationships,
- Cost, and
- User support, including documentation and training.

Contract Administration

A critical element of system implementation and project management is the administration of the construction contract. Contract administration includes:

- Technical inspection,
- Witnessing of acceptance tests,
- Other technically oriented tasks, and
- Administrative tasks such as:
  - Processing payment requests,
  - Negotiation of change orders, and
  - Detailed record keeping in accordance with State and Federal requirements.

From a workload viewpoint, varied personnel with the required technical and administrative expertise may be required over the life of the project. A single project engineer (or project manager) performs or directs contract administration duties.

An agency should use various tools as leverage to ensure successful project completion by the contractor. Such tools may include:

- Withholding payments -- A certain percentage of each payment, and/or the last payment (normally 5 to 10 percent of the overall contract) is withheld until the contractor satisfactorily completes a milestone associated with that payment.
- Liquidated damages -- A clause often included in the contract stating the procedures and amount of such damages and exercised in relation to performance. For example, for every day completion is past due, the contractor owes a certain amount of money to the agency as a penalty.

  Courts have held that liquidated damages must not be used as a penalty but must actually reflect a reasonable forecast of the harm that will result to the owner (14).

  When disputes reach the courts, most jurisdictions will not grant both liquidated and actual damages unless the contract states that the liquidated damages are limited to specific types of owner damages such as extended engineering or interest. The owner can then recover other damages as actual damages.

  In preparing a liquidated damages clause, a reasonable estimate of damages must be used. Examples of such damages are (15, 16):

  - Additional architectural and/or engineering (systems integrator's) and/or construction manager's fees,
  - Claims by other third parties waiting on the completion so they can perform/finish their projects,
  - Extra rental of other buildings that might be required because the one being built is not completed,
  - Extra maintenance and utility costs that may be incurred either in the continued use of an old high-cost building or equipment or in the maintenance of a new area before beneficial use,
  - Interest on the investment or borrowed capital,
  - Extra training required to maintain worker skills pending availability of the building or equipment,
  - Additional operating costs that may result from the continued use of an inefficient facility or equipment,

- Extra costs of split operations resulting from partial occupancy or use of equipment, and
- Loss of revenue, e.g., bridge tolls, sale of power from a power plant, building rentals, etc.

- Performance bond -- As discussed previously, the contractor normally posts a performance bond for the contract amount.

Scheduling

Effective construction management requires a robust project scheduling technique. Project scheduling sets forth the required tasks and shows their interdependency. Commonly used methods of project scheduling include:

- Critical Path Method (CPM), and
- Bar charts.

Critical Path Method (CPM)

The critical path method (CPM) has proved a successful method for planning, organizing, and controlling projects. Initially, this management tool outlines the project graphically in the form of a network diagram. This representation, shown in figure 12-5, illustrates:

- The required operational sequence,
- Which operations are concurrent, and
- Which must be completed before others can be initiated.

CPM operations are referred to as activities.

In figure 12-5, an example of the application of CPM to the installation of a traffic control system, the activities necessary to complete the project are denoted by a line with an arrowhead. The circled numbers represent events which mark the beginning or completion of an activity. Dashed lines represent dummy activities that do not require any time but must be completed before another event can occur. The number below the activity represents the amount of time required to complete the activity. The critical path represents the project duration. In the example, the critical path is represented by the activities associated with events 1-11-15-19-23-27-29-31.

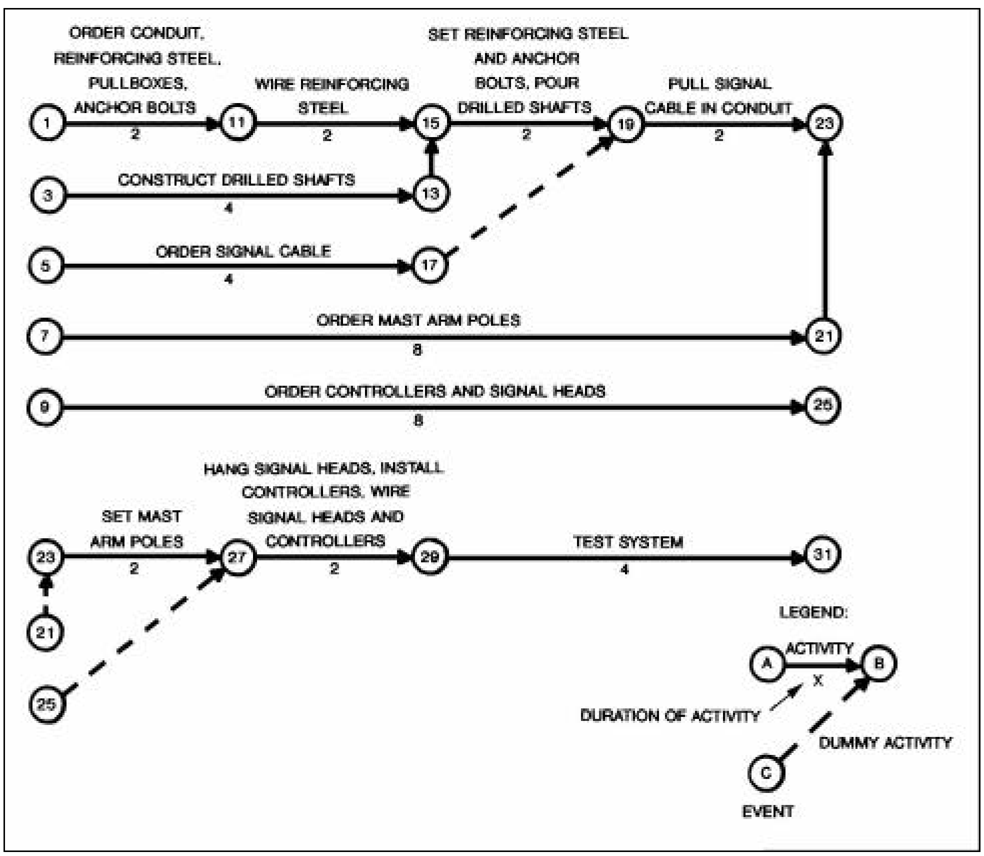


Figure 12-5. Example of CPM network diagram.

In the example, if activity 7-21 required a time of 10 instead of 8, then the critical path would become 7-21-23-27-29-31 because this sequence of activities would require a longer time. In this case, the receipt of mast arm poles would establish the critical path because they must be received before they can be set in place.

The network diagrams should be updated periodically to account for factors that would delay project completion. These factors include longer delivery dates, delays caused by weather, change orders, etc.

Software to facilitate development and updating of CPM networks is commercially available.

Bar Charts

Figure 12-6 shows the use of bar charts as a method of project scheduling (17). This bar chart for the Greensboro, NC, Traffic Control System depicts the time relationship for completion of the various project tasks. Starting and ending dates and durations are shown for the various tasks as are milestones (the start or completion of a task). The interdependency of tasks may be indicated by a dashed line or other symbol (e.g., M6 indicates the interdependency of acceptance tests for controller assemblies and the installation of communications lines).

Gantt Charts

The Gantt Chart technique uses an upper horizontal bar to present the planned schedule for the task (18). Another bar, just below this bar, charts the completed portion of the schedule. Colors usually facilitate legibility. Gantt Chart techniques prove most useful when the different tasks depicted are not related.

12.7 Implementation Pitfalls

The previous discussions of system design and implementation have focused on those positive steps that lead to successful system acceptance. O'Malley summarizes these as follows (6):

- Commitment, on the part of all parties, to work through difficulties with an attitude of cooperation,
- Contract management, which balances firm control and fairness through a single person in charge,
- Systems engineering expertise, with the experience and capability to integrate hardware and software,
- System and component acceptance testing, which assures compliance with specifications, and
- Documentation and training, for all elements of the system, presented in a timely fashion to meet the needs of different levels of operations and maintenance personnel.

The following discussion presents the reverse perspective. Gleaned from the results of discussions and contact with system users, these pitfalls should assist in avoiding mistakes made in the past. In each case, the discussion presents the generalized pitfall and then describes suggestions for avoidance. They are not presented in order of importance.

Inexperienced Contractors

Some contractors view the installation of traffic control systems as just another highway job. Failure to recognize the systems integration needs of such a project results in delays and additional costs to the contractor. In some cases, traffic control projects represent a small portion of a large general construction project. This virtually ensures that a subcontractor will perform this critical element. Additional control of contractor and hardware selection may be required for this situation.

This pitfall can best be avoided by:

- Separating control system elements from large projects where they may be lost, and
- Where procurement regulations permit, requiring contractor prequalifications on the basis of demonstrated experience.

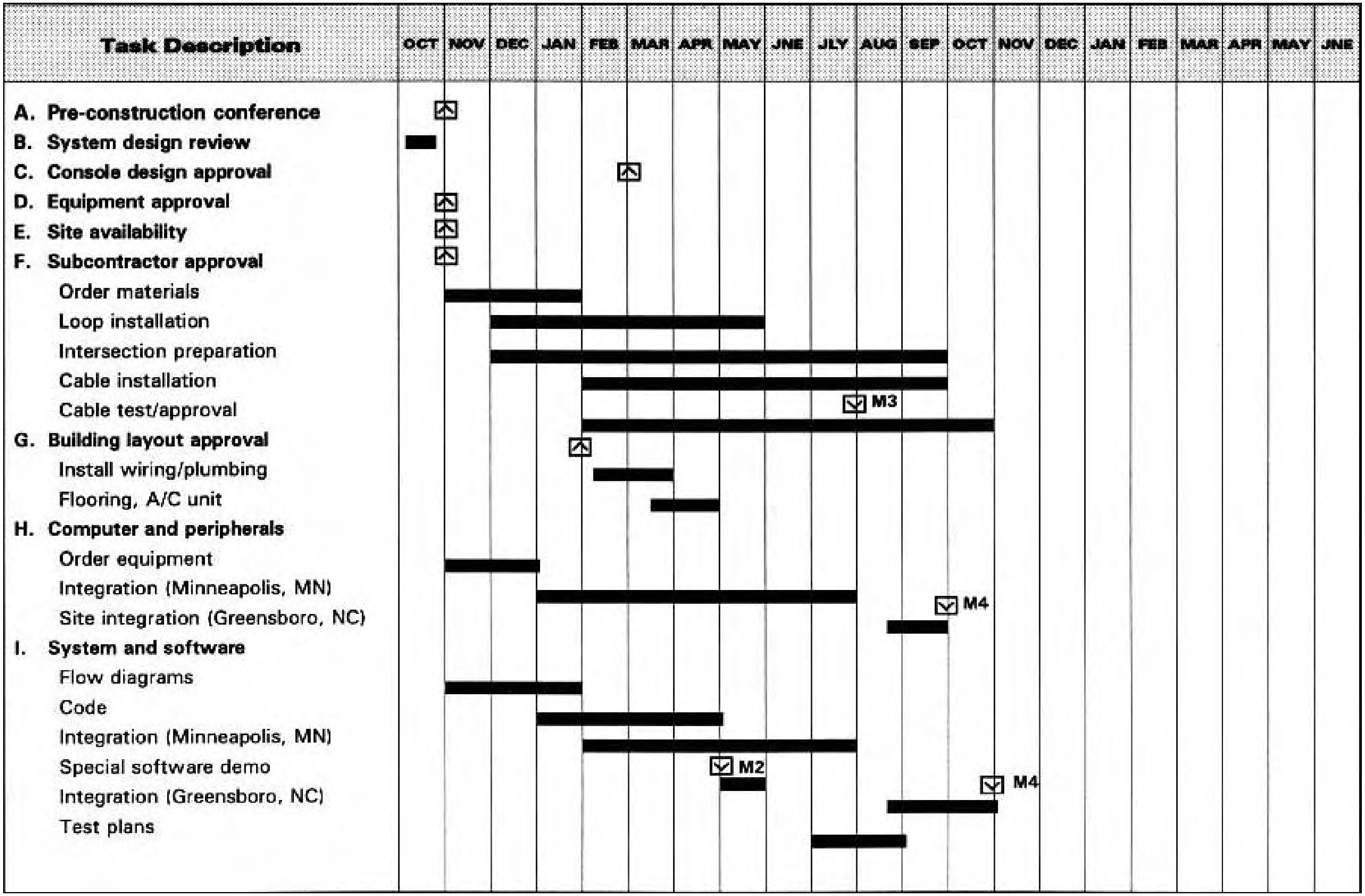
Construction Management

Construction management entails the following activities by the project engineer:

- Inspection of day-to-day construction activities,
- Witnessing of acceptance tests, and
- Other technically oriented duties.

Further, it involves record keeping, in accordance with State and Federal requirements, of items such as:

- Review and approval of shop drawings,



Source: Reference 17

Figure 12-6. Greensboro, NC traffic control project milestone schedule.

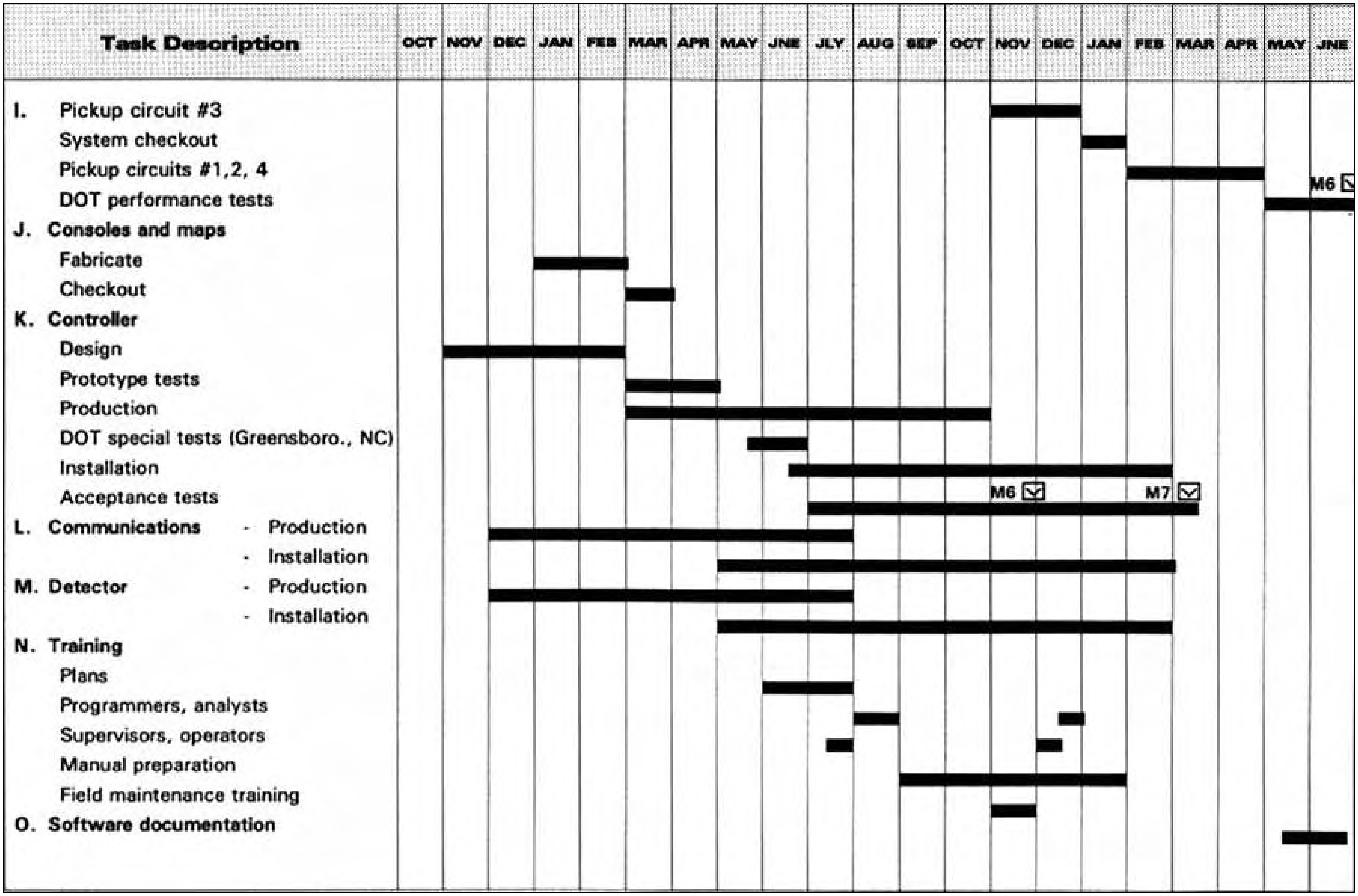


Figure 12-6. Greensboro, NC traffic control project milestone schedule (continued).

- Identification of need for change orders (including negotiation with the contractor on the change and compensation), and
- Obtaining necessary reviews and approvals prior to authorization.

Construction management requires both a high degree of technical knowledge and experience in managing contracts. While typical state project engineer and inspection personnel are generally proficient in project management for typical highway construction jobs, they may lack electronics and control system technical expertise. In contrast, city traffic engineers and signal maintenance personnel may have the technical expertise but little experience in project administration. Project engineers assigned from either background may tend to retreat to the familiar, with an attendant negative impact on effective project management.

Some projects have experienced problems with the inspection of system construction, ranging from token, ineffective inspection to unyielding insistence on a strict interpretation of specifications. Most common is the failure to anticipate the contractor's schedule and pace of construction and thus not match it with qualified inspectors. In some cases, inexperienced or inadequate numbers of personnel have been assigned. The best technical inspectors for any system are individuals who will operate and maintain the system once completed. If possible, they should be assigned inspection duties and have their other routine activities rescheduled to minimize conflicts.

These needs should be carefully considered in planning the project. Desirably, a team approach will be taken, with a project engineer having access to technically qualified personnel for specialized inspection tasks as necessary.

The channels of higher authority should also be identified and a working relationship established. A formal or informal project committee may be useful so that everyone involved can:

- Periodically meet,
- Be apprised of the broad picture,
- Review progress, and
- Address potential problems before they become critical.

Timing Coordination During Construction

Disruptions to traffic during construction are expected. Most designers specify how many lanes can be closed simultaneously for detector installation, or what hours are permitted for construction to avoid peak-hour interference. But what about construction impacts downtown during a Christmas shopping rush? Or, of more frequent concern, what about signal coordination during construction, i.e., how many signals can operate non-interconnected (or uncoordinated) and for how long? In one case, interconnect conduit was to be reused. Old cables were removed and extensive delays encountered in the installation of new cables and interconnection, all with predictable inefficient flow and negative public relations. Perhaps a redundant backup system might be needed, or time-based coordination could be used. To avoid such pitfalls, formal plans for maintenance of traffic during construction are necessary (19).

Database Development

Computer-based traffic control systems require an extensive database to operate. Database development may be required at the system level, subsystem or section level, and at the local level or intersection level. Computer generated color graphics files may also be required at these levels. Frequent problems have been encountered when no specific organization was assigned responsibility for necessary traffic surveys and developing, coding, input, and debugging of database information. Without clear definition, this responsibility may inadvertently fall on the user.

Databases can be developed by:

- Agency or consultant prior to PS&E completion,
- Agency or consultant after PS&E completion,
- Contractor, or
- Shared by consultant and contractor.

It is recommended that one of the above alternatives be determined early in the process. The specifications should clearly identify the contractor's responsibilities. If a consultant prepares the database, the necessary contractual arrangements should be established.

Insufficient Staff for Operations and Maintenance

Overselling the capabilities of traffic control systems as alternatives to staff can prove a mistake. Systems must be maintained and actively managed to provide effective service. Although new hardware may indeed eliminate unreliable, high-maintenance equipment that has exceeded its useful life, perhaps even more sophisticated maintenance may then be required. In addition, equipment with greatly expanded capabilities may actually require more operations staff to realize its full potential.

The timing of staff additions is also critical. For example, system operators need to be employed and available to receive training provided by the contractor.

Utility Coordination

The installation of underground conduits and/or overhead cables may cause conflicts with other public utilities. Regardless of how thoroughly the designer locates and documents existing utilities, some will be found in unexpected locations when construction begins. The Contractor must understand that utility runs shown on the plans are approximate and that it is the Contractor's responsibility to confirm utility locations.

Good documentation of existing conditions can avoid serious problems in utility coordination, but unforeseen situations will undoubtedly arise. The design process should visualize the most likely problems and plan a response. For example, if plans call for reusing existing conduit, it is likely that old cable cannot be removed because of conduit collapse and, therefore, the conduit cannot be reused. The planned response might include a bid item for conduit replacement to adequately compensate the contractor for attempted reuse of existing conduit followed by replacement. An alternative approach would test the conduit during the design phase to avoid expensive change orders and delays.

Planned Use of Untested Facilities or Techniques

Problems have been experienced in two different ways with the planned use of untested facilities or techniques.

First, from a construction viewpoint, one agency planned to use existing telephone company underground ducts for interconnect cables. Routing and design were based on available mapping and duct-use records of the company. No funds were allocated during the design process to rod the ducts and verify open paths - a task that was placed on the contractor. During cable installation, since a number of blocked paths were found, duct replacement was not possible during the available timeframe. Therefore, alternate paths with inefficient routing and resulting contractor change orders were necessary.

Second, with respect to hardware and applications software, use of new technology may engender unexpected problems. Being the first to use a product, software, or technique that attempts to advance the state-of-the-art poses risks.

Alienation of Maintenance Staff

The acceptance of new traffic control systems by all levels of an operating staff proves very important to successful system operation. It is fostered by active involvement - not only during installation but also during both the design and predesign activities.

Maintenance staff in particular may feel threatened by a new system, particularly if it contains a large amount of unfamiliar new hardware. They may have unexpressed concerns about the system's impact on their job security, doubts about their skills to maintain it, and feelings that the engineer's new toy just means a more difficult job for them. The following may minimize such fears:

- Early involvement of maintenance (and other) staff in system feasibility studies and system selection to ensure proper consideration of reliability and maintainability issues,
- Assurance of early, thorough training tailored to staff needs, and
- Opportunities for involvement through construction inspection.

Privatization of Operations and Maintenance

A number of traffic agencies and jurisdictions have used contract maintenance in the past. Privatized operations have increased in recent years. Problems such as union contracts for the privatized or related positions or the alienation of the remaining staff may present problems. However, the cost savings or larger base of experienced personnel available in the private sector may outweigh these problems.

This discussion of *pitfalls* is by no means complete. Because traffic control systems must be installed in full public view and have daily impact on motorists, they offer highly visible opportunities for criticism when things go wrong. Thoroughness in design and construction planning is a necessity, along with strict attention to details during construction. Hardware problems can be identified and corrected - but people problems require constant attention.

References - Chapter 12

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CHAPTER 13
SYSTEMS MANAGEMENT

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CHAPTER 13
SYSTEMS MANAGEMENT

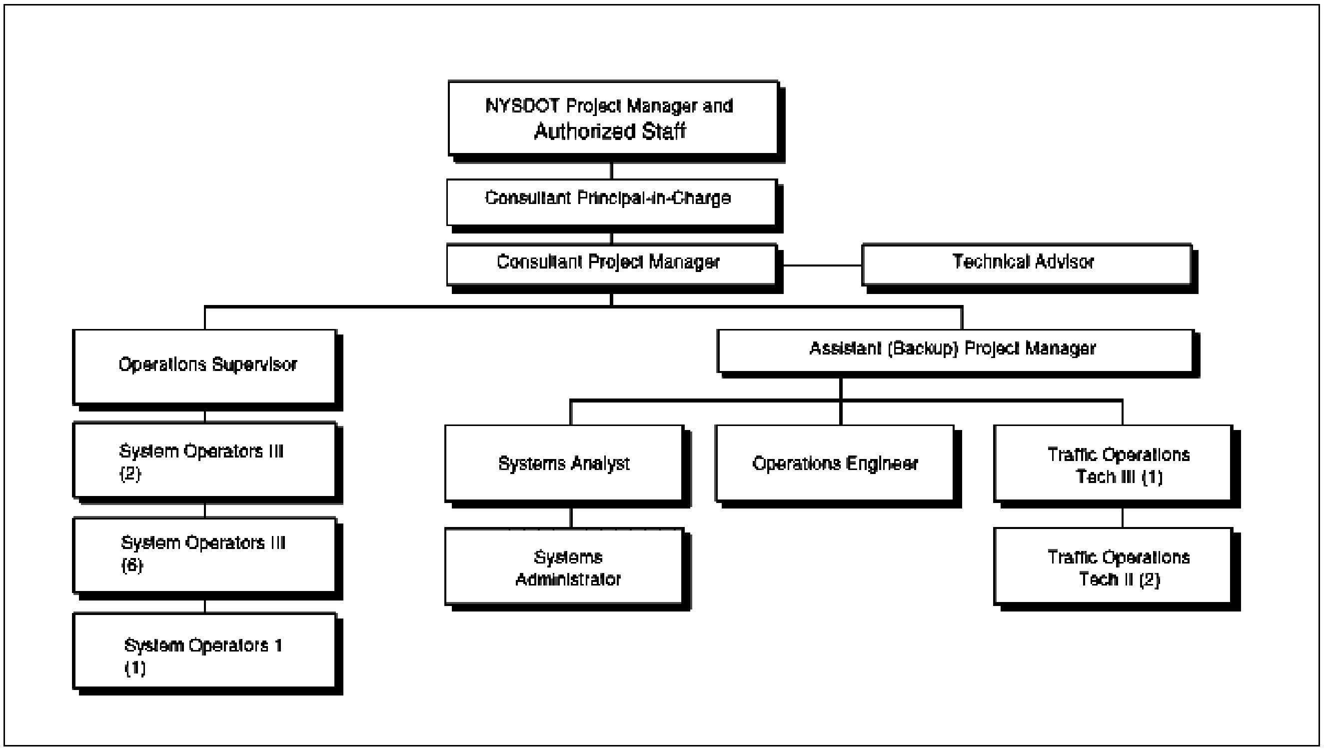

Figure 13-1. INFORM organization chart.

13.1 Introduction

Increasing traffic demand and the need for reducing vehicle emissions and fuel consumption place new emphasis on management of both freeway and traffic signal control systems. This will intensify with ITS deployment and more widely integrated operations.

The agencies responsible for traffic control system management have increasingly discovered that an *install-and-operate*, or a *set-it-and-forget-it* policy does not prove sufficient. The potential of the system(s) will only come to fruition with a policy of install, operate, and *manage*. A recent report (1) indicates that the benefits of traffic control systems are not being fully realized, largely as a result of inadequate management.

Managing traffic control systems includes four basic functional responsibilities:

- Teamwork,
- Operation,
- Maintenance, and
- Evaluation.

A traffic control system represents more than just a combination of hardware and software. The agency's organization and personnel become part and parcel of the system. For a traffic control system to realize its potential, the agency must have available:

- Technical skills to match the equipment, and
- Advanced management skills to assure that the entire system performs efficiently and effectively.

The flexibility and real-time evaluation capabilities of today's systems demand operational and managerial supervision. Successful traffic control systems show that such attention reaps rewards.

Effective traffic control system management begins with the design process. A traffic control system design should offer the flexibility to serve as a platform for future modification and addition of new systems. This could include the:

- Addition of real-time traffic responsive systems such as SCOOT, SCATS or OPAC/RT TRACS where needed,

- Coordination with other systems, and
- Implementation of ITS components.

The design should include a management approach and operations and maintenance plan. This might include a requirement for bar codes for parts inventory, maintenance and repair records.

In addition, communications with Advanced Traveler Information Systems need incorporation into the overall system. Examples include:

- Changeable Message Signs,
- Highway Advisory Radio,
- In-Vehicle Communications, and
- News media and other sectors of private enterprise involved with transportation.

Integrated traffic management becomes increasingly important because of growing requirements for reduced vehicle emissions and fuel consumption which often requires mitigation on a region-wide basis.

In urban areas which have traffic control systems in two or more adjacent jurisdictions, all agencies must have a close working relationship to develop integrated traffic management. This includes coordination of traffic control system operation within the urban area and extends to the development of a central database for monitoring and improving operations and safety.

Table 13-1 shows the organization of this chapter.

Table 13-1. Chapter 13 organization.

Section Title	Purpose	Topics
An Integrated System Management Concept	Describes the need for agencies to work together	• Agency Support • Operations • Evaluation • Maintenance
Operations	Describes the required aspects of operations	• Practical aspects - control and supervisory periods • Typical work tasks - specific operational tasks for intersection control systems - specific operational tasks for freeway control systems • Staff requirements and organization - staffing examples - factors to consider in staffing - organization
Maintenance	Describes the need for and types of maintenance	• Types of maintenance - functional - hardware - software • Results of inadequate maintenance • Staff requirements • Skills required
Evaluation	Describes the assessment process used in traffic control systems	• Techniques - before and after measurements - sampling considerations - descriptions of measures of effectiveness

13.2 An Integrated System Management Concept

Effective traffic control systems require both *intra-organizational* and *interorganizational* communications and teamwork. It proves essential to establish and maintain a team concept within an agency and among the involved governmental agencies within an urban area.

Within each agency, administrative, traffic management, design and maintenance personnel should remain involved in developing and operating the traffic control system. Enforcement personnel also should participate. These organizations must work together and coordinate their activities. For example, operations, planning and enforcement personnel from each transportation related agency must coordinate to plan a high occupancy vehicle (HOV) lane. Similarly, a team approach applies to the administrators (e.g., city manager, director of public works, district engineer) from the agencies in an urban area.

For integrated systems, the development of both administrative and technical teams assures the required:

- Agency support,
- Administrative support and funding,
- Resource integration,
- Information exchange, and
- Coordinated design, operation and maintenance.

Every level within each agency must provide support. Every level of the agency must assure that:

- Concept is sound,
- Support the concept, and
- Work together to obtain necessary funds.

Administrative support and teamwork prove key to achieving:

- Initial funding for installation, and
- Ongoing funding for operation, maintenance and evaluation.

Without this support, a system will not achieve its goals and objectives.

Resource integration involves the joint use of:

- Available funds,
- Personnel, and
- Coordinated scheduling of the agencies' development programs.

Coordination of resources accomplishes much more than if each agency works alone.

Agencies in an urban area should exchange historical and real-time information on a continuing basis. Historical traffic information permits each agency to analyze trends for making operational changes. Real-time information includes traffic information from vehicle detectors and information on scheduled roadwork and special events. Sharing real-time information permits joint incident management by two or more agencies. It also provides for integrated communications with:

- Motorists,
- Commuters, and
- Commercial vehicle operators.

Achieving certain traffic control system goals such as reduction of vehicle emissions and delay and improving safety requires region-wide approaches. This mandates that multiple agencies within an urban area design and develop systems on a broad traffic management basis to allow operations across jurisdictional boundaries. Carrying out operations and maintenance jointly on an agreed level of effort can also prove beneficial. This includes:

- Operating traffic control systems, and
- Advising travelers within the urban area of traffic conditions.

Cooperative efforts should include the present and future installation, operation and maintenance of ITS systems.

All agencies in an urban area must work together to achieve the desired operational and safety benefits. There is no substitute for interagency teamwork to realize:

- Communications,
- Cooperation, and
- Coordination.

A team involving city, county, state, federal and public transportation agencies provides the base for developing an integrated system within the urban area. The team also needs representation from:

- Traffic operation agencies,
- Metropolitan Planning Organization, and
- Law enforcement agencies.

Research results can improve traffic operations. In turn, integrated system development and operation often uncover opportunities for further research (2).

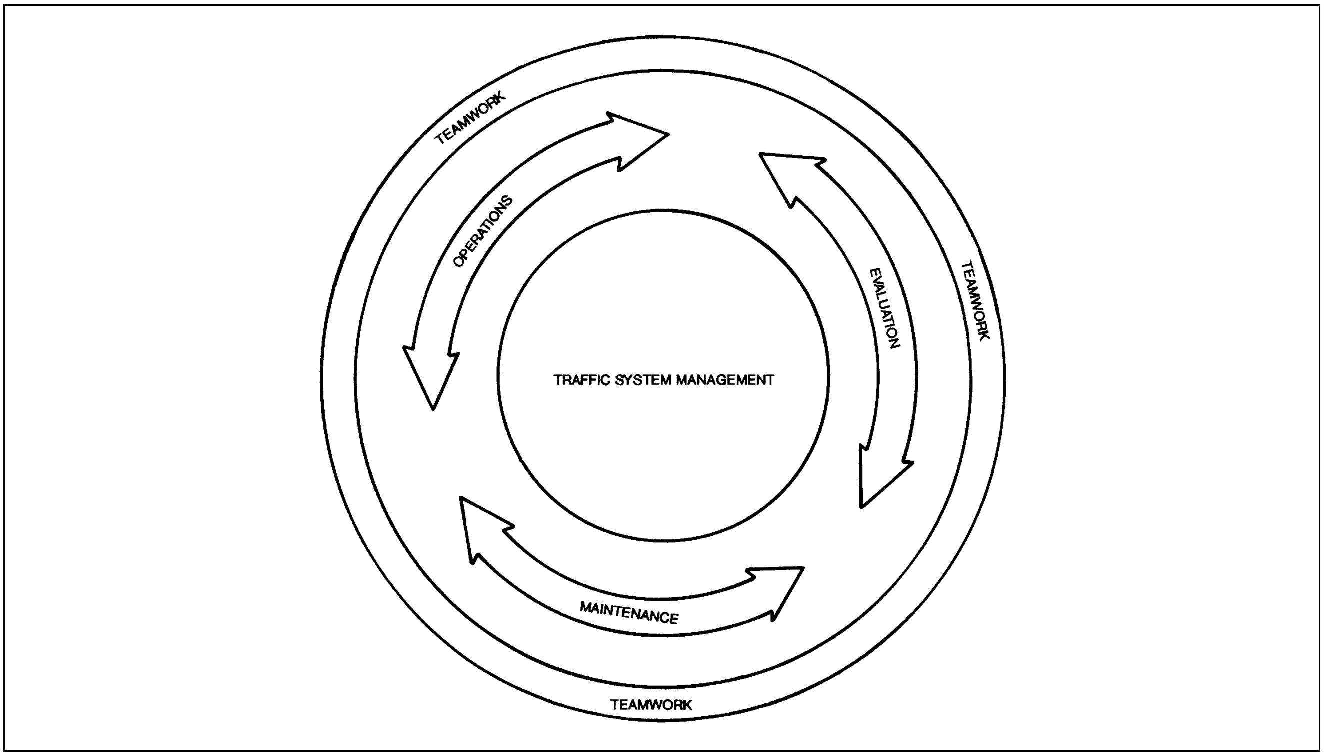

Figure 13-2. System management team concept.

Figure 13-2 shows the interdependence of the four functional responsibilities for effective system management. They share the following relationships:

- System operation requires proper system maintenance,
- Effective and efficient operation depends on evaluation results,
- System maintenance improves with a close working relationship among operational and maintenance personnel. Information on the nature and extent of equipment failures and anomalous operation usually originates from the system operators, and
- System evaluation depends on both operation and maintenance. Effective evaluation of a control strategy requires the system to operate as error-free as possible, with a minimum of hardware failures.

Considering the above interrelationships, management must organize personnel into a cohesive unit. The resulting management team assures that the traffic control system lives up to expectations and produces the greatest benefits for the motoring public.

13.3 Operations

Successful management of a traffic control system must achieve the end result of effective operations.

This section deals with the following aspects of operations:

- Practical aspects,
- Typical work tasks, and
- Staffing requirements and organization.

Practical Aspects

Traffic control systems function in the most demanding of physical environments, subject to:

- Weather extremes,
- Wide temperature variations,
- Electrical noise and disturbances,
- Physical damage from vandals,
- Knockdowns from vehicles, and
- Vibration from nearby traffic.

Yet, the system must operate reliably and continuously, 24 hours each day of the year.

The system's operational environment proves even more demanding. Its daily operation remains in public view where it directly affects each user. This justifies intense monitoring of system performance to locate equipment malfunctions and to effect timely repair. Likewise, modifications in system performance must accommodate changes in traffic flows for:

- Optimum operating safety,
- Providing support to transit and paratransit services,
- Convenience of motorists, and
- Public acceptance of the system.

It often proves difficult to interrupt traffic control system operation. Degradation to backup or fail-safe operation may be acceptable in emergencies, but should not occur over an extended period. This emphasizes the need for highly reliable and well maintained equipment, and illustrates a basic principle which influences virtually all operational decisions. The system must *work*; it must *work well*; and it must *work well virtually all the time*, to adequately serve the public.

Control and Supervisory Periods

While many traffic control systems operate continuously, some may only operate for certain periods. For example, a freeway control and monitoring system may use ramp metering only during periods of congestions thus limiting control to peak periods.

These systems, however, may use other information and control techniques (e.g., CMS) which operate for longer periods. Because systems increasingly perform a greater number of control and monitoring functions, trends point towards an increase in operating periods. Some agencies may not continually staff the system during the entire operational period, but periodically monitor equipment malfunctions. During off-hours, a maintenance facility terminal commonly monitors equipment operation.

Most current traffic control systems enable on-line database changes. Similarly many modern systems support software modification in the background or in a separate processor where the system does not permit background processing.

Using computer time for applications other than system control can impact the decision on the operating period. For example, the system can run these off-line applications at night or on Sundays.

Typical Work Tasks

Effective day-to-day operation of the control system requires a number of routine tasks and procedures to:

- Assure continuity of operation,
- Obtain and retain archival data,
- Assure security of the system database and software, and
- Insure that the system is operated by authorized personnel.

Table 13-2 lists some suggested procedures and tasks. Many operators of freeway surveillance systems also maintain a log of lane blocking incidents which were identified by the system or by other means.

Documentation is one of the most important operation tasks. Control system performance eventually reflects incomplete, incorrect, or non-existent documentation. Careful documentation control and distribution to the management team proves essential to successful system operation and maintenance. Document every change in:

- Software,
- Operational control parameters, and
- Hardware components.

Remember to update all copies of the documentation. Any team member, whether technician, programmer, engineer or systems manager should document changes.

Specific Operational Tasks for Intersection Control Systems

System Monitoring/Intervention

Most intersection traffic control systems have the capability of virtually unattended operation. The system automatically invokes predetermined schedules for:

- Time-of-day control,
- Traffic responsive implementation of timing plans, or
- On-line generation of timing plans (including possible section or subsystem reconfigurations).

In normal operation, the system determines when signal timing changes occur based on:

- Time-of-day, or
- Processed traffic flow data.

The system status monitoring element then verifies proper execution of the timing on the street. Figure 13-4 shows this closed control loop.

As shown in Figure 13-4, an operator can modify the normal automatic implementation of system configuration and timing through manual override. From the keyboard an operator can change:

Table 13-2. Suggested routine operations tasks.

Task	Description
Maintain daily control log	Covers entire control period. Should include checklist of items and tasks to remind each shift operator of responsibilities concerning duty routines necessary for proper system operation. Entries in the log concerning system functions or component failures serve: • As a written record of events per shift. The log should include the implementation of backups to programs and databases. • To provide continuity in operation from one shift to the next The log can take handwritten or computer based form. Figure 13-3 shows an example of a daily control log form.
Maintain event log	Most computer based traffic systems provide a hard copy event log which lists: • Equipment failures and repairs • Mode changes • Timing plan changes • Operator commands in chronological order Preserve event log along with control log. The system often generates the event log at midnight for the entire day. The system usually outputs it on demand, at any time during the day. Some systems generate the event log in hard copy on a continuing basis.
Maintain a ledger of timing plan modifications	Ledger should list: • Date and time implemented • Requester • Type of change (temporary or database implemented) • Reason for modification A computer based ledger should be stored on disk
Retain daily summary reports	Reports should include: • Volumes • Occupancies • Failures Summary report should be retained indefinitely for reference

- System status display,
- Map display, or
- Graphics display.

Manual intervention typically responds to congestion or maintenance problems to accomplish the following:

- Remove a controller unit or other component which shows repeated intermittent failures and dispatch maintenance personnel for repair,
- Return repaired controller units or other components to system control if this does not occur automatically after the repair,
- Implement an emergency configuration and/or timing strategy,
- Change subsystem or system timing parameters on a temporary basis, and
- Change individual intersection timing parameters on a temporary basis.

Data Collection and Analysis

In traffic control systems with limited data acquisition capabilities, the traffic engineer must rely on manually gathered field data and field observation to measure the effectiveness of implemented control strategies. Analysis of the data and observed field conditions provides the basis for modifying signal

TRAFFIC OPERATIONS CENTER

CONTROL LOG FOR:

DAY: ______ DATE: ______

OPERATORS ON DUTY:

A.M.	MID	P.M.	SPC.EV.

STA. 10 ON THE AIR: ______ FAILURE STAT. HARD COPY: ______

RETRIEVE MIDNIGHT REPORTS: ______ CONTROLLERS REPAIRED BY ACRP: ______

TEMP CHECK: ______ PAPER CHECK PR 1: ______ CONSOLE: ______ DISPLAYS ON: ______

CARRY OVER FROM PREVIOUS CONTROLS: ______

	6–8	8–10	10–12	12–14	14–16	16–18	18–
CONTROLLER FAILURES :							
CONTROLLER REPAIRS :							
CONTROLLERS REPORTED:							
COMM. EQUIP. REPAIRED:							
COMM. FAILURES REPORTED:							
DETECTORS REPAIRED/STANDBY:							
SYSTEM TIMIMG PLAN CHECK							
ASSISTED FIELD TECHNICIAN:							
ASSISTED PROGRAMMER:							
ASSISTED ENGINEER:							
INT. CK. REQUESTED BY:							
DATA BASE UPDATING:							
DISK OR TAPE BACKUP:							

COMMENTS: ______

INT. # INT. NAME

ALARM DISABLED: ______ DISPLAYS OFF: ______ COFFEE MACHINE OFF: ______

Figure 13-3. Typical daily control center log form.

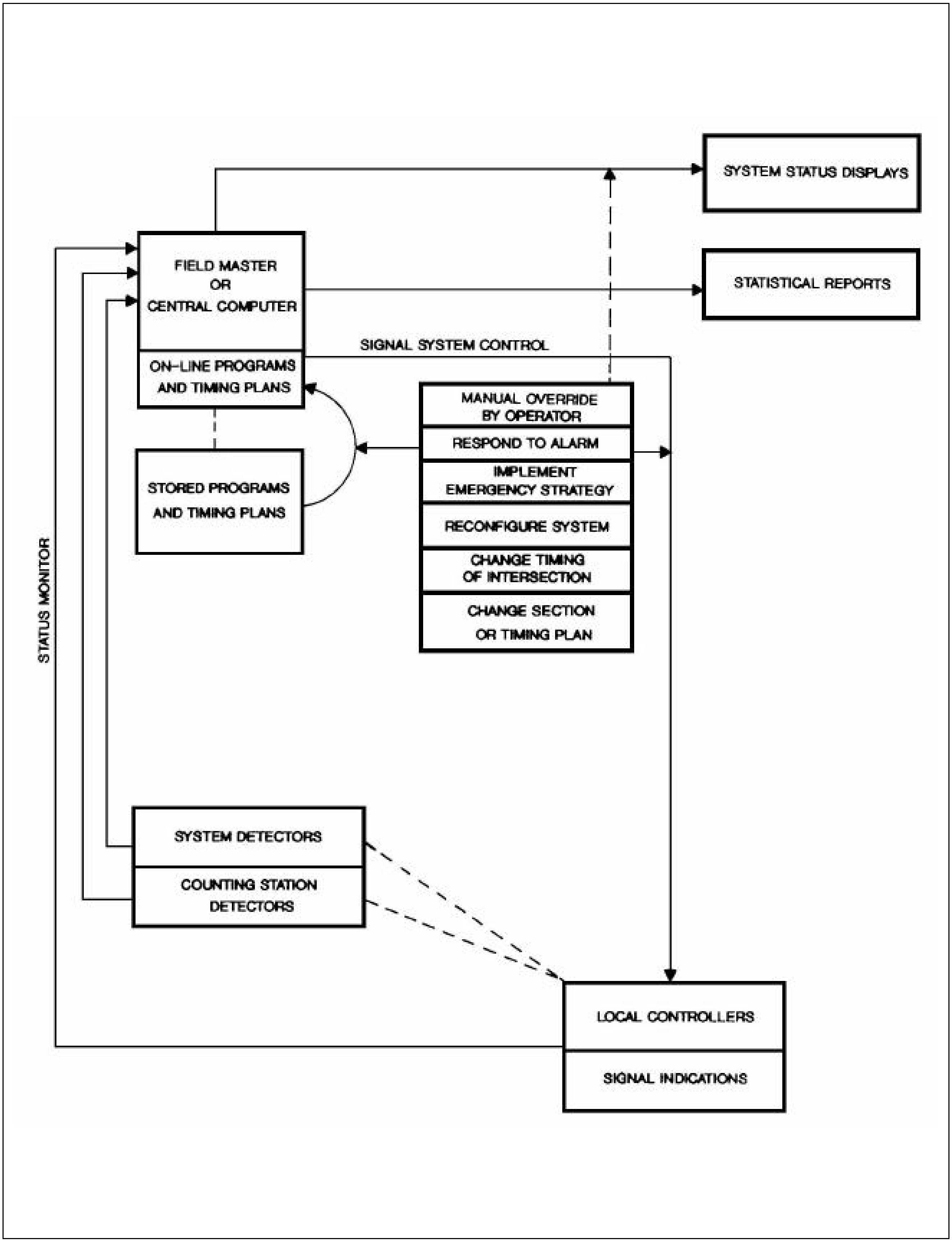

Figure 13-4. Typical daily control and operations architecture.

timing and plan scheduling. In normal operation traffic control systems with more extensive data acquisition capability can automatically gather, tabulate and analyze significant amounts of traffic data. This tabulated and analyzed data produce measures of effectiveness (MOEs) for the system (see Section 3.12). Examples of data which generate MOEs include:

- Volume,
- Average speed,
- Occupancy,
- Queue lengths,
- Vehicle delay,
- Number of stops, and
- Travel time.

To easily analyze operational effectiveness, the system must assemble MOEs in usable form. To use the data effectively, personnel must understand what the respective printouts and graphics represent and how they relate to system control. The system should also aggregate linked based MOEs for sections and the overall system.

Table 13-3 shows possible MOE formats for VDT and hard copy and their usage.

Effective data collection and analysis establishes a structured procedure to schedule and assign a specific individual or team to review current MOEs and other

Table 13-3. MOE formats.

• A color graphic presentation of system or section aggregate MOEs in contour form showing various measures and their relationships during the implementation period of a given signal control plan, as shown in figure 13-5
• Graphic charts and tables of aggregate MOEs by section and systemwide for an entire 24 hour period
• A level of service check for each link and group of links. This can take tabular form as a volume to capacity ration, and average speed to calculated speed ration. These can be shown on a computer graphics map through use of red, yellow and green lines for each section of roadway depending on the MOE. The computer printer can print the color graphic display.
• The delay and stops for each intersection approach, for each intersection and each grouping of links for level of service analysis
• A list of the worst links and sections based on MOE, time-of-day, day-of-week oriented
• The posting of some pertinent MOEs on a daily basis to keep all personnel aware of the importance of the quality of traffic flow in the system

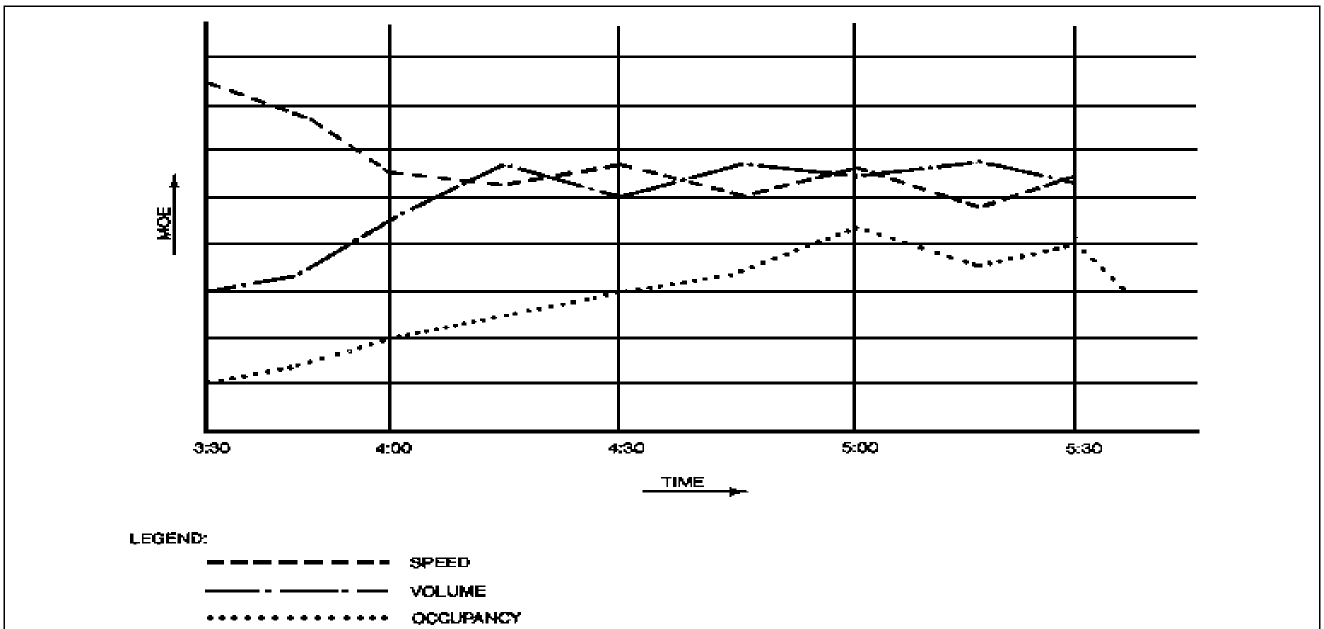

Figure 13-5. Typical aggregate MOE contour timing plan graphic.

data. This assures timely review of changing traffic patterns and the subsequent action needed to improve operation.

System Modification and Updates

Traffic control systems require constant scrutiny to determine the need for operational changes. Examples of system upgrading include:

- Control strategy and timing modifications,
- Operating and control software updates, and
- Addition of new control features.

Each type of system modification has a different implementation time-frame.

In addition, the street system often undergoes changes (e.g., reversible lanes, one-way pairs, intersection channelization, HOV lanes and bicycle lanes). Operational changes must take place with system upgrades and changes to the street system.

Updating System Timing

In the case of a traffic control system with few data acquisition features, the traffic engineer relies on field data acquired manually for timing plan updates and modifications. However, the engineer may use these data, together with the network's physical characteristics to run one of several available signal timing optimization programs for PCs, such as PASSER, TRANSYT and AAP (see Section 3.9). Many traffic systems either directly support these programs or allow migration of the database from PCs to the traffic control system.

Figure 13-6 shows a typical flow chart for system modifications. The engineer may have to collect turning movement counts to supplement system derived data. Traffic systems with 1.5 GC capability and advanced systems such as SCOOT and SCATS reduce the manual effort required to update timing plans and generate on-line timing plans.

Traffic control systems should operate as designed from the beginning of system operation. Thus, databases and signal timing plans should be available at this time. In some cases, the system can collect data to support the database and timing plan development process.

If a city or other agency does not have in-house personnel to develop and implement the needed plans and system timing, outside assistance such as a consultant can be engaged to perform this task. An alternative approach includes the task in the installation contract. For example, St. Paul, Minnesota required signal timing and system evaluation in their traffic signal system installation contract (3). Even if a contractor performs signal timing, agency personnel, as part of their training, should work with the contractor to develop the signal timing plans.

The integration of traffic signal systems and freeway control systems requires teamwork among agencies to develop the signal timing plans and freeway control plans. This allows smooth traffic flow across agency boundaries and throughout the entire urban area. Agencies should update existing plans when developing plans for a new system addition.

Changes in traffic flows create a need to implement signal timing changes. Factors changing traffic flow patterns include:

- Land-use and population changes,
- Addition or deletion of signals,
- Development of major traffic generators,
- Street geometric changes,
- Operational changes in a corridor, such as one-way streets,
- Provision of traffic condition or route guidance information, and
- Roadway construction.

Regardless of the cause, signal system timing and control strategies must adapt to new requirements. Modifications include micro-level and macro-level changes involving:

- Interval lengths,
- Splits,
- Cycle length,
- Offsets,
- Metering rates (in freeway control),
- Duration and scheduling of control plan periods including traffic responsive operation, and
- Phasing changes.

When done on a macro-level, these changes will probably result in development of an entirely new timing plan or control technique. Systems with data acquisition capability provide for control plan implementation, and produce MOEs, a means of defining the needed timing and/or operational changes.

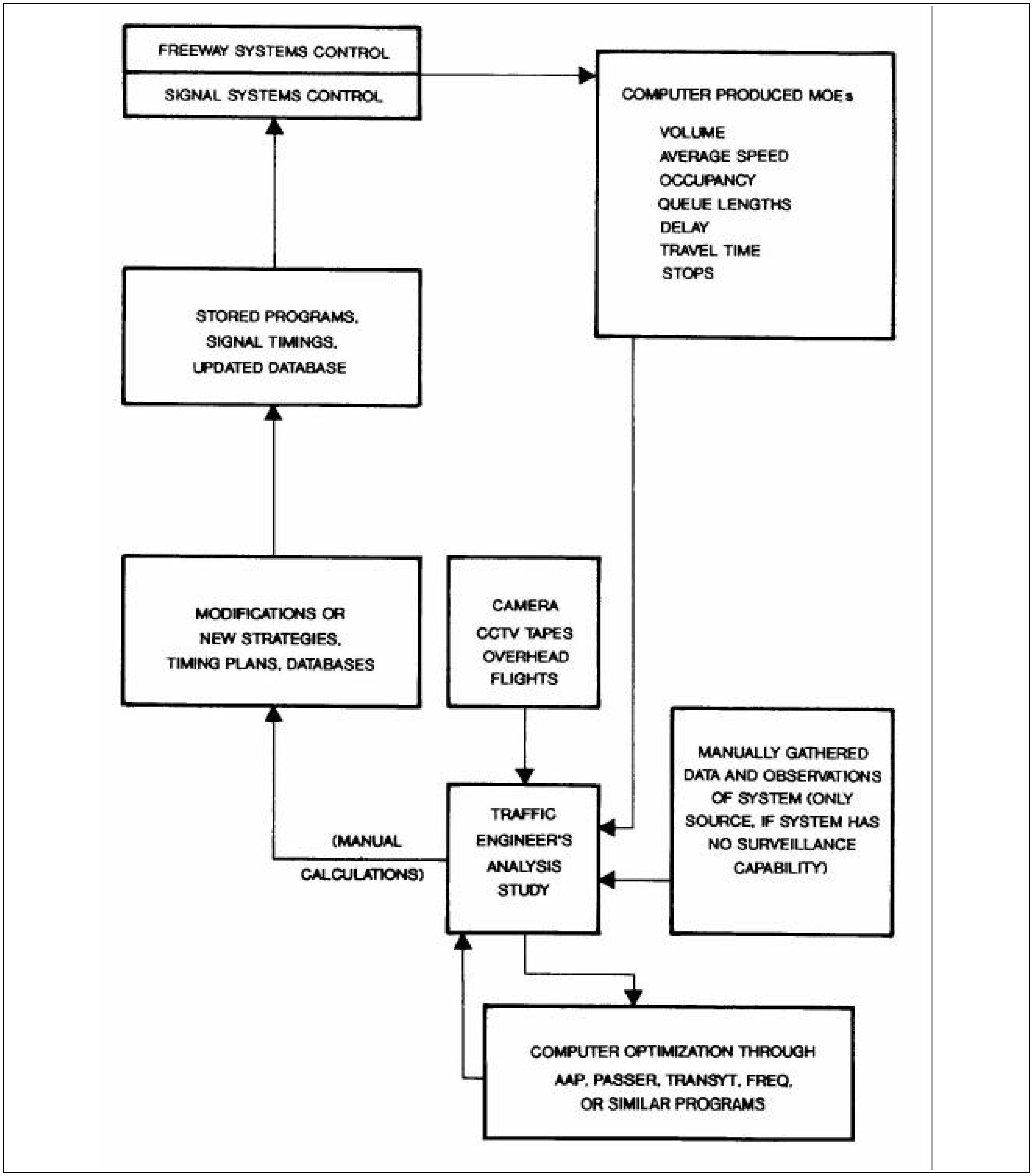

Figure 13-6. Typical flow chart for system modification and update.

Specific Operational Tasks for Freeway Control Systems

Because incidents normally impact freeways more than surface streets, more traffic control and management is required for freeway incidents. Other differences between intersection and freeway control system operations include:

- System monitoring/intervention,
- Data collection and analysis, and
- System modification and updates.

System Monitoring/Intervention

Operators monitor freeway traffic control systems primarily through:

- Graphic map displays which represent the basic MOEs via red, yellow, and green,
- Graphic charts and tables detailing arterial traffic conditions, and
- Closed circuit television (CCTV).

Based on this information, the operator can manually adjust the controls commanded by the central computer in traffic responsive mode. This can include changing system parameters on a temporary basis.

The operator can also:

- Remove a ramp meter controller from system operation due to intermittent failure, and
- Allow the ramp meter controller to operate in an isolated traffic responsive mode until repaired.

Any changes by manual intervention should include gathering sufficient information to allow analysis and possible permanent change in traffic control plans and preplanned response scenarios.

Other common operator tasks include:

- Implementation of CMS and HAR messages,
- Communication of traffic information to the media, and
- Assistance in managing incidents, including communication with motorist aid patrols and traffic management personnel in the field. Logs of incidents are often maintained by traffic personnel.

Data Collection and Analysis

Traffic responsive freeway control systems collect traffic data for analysis purposes from:

- The main lanes,
- Entrance and exit ramps, and
- Freeway to freeway direct connectors.

This traffic data together with the computer graphic MOE printouts allow the traffic engineer to:

- Locate bottlenecks along the freeway, and
- Determine changes needed in traffic control plans and threshold parameters.

Examples of traffic data used to calculate MOEs include:

- Volume,
- Occupancy,
- Density,
- Average speed,
- Vehicle delay, and
- Travel time.

MOEs must appear in usable form for personnel to use them effectively for analysis and real-time implementation. Freeway systems often gather and present traffic data by link (roadway between ramps). MOEs should be both link oriented and section (two to three miles) oriented and presented in five and 15 minute periods. Average speed contour data plotted on five minute intervals can prove valuable in determining the location and extent of bottlenecks.

Designated personnel should review the traffic data and MOE information periodically unless the operator recommends more frequent review on specific sections. Include the system operator(s) in the analysis process. It is recommended that two or more trained personnel analyze the same data to confirm results.

A simulation model such as FREQ (see Section 4.6) can study specific problems and determine locations of proposed improvements. Example improvements for simulation studies include:

- Reversal of entrance and exit ramps, or
- Addition of an auxiliary lane between ramps.

The model permits the analysis of what if alternatives in determining the most cost effective design.

Verify the analysis periodically by driving the freeway during peak periods. The cause of a problem (e.g., heavy vehicle weaving or high percentage of truck traffic) can be found or confirmed by traveling the freeway.

Aerial photographs and visual observation also prove useful in observing traffic conditions during peak periods. A videotape from a television camera can also help find an answer to an otherwise unexplainable event.

System Modification and Updates

System analysis can result in the change of traffic control plans and threshold values for changing traffic control plans. The analysis may also underscore the need to:

- Extend the freeway traffic control system,
- Implement freeway to freeway connector control not initially required, or
- Implement additional control strategies.

After implementation of changes, analyze the resulting operations over a period of time.

It is important to initiate and terminate ramp meter control at the proper time. Beginning operation too soon or ending it too late results in disrespect for and violation of the ramp meter. Conversely, if control begins too late or ends too early, freeway mainline congestion lasts longer than necessary. Observe and modify the operating period as traffic patterns change. By establishing appropriate thresholds, operating periods may be implemented on a real-time basis.

Staff Requirements and Organization

The expanded flexibility and ever-increasing capabilities in contemporary control systems allow the agency extensive opportunities for staff involvement in traffic management. However, in many existing systems full use of the system's potential remains untapped due to staff limitations. To attain full system potential, consider the operating staff as much a part of the system as the computer itself.

Staffing Examples

The experience of currently operating systems proves valuable in assessing staffing needs for various types of traffic control systems. Tables 13-4 and 13-5 give staffing examples for existing traffic signal and freeway systems of various types and sizes.

Factors to Consider in Staffing

Regardless of control system size, the staffing organization requires the two basic skills shown in Table 13-6.

The skills will realize the full performance potential and capabilities of a control system and accommodate modifications. Many agencies operating computer-based control systems have at least one person with some programming experience. While very few agencies change on-line software in-house, they often change off-line programs to process MOE data, for example. Some agencies rely on outside contracts for programming skills, as discussed later under software maintenance.

In assessing staffing needs, agencies must consider other factors such as the level of available resources. Do not assume that the sophistication and capabilities of a traffic control system can reduce the size and/or technical talent of the operations staff.

Table 13-7 describes other factors the agency should consider in assessing staffing requirements.

Organization

Organization of a traffic control system team should center around a nucleus of a functioning traffic operations section or division of a transportation department (or an equivalent section of a comparable entity). In that nucleus lies the tradition of effective traffic control - day-to-day and year-to-year practical experience. With this organizational structure, present operations personnel can absorb the new traffic control tool and, with proper training, use it to achieve performance improvements in the street or freeway system. Likewise, new operations personnel incorporated within the team structure can benefit from the practical experience of longer term personnel.

To assure close coordination and cooperation, it can prove advantageous for the same organization to have responsibility for both operations and maintenance. This logical tie-in of two essential system management functions improves the cohesion necessary for effective operations.

13.4 Maintenance

The successful performance of any operational traffic signal and freeway traffic control system depends on the commitment of the operating agency to an effective maintenance management program.

Maintenance has sometimes received insufficient emphasis in system management. Some agencies have erroneously presumed that high-technology systems possess fewer maintenance requirements, and consequently underestimated budget and staffing needs for proper system maintenance. Similarly, agencies have failed to recognize the higher personnel skill levels required to maintain complex traffic control systems. This illustrates the need for cost tradeoff analyses during the design phase to

Table 13-4. Traffic signal control systems in urban areas.

City	Population	No. of Signals In System	Type System *	Type Intersection Controller	Number of Personnel****		Comments
					Operations	Maintenance	
College Station, TX (4)	54,000	37	Eagle Marc	NEMA	1	2	Installed in 1992
Richardson, TX (5)	76,800	86	**2M	NEMA	8	6	N/A
Anaheim, CA (6)	265,000	180	UTCS Enhanced	NEMA	4 equivalent full-time and 3 student interns	Maintenance Contract	Personnel shown provide for operations and for maintenance contract supervision
St. Paul, MN (3)	270,000	108	Computran UTCS	170	3	10	108 of 347 under central control; others under commercial closed-loop control; central control system installed in 1992
Oakland County, MI (7)	1,100,000	95	SCATS	NEMA	6	Number not designated for system	Coordinated with MDOT freeway traffic management and Siemens Ali-Scout Route Guidance System
Toronto, ON (8)	***3,600,000	1,641	N/A	N/A	38	Maintenance Contract	Total of 1,641 traffic signals of which 75 are in the SCOOT system and 1,585 are in the older UTC computer traffic system. Personnel shown provide for operation of maintenance contract.
Los Angeles, CA (9)	***3,500,000	1,566	UTCS 1.5 Gen	170	15	75	Total of 4,000 traffic signals of which 1,566 are under the ATSAC system computer control

Table 13-5. Freeway traffic management systems.

System	Population	Miles (Kilometers) of Freeway	Ramp Meters	CCTV	CMS	HOV	Number of Personnel**		Comments
							Operations	Maintenance	
Seattle, WA (10)	516,000	86.5 (139.2)	31	118	30	Yes	12	4	
Minneapolis/ St. Paul, MN (11)	641,000	97.0 (156.1)	316	108	34	Yes	14	7	
Detroit, MI (12)	1,028,000	32.0 (51.5)	49	11	14	No	9	4	
Chicago, IL (13)	2,783,000	130.0 (209.2)	95	0	23	Yes	14	5	14 full-time operations personnel plus 16 part-time tech co-op students; 5 full-time maintenance personnel plus maintenance contract
Los Angeles, CA (14)	3,500,000	315.0 (506.8)	*1100	17	62	Yes	---	---	24 full-time operations, system support and maintenance personnel; 8 full-time incident management and special events personnel
Long Island, NY (15)	3,300,000	136.0 (218.8)	75	44	101	Yes	28	8	23 full-time operations personnel plus 5 full-time State personnel; 8 full-time maintenance personnel

Table 13-6. Basic staffing skills.

Skill	Required Knowledge
Traffic Operations	• Traffic flow principles • Control concepts • Local conditions • Signal timing and freeway traffic control requirements • Conditions of existing equipment • System planning, design, installation and operation • Operations of other traffic control systems in the area and good working relationships with their operating staff
Systems	• Local signal controllers • Data communications • Database structure • System software structure • Programming • Equipment integration

identify techniques for reducing maintenance requirements.

An effective maintenance management program requires accurate record keeping and overall system configuration documentation including:

- Up-to-date timing plans,
- Database, and
- Software and hardware information.

Updating should be performed daily.

An effective maintenance management program relies on these records to:

- Predict future maintenance needs,
- Analyze costs, and
- Use for special purposes such as litigation.

The following paragraphs focus on management aspects of traffic control system maintenance.

Types of Maintenance

Traffic control system maintenance activities classify as:

- Functional,
- Hardware, and
- Software.

Functional

To achieve the full potential of traffic control systems, agencies should continually expand effort on updating the database and optimizing signal timing plans.

Computer-based traffic control systems use extensive databases which include:

- System control input parameters,
- Operating thresholds,
- Functional characteristics, and
- Hardware characteristics.

Typical requirements for database updates include:

- Detector relocations,
- Subsystem reconfiguration,
- System expansion,
- Changes in controller types, and
- Changes in preemption routes.

For sample locations, Table 13-8 summarizes the resources required to update timing plans and fine tune ramp meter control algorithms.

Hardware

Traffic control system hardware maintenance generally falls into three categories (17):

- Remedial,
- Preventive, and
- Modification.

Remedial, usually commanding the highest priority, results from malfunctions and equipment failures, including emergency repair activity to restore operation. Most centrally controlled computer traffic systems and closed-loop systems incorporate software which can diagnose the malfunctioning of many field components. During operating periods

Table 13-7. Staffing factors.

Factor	Description
Assignments	In smaller traffic control systems, 1 or 2 qualified individuals can perform typical operational tasks. In larger systems, specific tasks must be identified and assigned to appropriately skilled personnel. Individual team members must know their specific responsibilities and relationships with other team members to assure proper system operation and updating.
Training	• When systems are initially installed, the system installation contractor (see chapter 11) typically provides training in system operation • Scheduling, supervising, and conducting in-house, on-the-job training programs • The agency must conduct on-going training because of: – personnel turnover – advancement of personnel to other positions – terminations Regular in-service and on-the-job training should be initiated as soon as practical after system implementation. Such a program provides continuity of operation as personnel changes occur, and increases general interest in operations among team members.
Tours	Hosting visitors to the control center - usually most intense during the first 18 months.
Public relations	Developing public relations and citizen information programs through press releases, and compilation and printing of literature, based on the operation and performance of the control system
Shifts	Traffic control systems perform their functions around the clock, handling their more critical traffic loads during recurring control periods of higher demands. Most current operating systems provide on-site personnel for operations duties covering at least the period from the beginning of the morning peak to the end of evening peak. Smaller systems may limit staffing periods to peaks only. Other systems are staffed on a 24 hour basis. Appropriate staffing periods can be determined only by experience with the system's operation over a reasonable period of time. Start with a 2-shift operation from approximately before the onset of the morning peak to the end of the evening peak. Supplement by some form of alarm response for the balance of each 24 hour period. Staff the system at least an hour before the morning peak to: • Clear possible system problems • Restore and repair controllers to on-line status • Alert maintenance personnel • Have staff available if an event occurs which requires manual intervention before the peak period

Table 13-8. Resources to update timing plans.

Location	System Type	System Size	Task	Hours	Cost
College Station, TX (4)	Signal	37 intersections 7 subsystems	Traffic Data Collection	650	N/A
		4 to 6 plans per subsystem	Timing and Fine Tuning	1100	N/A
St. Paul, MN (3)	Signal	108 intersections 6 zones 4 timing plans per zone 4 special event timing plans	New Database		*
			Timing and Fine Tuning		$115,050 (timing plans and fine tuning) (1992)
Seattle, WA (16)	Ramp Metering	Per ramp installation	Initial Database and Bottleneck Equations	6	N/A
			Turn-On Test	6	
			Data Collection	2	
			Table Calculation	2	
			Observation of Operation	10	
			Fine Tuning	3	
			Total per Ramp	29	

** Total signal system - $2,000,000; timing plans and fine tuning - $115,050.*

when such systems are not monitored by an operator, failure reports generated by such systems may be displayed at a terminal in the maintenance shop. *Preventive* maintenance includes work done at scheduled intervals to minimize the probability of failure. *Modification* or reconstruction becomes necessary when:

- A manufacturing/design flaw is identified, or
- Changes are needed to improve equipment characteristics.

Annual budgets must fund all three categories.

Sophisticated data communications, changeable message signs and CCTV increase maintenance and require more highly trained personnel. As technology advances, special skills may become necessary to provide adequate maintenance capability. The increased numbers of detectors in advanced traffic control systems also require added maintenance.

Maintenance personnel should regularly check the operation of local controllers and detectors which operate as part of a coordinated system. Check both the system and the local operational modes. Interconnect cable connections should be checked concurrently.

Scheduled maintenance includes such traditional activities as:

- Relamping, cleaning of signal heads, and
- Inspection of:
  - Poles,
  - Foundations,
  - Wiring, and
  - Pedestrian pushbuttons.

Field Masters and Central Computer

Most contemporary field located system masters require maintenance normally associated with local controllers. Check system masters monthly with particular emphasis on:

- Operations,
- Timing, and
- System-sensor performance.

Check each local controller to verify its operation with respect to the system master.

Central computer systems may use:

- Minicomputers,
- Microcomputers, or
- Personal computers.

While service for personal computers is readily available, agencies often maintain the other computer classes under contract.

A maintenance contract usually specifies a response time. Typical contracts provide for both routine and emergency maintenance, including parts and labor, for a fixed monthly fee. Computer maintenance service can also be obtained on a time-and-materials basis.

Software

Agencies often overlook traffic control system software in assessing total system maintenance requirements. Software packages commonly experience isolated failures or bugs. A computer program can prove highly complex, making it impossible to test and debug every possible logic path. Warranties therefore take on major importance.

While an operating package may never eliminate all software failures, certain steps can reduce resulting problems to manageable proportions. Table 13-9 shows some guidelines (18) to help mitigate software problems.

Carrying out the procedures in Table 13-9 can recreate an erratic condition diagnosed as a possible software bug. Software testing and debugging is accomplished by a highly trained systems analyst/programmer familiar with:

- Real-time programming techniques, and
- Functional characteristics of the software being tested.

As part of the system software package, the operating system supplier typically provides programmer tools, including programs for:

- Diagnostics,
- Tracing logic, and
- Memory dumps.

These tools and others can prove critical to effective software maintenance. Their availability should be specified and evaluated during the system design and installation process.

Table 13-9. Guidelines to minimize software problems.

- Use a compiler-level language where possible, rather than assembly language. This will encourage use of straight-forward programming techniques. It will also simplify the task of error analysis and correction.
- Maintain software with complete and accurate documentation. During the O & M phase, documentation of all software and databases *must* be kept up to date.
- Maintain operating logs continuously and save permanently. The operating logs include:
  - exception reports
  - written reports of all repairs
  - hardware/software changes
- Monitor environmental conditions. The operations center may have recorders that keep track of temperature and voltages. This may prove important in determining whether hardware or software caused the failure. The recorders may indicate the possibility of marginal equipment operation.

Software maintenance includes:

- Correction of program errors, and
- Continuing process of program modification or refinement resulting from physical changes in the system or enhancements to system operation.

Results of Inadequate Maintenance

An inadequate maintenance program can have serious implications. For example, signal failures can directly impact accident potential. When accidents do occur, courts increasingly hold operating agencies liable if malfunctions were not corrected in a timely manner. This has resulted in increased emphasis on both maintenance and maintenance-record systems.

Maintenance also impacts the ability of a control system to optimally perform its functions. Failure of a single component may degrade system performance. For example, the selection and implementation of timing plans usually depends on input data from selected detectors. Failure of critical detectors could result in an inappropriate traffic control plan.

Maintenance deficiencies also result in the following types of equipment failure:

- Malfunction - Any event that impairs the operation of a control system without losing the display and sequencing of signal indications to all approaching traffic. Malfunctions include detector failures, loss of interconnected control, and other similar occurrences.
- Breakdown - Any event that causes a loss of signal indication to any or all phases or traffic approaches. Breakdowns include:
  - Controller failures,
  - Cable failures, and
  - Loss of power.
- Reduced life - Lack of maintenance can also reduce equipment service life.

Staff Requirements

In planning maintenance staff for an advanced traffic control system, agencies must consider the:

- Impacts of the new system on overall maintenance activity, and
- Attendant maintenance skill level requirements.

Planning should assess:

- Present and projected maintenance skill level requirements,
- Present maintenance capability with respect to:
  - Staffing,
  - Equipment,
  - Training and budget, and
- Projected workload impact associated with the new traffic control system.

Skills Required

A staff of well trained and experienced personnel proves key to an effective maintenance management program. More sophisticated systems often require:

- Specialized training for existing technicians, or
- Expansion of staff to accommodate specialists in technologies such as:
  - Computer,
  - Communications, and
  - Detection.

Agencies may have difficulty:

- Finding competent specialists, and
- Paying competitive salaries for such personnel.

Agencies planning complex computer control systems should consider the alternative of contractual maintenance services. In cases where additional staff training and expansion prove appropriate, the training should be:

- Thorough,
- Both classroom and hands-on, and
- Intensive in troubleshooting and diagnostic techniques.

In an urban area, agencies can support each other by sharing maintenance resources on an on-going or as needed basis. For instance, one or more maintenance technicians could support systems in two nearby cities with the cities sharing salary and other costs.

The use of one type of hardware and one software package in systems increases personnel familiarity with the system reducing the time for:

- Troubleshooting,
- Training, and
- Equipment inventory.

Tables 13-4 and 13-5 show the number of personnel assigned to several operating traffic signal and freeway traffic management systems.

13.5 Evaluation

Evaluation (see Figure 13-2) assesses performance levels of the operations and maintenance functions. Evaluate the effects on safety and traffic flow quality of new systems, control strategies, and other operational improvements with *before* and *after* measures of effectiveness (MOE) such as:

- Volume,
- Accidents,
- Travel speed,
- Travel time,
- Delay,
- Stops,
- Periods of congestion, and
- Queue length.

Evaluation provides the framework to measure system effectiveness.

Evaluation techniques vary depending on their application and may include simulation as an alternative to real-world measurements. Similarly, data requirements and accuracy needs vary depending on:

- Measures of effectiveness used,
- Test conditions, and
- Nature of the improvement.

Information provided by the various evaluation techniques may:

- Prove useful for traditional comparison of traffic parameters, and
- Estimate other important performance measures such as fuel consumption and vehicle emissions (see Chapter 4).

As previously indicated, system evaluation is one of the primary functions of a traffic control system. Short-term evaluations assess the immediate effects of an operational strategy or timing change.

The agency should make a more in-depth evaluation of system operation and maintenance periodically (e.g., every one to three years) and when adding new locations and functions. This assures that the system still meets overall system needs.

Traffic control system improvements are usually proposed to decision-makers based on some forecast of the resulting benefits.

Evaluation sustains the credibility of the traffic system and its staff. It also identifies ways to further increase benefits.

Techniques

The first step in evaluation should establish objectives which define a desired level of performance improvement within the framework of broader regional goals and objectives. Examples include:

- Improve the safety of the existing transportation system,
- Reduce travel time on the existing transportation system,
- Reduce transportation system air quality impacts and energy consumption,
- Provide rapid detection and removal of capacity reducing incidents, and
- Increase person movement capacity of the existing transportation system to serve demand.

The second step selects appropriate measures of effectiveness (MOEs) to serve as a basis or standard of comparison (see section 3.12). These MOEs define the:

- Form of the data needed to evaluate strategies/tactics, and
- Structure of the *before* and *after* studies.

The third step implements the evaluation. Evaluation techniques based on traffic measurements usually prove more credible to decision makers than simulation results, thus, it is desirable to perform at least a portion of the evaluation in this way. If staff resources are insufficient, a qualified consultant can perform the evaluation.

Certain parameters such as volume may be obtainable from the traffic system. Caution must be exercised in using MOE such as delay, stops and speed from the traffic system as these MOE may have estimation errors or might not be truly representative of conditions which are not in close proximity to the detector.

Simulation techniques may be used to reduce the cost of evaluation, particularly for large systems. Credible evaluations require such simulations to be validated and, if necessary, calibrated against physical measurements for a portion of the system.

Before and After Measurements

Measurement of conditions *before* and *after* project implementation is perhaps the most common approach for evaluating improvements. This approach establishes the *before* measurement as the base and assumes that the *after* conditions represent the effect of the improvement.

This approach can prove susceptible to errors caused by time-related factors, especially when measuring the effects over a long period. Factors that may influence conditions between the *before* and *after* measurements include:

- Population growth,
- Economic fluctuations,
- Completion of major traffic generators, or
- Other changes.

As indicators of change, *before* and *after* measurements cannot easily distinguish the effects of individual improvements made at the same time.

To some extent these issues can be mitigated using the traffic system itself as an evaluation tool. For example, evaluation can use the following procedure:

After completion of construction, restore the database to pre-construction timing plans and control strategies,

- Measure *before* conditions,
- Implement new timing plans and strategies, and
- Measure *after* conditions.

The resulting shorter time period minimizes the effects of traffic demand changes during the evaluation period. Depending on the accuracy of the algorithms, system generated MOEs may provide cost effective evaluation data.

Even when long term demand changes do not impact evaluation, intermediate or short-term demand changes usually occur. Examples include demand variations resulting from:

- Seasonal effects,
- Holiday periods,
- Weather, and
- Special events.

The effects of improvements may be confounded when implementing two or more congestion reduction techniques concurrently. Examples include:

- Roadway improvements,
- One-way streets,
- Modified signal indications, and
- Revised timing patterns.

It may prove possible to evaluate in stages to emphasize the contribution of each technique.

Before and *after* studies can define specific test routes for evaluation. This approach is often selected when the evaluation uses *floating vehicle* measurements. Alternatively, intersection based measurements (or spot measurements on freeways) may be the basis for evaluation.

Sampling Considerations

The integrity of the sampling technique used for data collection critically impacts the level of precision expected in the evaluation. The level of precision associated with a *before-and-after* study depends on the:

- Importance of detecting a difference,
- Expected size of the difference, and
- Cost of the data collection activity.

In cases involving research the importance of the project may warrant high precision. Studies involving relatively small before/after differences, may also require high precision because a small scale study would prove inconclusive. Studies involving major changes at a particular location can tolerate lower precision. Carefully design the sampling procedure to measure the effects of the alternative strategies efficiently and accurately.

Box and Oppenlander (19) and other statistical references discuss techniques for selecting appropriate sample sizes.

Descriptions of Measures of Effectiveness (MOEs)

Measures of effectiveness appropriate to the evaluation of traffic monitoring and control systems fall into the following categories:

- Changes in congestion levels and travel patterns, reflected through the MOE described earlier in the section,
- Changes in system operation costs, both to the user and system operator,
- Community effects, evidenced by factors such as decreased accident rates and vehicle emissions,
- Improved accessibility, evidenced by:
  - Decreased delays,
  - Increased economic activity, and
  - Reduced travel time by commuters benefiting from HOV improvements, and
- Measures of effectiveness which account for manifest demand changes during the evaluation period.

Selecting MOEs for analysis and evaluation will likely prove an iterative process requiring subjective compromises among:

- Best MOEs,
- Availability and accuracy of estimation and data-collection techniques,
- Schedule, staff, and budget constraints.

MOEs should appear important and understandable to:

- Elected officials,
- Administrators,
- Citizens, and
- Other affected groups.

In addition, important factors to note include:

- Impacts of many alternative strategies frequently prove small in both absolute and percentage terms,
- Impacts frequently are confined to a small geographic area, and
- It may not be possible to estimate highly accurate, site-specific impacts using commonly available data and estimation procedures.

In developing MOEs, review the set of criteria presented in Table 13-10.

The MOEs commonly measured and computed from data acquired by traffic control systems include (see Section 3.12):

- Total travel time per unit time,
- Individual vehicle travel time per unit time,
- Total vehicle-miles of travel,
- Number and percentage of stops,
- Delay per vehicle and total delay,
- Individual vehicle speed,
- Network speed,
- Corridor throughput,
- Total minute-miles of congestion,
- Accident rate reduction, and
- Fuel consumption

Table 13-10. Criteria for developing measures of effectiveness (MOEs).

• **Relevancy to Objectives** Each MOE should have a clear and specific relationship to transportation objectives to assure the ability to explain changes in the condition of the transportation system	• **Broadly Applicable** Use MOEs applicable to many different types of strategies whenever possible
• **Simple and Understandable** Within the constraints of required Precision and accuracy, each MOE should prove simple in application and interpretation	• **Responsive** Specify each MOE to reflect impacts on various groups, taking into account, as appropriate, geographic area and time period or application and influence
• **Quantitative** Specify MOEs in numerical terms whenever possible	• **Sensitive** Each MOE should discriminate between impact sufficiently measured by other MOEs
• **Measurable** Each MOE should be suitable for application in pre-implementation simulation and evaluation (i.e., have well-defined mathematical properties and be easily modeled) and in post-implementation monitoring (i.e., require simple direct field measurement attainable within reasonable time, cost, and staffing budgets)	• **Not Redundant** Each MOE should avoid measuring an impact sufficiently measured by other MOEs • **Appropriately Detailed** MOEs should be formulated at the proper level of detail for the analysis

Source: Reference 20

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CHAPTER 14
ITS PLANS AND PROGRAMS

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CHAPTER 14
ITS PLANS AND PROGRAMS

Photo courtesy of New York State Thruway

Figure 14-1. E-Z Pass toll booth.

14.1 Introduction

This chapter overviews ITS activities in the U.S. and abroad, and reviews the Intermodal Surface Transportation Efficiency Act (ISTEA) and ITS planning in the U.S., including Federal, State and local government programs. It also reviews the role and status of ITS standards.

Table 14-1 shows the organization of this chapter.

Current U.S. ITS Programs

With regard to surface transportation systems, including the traffic control systems covered in this Handbook, the national ITS program in the United States has a significant impact on their:

- Planning,
- Design,
- Implementation, and
- Operation.

This results from the far-reaching requirements of the ISTEA legislation for Federal-Aid Funding and the Department of Transportation's ITS Strategic Plan submitted to Congress in 1992.

The USDOT Strategic Plan describes how the Department, acting as a catalyst, works with its partners in the private and public sectors to establish ITS in the United States. The Plan describes the USDOTs programs and program delivery processes for supporting the development and deployment of ITS technologies. Projects currently underway, many of them funded by the USDOT, fall into the 19 milestone areas listed in table 14-2.

Tables 14-3, 14-4 and 14-5 list projects in the 3 categories covered in this Handbook (1):

- Traffic Control Systems
- Traveler Information Systems, and
- Route Guidance and Navigation Systems.

14.2 ITS Program Planning in the United States

In the late 1980s, the United States had fallen behind Europe and Japan in the application of advanced technology to improve the safety and efficiency of the road transportation system.

Table 14-1. Chapter 14 organization.

Section Title	Purpose	Topics
ITS Program Planning in the United States	Discusses ITS planning at the National, State and local government levels	• ITS AMERICA • ISTEA • USDOT ITS program • National program plan for ITS • The ITS planning process - travel and transportation management - travel demand management - public transportation operations - electronic payment - commercial vehicle operations - emergency management - advanced vehicle control and safety systems - user service bundling • ITS planning at the State and local level • Minnesota Guidestar • Current ITS programs
Worldwide ITS Programs	Discusses worldwide ITS programs present and future	• European programs - DRIVE - PROMETHEUS • ITS Coordination in Europe • Japanese programs - RACS - AMTICS - VICS - SSVS • ITS Coordination in Japan
Standards Applicable to ITS Technologies	Discusses standards to facilitate ITS development and benefits	• Roles of major organizations in ITS standards development - Federal government - ITS AMERICA - Council of Standards - SAE • ITS standards activities

However, with the founding of the Intelligent Transportation Society of America (ITS AMERICA), the passage of the Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA), and initiatives taken by the US Department of Transportation, the tide has changed and a comprehensive ITS National Program has rapidly taken form.

This section describes ITS planning in the United States at the National, State, and local government levels.

ITS AMERICA

ITS AMERICA plays a major role in ITS. Table 14-6 summarizes its history, mission, roles, and activities.

Technical committees form the backbone of ITS AMERICA. They serve as the action arm, and address issues of significance to the ITS community. Prominent players from the private sector and State and local governments chair these committees, and the committee secretaries come from USDOT. The committees draw members from the ITS community at large.

In its role as a Federal Advisory Committee, ITS AMERICA prepared a strategic plan for ITS which laid out a course of action for the next 20 years in the areas of (2):

- Research,
- Testing, and
- Implementation.

Table 14-2. U.S. ITS milestone areas.

• Tools and Knowledge Bases	• Traffic Control Systems
• System Architecture	• Rural Applications
• Radio Frequencies	• Commercial Vehicle Applications
• Traveler Information Systems	• Commercial Vehicle Network
• Route Guidance and Navigation Systems	• Collision Avoidance
• Transit Fleet Management	• Automated Highway System
• Fare Collection and Smart Cards	• Benefits and Costs
• Transportation Demand Management	• Institutional and Legal Issues
• Transportation Management Database	• ITS Deployment
• Related Projects	

ISTEA (Intermodal Surface Transportation Efficiency Act)

With the completion of the Interstate Highway System in 1991, the passage of ISTEA has ushered in a new era for ground transportation in the United States. ISTEA clearly defines its purpose in its statement of policy: *to develop a National Intermodal Transportation System that is economically efficient and environmentally sound, provides the foundation for the Nation to compete in the global economy, and will move people and goods in an energy efficient manner.*

Table 14-7 summarizes highlights of ISTEA relevant to this Handbook.

ISTEA creates an expanded environment for traffic control, with increased emphasis on:

- Congestion management,
- Public transportation,
- Air quality,
- Rights-of-way for pedestrians and bicyclists, and
- Mobility for the elderly and disabled.

Table 14-3. Traffic control systems projects.

FHWA Research and Development

- Coordinated Operation of Ramp Metering and Signal Control
- Deployment Issues of Surveillance Systems for ITS
- Design of Support Centers for ITS Operation
- Incident Detection Issues
- Network-Wide Optimization
- Real-Time Traffic adaptive Control for ITS
- Responsive Multi-Modal Transportation Management Strategies
- Traffic Models for Testing Real-Time Traffic-Adaptive Signal Control Logic: Phase I
- Wide-Area Surveillance Systems

Operational Tests

- Freeway ATMS (CT)
- Genesis (MN)
- Satellite Communications Feasibility (PA)
- SMART Corridor (Los Angeles, CA)
- TravLink (MN)

Deployment Projects

- INFORM (Long Island, NY)
- TRANSCOM Congestion Management Program (NY, NY, and CT)

USDOT ITS Program

In accordance with the requirements of ISTEA, the USDOT submitted an ITS Strategic Plan to Congress which set forth the goals, milestones, and objectives

Table 14-4. Traveler information systems projects.

Research and development

- FM/SCA Prototype for Traffic Information Broadcast
- Traffic Management Information and Fleet Operation Coordination (Anaheim, CA)
- Transit Network Route Decision Aid (MI)

Operational Tests

- Smart Traveler (Bellevue, WA)
- SmarTraveler (Boston, MA)
- Smart Traveler (CA)
- DIRECT (Detroit, MI)

Table 14-5. Route guidance and navigation system projects.

Research and Development • Global Positioning System • Link Identification Format and Map Database Requirements **Operational Tests** • ADVANCE (IL) • FAST-TRAC (MI) • PATHFINDER (CA)

of the USDOTs ITS Program through 1997. Coordination is provided by representatives from:

- Office of the Secretary,
- Federal Highway Administration (FHWA),
- Federal Transit Administration (FTA),
- National Highway Traffic Safety Administration (NHTSA), and
- Research and Special Programs Administration (RSPA).

FHWA serves as the lead agency.

Programs include R & D and operational testing of promising technologies and system concepts. The program places special focus on nationwide system deployment and on long-term development under the Automated Highway Systems (AHS) program. Institutional and legal issues, public agency cooperation, and creative financing mechanisms receive special emphasis throughout the program.

The USDOT established a set of discrete milestones involving 18 different program areas for completion within the first 5-years of the ITS program (1993-1997). Beyond 1997, deployment of a nationally compatible ITS system will become the primary concern, with work shifting towards support of deployment of ITS user services and continuing progress in realizing long-term goals, particularly the AHS.

Public/private partnerships prove fundamental to a national ITS program that will require unprecedented levels of cooperation and coordination between the public and private sectors. Table 14-8 summarizes the responsibilities of the various partners.

Table 14-6. ITS America.

History • Founded as IVHS AMERICA in 1991, based in Washington, DC (changed to ITS America in 1994) • Non-profit public/private scientific and educational corporation • Chartered as a utilized Advisory Committee to the USDOT • Open to all public and private organizations or groups with ITS interests, from any country
Mission • To advance a national program for a safer, cleaner, more efficient and productive U.S. surface transportation system through research, development, testing and implementation of advanced technology
Roles • Provide a forum for discussion, coordination and development of programs • Foster, promote and coordinate ITS R&D • Advise, assist and inform public and private sectors about ITS • Disseminate information on benefits of ITS • Advise USDOT, other federal, state and local governments • Identify and recommend development of ITS standards and protocols • Maintain and use ITS information and databases • Address institutional issues • Provide support for development of ITS plans and programs • Foster international cooperation in ITS R&D and implementation
Publications, Information Transfer • ITS AMERICA, a monthly newsletter • ITE Review, a quarterly journal of opinion and analysis • National ITS Information Clearinghouse
Reports • Strategic Plan for ITS in the United States • Annual Federal ITS Program recommendations • Reports on special studies and topics
Conferences and Workshops • ITS AMERICA annual meeting • International ITS World Congress and Exhibition • Workshops on pressing issues and special topics

Table 14-7. Relevant highlights of ISTEA.

Metropolitan Planning
- MPOs must develop long-range transportation plans
- Transportation Improvement Programs (TIPs)
- Emphasis on intermodal transportation
- Access, connectivity and congestion relief are important

Statewide Planning
- States must develop own transportation plans and programs
- Congestion relief, transit and border crossings are important

Congestion Pricing Pilot Program
- Five congestion pricing pilot projects

Congestion Mitigation and Air Quality Improvement Program
- Funding for noncompliance with Clean air Act

Management System Requirements for States
- Traffic congestion
- Highway safety
- Public transportation facilities and equipment
- Intermodal transportation facilities and equipment

Intelligent Vehicle-Highway Systems Act
- ITS Corridors Program ($500 M over 6 years)
- ITS Research and Development ($158 M over 6 years)
- Compatible standards and protocols required
- Guidelines for ITS operational tests required
- National ITS program plan to be submitted to Congress
- Test of prototype automated highway system

National Program Plan for ITS

The National ITS Program Plan provides a commonly shared vision of how development and deployment of ITS services in a nationally compatible intermodal system will address highway and public transportation operational problems. The Plan serves as a common reference document to frame debate on how to advance ITS in the United States. USDOT developed the document largely with input from ITS AMERICA. Figure 14-2 shows the interrelationship of the components of the Plan.

Table 14-8. Partnership responsibilities.

Federal Government
- Provide national emphasis and perspective
- Fund and manage research and testing
- Remove institutional barriers
- Foster ITS standards

ITS AMERICA
- Maintain Strategic Plan and clearinghouse
- Provide a forum for solving problems
- Evaluate and advise

State and Local Government
- Deploy ITS
- Operate and maintain ITS

Private Sector
- Develop products
- Market products
- Act as research partner

Professional Societies
- Develop standards
- Disseminate information

Academia
- Educate ITS professionals
- Act as research partners

Table 14-9 summarizes the 4 main purposes of the Plan.

Table 14-10 summarizes the basic features of the ITS National Plan.

Figure 14-3 shows the stages leading to ITS deployment (3). The lower portion shows the stages which each user service will typically go through to reach deployment. The upper portion illustrates the development stages for the ITS systems architecture, which will serve as the broad framework of ITS deployment for the next twenty years. Table 14-11 summarizes the program steps. Although shown in a linear sequence, in reality many feedbacks and iterations will occur along the way.

The ITS Planning Process

The ITS program focuses on the development and deployment of a collection of *user services*. The national program planning process has defined 29 interrelated user services to date. User services do not necessarily correlate with technologies, but rather meet the safety, mobility, environmental, and other transportation-related needs of a specified user or group of users. Users of a particular service might

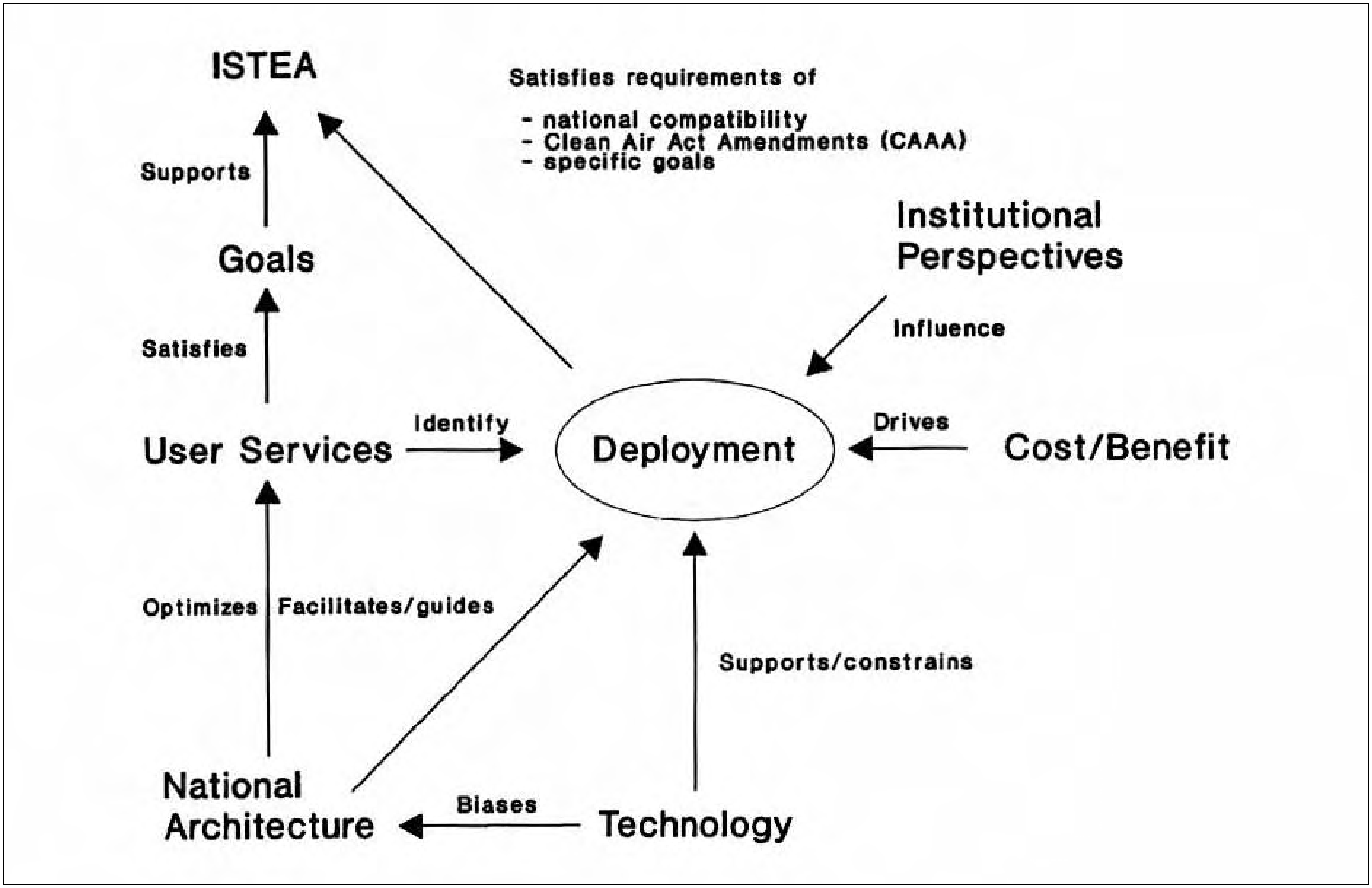

Figure 14-2. Component interrelation.

Table 14-9. Purposes and uses of the national ITS program plan.

- Provides a description for private and public sector leaders, including the Congress
- Provides a guide for investment decisions for public and private sectors
- Assures coordination and integration of deployment of user services
- Assures that program activities lead to deployment of user services in a nationally compatible system. It is not a research and development program.

Table 14-10. Features of ITS national plan.

Goal Oriented

- Pursues goals in ITS AMERICA Strategic Plan
- Deployment of ITS user services to meet these goals

User Oriented

- ITS is a collection of user services
- Provision of such services is focus of development

Deployment Oriented

- Program activities directed to deployment of user services
- Identifies early deployment opportunities

Commonly Shared Vision

- Presents a commonly shared vision of ITS in the United States
- Integration of public, private or public/private activities

Participative

- Developed cooperatively by USDOT and ITS AMERICA
- Input from many different organizations and individuals
- Annual assessment – plan is a *living document*

Specific

- Reflects consensus on specific activities and projects
- Lead to accomplishment of specific program milestones
- Tool for making investment decisions

include travelers using all modes, transportation management center operators, transit operators, Metropolitan Planning Organizations (MPOs), commercial vehicle owners and operators, State and local governments, and many others who benefit from ITS deployment.

Detailed User Service Development Plans that describe the activities needed to deploy each service constitute a major component of the National ITS Program Plan. Their features are described below.

Since user services constitute the ITS program building blocks, a brief description of each aids understanding of the Program Plan. The following narrative descriptions summarize each service. They fall into seven categories, or bundles, defined and described later in the section.

Travel and Transportation Management

- *En Route Driver Information* - Driver advisories and in-vehicle signing for convenience and safety.

  Driver advisories resemble pre-trip planning information, but are provided once travel begins. Driver advisories convey real-time information about traffic conditions, incidents, construction, transit schedules, and weather conditions to drivers of personal, commercial, and public transit vehicles. This information allows a driver to select the best route, or shift to another mode in mid-trip if desired.

  I*n-vehicle signing*, the second component of en route driver information, provides directly within the vehicle the same types of information found on physical road signs today. The service could also include warnings of road conditions, and safe speeds for specific types of vehicles (e.g., autos, buses, large trucks), but potential users include drivers of all types of vehicles. This service could prove especially useful to elderly drivers, in rural areas with large numbers of tourists, or in areas with unusual or hazardous roadway conditions.

- *Route Guidance* - Provides travelers with simple instructions on how best to reach their destinations.

  The route guidance service provides a suggested route to reach a specified destination. Early route guidance systems will use static information about the roadway network, as well as transit schedules. When fully deployed, route guidance systems will provide travelers with directions to their destinations based on real-time information

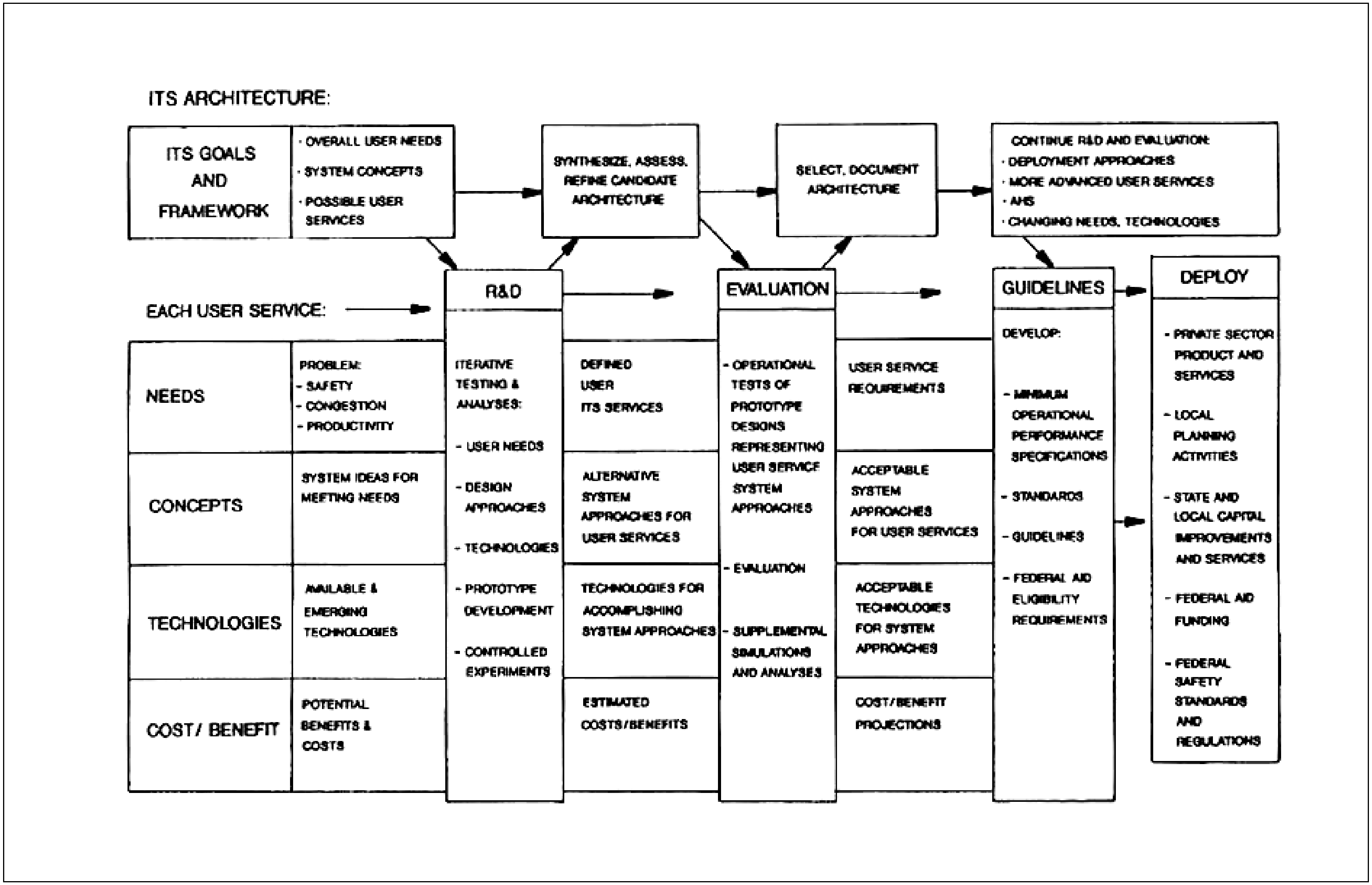

Figure 14-3. The ITS program.

Table 14-11. ITS program steps.

Setting the Goals • Broad consensus process, agreed to at a national level • Traceable to needs that have to be addressed
Conceptual Development • Functions required to support user services • Technologies required to implement functions
National System Architecture • The framework for national ITS deployment • Information flows to provide user services
Research and Development • Feasibility of innovative new technologies and systems • Top-down prioritizing based on goals and user needs
Operational Tests • Key step in evaluating potential ITS systems • For integrated systems and services, not technologies • Emphasis on system effectiveness and user assessments
Standards and Guidelines • ITS consensus standards • Development by standards-setting organizations
Deployment • Education of State and local agencies on ITS • Early deployment progress • Prioritizing areas which would benefit most • Arena for addressing institutional and legal issues

about the transportation system. The route guidance service will consider traffic conditions, status and schedule of transit systems, and road closures in developing the best route. Directions will generally consist of simple instructions on turns or other upcoming maneuvers. Users of the service will include not only drivers of all vehicle types, but also non-vehicular travelers, such as pedestrians or bicyclists, who could get specialized route guidance from a hand-held device.

- *Traveler Services Information* - Provides a business directory, or yellow pages, of service information.

  Traveler services information provides quick access to travel related services and facilities. Examples of information provided include the location, operating hours, and availability, of food, parking, auto repair, hospitals, and police facilities. Travelers could access information in the home, office, or other public locations to help plan trips, and for guidance on en route as well. When fully deployed, this service will connect users and providers interactively, to allow requests for and provision of needed information. A comprehensive, integrated service could also support financial transactions like automatic billing for purchases.

- *Traffic Control* - Manages the movement of traffic on streets and highways.

  This service will provide for the integration and adaptive control of the freeway and surface street systems to:

  - Improve the flow of traffic,
  - Give preference to public safety, transit or other high occupancy vehicles, and
  - Minimize congestion while maximizing the movement of people and goods.

  Through appropriate traffic controls, the service will also promote the safety of non-vehicular travelers, such as pedestrians and bicyclists. This service requires:

  - Advanced surveillance of traffic flow,
  - Analysis techniques for determining appropriate traffic signal and ramp metering controls, and
  - Communication of these controls to the roadside infrastructure.

  This service:

  - Gathers data from the transportation system,
  - Organizes it into usable information, and
  - Determines the optimum assignment of right-of-way to vehicles and pedestrians.

  The real-time traffic information collected by the Traffic Control service also provides the foundation for many other user services.

- *Incident Management* - Helps public and private organizations quickly identify incidents and implement a response to minimize their effects on traffic.

  This service enhances existing capabilities for detecting and verifying incidents, in both urban and rural areas, and takes the appropriate actions in response. The service uses advanced sensors, data processing, and communications to improve the incident management and response capabilities of transportation and public safety officials, the towing and recovery industry, and others involved in incident response. The service will help these groups to quickly and accurately identify a variety of incidents, and to implement a response that minimizes the effects of these incidents on the movement of people and goods. This service will also help transportation officials to predict traffic or highway conditions so that they can take action in advance to prevent potential incidents or to minimize their impacts. While the direct users of this service are the public and private entities responsible for incident detection and response, the ultimate beneficiaries are commercial and transit operators, and the traveling public.

- *Emissions Testing and Mitigation* - Provides information for monitoring air quality and developing air quality improvement strategies.

  This service uses advanced vehicle emissions testing systems to provide information to identify environmental hot spots and implement strategies to reroute traffic around sensitive air quality areas, or to control access to such areas. Other technologies provide in-vehicle or roadside identification of vehicles that are emitting levels of pollutants that exceed State, local or regional standards, and provide information to drivers or fleet operators to enable them to take corrective action. The service also provides transportation planning and operating agencies with information to facilitate implementation and evaluation of various pollution control strategies.

Travel Demand Management

- *Pre-Trip Travel Information* - Provides information for selecting the best transportation mode, departure time, and route.

  Pre-trip travel information allows travelers to access a complete range of intermodal transportation information at home, work, and other major sites where trips originate. Real-time information on transit routes, schedules, transfers and fares, and ride matching services encourage the use of alternatives to the single occupancy vehicle. Information needed for long, inter-urban, or vacation trips would also be available. Real-time information includes: accidents, road construction sites, alternate routes, traffic speeds along given routes, parking conditions, event schedules, and weather. Based on this information, the traveler can select the best route, modes of travel, and departure time, or decide not to make the trip at all.

- *Ride Matching and Reservation* - Makes ride sharing easier and more convenient.

  This service provides real-time ride matching information and reservations to users in their homes, offices, or other locations, and assists transportation providers, as well as van/ carpoolers, with vehicle assignments and scheduling. This service will expand the market for ridesharing as an alternative to single occupant automobile travel, and will provide for enhanced alternatives for special population groups, such as the elderly or the handicapped.

- *Demand Management and Operations* - Supports policies and regulations designed to mitigate the environmental and social impacts of traffic congestion.

  This service generates and communicates management and control strategies that:

  - Support the implementation of programs to reduce the number of individuals who choose to drive alone, especially to work,
  - Increase the use of high occupancy vehicles and transit, and
  - Provide a variety of mobility options for those who wish to travel in a more efficient manner, for example in non-peak periods.

  The service also allows employers to better accommodate the needs and lifestyles of employees by encouraging alternative work arrangements such as *variable work hours*, *compressed work weeks*, and *telecommuting*. Travel demand management strategies could ultimately apply dynamically, when congestion or pollution conditions warrant. For example, disincentives such as increased tolls and parking fees could apply during pollution alerts or peak travel periods, while transit fares would decrease to accommodate the increased number of travelers changing from modes that involve driving alone. Such strategies will reduce the negative impacts of traffic congestion on the environment and overall quality of life.

Public Transportation Operations

- *Public Transportation Management* - Automates operations, planning, and management functions of public transit systems.

  This service provides computer analysis of real-time vehicle and facility status to improve transit operations and maintenance. The analysis identifies deviations from schedule and provides potential solutions to dispatchers and drivers. Integrating this capability with traffic control services can help maintain transportation schedules and ensure transfer connections in intermodal transportation. Information regarding passenger loading, bus running times, and mileage accumulated will help improve service and facilitate administrative reporting. Automatically recording and verifying performed tasks will also enhance transit personnel management.

- *En Route Transit Information* - Provides information to travelers using public transportation after they begin their trips.

  This service provides information to assist the traveler once public transportation travel begins. Real-time, accurate transit service information onboard the vehicle helps travelers make effective transfer decisions and itinerary modifications, as needed, while a trip is underway.

- *Personalized Public Transit* - Flexibly routed transit vehicles offer more convenient service to customers.

  Small publicly or privately operated vehicles provide on-demand routing to pick up passengers who have requested service, and deliver them to their destinations. Route deviation schemes, where vehicles would leave a fixed route for a short distance to pick up or discharge passengers, provide another way of improving service. Vehicles may include small buses, taxicabs, or other small, shared ride vehicles. This service can provide almost door-to-door service, expanding transit coverage to lesser populated locations and neighborhoods - potentially providing transportation at lower cost and with greater convenience than conventional fixed route transit.

- *Public Travel Security* - Creates a secure environment for public transportation patrons and operators.

  This service provides systems that monitor the environment in transit stations, parking lots at bus stops, and onboard transit vehicles, and generates alarms, either automatically or manually, when necessary. The service thereby improves security for both transit riders and operators. Transportation agencies and authorities can integrate this user service with other anti-crime activities.

Electronic Payment

- *Electronic Payment Services* - Allows travelers to pay for transportation services electronically.

  This service will foster intermodal travel by providing a common electronic payment medium for all transportation modes and functions, including tolls, transit fares, and parking. The service provides for a common service fee and payment structure using smart cards or other technologies. Such systems could be truly multi-use, allowing personal financial transactions on the same medium. The flexibility that electronic payment services offer will also facilitate travel demand management, if conditions warrant. They could, if local authorities so choose, allow application of road pricing policies which could influence departure times and mode selection.

Commercial Vehicle Operations

- *Commercial Vehicle Electronic Clearance* - Facilitates domestic and international border clearance, minimizing stops.

  This service will enable transponder-equipped trucks and buses to have their safety status, credentials, and weight checked at mainline speeds. Vehicles that are safe and legal and have no outstanding out-of-service citations will be allowed to pass the inspection/weigh facility without delay.

  By working in conjunction with Mexico and Canada, the service would allow traffic to flow more efficiently at border crossings, and the deployment of technologies in these countries could ultimately prevent overweight, unsafe, or improperly registered vehicles from entering the United States.

- Automated Roadside Safety Inspection - Facilitates roadside inspections.

  Automated roadside inspections would allow real-time roadside access to the safety performance record of carriers, vehicles, and drivers. Such access will help determine which vehicles or drivers should stop for an inspection, and ensure timely correction of previously identified problems.

  This service would also automate as many items as possible in the manual inspection process. It would, for example, allow for more rapid and accurate inspection of brake performance at the roadside. Through the use of sensors and diagnostics, it would efficiently check vehicle systems, driver requirements, and, ultimately, driver alertness and fitness for duty.

- *Onboard Safety Monitoring* - Senses the safety status of a commercial vehicle, cargo, and driver.

Onboard systems would monitor the safety status of a vehicle, cargo, and driver at mainline speeds. Vehicle monitoring would include sensing and collecting data on the condition of critical vehicle components such as brakes, tires, and lights, and determining thresholds for warnings and countermeasures. Cargo monitoring would involve sensing unsafe conditions relating to vehicle cargo, such as shifts in cargo while the vehicle is in operation. Driver monitoring is envisioned to include the monitoring of driving time and alertness, using non-intrusive technology, and the development of warning systems for the driver, the carrier, and the enforcement official. A warning of unsafe condition would first be provided to the driver, then to the carrier and roadside enforcement officials, and would possibly prevent an accident before it happens. This service would minimize driver- and equipment-related accidents for participating carriers.

- *Commercial Vehicle Administrative Processes* - Provides electronic purchasing of credentials, and automated mileage and fuel reporting and auditing.

  Electronically purchasing credentials would provide the carrier with the capability to electronically purchase annual and temporary credentials via computer link. Use of this service would reduce burdensome paperwork and processing time for both the States and the motor carriers.

  For automated mileage and fuel reporting and auditing, this service would enable participating interstate carriers to electronically capture mileage, fuel purchased, trip, and vehicle data by State. It would also automatically determine mileage traveled and fuel purchased in each State, for use by the carrier in preparing fuel tax and registration reports to the States. The administrative burden on carriers to collect and report mileage and fuel purchased within each State has proven significant. This service would significantly reduce the cost of collecting both types of data.

- *Hazardous Material Incident Response* -- Provides immediate description of hazardous materials to emergency responders.

  This service would enhance the safety of shipments of hazardous materials by providing enforcement and response teams with timely, accurate information on cargo contents to enable them to react properly in emergency situations. If an incident involving a truck carrying hazardous material should occur, identification of the material or combination of materials involved would be electronically provided to emergency responders and enforcement personnel at the scene so they could handle the incident properly.

- *Commercial Fleet Management* - Provides communications among drivers, dispatchers, and intermodal transportation providers.

  The availability of real-time traffic information and vehicle location for commercial vehicles would significantly enhance the management of fleet operations by helping drivers avoid congested areas and by improving the reliability and efficiency of pickups and deliveries. These benefits would prove particularly important for operators of intermodal and time-sensitive fleets, who could use these ITS technologies to make their operations more efficient and reliable.

Emergency Management

- *Emergency Notification and Personal Security* - Provides immediate notification of an incident, and allows an immediate request for assistance.

  This service includes two capabilities: driver and personal security, and automatic collision notification. Driver and personal security capabilities provide for user initiated distress signals for incidents like mechanical breakdowns or carjackings. When activated by an incident, automatic collision notification transmits information regarding location, nature, and severity of the crash to emergency personnel.

- *Emergency Vehicle Management* - Reduces the time it takes emergency vehicles to respond to an incident.

  This service provides public safety agencies with fleet management capabilities, route guidance, and signal priority and/or preemption for emergency vehicles. Fleet management will improve the display of emergency vehicle locations and help dispatchers send the units that can most quickly reach an incident site. Route guidance directs emergency vehicles to an incident location, while signal priority optimizes the traffic signal timing along an emergency vehicle's route. Primary users of this service include police, fire, and medical units.

Advanced Vehicle Control and Safety Systems

- *Longitudinal Collision Avoidance* - Helps prevent head-on, rear-end or backing collisions between vehicles, or between vehicles and other objects or pedestrians.

This service helps reduce the number and severity of collisions. It includes the sensing of potential or impending collisions, prompting a driver's avoidance actions, and temporarily controlling the vehicle.

- *Lateral Collision Avoidance* - Helps prevent collisions when vehicles leave their lane of travel.

  This service provides crash warnings and controls for lane changes and road departures. It will help reduce the number of lateral collisions involving 2 or more vehicles, and crashes involving a single vehicle leaving the roadway.

  For changing lanes, a situation display can continuously monitor the vehicle's blind spot, and actively warn drivers of an impending collision. As needed, automatic control can effectively respond to situations very rapidly. Warning systems can also alert a driver to an impending road departure, provide help in keeping the vehicle in the lane, and ultimately provide automatic control of steering and throttle in dangerous situations.

- *Intersection Collision Avoidance* - Helps prevent collisions at intersections.

  This service warns drivers of imminent collisions when approaching or crossing an intersection that has traffic control (e.g., stop signs or a traffic signal). This service also alerts the driver when the proper right-of-way at the intersection proves unclear or ambiguous.

- *Vision Enhancement for Crash Avoidance* - Improves the driver's ability to see the roadway and objects on or along the roadway.

  Improved visibility will allow drivers to avoid potential collisions with other vehicles or obstacles in the roadway, and help the driver comply with traffic signs and signals. This service requires in-vehicle equipment for sensing potential hazards, processing this information, and displaying it in a way useful to a driver.

- *Pre-Crash Restraint Deployment* - Anticipates an imminent collision and activates passenger safety systems before the collision occurs, or much earlier in the crash event than currently feasible.

  This service identifies the velocity, mass, and direction of the vehicles or objects involved in a potential crash, and the number, location, and major physical characteristics of any occupants. Responses include tightening lap-shoulder belts, arming and deploying air bags at the optimal pressure, and deploying roll bars.

- *Safety Readiness* - Provides warnings about the condition of the driver, the vehicle, and the roadway.

  In-vehicle equipment will unobtrusively monitor a driver's condition and provide a warning if he or she becomes drowsy or otherwise impaired. This service could also internally monitor critical components of the automobile, and alert the driver to impending malfunctions. Equipment within the vehicle could also detect unsafe road conditions, such as bridge icing or standing water on the roadway, and provide a warning to the driver.

- *Automated Highway Systems* - Provides a fully automated, hands-off, operating environment.

  A long term goal of ITS is the deployment of automated highways systems that would provide vast improvements in safety by creating a nearly accident-free driving environment. Drivers could buy vehicles with the necessary instrumentation, or retrofit an existing vehicle. During a transition period, vehicles incapable of automated operation would drive in lanes without automation.

User Service Bundling

The user services previously described can be grouped into categories, or bundles, which provide a level of organization in addressing the services. Even a cursory assessment of the services suggests that inherent similarities justify these groupings.

Although a system can possibly be deployed that provides a single user service, in many cases combinations of user services can be considered related. These user service combinations have been termed *bundles*.

The commonality among user services in a bundle may relate to a number of different factors. In some cases, the institutional perspectives of organizations that deploy the services form the basis for arriving at a bundling rationale. In other cases, the determination of bundles centers around common technical functionalities.

The institutional and technical commonalities among the user services are discussed below.

Institutional commonalities might lead to bundling of all user services that:

- Address the same type of problem, such as travel demand management,
- Are deployed by the same types of organization, such as public transit authorities, or
- Service a similar beneficiary, such as the motor carrier industry.

These commonalties provide the most visible criteria for user service grouping. Institutional concerns and requirements will strongly influence planning and financial support for these services.

Technical commonalties arise from the application of similar core functions within the bundles. Technical commonalties allow user services to share functionality's, such as surveillance, communications, or databases. When assessing economies of user services, the cost of the functionality required for the first user service may be considered shared by all services requiring the same functionality. Alternatively, cost may be assigned to the initial user service, with subsequent services considered to be benefiting from a relatively lower incremental deployment cost.

User services have been analyzed for their institutional and technical commonalties. Institutional commonalties provide the most evident bundling concept. This approach allows for focused deployment of systems of user services to address a broad range of issues in each bundle. Commonalties that led to the bundling are discussed below.

- Travel and Transportation Management

  As the name implies, Travel and Transportation Management user services support 2 institutional functions: travel management and transportation management. These services belong in a single bundle because of the information they share about the surface transportation system. Transportation management services collect and process information about the surface transportation system, and provide commands to various traffic control devices. Travel management services disseminate this information to the traveler. When used in concert, these services provide a more comprehensive travel and transportation management system. This bundle will interest:

  - Transportation policy makers,
  - Public or private sector operators of transportation management centers,
  - Incident responders, and
  - Private sector vendors supplying travel information products and services.

  A technical commonality also influencing the bundling is the significant sharing of functional subsystems, such as a traffic database and data processing functions. Services such as Traffic Control will collect traffic data and process it into usable information. This information will become available for other services, such as En Route Driver Information or Route Guidance, and these services might provide data back to the Traffic Control service. Thus, these services will prove highly interdependent.

- Travel Demand Management

  Travel Demand Management user services support policies and strategies aimed at reducing vehicle demand by developing and encouraging modes of travel other than the single occupancy vehicle. The services in this bundle increase the use of high occupancy vehicles and transit by:

  - Providing *intermodal* information to travelers prior to the beginning of a trip, and
  - Making ride sharing and transit more convenient and easier to use.
  - These services also aim to:
  - Decrease congestion by altering the timing or routing of trips, or
  - Eliminate vehicle trips altogether.

  From a technical perspective, these services rely on information collected and processed by the Travel and Transportation Management services and the Public Transportation Operations services. Travel Demand Management services also interact with Travel and Transportation Management services to implement control strategies that provide incentives or disincentives to modify travel behavior.

- Public Transportation Operations

  This bundling reflects the commonality of the transit authority as the most probable provider of these services. The transit authority will retain responsibility to implement systems capable of:

  - Better managing the public transportation system, and
  - Providing improved transit and mode choice information.

  From a technical commonalties perspective, all these user services can use a common public transit database. The data collected by the management system will become available for all systems to customize for their specific function. This data will also support the Travel and Traffic Management bundle of services.

- Electronic Payment

  This bundle contains a single user service. However, it supports deployment of many other services, both within and outside the transportation arena, and will be developed, deployed, and operated by both public and private organizations.

- Commercial Vehicle Operations

  These user services support the goals of improving the efficiency and safety of commercial fleet operations, and will benefit both the States and the motor carrier industry. Thus, the CVO bundle reflects the commonality of using advanced computer and communications technologies to improve the safety and productivity of the motor carrier industry throughout North America.

  From a technical perspective, the foundation for all of the CVO user services is information systems. Each service will require some set of information on the motor carrier, the vehicle, the driver, and, in some cases, the cargo. The services interrelate via the specific types and functionality of information and data required. This network of information will become accessible by States and motor carriers nationwide.

- Emergency Management

  The grouping of this bundle's two user services rests on the commonality of the deploying organizations. Police, fire, and rescue operations will use these services to improve their management of, and response to, emergency situations.

  With respect to technical functionality, these user services have common elements such as vehicle location, communications, and response.

- Advanced Vehicle Control and Safety Systems

  The goal of improved vehicle safety proves the - institutional commonality among these services. Although each addresses a separate function, they all contribute to the common goal.

  Near-term reliance on *self-contained systems* within the vehicle characterizes all of these user services, with the exception of Automated Highway Systems. However, supplementing the on-board capabilities with additional sensors deployed in the *infrastructure* can enhance the functionality of these user services.

  Within the vehicle may also be found common functional elements (e.g., data storage, processing units, sensors, or actuators) shared among the user services in this bundle, including Automated Highway Systems.

ITS Planning at the State and Local Level

As indicated in table 14-7, ISTEA will significantly affect transportation planning at both the State and local level. In addition to the Transportation Improvement Programs (TIP) developed by the Metropolitan Planning Organizations (MPOs), the States also develop, for each region, plans and programs coordinated with metropolitan planning efforts. Both must comply with the Clear Air Act of 1990 and the American Disabilities Act.

Being integral to the total transportation system, ITS now becomes a major element in transportation planning. Some States and metropolitan areas have already developed plans for ITS implementation. The next section covers the basic steps involved in developing ITS plans, and illustrates the process with an example.

Minnesota Guidestar

Minnesota Guidestar represents the State of Minnesota's ITS Program, and serves as a good example of ITS planning at the State level (4, 5). Rather than focusing on a single technology application and a large-scale operational test, it seeks to develop a statewide intelligent transportation system.

Minnesota Guidestar has prepared a strategic plan that runs to the year 2000 and beyond. The plan addresses the broad requirement of program management by defining 4 basic activities and how to implement them:

- ITS Management Study (of which the strategic plan is a part),
- Program management and coordination,
- Participation in standard-setting activities, and
- Development of research facilities.

The strategic plan describes how Minnesota Guidestar relates to each of the seven ITS systems areas (categories), and defines a strategic direction for each area. It outlines the evolution of Guidestar over three time periods:

- Short term,
- 1996 to 2000, and
- Beyond 2000.

The plan remains a living document, revised periodically.

Figure 14-4 shows the organizational structure of Minnesota Guidestar. The committee structure provides the framework for managing and coordinating all Minnesota Guidestar activities, and provides a hierarchy with a clear chain of command and lines of accountability. The figure also shows the participation of the private sector.

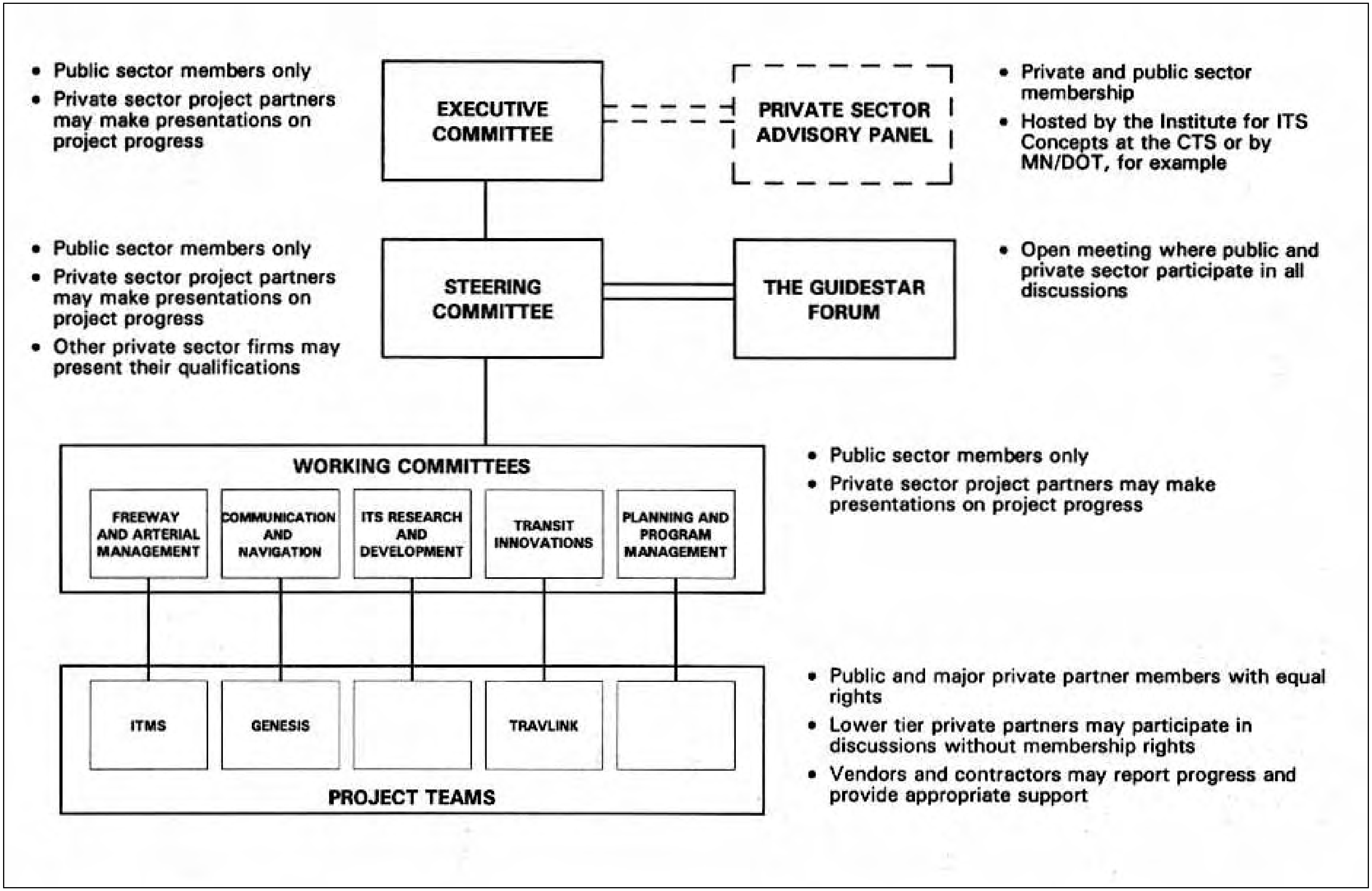

Figure 14-4. Private sector participation in MinnesotaGuidestar.

Minnesota Guidestar consists of a number of complementary initiatives, each dedicated to examining different aspects of ITS, but bound by the themes and goals of the overall program. Each project represents a fundamental building block in moving towards a statewide intelligent transportation system. Four principal initiatives currently exist, as shown in table 14-12.

Minnesota Guidestar has established a selection process, illustrated in figure 14-5, to handle new projects initiated as the program evolves. Project selection criteria derive from 4 main sources:

- Minnesota Guidestar Strategic Plan,
- ITS AMERICA Strategic Plan and annual tactical plans,
- USDOT ITS Strategic Plan, and
- USDOT Operation Test selection criteria.

The Minnesota Guidestar workplan serves as one of the key program management tools. Produced annually, it evolves from 3 sources of information:

- Minnesota Guidestar Strategic Plan,
- Progress data on current projects, and
- Recommendations from the Working Committees.

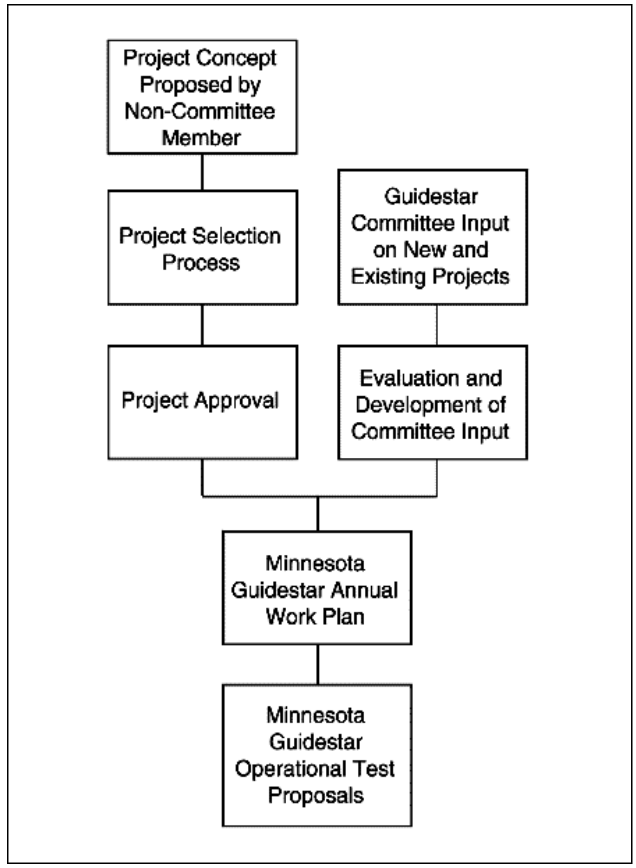

Figure 14-5. Minnesota Guidestar project selection and proposal development overview.

Table 14-12. Minnesota Guidestar projects.

Project	Participating Sponsors	Project Objective
Genesis	• MnDOT • Motorola • FHWA	Examine feasibility of using a personal, portable communications device (PCD) for ATIS applications
Travlink	• MnDOT • US West • FHWA • FTA	Evaluate effectiveness of enhanced transit information on influencing commuter mode choice and increasing HOV travel
ITMS (Integrated Traffic Management Systems)	• MnDOT • Mpls/St. Paul • Cities of Bloomington and Roseville • Univ. of Mn • 3M • FHWA	Evaluate effectiveness of fully integrated traffic management and control in the Twin Cities metropolitan area
Rural ITS	• MnDOT • FHWA	Evaluate by operational tests effectiveness of ITS applications in a rural environment

Consensus is obtained at the Working Committee level before submittal of the plan to the Steering Committee for approval.

Current ITS Programs

Reference 6 describes current U.S. ITS projects and operational tests.

14.3 Worldwide ITS Programs

European Programs

Europe has a number of large-scale ITS programs underway, most organized and coordinated in one of the following ways:

- Under the control of the Commission of European Communities (CEC), or
- As part of EUREKA, an industrial research initiative involving 19 countries.

DRIVE (now called ATT, the Advanced Transport Telematics Program) and PROMETHEUS represent the main programs. In Europe, RTI (Road Transport Informatics) has the same meaning as ITS in the United States.

Table 14-13. DRIVE I Program.

Project Area	Projects
Evaluation and modeling	15
Behavioral aspects and traffic safety	14
Traffic control	22
Public transport	2
Freight management	2
Digital maps and databases	3
Information and broadcasting systems	3
Telecommunications	8

DRIVE

Dedicated Road Infrastructure for Vehicle Safety in Europe (DRIVE) represents a CEC program intended to move Europe toward an Integrated Road Transport Environment (IRTE) by:

- Improving traffic efficiency and safety, and
- Reducing the adverse environmental impact of the motor vehicle.

It focuses on *infrastructure requirement*s, traffic operations, and *technologies* of particular interest to public agencies responsible for the road transportation system.

DRIVE I

Begun in 1989, the first phase comprised a 3-year $150 million research program consisting of 70 projects undertaken by international consortia from the:

- Private sector,
- Government agencies, and
- Research institutions.

It was a pre-competitive research program based on joint funding with industry and research organizations. Table 14-13 summarizes the DRIVE I Program, which proved successful and moved into a demonstration phase in 1992.

DRIVE II

Officially called the Advanced Transport Telematics (ATT) Program, DRIVE II represents a 3-year research program running to the end of 1995, with funding of about $250 million. The program emphasizes validation through field trials and pilot projects, based mainly on the results of DRIVE I.

The program includes 7 areas of major operational interest and has 3 parts, shown in figure 14-6 (7). DRIVE II includes 57 projects in all, involving more than 500 partners from:

- Government,
- Industry,
- A pool of service providers and users, and
- Universities and research establishments.

The program also includes cross-cutting projects devoted to:

- Systems engineering,
- Road-vehicle communications, and
- Standards.

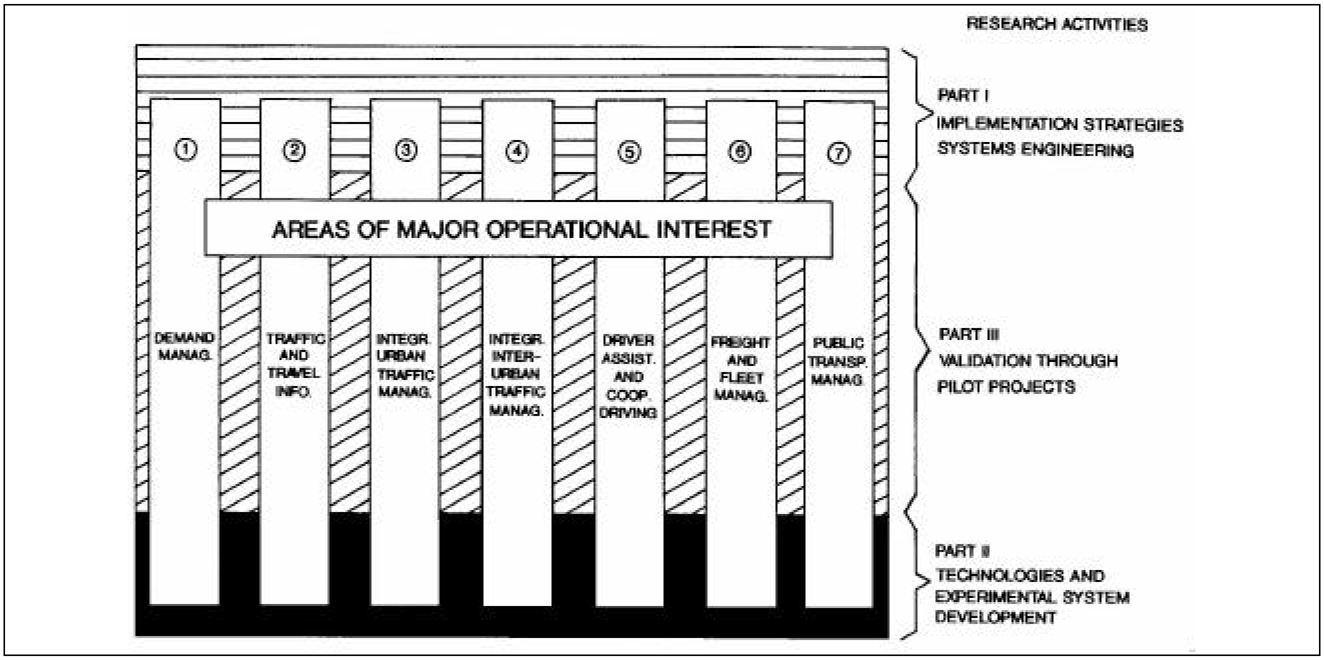

Figure 14-6. Relationship between areas of major operational interest and research activities in DRIVE II.

Two further initiatives, called POLIS and CORRIDOR, involve the infrastructure owner-suppliers. Although independent, these projects, listed in table 14-14, enjoy strong support from the CEC, because they emphasize field tests.

The next phase of the ATT Program (unofficially, DRIVE III) is in the planning stage.

PROMETHEUS

The Program for European Traffic with Highest Efficiency and Unprecedented Safety (PROMETHEUS) comprises a 7-year, $800 million program. It represents the largest of the Eureka projects dealing with road transport (others include CARMINAT, DEMETER and EUROPOLIS). In 1986, 18 European automobile companies formed PROMETHEUS, which has since expanded to include electronics companies. Table 14-15 describes the relationship between DRIVE and PROMETHEUS.

PROMETHEUS aims to make vehicles:

- Safer,
- More economical, and
- Less polluting.

It also aims to provide a common European roadway transportation system to improve traffic safety and increase efficiency. It emphasizes the vehicle, with improved safety a major technical goal. As a major economic goal, it aims to improve European competitiveness in the world automotive electronics industry.

PROMETHEUS envisions:

- Every vehicle in Europe equipped with an onboard computer and radio transceiver, and
- A 2-way pan-European communications network linking each vehicle with other vehicles and with a network of control centers.

PROMETHEUS combines:

- Applied research conducted by industry, and
- Basic research conducted by over 40 university and government research institutions.

As illustrated in figure 14-7, it includes 7 subprograms, 3 carried out by the motor industry, and 4 by the research community (8).

After a successful demonstration of PROMETHEUS achievements over the first 4 years, emphasis shifted to field tests and demonstrations. The program identified 10 Common European Demonstrators (CEDs) to evaluate developments in each of the areas shown in table 14-16. Although scheduled for completion in 1994, PROMETHEUS will likely continue afterwards. The program sponsors will likely modify the program to reflect the near-market status of some of the products under development at that time.

Table 14-14. Examples of European ITS (RTI) field tests.

Acronym	Name	Activity
RDS-TMC	Radio Data System - Traffic Message Channel (FM Sideband)	**RDS-ALERT Project** • Standards - location coding, messages • Field tests
SOCRATES	System of Cellular Radio for Traffic Efficiency and Safety	**Largest DRIVE Project** • Test site West Sweden (Gothenburg)
POLIS	Promoting Operational Links with Integrated Services through RTI between European cities	**Five Major Projects - 20 cities** • Auto Debiting/Demand Mgt/Smart Cards • Travel and traffic information • Urban traffic control • Traffic control and route guidance • Information exchange/route guidance
CORRIDOR	Cooperation on Regional Road Informatics Demonstrations on Real sites	**Two Major Projects** • Paris/London corridor • Lyon/Stuttgart corridor

Table 14-15. Comparison of European DRIVE and PROMETHEUS PROGRAMS.

	DRIVE	PROMETHEUS
Initiative	Public sector	Private sector
Primary Focus	Improvements to the infrastructure	Improvements to the vehicle
Sponsors	Commission of European Communities	EUREKA
Participants	Multi-national consortia from industry, government and academia	Automotive and electronics companies, universities and government labs
Start/ Duration/ Cost	DRIVE I - 1989/3 years/$150M DRIVE II - 1992/3 years/$250M DRIVE III - 1995/	1989/5 years/$800M
Funding	1/2 from EU 1/2 from consortia members	2/3 from private sector 1/3 from public sector
Focus/Scope	DRIVE I - R&D/70 projects DRIVE II - Field Tests/57 projects DRIVE III - Application	Precompetitive R&D Demonstration

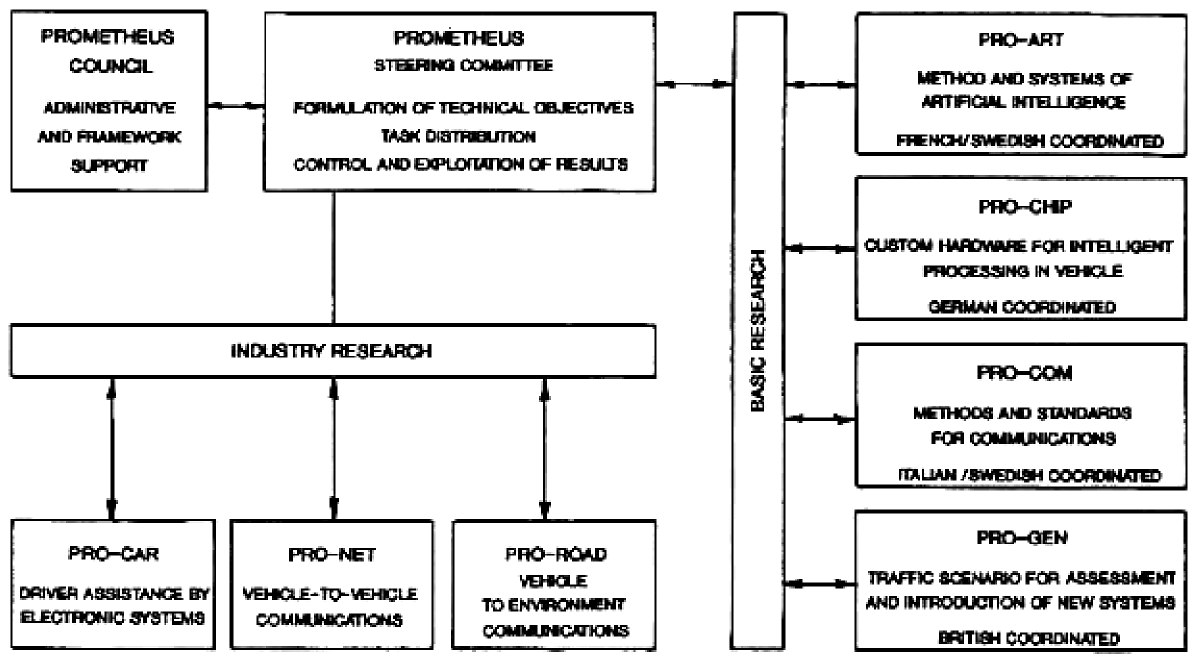

Figure 14-7. PROMETHEUS organization.

ITS Coordination in Europe

ERTICO (European Road Transport Telematics Implementation Coordination Organization) coordinates European ITS/RTI. Founded in late 1991, ERTICO encourages, promotes, and assists the coordination of ATT implementation in European transport to ensure a smooth and timely transition from pre-competitive R&D to market driven investments. It has 27 members from:

- Industry,
- A pool of service providers and operators,
- Public agencies, and
- Public transport.

These members are in addition to those from the CEC and ECMT (European Conference of Ministers of Transport).

ERTICO serves as the natural forum for the advancement of ATT in Europe, and for liaison with organizations outside Europe, as shown in figure 14-8 (9). Its functions resemble those of ITS AMERICA.

Table 14-16. PROMETHEUS common European demonstrator areas.

- Vision enhancement
- Emergency systems
- Proper vehicle operation
- Commercial fleet management
- Collision avoidance
- Traffic management test sites
- Cooperative driving
- Dual mode route guidance
- Intelligence cruise control
- Travel information systems

Japanese Programs

Japan, which experiences intense traffic congestion, also has major programs underway in all ITS areas. All large cities and most urban and inter-urban freeways have installed traffic control systems. These systems employ the latest technologies, such as:

- Fiber optics communications, and

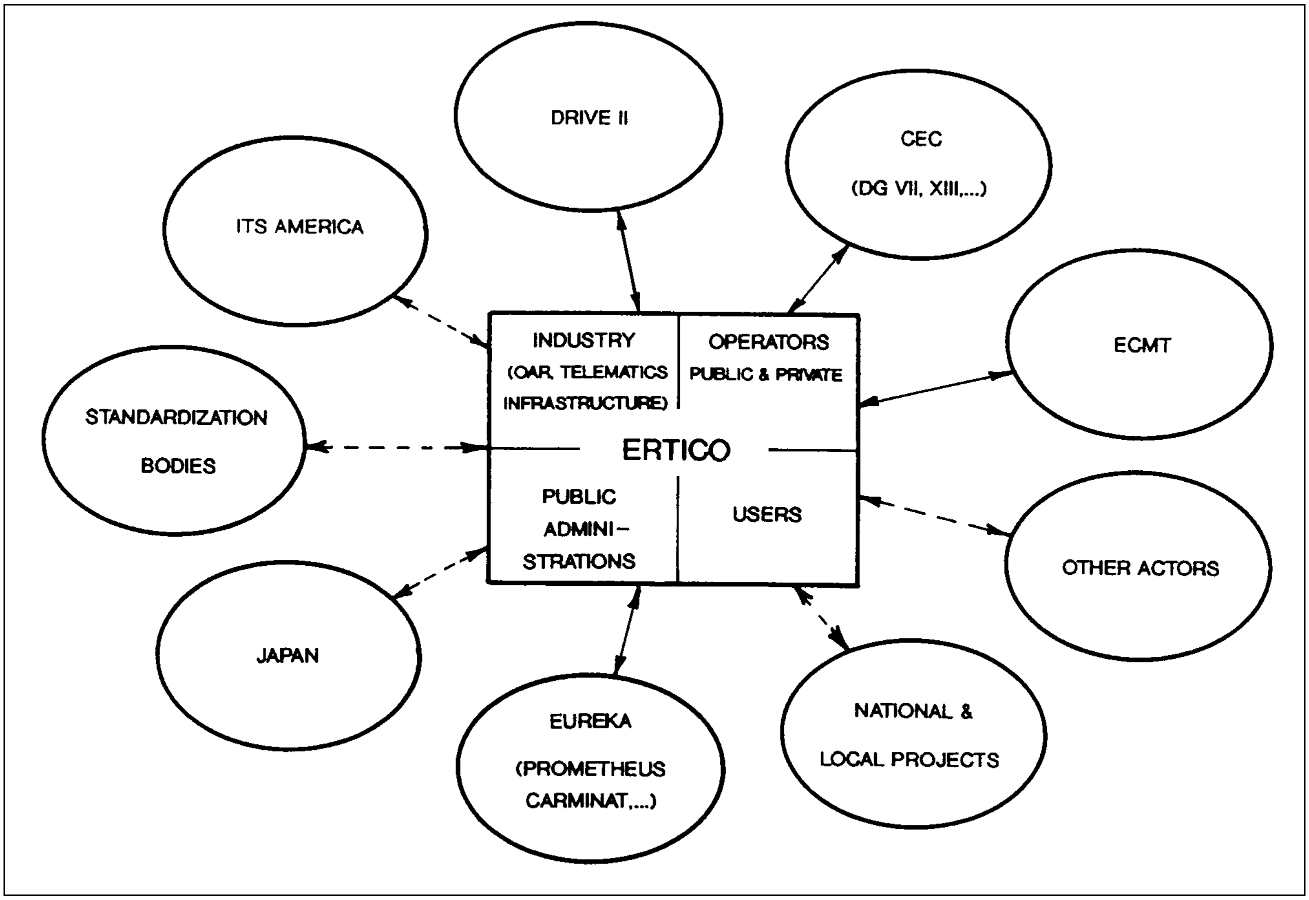

Figure 14-8. ERTICO relationship with other organizations.

- LED changeable message signs displaying both text and graphics in color.

Japan has also made substantial investments in the development of driver information systems. Typically, government has played a major role in these developments.

In recent years, the main ITS activities in Japan have centered around 2 large driver information projects, RACS and AMTICS, their successor VICS, and a number of advanced projects such as SSVS.

RACS

The Road/Automobile Communication System (RACS) was sponsored by the (10):

- Public Works Research Institute of the Ministry of Construction (MC),
- Highway Industry Development Organization, and
- 25 private companies.

The system consists of:

- Vehicles equipped with dead reckoning navigation systems,
- Roadside communication units (beacons) distributed throughout the road network (about 2 km (1.25 mi) apart), and
- Control center.

RACS saw extensive field testing in the cities of Tokyo, Osaka and Nagoya. Figure 14-9 shows the basic configuration of RACS (10).

Within RACS, the MC promoted and funded the Japan Digital Road Map Association (JDRMA) to prepare and maintain a national digitized road map database, available on compact disc in a standardized format. Both RACS and AMTICS (see below) use this database, as do the various manufacturers of autonomous vehicle navigation systems.

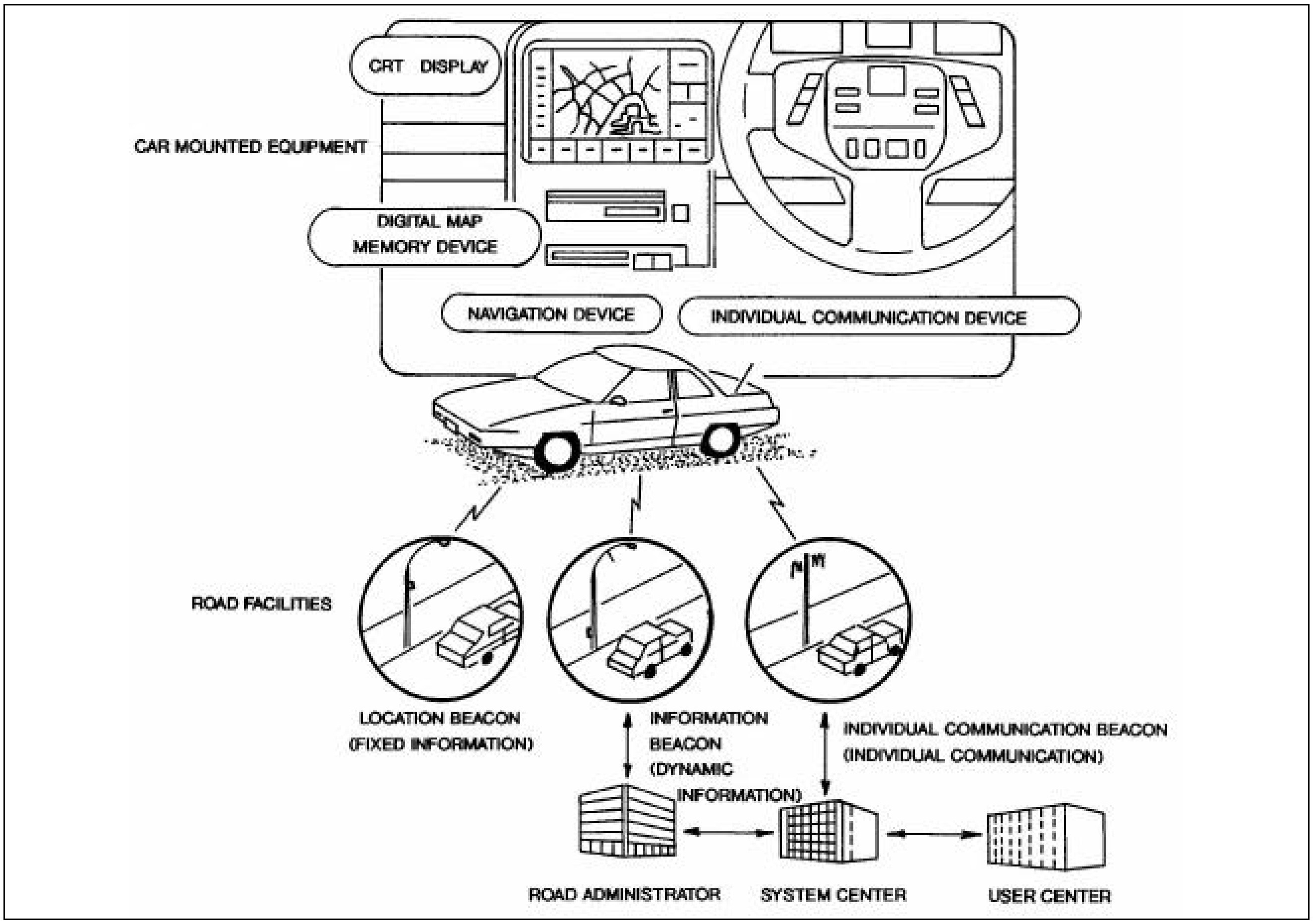

Figure 14-9. Road/Automobile communications system (RACS).

AMTICS

The Advanced Mobile Traffic Information and Communications System (AMTICS) aimed to provide a wide variety of travel information, such as (11):

- Congested routes,
- Travel time predictions,
- Traffic regulations,
- Railway timetables, and
- Special events.

The system made this information available in the vehicle and at static terminals in railway stations and hotel lobbies. AMTICS used a beacon for location information, and a cellular-type radio system called Teleterminal to broadcast traffic and other information to the vehicle. No link existed back from the vehicle. AMTICS receives sponsorship from the:

- National Police Agency (NPA),
- Ministry of Posts and Telecommunications (MPT),
- Japan Traffic Management and Technology Association (JSK), and
- 59 private companies.

Figure 14-10 schematically depicts AMTICS (11).

A large scale test of AMTICS in Osaka in 1990 resulted in individual travel time reduction of about 7 percent. This equates to individual travel time savings of about $300 million in Osaka with all cars equipped, and similar savings to the community at large because of reduced congestion.

VICS

RACS and AMTICS continued as separate competitive programs until 1990 when VICS (Vehicle Information and Control System) formed to develop a new system combining the best features of both. Figure 14-11 shows the candidate elements under consideration (12). A digital microcellular radio system has been proposed (with cells as small as 10 m (32.8 ft) across) to provide 2-way data road-vehicle commu nications and location information. The system may also provide in-vehicle

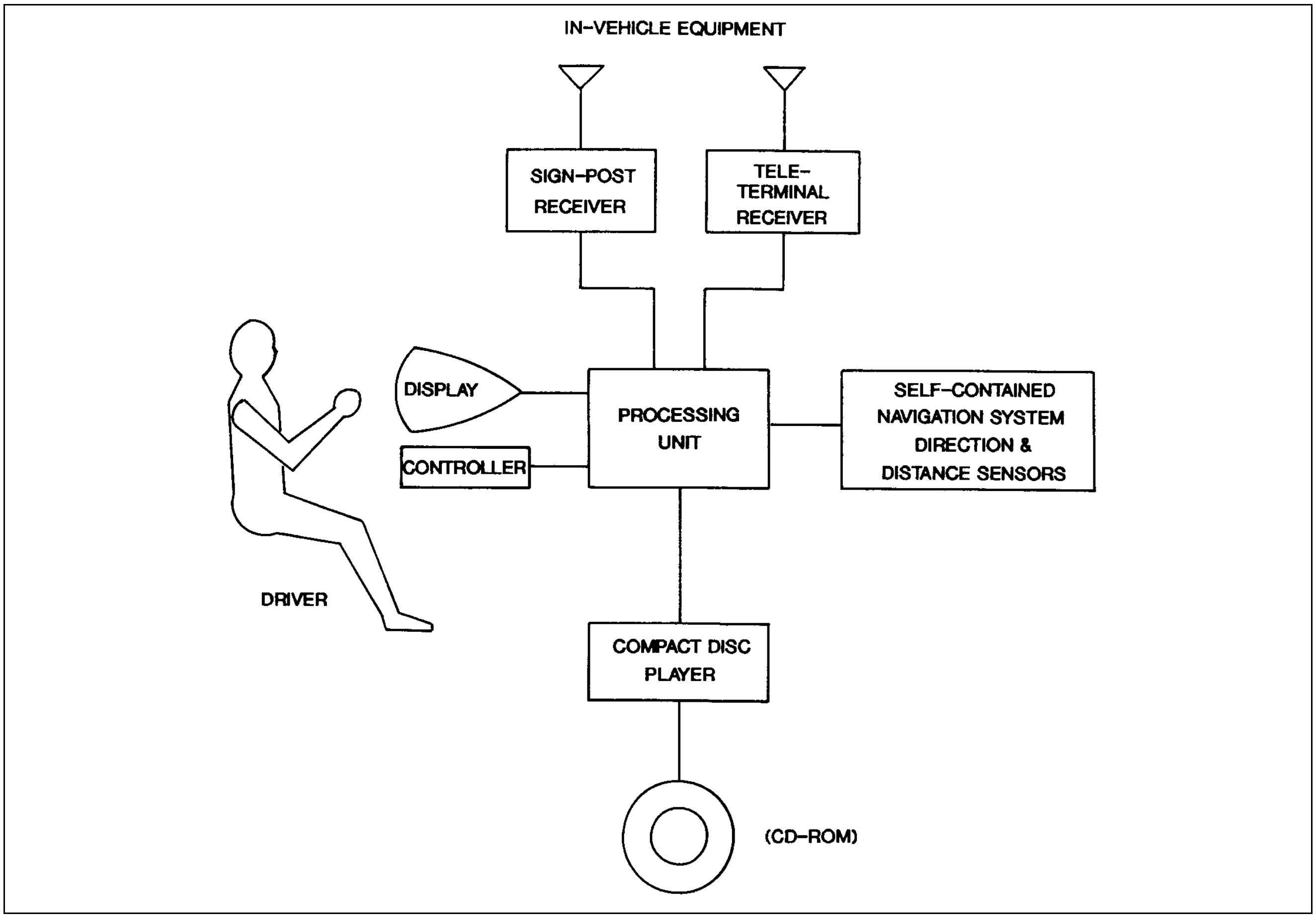

Figure 14-10. AMTICS system structure.

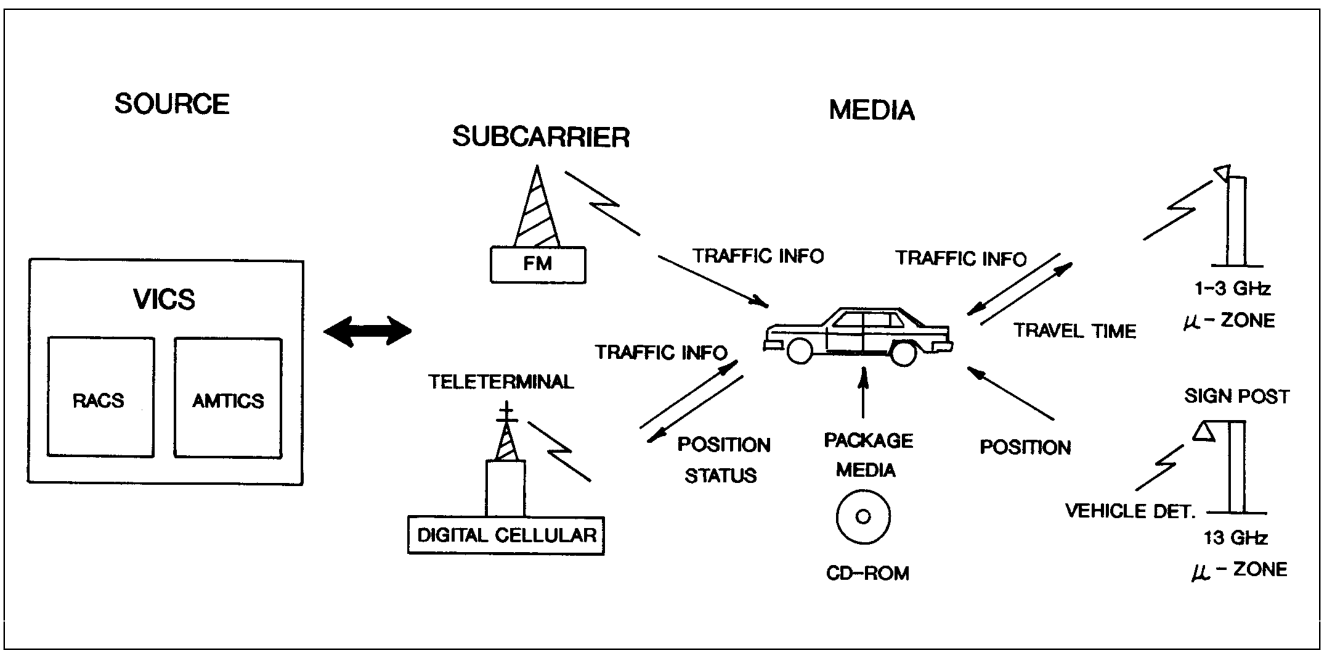

Figure 14-11. VICS collaboration – candidate elements.

route guidance, but the current concept primarily lets motorists plan their own routes based on traffic condition information. Figure 14-12 illustrates the VICS concept (13).

SSVS

Super Smart Vehicle System (SSVS) represents a relatively new national program to develop systems that assist drivers, perhaps eventually taking over some or all of the driving task. In scope it resembles the Advanced Vehicle Control and Safety Systems in the U.S. The proposed budget exceeds $200 million. Some features under consideration include:

- Automated lateral control for close proximity between vehicles in adjacent lanes (3 lanes in the space of 2),
- In-vehicle display of a plan view of the vehicle and its surroundings (including other traffic),
- Active roadside lighting, and
- In-vehicle dynamic signing.

ITS Coordination in Japan

Table 14-17 lists the principal Japanese ITS coordinating bodies, all formed within the past few years. Figure 14-13 shows that VERTIS plays a leading role in promoting and coordinating ITS activities in Japan (14).

14.4 Standards Applicable to ITS Technologies

Use of standards will ease the orderly and successful development of ITS, with its wide range of players who have little or no history of cooperation or interaction. Table 14-18 lists some of the tangible benefits that standards can provide (15).

Synergism among these benefits seems likely. For example, consumers will more willingly purchase ITS technology if they can use the same equipment wherever they drive. This development will create consumer demand and, in turn, foster ITS industrial development.

Table 14-19 lists some of the technical areas requiring ITS standards. The ITS Standards Tree shown in Figure 14-14 illustrates some of the many different standards prospects (15).

Table 14-20 identifies the 3 types of standards. The VHS video format and MS-DOS exemplify de facto standards. NHTSA bumper crash standards and EPA fuel emission standards typify regulatory standards. Many of the standards developed for ITS will become established by consensus.

Table 14-21 shows the 3 types of standards setting organizations.

Table 14-22 lists the organizations in the United States involved in the development of ITS standards (15).

Roles of Major Organizations in ITS Standards Development

Federal Government

Where no compelling government interest exists, the U.S. Government will play no role. When commercial benefits from the standards can be realized, the Government will facilitate their adoption by encouraging industry or voluntary groups to lead the standard-setting process. Examples include:

- Communications standards for wide-area broadcast,
- Vehicle/infrastructure communications, and
- Transponder protocols.

Once the standards are adopted, the Government can enforce their use by making them a requirement for Federal funding.

ITS AMERICA

Although not a standards-setting organization, ITS AMERICA plays a leading role in promoting the development of ITS standards. To this end, it established a *Standards and Protocols Committee*.

Council of Standards

The Standards and Protocol Committee of ITS AMERICA established the *Council of Standards* which has representatives from most of the standards-setting organizations listed in table 14-22. Chaired by ITS AMERICA, the council facilitates cooperation among these organizations and helps them reach voluntary agreement as to responsibility for each standard.

Figure 14-15 illustrates the standards-setting process.

SAE

SAE plays a leading role in the development of ITS standards, particularly those pertaining to vehicle components and systems interacting with the vehicle. Their standards and recommended practices develop with inputs and requirements generated by ITS AMERICA. SAE serves as the Secretariat for the ISO Technical Committee 204 (see table 14-23).

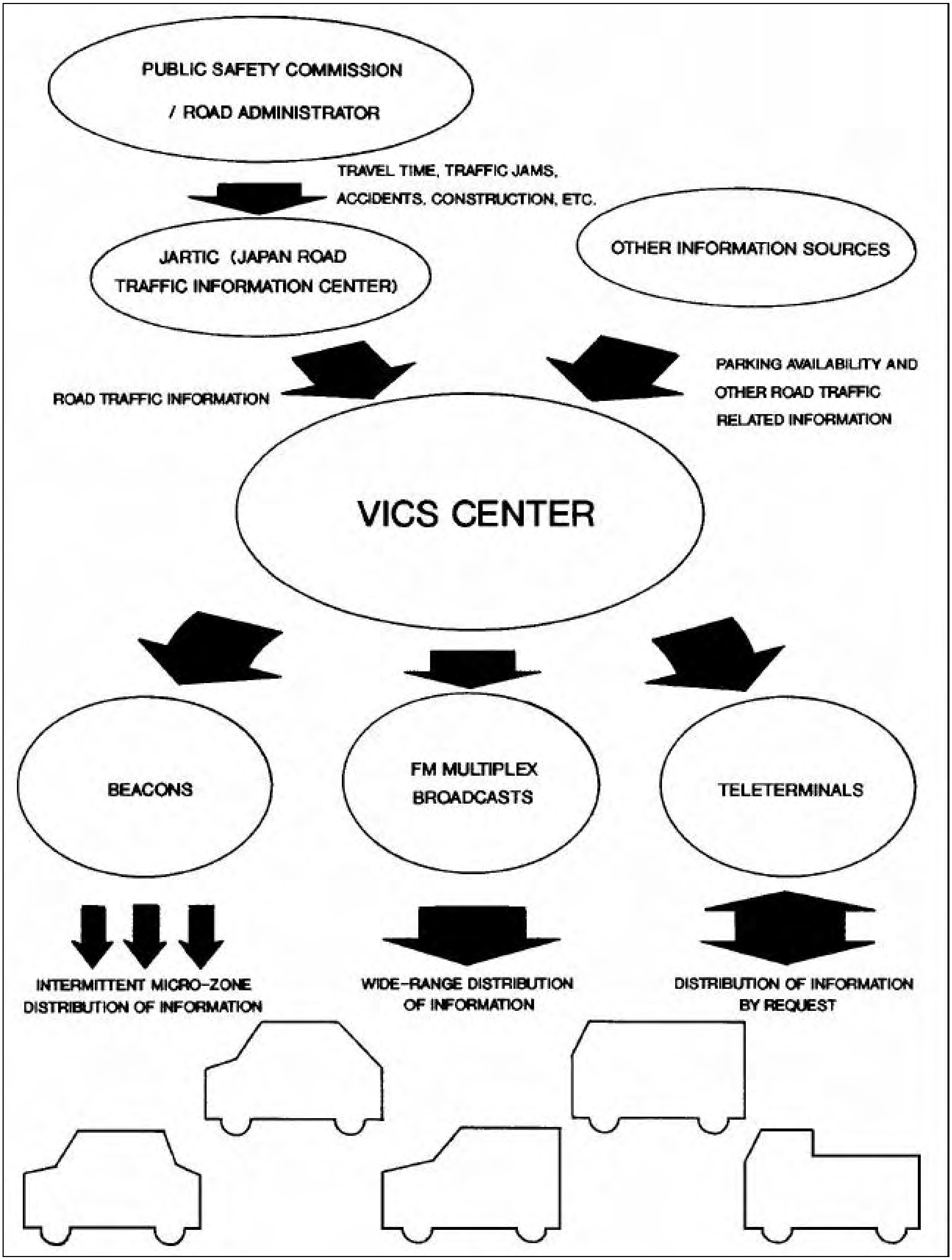

Figure 14-12. VICS information flow and concept.

Table 14-17. Japanese ITS coordinating bodies.

Name	Acronym	Members	Roles
Vehicle, Road and Traffic Intelligence Society	VERTIS	5 Government Ministries (MOC, MITI, MOT, MPT, NPA)	Promote cooperation among Ministries; coordinate private sector, academic sector, and ITS Associations (JSK, HIDO, JDRMA, VICS); liaison with outside Japan (ITS AMERICA, ERTICO, ATT/ITS World Congress, ITS CANADA)
Liaison Council for ITS/RTI Japan	---	JTMA, HIDO, JSK	Liaison/information exchange inside and outside Japan
Universal Traffic Management Society	UTMS JAPAN	All relevant sectors - sponsored by National Police Agency	Coordinate development of a new Universal Traffic Management System
Vehicle/Road Intelligence	VeRI	Society of Automotive Engineers of Japan (JSAE)	Promote cooperation with other ITS groups in Japan; assess impact of new technology on the automobile

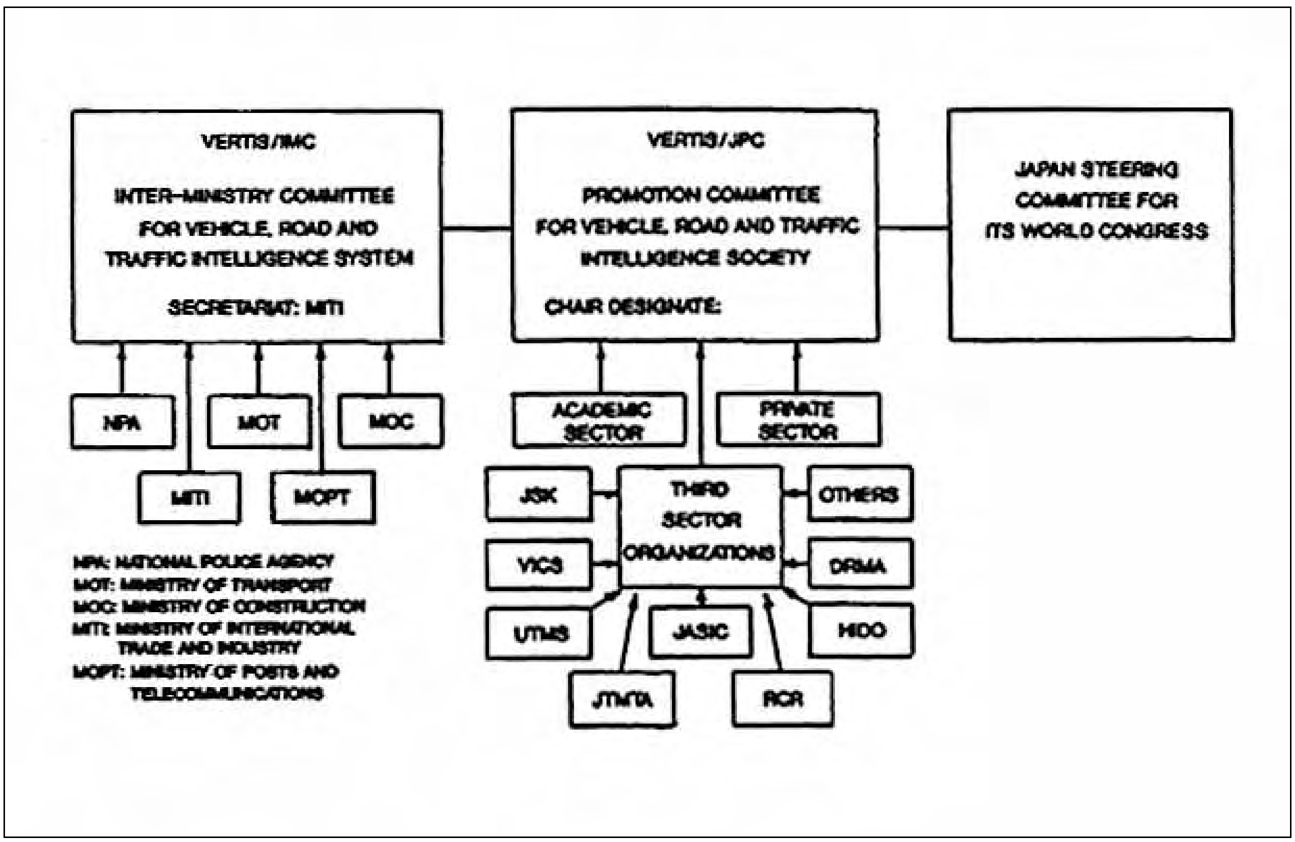

Figure 14-13. Organizational structure for Vehicle, Road and Traffic Intelligence Society in Japan (VERTIS).

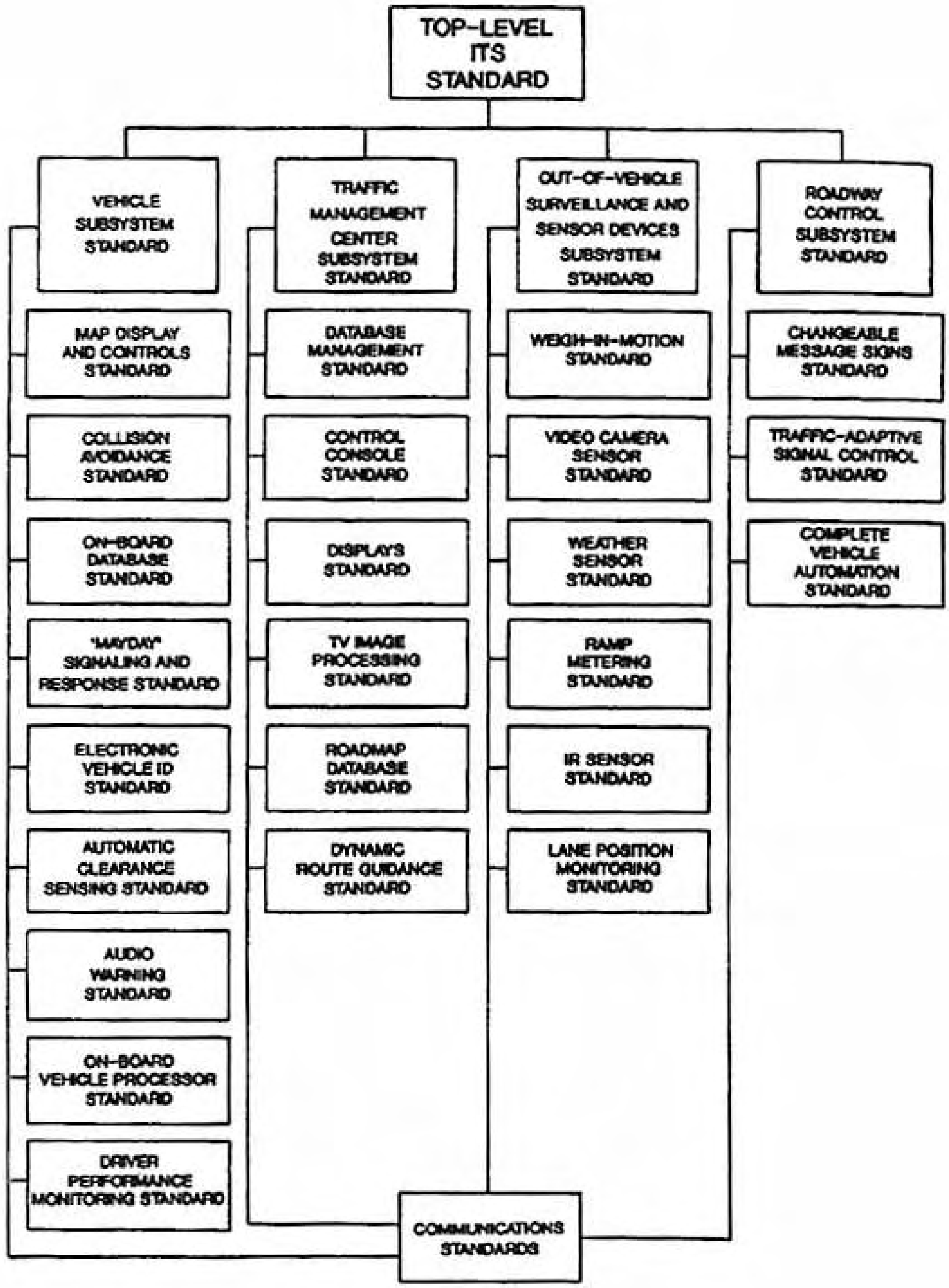

Figure 14-14. Partial ITS standards tree.

Table 14-18. Benefits of ITS standards.

- Eliminates unnecessary product development
- Assures interchangeability of system components
- Improves reliability, availability and maintainability
- Fosters widespread deployment
- Promotes stability in the marketplace
- Encourages investment and development
- Establishes a basis for limiting liability

Table 14-19. Representative areas requiring ITS standards.

- **Databases**
  Electronic maps, referencing systems
- **Interfaces**
  Physical interfaces, communications protocols
- **Human Factors**
  In-vehicle displays and controls
- **Hardware**
  Shielding from EMI, lightning protection
- **Information Systems**
  Information interchange formats and protocols
- **Definitions and Terminology**
  For all system areas

Table 14-20. Types of standards.

- **De Facto Standards**
  Evolve through the workings of the marketplace
- **Regulatory Standards**
  Mandated by government
- **Consensus Standards**
  Developed by national and multinational standards-setting organizations

ITS Standards Activities

Tables 14-23 and 14-24 summarize current ITS standards-setting activities (15). Table 14-24 shows the focus of the activities of the 8 SAE standards committees.

The activities of Working Group 9 on *Integrated Transport Information*, *Management and Control* (Australia is the Convenor) prove particularly relevant. Table 14-25 lists the various areas in which the group will develop international standards.

Working Group 1 on *System Architecture* (United Kingdom is the Convenor) is also especially relevant. It covers:

- Architecture,
- Taxonomy,
- Terminology, and
- Open system interconnect.

At this time, all these working groups remain in the preliminary stages of interpreting their goals and objectives and developing detailed work plans.

Table 14-21. Standards setting organizations.

Umbrella Organizations

- **International**
  - International Standards Organization (ISO)
  - International Electrotechnical Commission (IEC)
  - International Telecommunications Union (ITU)
- **United States**
  - American National Standards Institute (ANSI) (Serves as gateway to ISO and IEC)
- **Europe**
  - Comité European de Normalization (CEN)

ANSI Standards-setting Organizations

- Focused areas of interest
- Professional organizations (ASCE, IEEE, SAE, ASTM)
- Developed according to ANSI *community consensus* procedures
- Standards become ANSI standards

Non-ANSI Standards-Setting Organizations

- Certain professional and trade organizations (ITE, ATA, IBTTA, etc.)
- Associations of public and quasi-public agencies (AASHTO)
- Standards set by own membership, not the full community or manufacturers, fabricators, suppliers and users, as required by ANSI.

Table 14-22. U.S. organizations involved in ITS standards.

Name of Organization	Focus of Activities
ANSI American National Standards Institute	Clearinghouse for nationally coordinated, voluntary industry standards; international liaison
IEEE Institute of Electrical and Electronics Engineers	Full range of electrical and electronics engineering areas
SAE Society of Automotive Engineers	Automotive industry
ASTM American Society for Testing and Materials	Materials, products, systems, and wide range of services for industry
EIA Electronic Industry Association	Electronics components and systems for wide range of users
NAB National Association of Broadcasters	Commercial broadcast industry
NEMA National Electrical Manufacturers Association	Heavy current devices and products
TIA Telecommunications Industry Association	Telecommunications industry
ITE Institute of Transportation Engineers	Surface transportation industry
AASHTO American Association of State Highway Transportation Officials	Construction, maintenance and operation of surface transportation facilities

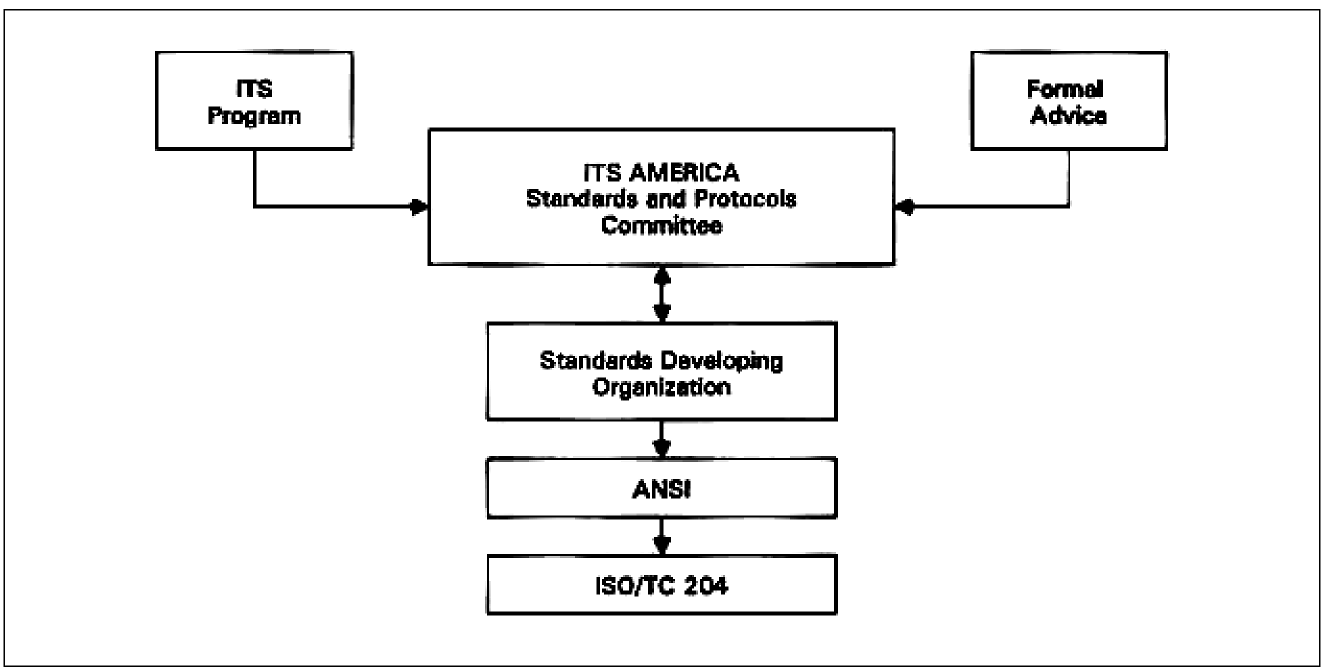

Figure 14-15. Standards setting process.

Table 14-23. North American ITS standards setting activities.

Organization	Committee(s)	Focus of Activity
SAE	7 committees Secretariat for ISO TC204	Vehicle-related (see table 14-24)
IEEE	ITS Standards Coordinating Committee (SCC32)	Vehicle/Road communications protocols Safety-critical software Definitions and terminology
ASTM	E17.51 Committee E17.52 Committee	Vehicle/Road communications protocol Traffic monitoring device interfaces
ANSI	X3T6 Technical Committee	Non-contact systems interfaces
ISO	TC204 Technical Committee:	Transport Information and Control Systems (TICS)
	ITS AMERICA S&P Committee	US TAG Administrator
	• WG1	• Architecture
	• WG2	• Quality and Reliability Requirements
	• WG3	• TICS Database Technology
	• WG4	• AVI/AEI (topics addressed now in WG1)
	• WG5	• Fee and Toll Collection
	• WG6	• General Fleet Management
	• WG7	• Commercial/Freight
	• WG8	• Public Transport/Emergency
	• WG9	• Integrated Transport Information, Management and Control
	• WG10	• Traveler Information Systems
	• WG11	• Route Guidance and Navigation Systems
	• WG12	• Parking Management/Off-Road Commercial
	• WG13	• Man/Machine Interface
	• WG14	• Vehicle Control Systems with External Interfaces
	• WG15	• Dedicated Short Range Communications for TICS Applications
	• WG16	• Wide-Area Communications/Protocols and Interfaces

Table 14-24. SAE ITS standards committees and working groups.

- Automatic Vehicle Identification
- Human Factors and Safety
- In-Vehicle Systems Interfaces
- International Traveler Information Interchange Standards
- Map databases
- Navigation
- Sensors
- System Architecture

Table 14-25. ISO TC204 working group 9 standards areas.

Integrated Transport Information, Management And Control

- Transport Data Fusion
- Motorway Operations
- Signal Coordination and Speed/Flow Control
- Traffic Control Systems
- Vehicles as Probes
- Infrastructure Sensor Technology Interface
- Interface between Traffic Control Systems and adjoining Services
- Collection of Dynamic, Static and External Data
- Dissemination of Information to all TICS Users

References - Chapter 14

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2. IMPLEMENTATION PLAN GUIDANCE (23 CFR 655.409))

a. An Operations Plan is the final element of a traffic engineering analysis according to 23 Code of Federal Regulations (CFR) 655.409 (f). Since an operations plan covers such a wide range of activities both prior to and after construction such as system design, procurement, personnel, operations and maintenance, the name **"Operations Plan"** is being changed to **"Implementation Plan"** to more accurately reflect its contents. The name change is being made in the CFR and will be used throughout the remainder of this guidance. The following is issued to provide State and other agencies, which are utilizing Federal funds, guidance that will provide consistency in the implementation of traffic control systems, ensure adequate planning by the sponsoring agency, and commit the sponsoring agency to use Federal funds efficiently.

b. Implementation plans are **required** both for new traffic control systems, as well as expansions of existing systems, which use Federal funds and are encouraged for those systems which do not use Federal funds. Traffic control systems are defined as systems which contain elements to monitor, guide, control, and/or process forms of traffic along the surface streets and/or freeways. Implementation plans can be for individual projects (i.e., standalone), or as a part of a larger system. For expansion projects, if an implementation plan had not previously been prepared, one **must be prepared** and include the expansion as well. The plan should be completed prior to authorization of construction. This will ensure that the system is designed, built, operated, and maintained so that it accomplishes its purpose in the most efficient manner possible, considering performance, cost, and schedule. Too often in the past, plans were developed after the system was operational and did not include the design approach and other information which should have previously been addressed and documented.

c. An implementation plan need not be a legal document; however, if it is to be effective, it must carry the weight of a memorandum of agreement (understanding) and should be signed by the head of the operating agency, State highway official, and Federal Highway Division Administrator, or their designates.

d. Before the guidance is explained, a few words need to be mentioned in regards to conformity and the planning process. Transportation Improvement Programs (Tips) and Statewide improvement Plans (STIPs) are areawide programs, while implementation plans are project specific. Hence, projects for which implementation plans are being developed have already been approved in the related TIPs and STIPs and the related conformity and management systems issues have been addressed. In non-attainment areas, the traffic control system being proposed for implementation must be consistent with what was proposed in a conforming transportation plan. If the traffic control system deviates from that design concept and scope, it may trigger a new conformity determination.

e. The following sections correspond to the implementation plan **requirements** listed in 23 CFR 655.409 (f) and provide discussion for each. The level of detail of the implementation plan will depend on the type and size of the system. Since some of the items required in an implementation plan will have been covered in other contract documents and other elements of the traffic engineering analysis (23 CFR 655.409), these items may be summarized and referenced in the plan.

(1) Legislation. This section includes the legal considerations, if any, for the project. **Existing** laws, regulations, and policies affecting the project need to be reviewed and assessed. In addition, State or local legislative changes such as authority for metering and HOV facilities, enforcement authority, and roadway clearance policies should be addressed if applicable to the project. Also, the operating procedures for the system may need to be defined to be sure that there are no potential legal problems.

(2). System design. A system contains elements which may monitor, guide, control, and/or process forms of traffic along the surface streets and/or freeways. System design consists of taking the recommendations from the planning phase, converting those needs into hardware/software requirements, and formulating the equipment needs into contract documents. The system design may be based on off -the-shelf, customized, or experimental technologies. Actual systems vary greatly in practice. For example, a system may contain several like devices such as an expansion of a traffic signal system, or it may consist of a traffic management center and its associated hardware/software. For the purpose of this guidance, system operation and maintenance must be the responsibility of a public agency. The conduct of the system operation and maintenance may be carried out either by (1) the public agency, (2) contract, or (3) franchise operation. An implementation plan should include the following elements for the system design portion:

(a) System Designer: Depending upon the complexity of the system and in -house expertise, consultant services are usually needed to design a system. The designer needs to be identified in order to resolve any conflicts.

(b) System Design Life: The functional operating life of the system should be identified. The design life and the costs can be used to perform an economic analysis to identify the return on the investment. The system design life will be helpful for a Life-Cycle Cost Analysis (LCCA).

(c) System Coverage: This should address the area that the system will cover. The coverage related to the future expansibility of the system should also be addressed. Ideally, the expansibility should be commensurate with the system's design life.

(d) System Design and Operations/Maintenance Philosophies: System operations philosophies have a significant impact on the system design. For example, system operations centers that are staffed only during rush hours do not require kitchen and/or shower facilities. However, operations centers that are staffed during the majority of the day, especially during special events and inclement weather, do require extra amenities. Ideally, system operations and maintenance functions as well as facilities should be close to each other to facilitate coordination.

(e) System Architecture: A discussion of the overall system architecture (i.e., central, distributed, or hybrid) should be addressed.

(f) Integration with Other Functions: Ideally, consideration should be given to integrating a traffic control system with other systems to provide for database exchange and other strategies so that the entire metropolitan area is covered and coordinated.

(g) System Components and Functions: Hardware components needed to perform sys-tem functions such as, surveillance, control, and coordination should be identified.

(h) Communication Subsystem Design Approach: Typically, the communication portion of the system, because of the necessary redundancy, represents a large portion of the system budget. Great care should be given to the subsystem design approach. An economic analysis of the design approach should be a key consideration.

(i) Traffic Operations Center Design Features: The design of a control center is largely dependent upon the agency's operating philosophies (time of operation, special event operation, tour accessibility, media facilities, etc.). The size of the system will also affect the design. (As an example, agencies utilizing large numbers of closed circuit television (CCTV) will need more space for wall monitors.)

(j) Project Phasing/Scheduling: A formalized tracking system should be used to manage the project. Many common methods utilize critical path analysis. Depending upon the approach used, these management tools don't necessarily have to be developed during the design phase but should be in place prior to any construction scheduling.

(k) Design Review: The system design is reviewed and the problems and concerns are addressed and documented. (The system design should be checked for consistency with the statewide and metropolitan plan, if applicable.)

(3) Procurement methods. An important element of the implementation plan is the method used for procuring and implementing the system (23 CFR 172). Regardless of the method used, the implementation plan should include the following procurement related items: (1) Method, (2) Schedule, and (3) Funding. A brief description of common procurement methods follows:

(a) Sole-Source - a single manufacturer's specifications are openly used, or they serve as the basis for contract negotiations between the owner and the supplier. The contract is then awarded without competition. Sole-source contracts can be used in Federal-aid projects, but only if there has been a finding that it is more cost-effective than a competitive low-bid process. This method is most common for system expansion.

(b) Engineer/Contractor (turn-key) - an engineer prepares a single set of contract documents (i.e., plans, specifications, and estimates (PS&E) for the proposed system), the contract documents go through the procurement channels, and the contract is awarded to the lowest responsive bidder. The winning contractor is responsible for providing a complete and fully operational system, including furnishing and installing all hard/software, system integration efforts, and training and documentation. This method is the traditional low-bid process.

However, there may be some significant potent ial problems with this method as it relates to traffic control systems: No single contractor may possess the necessary experience and qualifications to perform all of the work; administering multiple layers of subcontractors and suppliers is difficult; and the prime contractor may not have sufficient knowledge of some of the elements of a traffic control system to select appropriate or qualified subcontractors.

(c), Two-Step Engineer/Contractor - in the first step, the plans and functional specifications, along with a Request for Proposals (RFP), are submitted to contractors. The submitted proposals are evaluated and the qualified proposals go to the second step. In the second step, a formal request for bid is issued. From this point on, the standard bid/award process of the engineer/contractor approach is used.

(d) Systems Manager - instead of a single turn-key contract in which all of the work is outlined, several contracts for the various subsystems are prepared. The agency's normal procurement process is utilized to obtain the equipment, but the systems manager administers the contracts and is responsible for integrating the various subsystems into an operating system.

(e) Design/Build - this concept involves awarding a single contract to provide for bo th the design and construction of a project. For certain circumstances, design/build has the potential for improving the contracting process by allowing contractors the maximum flexibility in the selection of innovative designs, materials, and construction techniques. Under current statues and regulations, the design/build concept is a viable option for Federal -aid highway projects, as long as the following **requirements** are met:

1 The contracts are awarded following competitive bidding procedures;

2 If a warranty requirement is included, the period of coverage should only be sufficient in length (i.e., 1-5 years) to allow defects in materials and workmanship to become evident. Ordinary wear and tear, damage caused by others, and routine service maintenance should remain the responsibility of the State; and

3 Federal-aid projects which provide for evaluation of either the design/build or warranty concepts must be approved, under Special Experimental Project No. 14 (SEP 14), by FHWA Headquarters Office of Engineering (HNG-22), prior to project approval.

(4) Construction management procedures. Procedures which will be used for the particular system should be specified in the implementation plan. Construction management procedures provide the necessary framework for coordinating construction and installation activities to ensure the system is built in accordance with the contract documents. Implementation plan construction management procedures that can be addressed include, but are not limited to:

(a) Division of Responsibilities (identifying who is involved and their associated responsibilities).

(b) Scheduling and establishing mileposts (developing a construction schedule to keep track of system installation). This will also ensure a mechanism for monitoring progress, cost, and quality assurance.

(c) Conflict Mitigation (developing a procedure or mechanism for resolving contract disputes).

(d) Coordination with other projects (defining project's relationship with other projects) .

(5) System start-up plan**.** Integration is the "glue" that binds components together to form the system. Components are physically tied based on interfaces defined by the system architecture and tests are performed to verify and validate whether or not system requirements are met. Verification of a component or subsystem determines if the components or subsystems are interfaced as per design and are working properly. Validation consists of ensuring (through acceptance tests) that all interfaced components or subsystems meet system requirements. Software coding and database development are also important elements of this phase. The start-up process is typically performed in a limited time period immediately after system integration. A start-up plan is necessary to document the validation process (software and system evaluation). An implementation plan should include, but is not limited to, the following:

(a) Software acceptance tests (responsibilities of those involved, test procedures, equipment involved, test criteria, verification of specific software features, methods to correct errors, etc.).

(b) System acceptance tests (responsibilities of those involved, test procedures, equipment involved, test criteria, verification that system performs required functions, methods to correct errors, final acceptance, etc.).

(c) Partial acceptance (provisions for accepting a partially completed system).

(d) Documentation (detailed documentation pertaining to hardware and software should be discussed as well as references to operating manuals for the system).

(e) Transition from old to new control (procedures for transitioning from a previously functioning system to a system with new features and functions).

(f) Operational support and warranty period (provisions for initial or continuing operational support and a system warranty period). Federal regulations on guaranty and warranty clauses are defined in 23 CFR 635.413.

(g) Training (provided to system operators and maintenance technicians prior to system acceptance).

(h) Coordination with the media is very important and should be included in the system start-up plan. Public support is critical to the success and ongoing operations of the system.

(6) Operations and maintenance plan. Traffic control systems require active management to be effective, including periodic reassessment of the control strategies used. In order to have a system that is operated and maintained properly, there must be a staff and budget commitment by the operating agency. The resources required to effectively operate and maintain a traffic control system may represent a significant continuing investment, particularly if the agency responsible for the system is relatively small or is implementing a traffic control system for the first time, The process of defining system operations and maintenance activities during the preparation of the implementation plan can expose these issues and allow time for their resolution prior to system implementation. The operations and maintenance plan may include a section for evaluation and applicable maintenance policies:

(a) Evaluation . Federal-aid highway funds may be used for evaluation activities (23 CF 655-403 (C) (Systems Start-Up); 23 U.S.C. 307 (c) (1) (e) (State Planning and Research); 23 U.S.C. 133 (b) (6) (Surface Transportation Program); and 23 U.S.C. 103 (i) (8) (National Highway System). A comprehensive evaluation of a traffic control system determines if the system meets the goals and objectives established for it. A formal evaluation is recommended at appropriate stages. The evaluation should be completed as soon after the implementation of the system as possible, after traffic patterns have stabilized. Regular system re-evaluations should subsequently be planned every few years and should be executed by the operations and maintenance personnel. Key evaluation issues to be described in the implementation plan include:

1 The system evaluator. (Preferably, this should be an independent third party, **not** the system installer.) The system evaluator should be selected prior to the implementation of the system in order to properly perform the evaluation.

2 The method of evaluation (This should also include time period for evaluation.).

3 The cost of evaluation.

(b) Maintenance Plans. Development of maintenance plans cannot be performed by designers alone. Maintenance persons must be consulted. In addition, a system may require a higher and more responsive degree of maintenance than an agency may be accustomed to. Some agencies may choose to use contract maintenance as opposed to in-house staff. Whatever method of maintenance is selected, the following implementation plan issues will help the operating agency to determine the necessary maintenance resources (budget and staff):

1 Maintenance policies for preventative maintenance, system malfunctions (response times), etc. There should be a documentation of the policies, possibly as an attachment.

2 Formal maintenance management program (software and hardware agreements with the developers). There should be a documentation of the programs, possibly as an attachment.

3 Initial inventory of spare parts and all necessary test equipment.

4 Training in providing limited maintenance to software and equipment.

(7) Institutional arrangements. Nearly all projects involve numerous organizations and multiple levels of government, all of which approach the project from various perspectives. However, the institutional aspects of a system are likely to be even more complex because of the additional governmental entities and organizations (e.g., FHWA, regional organizations, State and local governments, traffic engineering departments, MPOs, fire, police, transit, private sector groups, media, utility companies, etc.) which are typically involved. The complex mix of governmental and private sector interests has the potential for difficulties: overlapping responsibilities, lack of understanding, and conflicting priorities and policies. To avoid these problems, it is important that close coordination be established during the early stages of planning. This will permit the various agencies to develop a better understanding of the system alternatives and the recommended system's features and functions; to identify overlapping responsibilities and determine which agency will take the lead in various areas; and to work harmoniously so that each agency can better fulfill its role. Developing a good, early working relationship with each involved organization and then maintaining this cooperation throughout the system process will help ensure that the system effectively meets the needs and expectations of each agency. An implementation plan should include, but is not limited to, the following institutional arrangement issues:

(a) A contact person/project liaison within each organization should be identified.

(b) Delineation of organizational responsibilities and the lead organization for the various elements of the system.

(c) Provisions for periodic project updates to be given to upper management to keep them informed.

(d) Utility arrangements.

(e) Written cooperative agreements for: personnel-sharing, cost-sharing, metering, traffic diversion, etc.

(f) Consideration should be given to the formation of an "Advisory Committee" which will meet to discuss and resolve system issues and to acquaint participants with the overall project goals, schedule, and work plan. All agencies involved in the project should be represented on this committee and should be involved throughout the entire project.

(8). Personnel and budget resources. Staffing for operations and maintenance of systems is a function of system complexity, hours of operation, and activities supported by the system. Ideally, staffing responsibility for operating and maintaining the system should be integrated into the operating agency's existing organizational structure. It is understood that institutional agreements may need to be developed for personnel/cost-sharing purposes. The following personnel and budget items, as a minimum, should be addressed:

(a) Staffing plan (listing of the job functions supported by the system and the number of persons who fulfill those functions).

(b) If shifts are to be used, the number of persons and their functions per sh ift.

(c) Contract operations staff agreement (if used).

(d) Provisions for training new staff on the system.

(e) Sources of budgetary resources, including Federal, and their committed contributions.

(f) Estimates of annual expenses by category (operati ons, maintenance).

(g) The last page should have a section for the signatures of the head of the operating agency, head of the State highway agency, and FHWA Division Administrator or their designates. This concurrence ensures that the necessary agencies are committed to the implementation plan.

GLOSSARY

A

Arterial Analysis &Executive Package (AAPEX)

General data processing package of arterial timing programs utilizing a common database that facilitates use of model as an integrated system.

Acceleration Noise

Basic variable describing quality of service. Usually considered as the disturbance of a vehicle's speed from a uniform speed.

Acceptable Gap

Time headway between successive vehicles in a traffic stream into which another vehicle is willing and able to merge.

Access Time

The time interval between the instant at which data is called from a storage device and the instant at which delivery of the data is completed.

Accident Rate

A common MOE for all traffic systems. It is expressed in terms of accidents per million vehicles (at intersections) and per 100 million vehicle miles (160 million vehicle kilometers) on freeways.

Actuated Controller Assembly

A controller assembly for supervising the operation of traffic control signals in accordance with the varying demands of traffic as registered with the controller by traffic detectors.

Actuation

The operation of any type of detector *(NEMA)*. The word operation means an output from the detector to the controller unit.

Adaptability

The quality of a traffic control system to maintain system operations over an extended time period under changing conditions.

Addressing

(1) Computer A method of specifying the location (address) of an operand involved in a part of an instruction. Addresses are usually numerical and specify a register, location in storage, or other data source or destination. (See Direct Addressing, Indirect Addressing.) (2) System The identification of specific intersections or locations for transmission of commands or the receipt of data. (3) Communications The process of selecting a specific receiving unit on a multidrop line so that the message can be sent to that unit alone. Usually, specific control of characters precede the message enabling the selected unit to accept the data that follows.

Advance Pulse or Interval Advance

A discrete command issued by the master computer which causes an online controlled unit to change condition, generally advancing the unit to the next position or state.

Advance Ramp Control Warning Sign

Component of an entrance ramp control system which indicates to traffic approaching the ramp that the ramp is being metered.

Advanced Driver Information Systems (ADIS)

ADIS is a major subset of the Advanced Traveler Information Systems (ATIS) category of ITS. ADIS provides the functions of navigation information, real-time route guidance, traffic data, and yellow pages. Examples of ADIS are the TravTek and Ali-Scout systems.

Advanced Mobile Traffic Information and Communications System (AMTICS)

This Japanese project provides a wide variety of travel information including congested routes, travel time predictions, traffic regulations, railway time tables, and special events, Sponsored by National Police Agency (NPA), Ministry of Posts and Telecommunications (MPT), Japan Traffic Management and Technology Association (JSK), and private interests.

Advanced Rural Transportation Systems (ARTS)

The Advanced Rural Transportation System Category of ITS functions. Includes road weather information systems and automated mayday systems

Advanced Traffic Management Systems (ATMS)

(1) The Advanced Traffic Management System category of ITS functions. Includes adaptive traffic signal control, electronic road pricing, and toll collection. (2) A microprocessor based traffic-responsive system developed by the Texas DOT. Used with success on continuous frontage roads and arterials with numerous traffic patterns. The system can change cycle length and offset at end of the two most recent sampling periods and can alter splits each sampling period.

Advanced Transport Telematics (ATT)

The European DRIVE II program.

Advanced Traveler Information Systems (ATIS)

The Advanced Travelers Information System category of ITS functions. Includes vehicle navigation, route guidance, in-vehicle signing, intermodal travel information, trip planning, and mayday communication.

Advanced Vehicle Control Systems (AVCS)

The Advanced Vehicle Control System category of ITS functions. Includes intelligent cruise control, lane following, and collision avoidance.

Advanced Vehicle Control and Safety Systems

The bundle of user services that includes: Longitudinal Collision Avoidance; Lateral Collision Avoidance; Intersection Collision Avoidance; Vision Enhancement for Crash Avoidance; Pre-Crash Restraint Deployment; Safety Readiness; and Automatic Highway Systems.

Agreement (Contract)

The written agreement between the owner and the contractor covering the work to be performed.

Algorithm

A procedure, process, or rule for the solution of a problem in a finite number of steps. An algorithm may be a set of computational rules for the solution of a mathematically expressed problem or for evaluating a function.

Ali-Scout ADIS

A state-of-the-art ADIS system. Incorporated into the FASTTRAC operational field test conducted in Oakland County, MI. System requires a network of communication beacons.

Allowable Gap

The time gap between successive moving vehicles at which a greater gap should terminate the green on one phase and transfer right-of-way to another phase.

Alphanumeric Display

Display consisting of letters (ROAD ICY), digits, or combinations of both (ROAD ICY, SPEED 30 MPH).

Alternative Systems Analysis

An analysis that critically examines alternative systems with respect to system needs, life cycle costs and performance. Criteria examined include personnel and budget implications, system costs, system benefits, and performance.

American National Standards Institute (ANSI)

The national clearinghouse for coordinated, voluntary industry standards and international liaison. Focuses on data processing systems and interfaces.

American Society for Testing Materials (ASTM)

A standards organization that supports ITS by focusing on materials and traffic monitoring device interfaces.

Amplifier (Detector Electronics)

A device that is capable of intensifying the electrical energy produced by a sensor. A loop detector unit is commonly called an amplifier, although its electronic function actually is different.

Amplitude Modulation (AW

A method of transmitting information by varying the strength of a carrier waveform in accordance with the instantaneous value of the intelligence-bearing signal (i.e., the digital "1" and "0" levels).

Analog

An electronic design that uses continuously variable quantities such as voltages, rather than numbers.

Analog Computer System

A control system that uses an analog computer as a master. An analog computer solves problems by operating on continuous variables that represent continuous data. Problems are solved by translating physical conditions (such as numbers, volumes, time or speed) into related electrical quantities and using electrical circuits as analogs to represent the physical phenomenon. Analog techniques have been used extensively in actuated controllers and arterial systems.

Analysis of Laws and Ordinances

Analysis of applicable local laws and regulations to assess impact on system operation of motorist noncompliance.

Applications Software

Computer programs developed by software engineers support specific traffic tasks such as: basic detector data processing; compute signal transitions from one timing pattern to another; transmit information to controls and displays; analyze equipment operation for malfunctions; and interpret operators commands.

APTS

The Advanced Public Transportation System category of ITS functions. Includes vehicle location and schedule monitoring, real-time transit, ride share, and HOV information.

Area Detection

The continuous detection of vehicles over a length of roadway wherein the call of a vehicle in the detection area is intended to be held for as long as the vehicle remains in the detection area. (Some detectors are not capable of holding the call indefinitely.) Frequently referred to as *large-area detectors* or *long loop presence detectors.*

Area Radio Networks (ARN)

Also called packet radio, broadcasts signals to an area rather that a specific location. ARN can operate traffic controllers and provide mobile voice communications. Requires FCC license.

Area-wide Control

A form of signal system control which treats all of the traffic signals in a city, metropolitan area, or major portion thereof as a total system.

Area-wide Integrated Strategy

A strategy that selects and adjusts ramp metering rates based on corridor flow optimization. Also adjusts traffic signal timing plans as part of overall strategy.

Arithmetic Unit

An electronic unit within a computer CPU which performs arithmetic and logic operations. Most arithmetic units can process an entire word of bits in a single cycle.

Array

(1) An orderly arrangement of items or of representations of items in a visual display (e.g., console or status panel). (2) Data in the form of signs, symbols, alphanumeric characters, etc., arranged so that the relative position of an element of an array has some bearing on the operation that will be performed on the element.

Arterial Control System (ACS)

An arterial control technique that operates as a three-level distributed microcomputer-based traffic data and control system. Consists of Local Control Units (LCU), System Control Units (SCU), and a Manager.

Arterial Intersection Control (Open Network Control)

A form of control for signalized intersections along an arterial street where major consideration is given to the provision of progressive traffic flow along the arterial. The signalized intersections usually operate as a system,

Arterial System

A linear sequence of signals on an arterial supervised to provide progressive flow in one or both travel directions.

Arterial Systems Control

A type of control applied to two or more traffic signals to ensure progressive traffic flow.

Arterial Timing Techniques

Two techniques for computing arterial timing plans are to maximize the bandwidth of the progression and to minimize overall delays and stops. MAXBAND, MULTIBAND, PASSER II-90, and AAPEX maximize progression. TRANSYT minimizes delays and stops.

ASCII (American Standard Code of Information Interchange)

A standard code that assigns special bit Patterns to each sign, symbol, numeral, letter, and operation in a specific test. The basic code uses 6-bit characters, allowing 64 different encoded characters.

Assembler

A computer program that prepares a machine language program from symbolic instructions.

Assembly Language

A machine-dependent symbolic language which must be converted to machine language instructions for symbolic instructions.

Asynchronous Transmission

The time intervals between transmitted characters may be of unequal length. Start and stop bits are transmitted before and after each character to synchronize the receiver clock. Most traffic systems use this transmission.

Attenuation

The loss in signal strength associated with the transmission process. Attenuation is usually expressed as the ratio of received signal strength to transmitted signal strength. This ratio is often expressed in decibels (dB), a logarithmic unit for expressing dimensionless ratios. For light-energy transmission the loss may result from absorption, scattering or microbends, and macrobends.

Attenuation Distortion

The distortion of a transmitted signal caused by the non-uniform loss or gain at different frequencies.

Attenuator

An electronic circuit element which reduces the strength or magnitude of a signal or action.

Audible Pedestrian Signals

Audible signal that indicates walk intervals for pedestrians.

Auto Restart

The integration of hardware logic and electrical circuitry with software programming capabilities enabling a computer system to be reactivated without operator intervention following a power failure.

Automated Highway Systems

This ITS user service provides a fully automated, hands off, operating environment for the motorist in his car.

Automated Roadside Safety Inspection

The ITS user service that provides and supports roadside inspections through real-time access to driver/vehicle records.

Automatic Highway Advisory Radio (AHAR)

An AHAR system automatically transfers a motorist's compatible radio to a designated station. This eliminates the need for advance signing and manual tuning. AHAR operates at 45.8 MHz (FM).

Automatic Repeat Request (ARQ)

An error detection technique that has the data automatically retransmitted.

Automatic Vehicle Identification Unit (AVI)

Device that has three functional elements: a vehicle-mounted transponder; roadside reader unit; and processing unit.

Auxiliary Equipment

Separate devices used to add supplementary features to a controller assembly.

Auxiliary Storage

A storage device which serves as an extension to processor storage. Data and instructions can be moved by the CPU between auxiliary storage and processor storage.

Available Systems Technology

The present state-of-the-art relative to the ability to readily obtain (purchase and install) a complete traffic control system.

Average Speed

A MOE expressed in miles per hour (kilometers per hour). Can be defined as either a point sample of average stream speed or the speed traces of individual vehicles.

B

Background Cycle

The term used to identify the cycle length established by a coordination unit and master control in coordinated systems.

Background Processing

The execution of low-priority programs in conjunction with high-priority or real-time processing. Background processing is interrupted as required to accomplish the foreground (high priority) operations, in real-time. (See ***Multiprocessing, Foreground,*** and ***Processing.***)

Backup System

A standby traffic signal control system that can be used to operate a computerized traffic signal system during computer downtime periods for routine maintenance or emergency failure periods. The backup system may be composed of components which, during normal operation, carry out other lower priority tasks or of components which are redundant during normal system operation. (See ***Standby System.***)

Band Speed

The slope of the green band on a time-space chart representing the progressive speed of traffic moving along the arterial.

Bandwidth

(1) The amount of green time available to a platoon of vehicles in a progressive signal system. Also referred to as through band. (2) A range of frequencies that a communications channel will carry without excessive attenuation. The larger the bandwidth the greater the information transfer capacity of the channel per unit time.

Batch Processing

An offline sequential-processing technique in which a number of similar input items are grouped for processing during the same machine run.

Baud

A unit for expressing the rate at which information is transmitted. A rate of one baud is one useful signal element per second. A bit rate is not necessarily equal to the baud rate in that a signal element may carry more than one bit of information, and some bits may be used for purposes other than carrying signal information.

Benchmark Program

(1) A program used to evaluate the performance of hardware or software or both. (2) A program used to evaluate the

performance of several computers relative to each other, or a single computer relative to system specifications.

Benefit-Cost Analysis

A specific evaluation technique used to determine the comparative worth of alternative systems. It establishes a dollar benefit from system operation and compares that to system cost including design, installation and 0 & M costs.

Bid Proposal

(1) A contract document that provides instructions and the format for preparation of the proposal. (2) A written document expressing a bidder's intention to perform certain work, in a proposed method, for an expressed amount of money, usually within a certain time frame. Includes bid price and authorized signature binding to bidder.

Binary

(1) A characteristic or property involving a selection or condition in which there are two and only two possibilities, Use of a binary system is predicated on the supposition that a duality exists: that is, a thing, state or condition is or is not. (2) A numbering system based on two which only uses the digits 0 and 1.

Binary Coded Decimal

A means of representing a decimal number by representing each individual digit as a group of bits.

Bit

(1) An abbreviation of ***Binary Digit.*** (2) A single character in a binary number.

Bit Rate (BR)

The speed at which bits are transmitted, usually expressed in bits per second.

Bits Per Inch (BPI)

Tape packing density on a tape drive. It is the number of bits on one track contained on one inch of tape.

Blocking Factor

The number of data records in a data block. (Also see ***Data Block***.)

Bonds

The legal document that binds a third party to make whole the system buyer for noncompliance or default on the contract. Types of bonds are: bid bond, performance bond, labor, and material payment bond.

Bootstrap

(1) An existing version, perhaps a primitive version, of a computer program that is used to establish another version of the program. (2) A technique or device designed to bring itself into a desired state by means of its own action, e.g., a machine routine whose first few instructions are sufficient to bring the rest of itself into the computer from an input device. (3) That part of a computer program used to establish another version of the computer program. (4) To use a bootstrap.

Bottleneck

Physical or geometric features of a street or freeway which reduce the facility's capacity (or ability to accommodate traffic flow) as compared to other locations on the same facility.

Breakdown

Any event that causes a loss of signal indication to any or all intervals or approaches.

Broad Band Communications

A band of communication frequencies above 4,OW Hertz, usually transmitted over coaxial cables.

Buffer

A device or system used to make two other devices or systems compatible, in particular: (1) A device or routine that compensates for differences in time of occurrence or rates of flow when data is transmitted between devices. (2) A circuit between two other circuits to prevent undesirable interaction. A second, redundant, usually temporary, area in memory or storage for data.

Bug

An error in a computer program.

Bus Detector (Active)

Device that consists of a bus mounted RF transmitter, receiver loop in pavement, and curbside receiver unit.

Bus Detector (Passive)

Pavement installed loop detector with digital device that analyses the signal so as to identify buses.

Bus Priority

Cycle-by-cycle timing of a traffic signal so the beginning and end times of green may be shifted to minimize delay to approaching buses. The normal sequence of signal displays is usually maintained.

Bus/Carpool Priority Control

Concept of traffic control which gives preferential treatment to buses and carpools.

Bypass Lanes on Entrance Ramps

Priority control technique which enables priority vehicles to avoid waiting in queues with non-priority vehicles on entrance ramps.

Byte

A sequence of adjacent bits used to represent a single character of information. The most common byte sizes are 8- and 16-bits.

C

Cable

A group of separately insulated wires wrapped together.

CAL3QHC

An emission control computer program used by the EPA to analyze air pollution at intersections where both idle and steady motion take place.

CALINE 3

An emission control computer program developed by CALTRANS. It calculates concentration of non-reactive air pollutants near highways.

Call

A registration of a demand for right-of-way by traffic at a controller unit. The call to the controller is via detector actuation.

Calling Detector

A detector installed in a selected location to detect vehicles which may not otherwise be detected, and whose output may be modified by the controller unit. This traditionally has meant a small-area detector near the stopline, to detect vehicles entering the roadway from a nearby driveway during a red or yellow interval. When the signal is green, the detector is disconnected so that extensions of the green can come only from the detector located upstream of the driveway.

Camshaft

The adjustable or selective controller device used to change signal indications upon activation by the dial unit.

Camshaft Control

A method of computerized control of an electromechanical-type controller. A hold-on-line signal puts the controller under computer control. Advance pulses are then used to operate the stepping motor or solenoid that advances the camshaft to the next interval position. (As contrasted to ***Dial Control*.**)

Candidate System

A complete traffic control system (defined in conceptual and functional terms) which can be considered as a feasible choice for implementation.

Capacity

The maximum volume that has a reasonable expectation of being accommodated by a roadway component under prevailing conditions, usually expressed as vehicles per hour (vph or v/hr).

Card-Rack-Mounted Detector Units

Units that do not have individual enclosures. They are connected by inserting printed-circuit boards into receptacles mounted within the cabinet. (Compare Shelf-Mounted Detector Units.)

Carrier Signal

The signal that is used to carry information during data transmission. The characteristics of the carrier signal are changed in accordance with the data that are to be transmitted. (See also ***Modulation***.)

Carryover Output

The ability of a detector to continue its output for a predetermined length of time following an actuation. Such a detector is called an extended-call detector or a stretch detector. It can be designed to begin timing of the carryover output when the vehicle enters the detection area, or when it leaves. The latter design is more common.

Cassette Tape Recorder

A peripheral auxiliary device that stores information on an encased magnetic tape.

Cathode Ray Tube (CRT)

An electronic vacuum tube similar to a TV picture tube containing a fluorescent screen on which information or patterns may be displayed

CCTV Monitoring Systems

Advanced traffic management systems with continuous CCTV coverage can serve as a motorist aid system. Operators can *observe* incidents and dispatch aid.

CEC

Commission of European Communities

Cellular Telephone System

Motorists with cellular telephones can call a dispatch office (or dial 911) to report a freeway accident or any other emergency.

Central Processing Unit: (CPU)

The hardware component of a computing system that contains the circuits that control and perform the execution of instructions. It consists of ft control unit(s), arithmetic unit(s), and special register groups.

Centralized Control

Form of traffic signal control in which the ability to make control decisions and to issue control commands is placed at one location.

Centralized System

A computer control system in which the master computer, central communication facilities, console, keyboard, and display equipment are all situated at a single location. From this center, the operating staff coordinates and controls traffic signals and related traffic functions throughout the area. (In contrast to Distributed System.)

CFR Section 655.409

The part of the FHWA Federal-Aid Policy Guide that specifies the requirements for implementation of a traffic system.

Changeable Message Signs (CMIS)

Signs that electronically or mechanically vary the visual word, number or symbolic display as traffic conditions warrant. A dynamic sip for dynamic traffic conditions. Commonly referred to as variable message signs (VMS).

Character

One symbol of a set of elementary symbols such as those corresponding to the keys on a typewriter. These symbols usually include the decimal digits 0 to 9, letters A through Z, punctuation marks, operation symbols, and any other single symbols, which a computer may read, store, or write.

Check Out

See ***Debug.***

Check-In Detector

A vehicle presence detector placed on the approach to the ramp metering signal so that the signal changes to green only at vehicle presence.

Check-Out Detector

Component of an entrance ramp control system which senses the departure of a vehicle past the ramp metering signal. Terminates the green signal after one vehicle has passed.

Checksum

An error code where an additional byte is added at the end of the message. An algorithm computes the checksum byte as a function of the message bytes. The same algorithm is performed at the receiver and the answers are compared.

Chip

See ***Integrated Circuit.***

Circuit

A closed path followed by an electric current.

Citizen Band (CB) Radio

CB radio can serve as an in-vehicle, two-way motorist aid system. The system allows motorists to remain in their vehicles when requesting aid. Channel 9 (27.065 MHz) is the official emergency channel.

Closed Grid Signal System

A network of signals forming an interlocking pattern are supervised to give progressive flow in all traveled directions within the network.

Closed Network Control

A form of control for a group of signalized intersections where relationships from a signal timing viewpoint, must be considered. A typical example is the control of signals in the central business district (CBD) of a city.

Closed Specification

A specification written around a particular item of material or equipment with the intent of limiting bids to one manufacturer.

Closed-Loop Control System

A system capable of controlling some operation by implementing certain strategies, receiving inputs that permit the rapid evaluation of the effects of the control, and then taking some action that modifies the strategy on the basis of the evaluation, all without the need of operator input

Closed-Loop Distributed Processing Signal System

A system that uses one or more on-street intelligent microcomputer master controller units. Each master can select signal timing plans and implement plans by supervision of local controllers in its subsystem.

Closed-Loop Signal System

A system that provides two-way communication between the intersection signal controller and its master controller. The master controller communicates to the traffic operations center.

Coaxial Cable (Coax)

A broadband communications technology with the capability of carrying many channels to transmit either data or video. Contains a single central conductor having a common axis with a second outer conductor.

Code Division Multiplexing (CDW

This technique encodes data by using a specified but different binary sequence for each channel.

Coded TV Transmission

Video compression standards are called the P x 64 (*P by 64*). Supports data rates in multiples of 64 Kbps ranging from 64 Kbps to 2 Mbps. Proposed by Consultative Committee for International Telephone and Telegraph (CCITT).

Command

(1) A signal that initiates a control function. (2) A machine language instruction.

Commercial Fleet Management

The ITS user service that provides communications between drivers, dispatchers, and intermodal transportation providers.

Commercial Radio Motorist Information Systems

Commercial radio has wide-area coverage and reaches a large segment of the motoring public. Many commercial stations schedule traffic information broadcasts at periodic intervals.

Commercial Vehicle Electronic Clearance

The ITS commercial user service that facilitates domestic and international border clearance, minimizing stops.

Commercial Vehicle Operations

The bundle of ITS user services including: commercial vehicle electronic clearance; automated roadside safety inspection; on-board safety monitoring; commercial vehicle administrative process; hazardous material incident response; and commercial fleet management.

Commercial Wireless Network Services

These services include cellular telephone and packet radio. Both services include monthly minimums and fee for use.

Common Carrier

One of several licensed corporations that offer data transmission services such as speech, television, or digital data transmission. A common carrier is required to supply communication service to all users at published rates.

Communication Channel

The logical and physical path over which information travels. The channel is described by the point-to-point path that it interconnects and the information capacity that it possesses (also communications link).

Communication Error

Any case wherein the data received from a channel does not agree with the data transmitted.

Communication Link

The means of connecting one location to another in order to transmit and receive data.

Communication Network

A composite of communication links.

Communication Noise

Fluctuations in the received signal caused by sources other than the transmitted signal. Impulse, interference and distortion are types of noise.

Communication System

The composite of communication links and associated communications equipment which interconnect all the control and surveillance components of a traffic control system.

Communications

Transfer of information from one location to another so that meaning is understood.

Communications Control Unit (CCU)

The portion of a system that handles the communication processes. The CCU may be a software program or a separate hardware unit. It handles message transmission, errors, control functions, and other communication-related tasks.

Compatibility Lines

A controller reference point in the designated sequence of a dual-ring controller unit at which both rings interlock.

Compiler

A computer program that translates a high-level language program to symbolic language.

Comprehensibility

A measure of a motorist's ability to understand the message intended to be conveyed by the sign.

Computer

See ***Digital Computer.***

Computer Adapter Unit

A device which allows a digital computer to interface with a local controller and thereby allow the computer to be in command of the signal indications. (See ***Control1er Interface unit.)***

Computer Control

Regulation and/or supervision of traffic control devices by a computer.

Computer Program

A series of instructions or statements in a form acceptable to the computer which will achieve a certain result.

Concentration

See ***Density***.

Concurrent Flow

Reserved lanes in the same direction as peak flow and on the same side of the median.

Conditioned Line

A communications cable specially compensated to provide improved transmission characteristics.

Conditioning

A common-carrier service whereby the electrical characteristics of a channel are timed so as to give improved data transmission.

Conditions to Contract

General and special conditions set forth in a written statement that forms part of the contract documents and prescribes the manner in which a contract is to be carried out.

Conductor

Same as Wire. Used to transmit information (i.e., electrical impulses) between computer and controller as well as within the computer and controller/signal subsystems.

Conflict Monitor

An electrical device that checks the green and yellow indications for each phase to protect against improper conflicting signals. Provides an output in response to conflict.

Congestion

A freeway condition where traffic demand exceeds roadway capacity. Normally occurs during peak travel periods or when a traffic incident reduces capacity by creating a bottleneck. Includes high densities, low Volumes, low speeds, stop-and-go driving, and increased delay.

Congestion Detection

A system of hardware and software designed and operated to provide data on the level of traffic congestion in the area being monitored.

Congestion Strategy

A strategy that optimizes corridor operations to minimize the spread of congestion.

Console

A device used for communication between the operator and the computer. A console includes display panels, CRT, some type of hardcopy printer, and a system control panel.

Conspicuity

A measure of a motorist's ability to see or notice a sign.

Construction Management

The process that entails the following activities: inspection of day-to-day construction tasks; witnessing of acceptance tests; review and approval of shop drawings; and review completed tasks.

Construction Phase

That part of the project which deals with construction.

Consultant/Contractor Approach

The traditional procurement approach for traffic system contracting. The consultant develops the plans, specifications and estimates (PS&E). A separate contractor bids the job, supplies the hardware and installs the system.

Continuous Flow Intersection

A patented intersection design that can solve operational problems caused by heavy turning movement at conventional intersections.

Continuous Presence Mode

Detector output continues if any vehicle (first or last remaining) remains in the field of influence. (This definition should not be understood to imply that the use of this mode guarantees that the output will continue for whatever length of time the vehicle remains in the detection area, as some detectors are not capable of holding a call indefinitely.)

Contract Documents

The design plans, technical specifications, bid proposal, bonds, notice of award, addenda, and modifications to the contract.

Contractor Qualifications

Contractors must be qualified to perform on the project. Qualification involves an evaluation and general review of contractor financials, past experience and conformance to state business regulations.

Contraflow Lane

Reserved lanes on the opposite side of the median where high occupancy vehicles (HOVs) move against the flow of traffic.

Control Area

A grouping of sections. (A section is the smallest grouping of intersections that the computer considers. These intersections are so interdependent or close together that they always work in coordination.) Control areas are generally defined by the physical proximity of sections and by the similarity of traffic conditions which permits independent control by the computer within the constraints imposed by required interface between sections and overall system requirements.

Control Center

Consists of the room(s) that contains the computer equipment, displays and controls, and houses the personnel which operate this equipment used in a computerized traffic control system. (See ***Traffic Operations Center***)

Control Interval

Period of time during which signal timing parameters are held constant.

Control Panel

(1) ***System Control Panel*** *A* panel for operation of the system. (2) A panel on the computer designed for use by the computer operator in communication with the computer.

Control Subarea

Subdivision of a single control area. (See ***Section***.)

Control Variables

Traffic condition indicators which are used as the basis for selecting traffic control strategy or tactics.

Controllability Index

A measure of the degree to which traffic responsive ramp control can vary the metering rates.

Controller Assembly

A complete electrical mechanism mounted in a cabinet for controlling the operation of a traffic control signal.

Controller Hardware -- Electromechanical

A 1970s pretimed signal controller standard. Consists of a dial unit (motor, gears, cycle and timing keys), and a camshaft (stepper motor, cams with switch breakouts and switch contacts).

Controller Hardware -- Solid State

Solid state controller assemblies include the controller unit, conflict monitor, auxiliary devices and terminals.

Controller Interface Unit (CM

The piece of equipment inserted between the local intersection communication terminal and the intersection controller unit to translate the instructions from the computer into commands that are recognized and responded to by the controller unit.

Controller Unit

The part of the controller assembly which performs the basic timing and logic functions.

Conversational Mode

A mode of operation of a data processing system in which a sequence of alternating entries between a user and the system resembles a conversation between two persons.

Coordinated Controls for Incident Management

A strategy that coordinates a set of changeable message sign messages, lane control signals and variable speed limit signs to implement incident management plans.

Coordination

The establishment of a definite timing relationship between adjacent traffic signals.

Coordinator

A device used to relate the timing of one controller unit to others.

Cordon Counts

Number of vehicles crossing a line defining an enclosed area. Both entries and exits from the enclosed area are recorded during selected time periods.

Core Resident

The word *resident* as used here denotes a program or routine which is available in the processor memory. Nonresident programs are taken from peripheral storage devices.

Core Storage

See ***Processor Storage***.

Corridor

A freeway and the system of roadways influenced by the freeway which accommodates travel demands over a large geographical area.

CORRIDOR

The European ITS field test for Cooperation on Regional Road Informatics Demonstrations on Real Sites.

Corridor Control

The coordinated set of strategies that include ramp metering, diversion control and arterial signal control to optimally distribute the traffic load among all corridor routes.

Corridor Control Strategies

A set of four control strategies that optimize operation of a traffic corridor. Strategies include: Local Coordinated; Areawide Integrated; Diversion; and Congestion.

Corridor Control Strategy

Procedure used to integrate the operation of the various control and driver information systems in a corridor in order to optimize the use of corridor capacity.

Council of ITS Standards

The council established by ITS America (Standards and Protocol Committee) to coordinate the standards-setting efforts in USA and international. Includes representatives from ANSI, IEEE, SAE, ASTM, EIA, NAB, NEMA, TIA, ITE and AASHTC.

Credibility

A quality of CMS that implies that the supplied information is timely, accurate, and reliable.

Critical Approach Lane

The approach lane that exhibits the highest ratio of flow to saturation flow.

Critical Density

The traffic density occurring at maximum volume flow. The highway capacity manual considers 67 passenger cars per lane mile as critical. At this density, flow becomes unstable.

Critical Intersection Control (CIQ

(1) An algorithm employed to dynamically control the split at signalized locations where the traffic patterns are such that special control, responsive to changing conditions, is needed. (2) Within the UTCS control operation, a specific algorithm that is implemented at saturated intersections. It adjusts splits in accordance with phase demand using the nonrandom traffic trend data.

Critical Lane Detection

A system of hardware and software designed to provide data on traffic flow for a selected lane, usually the heaviest volume lane on an approach to a signalized intersection.

Critical Path Method (CPM)

A project management tool for planning, organizing and controlling projects. Uses a network diagram based on scheduled activities and events with time durations assigned to activities. Monthly status of planned versus actual activities establishes a snapshot of percent project completion.

Crosstalk

Mutual coupling of magnetic fields, producing interaction between two or more detector units in the same cabinet, when the units are operating at similar frequencies. Crosstalk results in a detector outputting an actuation in the absence of a vehicle.

CTA Smart Bus

An example of a transportation corridor that includes an Automobile Vehicle Location (AVL) function and bus traffic signal preemption technologies. Located in Chicago metropolitan area.

CVO

The Commercial Vehicle Operations category of ITS functions. Includes automation of administrative and regulatory aspects, fleet dispatch and management and automatic vehicle identification and weigh-in motion.

Cycle

In a pretimed controller unit, a complete sequence of signal indications. In an actuated controller unit, a complete cycle is dependent on the presence of calls on all phases.

Cycle Length

The time required for one complete sequence of signal phases.

Cycle Locking

When cycle lengths of approximately the same length are selected by the computer for two or more sections of the system, one consistent cycle length is selected and imposed on these sections. The sections are then, in effect, locked together on the same cycle length.

Cycle Selection

The process by which cycle lengths are chosen or calculated by the computer to be imposed on the individual sections of the control system.

D

Data Acquisition

The process by which a computer acquires data from controllers, detectors, and other remote sensors and assembles this raw data for use.

Database

The assemblage of data constraints and parameters used by computer algorithms is the execution of the traffic control function. Normally included are timing parameters, adjustment coefficients, algorithm coefficients, limit parameters, etc.

Database Generator

The program used to assemble a database prior to the initiation of system operation.

Database Updating

The process by which the database is modified to current value levels.

Data Block

One or more data records stored on an auxiliary storage device in a contiguous block in order to make more efficient use of the storage capacity of the device.

Data Collection and Analysis

Operations task to collect traffic data either through gathering of field data or through installed traffic sensors. Data analysis provides basis for modifying signal timing and plan scheduling. Measures of effectiveness are calculated from data.

Data Element

A single unit of data, such as a name or a serial number.

Data Packing

The process of fitting together information which requires less than a full computer.

word into groups so as to effectively use storage in the computer memory.

Data Record

A group of related data elements treated as a unit in input-output operations.

Data Register

A small capacity (usually one word) data storage area in the CPU.

Data Set

(1) A particular complement of data used for a specific traffic control purpose. (2) A modem which performs modulation, demodulation, and control functions that are necessary to provide compatibility between communications facilities and a computer or remote terminal equipment. (***Data Set*** is a registered trademark of the Bell System.)

Debug

To detect, locate, and correct mistakes in a computer program. A program that is completely debugged is said to be checked out.

Decentralized Control or Decentralized System

A form of traffic signal control in which the ability to make control decisions and issue control commands is placed at more than one location.

Decibel Random Noise (DBRN)

A measurement of noise power is decibels.

Decoder

A mechanism for translating a code into its various components.

Dedicated Lines

Communication lines used solely to interconnect two or more locations not normally switched.

Dedicated Road Infrastructure for Vehicle Safety in Europe (DRIVE)

A European program intended to move Europe toward an Integrated Road Transport Environment. It focuses on improving traffic efficiency and safety and reducing the adverse environmental impact of motor vehicles.

Delay

(1) A measure of the time elapsed between the stimulus and the response. (2) The retardation of the flow of information in a channel for a definite period of time.

Delay Distortion

The degradation of a signal transmitted on a communications line that results from differences in the delay experienced by the various frequency components of the signal.

Delayed Output

The ability of a detector to delay its output for a predetermined length of time following the arrival of the vehicle into the zone of detection.

Deliverable Services

Those services associated with the implementation of a control system which relate to system documentation, training and maintenance.

Demand

The need for service, e.g., the number of vehicles desiring use of a given segment of roadway during a specified unit of time.

Demand Control (Loop Occupancy Control)

A detector/controller design using long detection loops (normally 30 ft (9 in) or longer), with the unit operated in the nonlocking mode. A loop occupancy controller may, but need not necessarily, be designed to rest in all red in the absence of any traffic demand. Loop occupancy control can use magnetometer detectors as well as loop detectors.

Demand Management and Operations

The ITS user service that supports and implements policies and regulations designed to mitigate the environmental and social impacts of traffic congestion.

Demand Operation

A mode of operation in which the service provided at an intersection reflects the presence of demand for that service often without regard for background cycling.

Demand Strategies

The TSM strategies that focus on decreasing the quantity of vehicular travel. Demand actions include: carpools, vanpools, HOV priority treatments, and variable work hours.

Demand-Capacity Control

An entrance-ramp control strategy for selecting metering rates based on a real-time comparison of upstream volume and downstream capacity.

Demodulation

The process of retrieving information from some previously modulated source. . The reverse process of modulation.

Demultiplexing

The process of retrieving two or more communication channels from a multiplexed transmission media.

Density

(1) A measure of the number of vehicles per unit length of roadway (i.e., per lane mile (kilometer)). (2) The number of bits that can be recorded per inch of magnetic media.

Density Contour

Plotting of density levels on a roadway using distance along the roadway as the x-axis and time-of-day as the y-axis.

Density Controller Unit

An actuated controller unit that has timing adjustments for the selection of the allowable gap independent of the passage time.

Design Plans

Drawings indicating the manner in which components of a control system are to be constructed and installed.

Design Plans and Specifications

The principal elements of contract documents are plans (drawings) and specifications. Plans define the physical relationship of the system. Specifications define the minimum acceptable requirements for equipment and materials.

Design/Build Approach

This approach uses a single contractor to perform all work associated with deployment of the traffic system. The single contractor has full responsibility for system implementation. The public agency's role is to monitor the contractor.

Detection/Verification Techniques

Techniques available for implementing the detection and verification surveillance functions.

Detector

A device for indicating the presence or passage of vehicles or pedestrians. This general term is usually supplemented with a modifier, i.e., loop detector, magnetic detector indicating type.

Detector Failures

The occurrence of detector malfunctions, including non-operation, chattering, or other intermittently erroneous counting.

Detector Memory

The retention of an actuation for future use by the controller assembly.

Detector Mode

A term used to describe the duration and conditions of the occurrence and conditions of the occurrence of a detection output

Detector Setback

Longitudinal distance between stopline and detector. ***Detection Zone***: That area of the roadway within which a vehicle will be detected by a vehicle detector.

Detector System

The complete sensing and indicating group consisting of the detector unit, transmission lines (lead-ins), and sensor.

Detector Unit

The portion of a detector system other than the sensor and the lead-in, consisting of an electronics assembly.

Diagnostic

(1) Pertaining to the detection, discovery, and farther isolation of a malfunction or mistake. (2) A program that facilitates computer maintenance by detection and isolation of malfunctions or mistakes.

Diagrammatic Guide Signs

Signs that graphically depict the exit/entrance arrangement in relation to the main roadway.

Diagrammatic Sign

Class of sign which combines graphics or symbols with selective alphanumeric displays.

Dial Control

An alternative method of computerized control of an electromechanical type controller. The computer controls the dial motor by issuing a dwell signal. When the dwell signal disappears, the dial restarts and follows the fixed interval pattern (i.e., vehicle change and clearance intervals, pedestrian clearance intervals, leading/lagging greens, etc.), as contrasted with camshaft control. (Same as ***Dial Supervision***.)

Dial Disconnect

The process of interrupting the connection between the dial pulsing circuit and the signal camshaft rotational device in some types of intersection controllers.

Dial Supervision

The technique for allowing the dial to dwell for an adjustable period of time in one or more of the intervals comprising the cycle. This permits the computer to independently extend the duration of each phase beyond its preset minimum. (Same as ***Dial Control***.)

Dial Unit

Consists of a dial graduated in one percent increments from 0 to 100 percent. Timing keys placed in the dial unit are used to effect changes in signal indications.

Diamond Interchange Operation

The operation of a standard 8-phase controller unit with modified software for signalization of a full diamond interchange.

Digital Computer

An electronic device capable of accepting information, applying prescribed processes to the information, and supplying the results of these processes. It usually consists of input and output devices; storage, arithmetic and logic units; and a control unit.

Digital Logic

(1) Logic related to numbers through the use of arithmetic and logic processes. (2) Hardware to effect these processes.

Digital Signal Transmission Standards

The standards for transmission based on data rates and formats. Standards are specified for: serial ports; high-speed Data Rate Channels; Optical Interface Channels; CCTV and Video Transmissions, including full motion, coded TV; and freeze frame video.

Digital Traffic Control Computer System

A control system that uses a digital computer to control traffic signal controllers.

Dilemma Zone

A distance or time interval related to the on-set of the yellow interval. Originally the term was used to describe that portion of the roadway in advance of the intersection within which a driver can neither stop prior to the stopline nor clear the intersection before conflicting traffic is released. That usage pertained to insufficient length of timing of the yellow and/or red clearance intervals. More recently the term has been used also to describe that portion of the roadway in advance of the intersection within which a driver is indecisive regarding stopping or clearing, although the signal timing is long enough to permit either. That portion of the roadway in advance of the intersection within which a driver is indecisive regarding stopping prior to the stopline or proceeding into or through the intersection. May also be expressed as the increment of time corresponding to the dilemma zone distance.

Dilemma Zone Protection

Any method of attempting to control the end of the green interval so that no vehicle will be in the dilemma zone when the signal turns yellow, or delay the onset of an opposing green indication if a vehicle is in the dilemma zone.

Direct Access

Data in storage can be read and written without processing the data which precede it on the storage device. The time required for data access is effectively independent of the location of the data. Disks and drums are direct access devices. (Also see ***Random Access***.)

Direct Addressing

An immediate and explicit indication of the referenced location. It is usually a part of the computer instruction specifying the location of the operand or the location of another instruction. (In contrast, see ***Indirect Addressing***.)

Direct Memory Access (DMA)

A method used in computerized systems to allow high-speed peripheral equipment to obtain stored data on a cycle-stealing basis. This allows simultaneous processing and input/output data transfer.

Direct Wire

A communications method that uses wire interconnect between the transmission and reception points with no multiplexing. (See ***Dedicated Line***.)

Directional Detector

A detector capable of being actuated only by vehicles traveling in one direction.

Directional Lane Controls

Lane controls are desirable when significant unbalanced flows change direction during or between peak periods. Often used in tunnel or bridge operations in response to incidents or maintenance actions.

Disc (Disk)

(1) The circular-shaped device used in the production of some changeable message sign legends. It may be retro-reflective or solar. (2) A peripheral device used in computer systems to provide large volumes of storage that is available to the computer in blocks with an access time delay on the order of 100 milliseconds or less.

Disk File

A segment or block of disk memory separated for storage of particular information.

Display Map

A graphic display of the street or freeway system being controlled showing the status of the signal indications and possibly the status of traffic flow conditions.

Distortion Noise

Changes the shape of the received waveform from the transmitted waveform.

Distributed System

A control system in which individual computers are installed in each of the major control areas of a total system, and a supervising master is used to provide interface between the individual areas and to make decisions on timing patterns affecting two or more areas.

Diversion

An aspect of corridor control which refers to the directing of traffic from corridor links with excess demand to those with excess capacity.

Diversion Strategy

A strategy that optimizes corridor operations in response to corridor incidents.

Diverted Traffic

Vehicles which choose not to use the freeway, or enter it from another location or at another time instead of waiting to enter at a particular entrance ramp. Also refers to drivers that choose to use another mode of transportation (e.g., carpools or public transit) instead of driving on the freeway.

Documentation

A deliverable that reflects the as-built system and fully describes the operation and maintenance procedures for the system hardware and software.

Doppler Effect

A change in the frequency with which waves from a given source reach an observer, when the source and the observer are in rapid motion with respect to each other, by which the frequency increases or decreases according to the speed at which the distance is decreasing or increasing.

Double Alternate

A progressive timing technique based on fixing the same offset at two adjacent intersections with a half-cycle shift every two intersections.

Downtime

The time during which a device is unavailable for normal operation.

Downtime Accumulator

A clocking mechanism activated during the interval when a device is inoperable. It provides a measure of the cumulative total elapsed downtime. Usually used to determine the length of a power outage.

Downloading

A function of a traffic system whereby the master controller can access the local controllers memory to update or modify a stored timing plan or controller settings.

Downstream

The roadway extending, from a reference point, in the direction of the traffic movement that is being discussed.

Drift

Change in the electrical properties of the detector system or a portion of it due to environmental changes, particularly temperature variations and rain water.

DRIVE I

The first phase of DRIVE (Dedicated Road Infrastructure for Vehicle Safety in Europe). A three-year pre-competitive research program, sponsored by the Europe CEC, with joint industry and public funding for planning of ITS projects. It emphasizes infrastructure requirements, traffic operations, and technologies.

DRIVE II

Called the Advanced Transport Telematics (ATT) program. A three-year European CEC program emphasizing ITS field trials and pilot projects. Includes Demand Management, Integrated Urban Traffic Management, Traffic and Travel Information, Integrated Inter-Urban Traffic Management, Driver Assistance and Cooperative Driving, Freight and Fleet Management, and Public Transportation Management projects.

Driver Information System

Concept of traffic control which advises motorists of prevailing traffic conditions and, in some cases, provides recommendations as to the best routes to travel. Devices including message signs and roadside radio, provide information to motorists to drive safely and divert to alternate routes.

Drop Procedures

(1) The orderly processes or operations to remove a controller from the control of the computer. (2) The process followed at the local intersection when a communications failure occurs.

Drop/Insert Unit

A dual fiber optics repeater with an electrical port that can interface with the TS2 NEMA and Model 170 type controllers.

Dual Entry

A fully activated operating mode in a dual-ring controller unit in which one phase in each ring must be in service.

Dual-Ring Controller Unit

A controller unit that contains two inter-locked rings arranged to time in a preferred sequence and allow concurrent timing of respective phasing in both rings subject to compatibility lines.

Dummy Interval

A redundant interval in the cam switching mechanism incorporated to allow the total number of intervals in the cycle to correspond integrally with the total number of intervals provided on the cam switching mechanism.

Dump Programs

Software used to output specified areas of storage which is useful in debugging computer programs and system diagnosis.

Duplex

Two-way communication on a single communication channel. (See ***Half Duplex*** **and** ***Fall Duplex****.)*

Dynamic Artery Responsive Traffic Signal (DARTS) System

An open-loop arterial system consisting of a series of NEMA-type, fully-activated traffic signals each with an external logic modular coordination unit. DARTS achieves platoon progression on an intersection-to-intersection basis.

Dynamic Range

The difference between the maximum and minimum acceptable input power levels at communication receivers.

Dynamic Split Adjustment

The process or computer program used to vary the split among the various phases of a cycle in real-time in accordance with the conditions to be satisfied. (Same as ***CIC.*****)**

E

Ease of Operations

The quality of a traffic control system to easily develop, maintain and update system databases including timing plans.

Echo Distortion

The distortion caused by an impedance mismatch or by a sudden change in the properties of a line which results in an echo or reflected wave which lowers the quality of the transmitted signal by distorting the shape of the wave.

Electrically Erasable Programmable Read-Only Memory (EEPROM)

An electrically erasable PROM. The contents of this device are modified through the application of an electrical voltage that is higher than voltages that are applied by the microprocessor during normal operation. Also designated as the ***Electrically Alterable PROM, EARPROM.***

Electromagnetic

Produced by electromagnetism resulting from magnetic material surrounded by a coil of wire through which an electrical current is passed to magnetize the material.

Electromagnetic Reflective Disk Matrix

Signs formed by a grid of disks. Each disk is a pixel of a typical 5 x 7 array of pixels that form a character. Each disk has a side of white and one of dark. The disks are flipped to create characters and create a message.

Electromechanical Controller Unit

A controller unit which performs its functions on the basis that an electrical impulse causes a mechanical action to take place.

Electronic Industries Association RS 232 (EIA 232)

The standard interface between data terminal equipment and data communications equipment employing serial binary data interchange. Restricted to 50 ft (15 in) and relatively slow speed.

Electronic Monitoring (of incidents)

The detection of roadway incidents using specific algorithms operating on mainline detection data. Typical algorithms are the California, APID, and McMaster.

Electronic Payment Services

This ITS user service allows travelers to pay for transportation services electronically.

Emergency Management

The bundle of ITS user services that includes: emergency notification and personal security, and emergency vehicle management.

Emergency Notification and Personal Security

The ITS user service includes two capabilities: driver and personal safety; automatic collision notification. Driver and personal safety provides for user initiated distress signals for mechanical breakdowns or carjackings. Automatic collision notification transmits information regarding location, nature, and crash severity to emergency safety.

Emergency Repairs

All work required to restore a signal installation, or system, to its original state after a service failure.

Emergency Vehicle Management

The ITS user service that reduces the time for emergency vehicles to respond to an incident.

Emergency Vehicle Preemption

The transfer of the normal control of signals to a special signal control mode for emergency vehicles.

Emissions Testing and Mitigation

This ITS user service provides information for monitoring air quality and developing air quality improvement strategies.

En Route Driver Information

This ITS user service includes driver advisories and in-vehicle signing. Driver advisories resemble pre-trip planning information, but are provided once travel begins. In-vehicle signing provides in the vehicle the same type of information on physical road signs today.

En Route Transit Information

This ITS user service provides information to travelers using public transportation after their trip begins.

Encoder

(1) A device which converts data into a form for transmission over the communication link between two points in a system. (2) A circuit to transform data from one form to another, e.g., convert discrete decimal characters into binary characters. (3) A system which converts signals which have been fed into the system individually into combinations of outputs.

Entrance Ramp Control

Regulation of the number of vehicles per unit time entering a freeway so that demand on the freeway does not exceed capacity; and/or the guidance of vehicles entering a freeway into gaps in the freeway traffic stream, in order to improve the safety and capacity of the merging operation.

Envelope Delay

(1) ***Absolute Envelope Delay*** refers to the amount of delay encountered by the modulating energy in a signal between the sending and receiving end of any circuit. (2) ***Relative Envelope Delay*** is a difference in delay at various frequencies but with a specific frequency selected as a reference point for all other frequencies.

Environmental Detectors

Detects adverse weather conditions, so systems can control or advise travelers appropriately.

Equipment Breakdown

Any event that causes a loss of signal indication to any or all phases on traffic approaches. Breakdowns include: controller failure, cable failure, and loss of power.

Equipment Malfunction

Any event that impairs the operation of a control system without losing the display and sequencing of signal indications to an approaching traffic. Malfunctions include detection failures and loss of interconnect.

Equipment Status Monitoring

The ability to determine the operational characteristics of a remote device in terms of *operating normally, malfunction, communications errors, etc.*

Equipment/Material Specifications

This specification type describes in detail the individual capabilities and features of each component or subsystem.

Erasable Programmable ReadOnly Memory (EPROM)

A device that stores data which can be altered through the use of a special device.

Error

Any case wherein the data received from a channel does not agree with the data transmitted.

Error Correction

The process by which sufficient redundant or check information is included with data that are transmitted so that the receiver can, within certain ranges or error, reconstruct the correct message from a message that is received in error.

Error Detection

Similar to error correction except that check information is used only to identify erroneously received data, and no correction is made. Requires far less redundancy and check information.

Error Rate

The expected frequency of transmission errors over a channel, usually expressed as the ratio of bits-in-error to total bits transmitted. One error per 100,000 bits transmitted gives an error rate of 10.

ERTICO

The European Road Transport Telematics Implementation Coordination Organization that coordinates European RTI/ITS. Coordinates DRIVE II implementation and other projects to ensure a smooth transition front R&D to a commercial market. Its function resemble those of ITS America.

Evaluation Process

The process for system evaluation includes the following steps: establish objectives that define a desired level of performance improvement; select MOEs for the standard of comparison; and implement the before-and-after evaluation.

Evaluation Sampling

Sampling techniques effect the level of error in an evaluation process. Factors that influence the design of sampling include: importance of detecting a difference; expected size of difference, and cost of data collection activity.

Enhanced Value Iteration Process Actuated Signals (EVIPAS)

An automated computer program for calculation of intersection signal timing plans for activated signals.

Exclusive HOV Ramps

Ramps provided exclusively for the use of HOV vehicles or buses. Applications include bus terminals, park and ride facilities, tunnel and bridge approach ramps.

Executed Cycle

The portion of a CPUs operational cycle during which the decoded instructions is executed.

Executive Routine

A supervisory program used to control the processing of specific programs.

Exit Ramp Closure

Type of exit ramp control which allows no vehicles to leave the freeway at a particular egress or exit point.

Exit Ramp Control

Regulation of traffic flow leaving a freeway at a point of egress or exit.

Exit Ramp Metering

Restriction of traffic flow leaving a freeway at a point of egress or exit.

Expansion Wave

Boundary, moving downstream of an incident, between the region of traffic flow affected by the incident and that region of traffic flow not affected by the incident.

Explicit Signal Coordination

A controller coordination technique that links local controllers with a communication channel. A master controller establishes the coordination or sync pulse for all controllers in a system.

Extended Binary Coded Decimal Interchange Code (EBCDIQ

An 8-bit representation of original 6-bit BCD codes.

Extended Call Detector

A detector with carryover output. It holds or stretches the call of a vehicle for a period of seconds that have been set on an adjustable timer incorporated into the detector. It can be designed to begin the timing of that period when the vehicle enters the detection area, or when it leaves.

Extension Detector

A detector that is arranged to register actuations at the controller only during the green interval for that approach so as to extend the green time of the actuating vehicles.

Extension Green Interval

For a fully-actuated controller, that portion of the green interval in which timing resets with each subsequent vehicle actuation.

Extension Unit

The timing interval during the extensible portion which is resettable by each detector actuation. The green interval of the phase may terminate on expiration of the unit extension time.

F

Failsafe (output-relay design)

A type of output-relay design that produces a constant call, thereby keeping traffic moving, in the event that the detector unit loses power.

Fetch

The procedure by which one or more bytes of data are collected, then transferred from processor storage to the CPU.

FHWA

Federal Highway Administration, formerly the Bureau of Public Roads.

Fiber Light Detectors

Optical conversion devices including the P-n junction photodiode (PIN) and Avalanche Photo Diode (APD), that convert the optical energy into modulated electrical signal.

Fiber Light Sources

Optical devices, including Light Emitting Diodes (LED) and Injection Laser Diodes (ILD), that provide the modulated light energy coupled into the fiber. These devices operate in the infrared portion of the EM spectrum.

Fiber Optics

A broadband communication technology based on an optical wave-guide that channels the light in the fiber with total internal reflection at the boundary.

Fiber Splices

A splice permanently joins two optical fibers. Two types of splices used are fusion and mechanical. Typical power loss at a splice is 0.35 to 0.70 dB.

Fiber-Optic/Flip Disk Signs

These signs come from the electromagnetic reflective disk matrix type. The disk surface that reflects has an opening to pass fiber-emitted light, the black disk surface blocks the light transmission.

Filtering Equation

An equation used to smooth discrete data and determine the average trend of the data. The equation is used in an iterative process to determine smoothed data Points.

Firmware

Memory and its contents that cannot be changed readily.

First-Generation Control (1-GC)

This type of control is based on a table lookup approach. A number of fixed timing plans have been precomputed and stored. Timing plans are selected based on sensing certain demand parameters at strategically located detectors. As thresholds we reached, predeveloped and stored timing plans are implemented. During the 1980s, this procedure was used in most of the operational digital computer control systems.

Fixed Delay

Time loss caused by traffic control devices (e.g. signals, stop signs, railroad crossings) which occurs regardless of the amount of traffic volume and interference present.

Fixed Grid Fiber Optic Sign

A fiber-optic sip disperses light energy from a point light source through fiber bundles dig form messages on the sign's face.

Fixed Grid Light Emitting Diode Sign

A blank out sign that uses light emitting diodes in fixed formats to represent characters and messages.

Fixed-Head Disk

A magnetic disk system in which read/write head is permanently positioned over a given track on the disk.

Fixed-Tuned Loop

Describes a loop-detector unit whose output frequency must be adjusted manually to effect detection.

Flip Flop

An electronic device used to temporarily store one bit.

Flow Rate

Number of vehicles passing a point on the roadway during a specified time period.

Flowchart

A graphical representation showing the interconnected sequential logical steps required for the definition, analysis, or solution of a problem. Used to describe a process by displaying its functions in the order and priority of flow.

Foldout Sign

The foldout sign is a relatively simple message sign, using a small motor to swing two panels across the face of a standard metal sign

FORCAST

A timing plan generation product, developed by Computran Systems Corporation, implements 1 1/2 Generation Control.

Force-off Controller Command (FO)

Is used by master controller to begin termination of an activated phase.

Forced Flow

The zone of traffic flow at which flows are below capacity and storage areas consisting of queues of vehicles form. Speeds are reduced substantially, and stoppages may occur for short or long periods of time. Normal operation in not achieved until the storage queue is dissipated.

Foreground Processing

A term describing the higher priority tasks to be processed in a multilevel computer processing environment. (See ***Multiprocessing, Background Processing***.)

FORTRAN (Formula Translation)

A high-level, procedure-oriented, computer programming language. Used for scientific applications characterized by lengthy, intricate computations.

Forward Error Control (FEC)

An error detection technique which includes error correcting codes to catch a limited number of errors.

Free Flow

The zone of traffic at which there is little or no restriction in maneuverability due to the presence of other vehicles. Drivers can maintain their desired speeds with little of no delay.

Freeway

Divided roadway with more than one lane in each direction, with grade separations at cross streets, and with access and egress limited to specially designed locations.

Freeway Entrance Ramp Control

Control at freeway entrance ramps that modulates the flow rate of entering traffic and alternatively shuts the ramp with barriers or gates.

Freeway Operational Tasks

Operations tasks associated with freeway systems include: system monitoring/ intervention; data collection and analysis; system modifications and updates; incident management; and motorist communication through CMS, HAR and the media (i.e., ATIS).

Freeway Surveillance

Process or method of monitoring freeway traffic performance and control system operation.

Freeway-to-Freeway Ramp Metering

A strategy used to improve traffic conditions downstream of major freeway merges.

Freeway Traffic Control Concept

Ideas which express the objectives, principles of operation, control variables, and functioning components of a freeway traffic control system.

Freeze Frame Video Transmission

A video image is captured and coded for transmission. After transmission, the coded signal is reconverted and a still image displayed on a monitor.

Frequency

(1) The number of oscillations of a signal per unit of time; referred to in Hertz (11z) or cycles per second (cps). (2) The number of times an event (i.e., accident, vehicle stop, etc.) occurs per unit of time.

Frequency Division Multiplexing (FDM)

This technique splits the available transmission frequency range into narrower bands, each constituting a distinct communication channel.

Frequency Modulation MMO

A method of data transmission whereby the frequency of a sinusoidal waveform (carrier) is changed in accordance with the information that is to be carried. Two frequencies are necessary to represent binary signal values.

Frequency Response

The plot of frequency versus the ratio of output to input signal for a conductor.

Frequency Shift Keying (FSK)

A form of frequency modulation, typically with mark signals represented by one frequency and space signals represented by another frequency. The transmitter is changed from one frequency to another, i.e., keyed to represent a different information character.

Full Duplex

A communication facility providing simultaneous transmission and reception in both directions.

Fall Motion Video Transmission

Video cameras used for traffic control applications conforming to standards defined by National Television Standards Committee (NTSC).

Full-Traffic-Actuated Controller Assembly

A type of traffic-actuated controller assembly in which means are provided for traffic actuation all approaches to an intersection.

Functional Maintenance

The maintenance task that updates the system database and optimizes signal timing and metering plans. Database updates are required for: detector reallocations; equipment reconfigurations; system expansion; changes to controller types, and preemption routes.

Functional Specifications

This specification type describes what the system, subsystem, or equipment must do in terms of its performance requirements.

Fundamental Traffic Flow Relationship

The relationship between volume (q), density (k), and space-mean speed (u). Each freeway section has a specific volume-density-speed relationship.

G

Gamma Correction

A feature installed on a special circuit in a CCTV camera which expands or increases the ratio between bright and dark objects.

Gap-Acceptance Merge Control

Concept of entrance ramp metering which releases and/or guides ramp vehicles into acceptable gaps in the freeway traffic stream by stopping them at a ramp metering signal and then releasing them, usually one at a time, at a time calculated in accordance with the predicted arrival of an acceptable gap at the nose of the ramp.

Gap-Out

Termination of a green interval due to an excessive time interval between the actuations of vehicles arriving on the green, so as to serve a conflicting phase.

Gap-Reduction

A feature whereby the allowed time spacing between successive vehicles on the phase displaying the green during the extensible portion is reduced.

Gap/Speed Detector

Component of a merge control system which measures gap sizes and vehicle speeds in the right lane of the freeway.

Gardiner-Lake Shore Corridor

A traffic corridor in the Toronto metropolitan area. Consists of over 13.5 kin of the F.G. Gardiner Expressway and Lake Shore Boulevard into downtown Toronto. Utilizes SCOOT traffic signal control strategy and coordinated response plans for incident management.

General Conditions

That portion of the contract documents which relates to general requirements for execution of a contract, work, supervision of work, public safety, payment, etc.

Generation (First, Second, Third)

Denotes significantly different approaches in control philosophies for computerized traffic signal systems: (1) ***First Generation*** Uses prestored timing plans developed offline based on previously collected traffic data. Timing plans can be selected on the basis of time-of-day, operator selection, or automatic matching of the timing plan best suited for existing traffic pattern conditions. (2) ***Second Generation*** Contains an online optimization process to develop the timing plans in real-time based upon current traffic conditions. (3) ***Third Generation*** Deals with individual intersections on a cycle-by-cycle basis using an area-wide optimization criteria.

Genesis

A Guidestar project examining feasibility using a personal communications device (PCD) for ATIS applications.

Global Variable

A variable applying to the total system.

Goal

Broad statement which expresses long-range overall desires, policies, and positions. (See ***Objective***.)

Government-Furnished Equipment (GFE)

Equipment relevant to a job which is supplied by the governmental body letting the contract.

Green Band

The space between a pair of parallel speed lines which delineates a progressive movement on a time-space diagram.

Green Control

A scheme for controlling an intersection controller assembly whereby a control circuit causes the controller unit to dwell in green intervals until released by the master control unit. Minimum green times and all fixed intervals are timed by the local controller; offset, split, and cycle length are controlled by the master controller.

Green Extension System

Hardware assembly of extended call detectors and auxiliary logic. The logic can monitor the signal display, enable or disable the selected extended call detectors, and hold the controller in artery green.

Guard Band

A region of unused frequencies that separates the different frequency regions assigned within a transmission system. The guard bands facilitate the separation of the signals. (See also ***Frequency Multiplexing***.)

Guide Signs

Signs that inform motorists of directions to common destinations. Roadway identification via route markers and other information.

H

Half Duplex

A communication facility providing both transmission and reception in both directions, but not simultaneously. (See ***Full Duplex*****.)**

Hard Copy

Data permanently recorded on paper, film, etc., for later reference.

Hard-Wired Conflict Monitor

Electrical wiring or circuit in a local controller assembly which acts to prevent certain combinations of signal indications which could result in direct traffic conflicts.

Hardware

The physical equipment in a computer system. (In contrast, see ***Software***.)

Hazardous Material Incident Response

The ITS user service that provides immediate description of hazardous materials to emergency personnel.

Headway

Time or distance spacing between front of successive vehicles, usually in one lane of a roadway.

Hertz (Hz)

A measure of frequency or bandwidth. One Hertz (Hz) is defined as one cycle per second (cps).

Hierarchical System

A system having various levels of priority or preference.

High Data Rate Channel Standards

The American National Standards Institute (ANSI) T1 standard defines data rate of 1.526 Mbps. Standard applies to traffic systems with high data multiplexing and digital video.

High Occupancy Vehicle Priority Controls

The application of control techniques for HOVs on freeways provides preferential treatment for buses, van pools and carpools in the form of travel time advantage and reliability over lower occupancy vehicles. Methods of control include: separated facilities; reserved lanes; and priority access control.

High-Level Language

A computer programming language using familiar, notation, such as English or mathematics, which is easy for the programmer to understand. A high-level language statement will usually generate several machine language instructions. Languages include FORTRAN, C, C + +, ADA.

Highway Advisory Radio (HAR)

Also known as Travelers' Information Stations (TIS). These systems provide travel or roadway information to motorists via their radios set to 530KHz or 1610 KHz in the AM band. The FCC regulates the use of HAR.

Highway User Costs

Highway user costs are the total of vehicle operating costs, travel time, and accident costs.

Hold

A command that retains, the existing right-of-way. A command to the controller unit which causes it to retain the existing green interval.

Hold Controller Command

Is used to guarantee a minimum green time to a phase.

Hold-Online Signal

A signal to an intersection controller commanding it to remain under computer control.

Houston Smart Commuter

An ITS operational test project that is applying a variety of innovative advanced technologies to introduce ITS functions and encourage greater use of high-occupancy commuter modes. Includes 145 North Bus Lane and 110 West Carpool Lane.

HOV Priority Systems

Lane priority assigned to high occupancy vehicles. Techniques on surface streets include: exclusive contra-flow lanes on one-way streets, and exclusive left-turn movements.

Hybrid CMS

A CMS that incorporates both Light Reflecting and Light Emitting message characters.

Hysteresis

A lagging in the return of values to their previous levels, as if from internal friction. Used to describe the delay in recovery of traffic service rate following a breakdown due to congestion.

I

Implementation

The process of bringing a traffic control system from concept to operation. Includes feasibility study, design, and installation.

Implementation Plan

Includes development of a system design, finding qualified source(s), procurement strategy, construction management plan, system startup plan, and operations and maintenance plan.

Impulse Noise

Voltage spikes which are impressed on a line or circuit as a result of momentary voltage surges.

Incident

An occurrence in a traffic stream which causes a reduction in capacity or abnormal increase in demand. Common incidents include accidents, stalled vehicles, spilled loads, etc.

Incident Detection

The arrangement of detectors and processing of detector information to arrive at the decision that some type of incident has probably occurred in the traffic stream. May also be done by visual and third-party reporting means.

Incident Detection Algorithms

Algorithms used to detect incidents based on mainline detector data. Algorithms can be based on pattern recognition, statistics, catastrophe theory, or neural networks.

Incident Management

The coordinated preplanned use of human and technological resources to restore full capacity after an incident occurs and to provide motorists with information and directions until the incident is cleared. This is an ITS user service.

Incident Response Plan

The plan among agencies that establishes the activation, coordination and management of people, equipment communication and information media designed to mitigate the effects of a roadway incident.

Incident Verification

The surveillance function that determines the location and nature of an incident as well as display, recording, and communication to appropriate agencies.

Indemnification

The act of being secured against hurt, loss, or damage.

Indexing

The method of retrieving data elements from arrays.

Indirect Addressing

A method of computer cross reference in which one memory location register, or operand indicates the correct address of the intended location. (In contrast, see ***Direct Addressing.***)

Inductance

That property of an electric circuit or of two neighboring circuits whereby an electromotive force is generated in one circuit by a change of current in itself or in the other. The ratio of the electromotive force to the rate of change of the current.

Induction Cable Antenna HAR Systems

A Highway Advisory Radio (HAR) system that uses a roadside cable. The directional induction radio transmission narrowcasts the radio signals to the width of a multilaned highway.

Inductive Loop Detector (ILD)

A pavement installed active device that senses a decrease in loop inductance during vehicle presence. (See ***Loop Detector System*** and ***Unit***.)

INFORM

A major traffic corridor in the Long Island, NY area with two major freeway facilities Long Island Expressway and Grand Central/Northern State Parkway and several Parallel and crossing arterials and freeways. Includes a total of 136 miles (219 kilometers *)* of controlled roadways over 40 miles (64 kilometers) in length.

Infrared *Detectors*

Passive and active aboveground mounted vices used for pedestrian and/or vehicle presence. Some devices provide counts, speed, length, and queue.

Input

The introduction of data from an external storage medium into a computer's internal storage unit.

Input-Output Study

Determination of the number of vehicles moving into, out of, or being accumulated in a closed system over a given time period.

Input/output (I/0)

A general term for equipment used to communicate with a computer.

Institute of Electrical and Electronics Engineers (IEEE)

Organization that supports ITS for vehicle/road communication protocols, safety critical software, definitions, and terminology. Serves on ITS Standards Coordinating Committee (SCC 32).

Instruction

A set of characters used to define a basic computer operation. An instruction has two basic parts: (1) ***Operand Code* --** Specifies the operation to be performed. (2) ***Operand*** or ***Operand Address* --** Specifies the data or the address of the data to be operated on.

Instruction Repertoire

The set of instructions which the CPU is capable of performing.

Instruction Set

The complete repertoire of instructions that a CPU is capable of performing.

Instruction to Bidders

A contract document that tells each bidder how to prepare a bid so that a fair comparison can be made.

Integrated Circuit (IC)

An electronic circuit containing many interconnected circuit elements formed on a single body, or chip, of semiconductor material.

Integrated System Management

A management process that uses a team approach to the design, installation, operation, maintenance, and upgrade of all the traffic control and motorist information systems in a specific geographic region. Requires coordination, cooperation and teamwork among management, and operating and maintenance personnel.

Integrated Traffic Management System (ITMS)

(1) The system that integrates all hardware and software elements of transportation management within a geographical region. It includes: traffic signal systems; freeway management systems; traveler information systems; and incident management systems. (2) A signal system that consists of a master control assembly at the control center and field controllers. Originally developed by Intersection Development Corporation. Can work with compatible Multisonic, Model 170 or NEMA controllers. (3) A Guidestar project evaluating effectiveness of fully integrated traffic management and control in Twin Cities metropolitan area.

Intelligent Transportation System (ITS)

The collection of transportation services and infrastructure that will implement the goals of ISTEA. The seven categories of service are: travel and transportation management; travel demand management; public transportation operations; electronic payment; emergency management; advanced vehicle control and safety systems; and commercial vehicle operations. ITS uses advanced technologies to provide the range of traffic-based user services.

Interconnect

The communication media usually consisting of electrical cable connecting the system master with local controllers.

Interconnected Signal System

A number of intersections which are connected by wire, radio, or some other means to effect traffic progression.

Interconnection

The topology for connecting data receivers and transmitters into a network.

Interface

A common boundary at which two separate systems or portions of each join or interact. An interface can be mechanical, as in adjoining hardware surfaces, or it can be electrical, as in signal level transformation points. Moreover, it can also refer to human and machine interface and interaction between the operator and the computer.

Intermodal Surface Transportation Efficiency Act of 1991 (ESTEA91)

A Congressional act whose purpose is to develop a National Intermodal Transportation System that is economically efficient and environmentally sound, provide the foundation to compete in the global economy and move people and goods in an energy efficient manner. Provides governmental basis for research and implementation of ITS technologies.

Internal Storage

See ***Processor Storage***.

International Standards Organization (ISO)

International standards setting organization. ITS standards coordinated through ISO TC204 committee, and subordinate working groups. Working groups include quality/reliability, public transport, man/machine interface, general fleet management, commercial fleet management, and integration.

Interrupts

A break in the normal flow of a system or routine such that the flow can be resumed from that point at a later time.

Intersection

The common area of roadways that meet or cross.

Intersection Capacity

Capacity at a signalized intersection is controlled by two factors. Conflict resolution that allocates right-of-way to one line of vehicles while the other waits. Flow interruption for assignment of right-of-way that introduces additional delay.

Intersection Collision Avoidance

The ITS user service that helps prevent collisions at intersections.

Intersection Status

(1) The knowledge of whether a controlled intersection is online or operating in its standby mode. (2) In some systems, the knowledge of whether the intersection is displaying Major Street Green or not. (3) in other systems, the knowledge of the particular indication being displayed.

Interval

A discrete portion of the signal cycle during which the signal indications remain unchanged.

Interval Sequence

The order of appearance of signal indications during successive intervals of a cycle.

Interval Timing

The passage of time which occurs during an interval.

Invitation for Bid (EFB)

In selecting the contractor for system installation, it is required that an invitation for bid be released and that all qualified contractors be permitted to submit proposals. The IFB process then requires that the local agency select the contractor who has submitted the lowest and best bid.

Invitation to Bid

A contract document that contains a brief summary of the project along with bidding and construction procedures.

Isolated Actuated Intersection Control

A fully-actuated controller design that uses small and large-area detectors to cost-effectively optimize traffic flows at isolated intersections.

Isolated Controller Assembly

A controller assembly for operating traffic signals not under master supervision.

Isolated Intersection Control

A type of control that operates an intersection signal independent of other adjacent intersections and conditions.

Isolated Local Controller

A local controller that is a standalone unit and times right-of-way assignments independently of other controllers.

Isolated Ramp Metering Pretimed

A strategy based on coordination of time-of-day metering for a selected set of entrance ramps. Distributes the metering task over a number of upstream ramps.

ITS America

A nonprofit public/private organization chartered as an advisory committee to the U.S. DOT. Its mission is to advance a national transportation program through development and implementation of advanced technology. Founded in 1991.

ITS National Plan

The plan that provides a commonly shared vision of how development and deployment of ITS services in a nationally compatible intermodal system will address highway and public transportation operational problems.

ITS Planning Process

The planning process for developing and deploying the ITS user services within a particular transportation planning region or transportation mode. A major output of the planning process are User Service Development Plans describing activities needed to deploy each service.

ITS Strategic Plan

The plan developed by the U.S. DOT and submitted to Congress. It sets forth the goals, milestones, and objectives of the Transportation Department to implement ISTEA.

J

Jam Density

Density at which congestion on a roadway causes traffic flow to stop.

Japan Digital Road Maps Association (JDRMA)

The association that prepares and maintains the national digitized roadmap database for Japan.

Jump Instruction

A computer instruction whose execution causes the address portion of the instruction to overlay the content of the location counter. This causes a departure from the normal sequence of executing instructions. (Also called a ***Branch Instruction*** or a ***Transfer Instruction***.)

K

Keyboard

An array of keys which, when depressed, cause the generation of a specific character or symbol in electrical, printed, or other form. Used in conjunction with appropriate gating elements, the keyboard permits the generation of coded symbols for interpretation by, or storage in, the computer. Thus, the keyboard may be part of a manual input device for a computer, a keypunch, a CRT, a paper tape perforator, or part of an electric typewriter.

KHz

Kilohertz, or thousands of hertz. Hertz means cycles per second, a measure of frequency.

Kinetic Energy

Relative to a traffic stream, kinetic energy is the product of volume and speed (or the product of density and the square of the speed). Usually expressed in terms of vehicle-miles per hour (vmh or vm/hr) (vehicle-kilometers per hour).

L

Lamp Matrix Sign

An array of incandescent lamps for each message line forms the face of a lamp matrix display. Selectively illuminating the lamps in a character module permits the display of characters to form a message.

Lane Closure & Lane Control

(1) A strategy that prohibits entry to one or more freeway mainlines. Lane control provides a mechanism to assist in reversible lane control. (2) A concept of mainline control which prohibits travel on particular lanes of a freeway.

Lane Control Signal Displays

Signal Displays for lane controls include steady downward green arrows (lane permitted for use) and steady red "x" (lane not permitted for use).

Lane Control Signals

A special signal that permits/prohibits use of specific street or highway lanes.

Lane Occupancy

A measurement of vehicle presence within a zone of detection, usually expressed as the percent of time a given point or area is occupied by a vehicle.

Lane Use Control Signs

Special overhead signals having indications to permit or prohibit the use of specific lanes or the impending prohibition of use. Reversible lane control is the most common use of lane control signs. The MUTCD defines the features of these signs.

Language Translator

A computer program used to translate a source language program into a machine language program.

Large Scale Integration (LSIO

In integrated circuitry, a silicon chip with more than 1,000 logic elements.

Large-Area Detectors

Devices that register vehicle presence in a detection zone as long as a vehicle is present.

Last Car Passage

A selected feature of a volume-density controller unit which, upon gap-out or max-out, will cause the timing of a full extension unit rather than the reduced gap time before terminating the green interval. The last vehicle to have been detected, known as the ***Last Car***, will therefore retain the green until it reaches the stopline. Thus, it is assured of avoiding the dilemma zone problem and of clearing the intersection.

Latent Demand

Total number of potential users desiring to use a facility (street or freeway) at a given point.

Lateral Collision Avoidance

The ITS user service that helps prevent collisions, when vehicles leave their lane of travel.

Lateral Detector Placement

Detector positioning across the traffic lanes to obtain highest lane approach volume.

Lead-In Cable

The electrical cable which serves to connect the lead-in wire to the input of the loop detector unit. (Sometimes called a ***Home-Run Cable*** or ***Transmission Line.)***

Lead-In Wire

That portion of the loop wire between the physical edge of the loop to the splice box; for a magnetic detector and magnetometer it is the wire which runs from the sensor (probe) to the splice box.

LED/Flip Disk Sign

The hybrid LED/flip disk sign stems from electromagnetic reflective disk matrix technology. In this case an LED provides the light for the opening in the reflective sign face. The black face blocks all light.

Left-Turn Phasing

The phasing options for controlling left-turning traffic. Includes: traffic actuated left-turn phase; protected/permissive left-turn phase; and left-turn phase sequence with timing plan.

Legibility

A measure of a motorist's ability to read the sign's legend.

Level of Service

Defines operating conditions that may occur on a given lane or roadway when it is accommodating various traffic volumes. It is a qualitative measure of the effect of a number of factors including speed, travel time, traffic interruptions, freedom to maneuver, safety, driving comfort and convenience, and operating costs. In practice, selected specific levels are defined in terms of particular limiting values of certain of these factors.

Liaison Council for ITS/RTT Japan

Liaison information exchange inside and outside Japan.

Light Emitting CMS

A CMS that incorporates message characters that emit directly to the motorist, light generated within the sign itself.

Light Emitting Diode Matrix Signs

LED sips can be constructed in a clustered or discrete format. The clustered format consists of LEDs encapsulated closely together to form a removable pixel fixture. The discrete format mounts individual LEDs to a sign face, groups of them mounted to form pixels.

Light Emitting Non-Matrix

This sign, also called a blank-out sign, offers a fixed selection of messages. Messages are selected by activating the correct light source.

Light Emitting Signs

The messages are formed by lighted pixels or characters against a dark or black background. When all light sources are out, no message is visible.

Light Emitting-Matrix Sign

These signs use matrices of pixels, each pixel representing an individual light source. Characters and messages form by activating the appropriate pixel/light source.

Light Reflecting CMS

A CMS that incorporates message characters made from materials which reflect light back to the motorist from an external source. Device is based on electromechanical technology.

Light Emitting Diode (LED)

A solid state device with illumination properties similar to that of a low power incandescent lamp.

Line Adapter

Another term for a ***Modem.***

Line Printer

A printer in which an entire line of characters is printed at once. Line printers are used to print large volumes of information as well as specific formatted reports and other data developed during the operation of the computer control system.

Link

(1) ***Computer*** -- A process to gather or write two or more separately written, assembled, or compiled program or routines into single operational entities. Some computer systems have special programs called linkage editors to connect address components into symbols or to perform relocation to avoid overlapping. (2) ***Traffic*** -- The length of roadway between two signalized locations. (3) ***Communications*** -- Another term for ***Channel.***

Listing

(1) ***Higher Order Language -- A*** listing of the source program(s) which reflect the computational processes. (2) ***Assembly Language*** -- An optional binary-output program of the compiler. The listing contains the symbolic instructions equivalent to the binary-code output of the assembler. This assembly-output listing is useful as a debugging aid.

Loader

A user-assistance software program which loads the object program into memory for execution. The loader also links subroutines and manages overlay modules.

Local Controller Assembly

A controller assembly supervising the operation of traffic signals at a single intersection. (Also see ***Controller Assembly*** and ***Controller Unit)***

Local Controller: Pretimed

A device that controls all timing intervals to a fixed predetermined plan. Works best where traffic is predictable and constant.

Local Controller: Full-Actuated

A device that controls the length of all timing intervals based on detected traffic demand on the associated approach. Adjusts cycle and split to fit changing demands.

Local Controller: Semi-Automatic

A device that controls some approaches on the basis of detected traffic demand. Non-actuated phases receive minimum green interval that extends until interrupted by actuation on other phases.

Local Controller: Volume-Density

A device that is programmed to control the intervals on selected approaches and phases based on evaluation of approach traffic conditions. Can have added intervals and a reducible gap feature.

Local Coordinated Strategy

A strategy that selects and adjusts ramp metering rates based on local conditions such as traffic signal timings at each interchange.

Local Exchange Carriers

The local provider of the standard twisted pair communication channel and other standard communications channels. Can be the local telephone or cable company.

Local Signal Preemption

The emergency or transit vehicle transmits a signal to the intersection controller where a special control phase assigns right-of-way.

Local Traffic intersection Controller

An electromechanical or electronic device that controls the signals at a single intersection, closely spaced multiple intersections, and mid-block crosswalk.

Locking Detection Memory

A selectable feature of the circuit design for a controller phase whereby the call of a vehicle arriving on the red (or yellow) is remembered or held by the controller after the vehicle leaves the detection area until it has been satisfied by the display of a green interval to that phase.

Logic Element

The smallest building block is a computer that can be represented by a logical operation in an appropriate system of symbolic logic.

Longitudinal Collision Avoidance

The ITS user service that helps prevent head-on, rear-end or backup collisions between vehicles or vehicles and objects or pedestrians.

Longitudinal Detector Placement

Detector positioning on a roadway link between two intersections. Placement is influenced by link lane-changing behavioral and source/sink locations.

Longitudinal Redundancy Check

An error code with an additional word is provided after an entire message or portion of a message (block). A bit in the new word is computed from the corresponding bit in each data word in a way similar to the parity check.

Loop

A sequence of computer instructions that is executed repeatedly until a terminal condition prevails.

Loop Detector

See ***Inductive Loop Detector***.

Loop Detector System

A vehicle detector system that senses a decrease in inductance of its sensor loop(s) during the passage or presence of a vehicle in the zone of detection of the sensor loop(s) . Means the same as loop detector but is clearer in its inclusion of the wire as well as the electronics package.

Loop Detector Unit

An electronic device which is capable of energizing the sensor loop(s), of monitoring the sensor loop(s) inductance and of responding to a predetermined decrease in inductance with an output which indicates the passage or presence of vehicles in the zone of detection. It is the electronics package, exclusive of the loop(s) and lead-in wire.

Loop Occupancy Control

A detector/controller unit design using long detection loop(s) (normally 30 ft (9 in) or longer), and a controller unit operated in the non-locking mode. A loop occupancy controller unit may, but need not necessarily, be designed to rest in all red in the absence of any traffic demand.

Loop System

A combination of loops of wire connected through transmission lines (lead-ins) to the detector input terminals.

Low-Level Language

A computer programming language that Is closely related to machine language. A low-level language statement will usually generate a single machine language instruction.

Low-Power Radio

Noncommercial radio used for driver communication.

M

Machine Independent

A term used to indicate that a source program written for a particular computer can also be translated for and executed on other computers. (i.e., follows open system standards)

Machine Language

(1) A set of symbols, characters, or signs, and the rules for combining diem, that conveys instructions or information to a computer (2) A language that can be directly interpreted by the control section of the machine (3) Information or data expressed in code that can be read directly, used, or written by the computer or peripheral machines without further processing. (See ***Assembly Language*** and **Compiler** ***Languag****e.)*

Magnetic Detector

A pavement installed device of coiled wire with a highly permeable core. Vehicle induced flux changes causes an induced voltage pulse. Not to be confused with a magnetometer detector.

Magnetic Gradient Vehicle Detector (MGVD)

A device which uses a magnetic principle to detect vehicles.

Magnetic Tape

A tape with a magnetic surface on which data can be stored by selective polarization of portions of the surface.

Magnetic Tape Unit

A computer peripheral device which is used to transmit data to and from a magnetic tape. (Same as ***Tape Drive****.)*

Magnetometer Detector

A pavement installed device that detects change in the vertical component of the earth's magnetic field caused by presence of a vehicle. Not to be confused with a magnetic detector.

Mainline

The freeway proper as distinguished from the entrance ramps, exit ramps, and interchange geometry of the freeway.

Mainline Control

A strategy for the regulation, warning and diversion of mainline freeway traffic. Techniques used include: changeable message signs; variable-speed limit signs; reversible lane control; and controls for incident management.

Mainline Metering

A strategy that restricts traffic flow on a freeway. It is used to mitigate specific freeway conditions. Situations include: to deter traffic from freeways in bottleneck areas; equitable distribution of delay penalties; and minimize emissions in environmental area.

Maintenance Assistance

A contractor support service that must be clearly specified by the bid package when required after system acceptance.

Maintenance Level

An indicator of system condition expressed in terms of hours of maintenance per year.

Maintenance Rate of Increase

An indicator or system condition expressed as maintenance time per intersection averaged over some time period, usually a year.

Maintenance Skill Requirements

Personnel skills for maintenance include: computer and communications equipment; traffic equipment; technicians; and software maintenance programmers.

Major Street Green (MSG)

Data sent from the intersection controller to the computer indicating that the controller is displaying a green signal to the main traffic phase. Commonly referred to as ***A-Phase Green.***

Malfunction

Any event that impairs the operation of a control system without losing the display and sequencing of signal indications to all approaching traffic.

Man-Machine Interface

A device, usually combination of a CRT, keyboard, or control panel, which allows the system operator to communicate with the computer system. In some cases, a specialized language is termed a ***Man-Machine Interface*** because of its ability to simplify the conversion between the system and its operator.

Manifest Demand

The number of users observed to use (or actually using) a facility (street or freeway) at a given point.

Manual Intervention

The ability of the system operation to manually select certain system operations when warranted.

Manual of Uniform Traffic Control Devices (MUTCD)

The manual that is the principal source of standards for static signs. Provides guidance in the areas of: use; application; placement; and operation and maintenance.

Manual Pattern Selection (MAN)

Signal timing plans selected manually by the operation of a computerized traffic control system. Manual selection is higher priority than a other modes of plan selection.

Map Display

A device which graphically portrays the geometric representation of the system of streets under control. Indicators represent signalized intersections or freeway locations which may display various information provided by the computer system.

Mass Storage

A memory device capable of retaining large amounts of data. (See ***Disk, Magnetic Tape unit)***

Master Controller Assembly

A controller assembly for supervising multiple secondary controller assemblies and/or multiple submaster controller assemblies.

Master Controller Commands

Time-based commands occur during each background cycle to guarantee a green interval for each non-actuated phase and to select time slots for each remaining actuated phase. Commands include force-off, hold, and yield.

Master-Secondary Controller Assembly

A controller assembly operating traffic signals and providing supervision of other secondary controller assemblies.

MAXBAND

Arterial timing program that optimizes bandwidth based on a mixed integer linear programming technique

Maximum Extension

For a fully-actuated controller, the length of time that a phase may be held in green in the presence of an opposing serviceable call.

Maximum Green

In actuated controllers, the longest time for which a green indication will be displayed in the presence of a call on an opposing phase.

Maximum Limit

The maximum green time after an opposing actuation, which may start in the initial portion.

Mean Time Between Failures (MTBF)

The average length of time for which the system, or a component of the system, works without fault.

Mean Time to Repair (MVIR)

When the system or a component of the system develops a fault, this is the average time it takes to correct the fault.

Mean Velocity Gradient

Computed acceleration noise divided by the mean speed.

Measures of Effectiveness (MOE)

The quantitative variables derived from traffic measurements that measure the improvement in traffic operations from a single intersection to a complete system. Common MOEs are: total travel time; total travel; number and percent of stops; delay; average speed; accident rate; and throughput.

Medium Scale Integration (MSI)

In integrated circuitry, a silicon chip with between 100 and 1,000 logic elements. (Also see ***Integrated Circuit*** and ***Logic Element****.)*

Memory

(1) ***Detector Memory* --** The retention of an actuation for future use by the controller unit assembly. The phrase might better be detection memory to make it clearer that the memory is within the controller, not the detector. *(2)* ***Non-locking Memory* --** A mode of actuated-controller unit operation which does not require memory. In this mode of operation the call of a vehicle arriving on the red (or yellow) is forgotten or dropped by the controller as soon as the vehicle leaves the detection area. (3) Also used to indicate computer memory

Memory Chip

An integrated circuit used for computer memory.

Memory Cycle Time

The interval between the call for, and the delivery of, information from a computer central memory. (See ***Access Time***.)

Memory Off

A selectable feature of an actuated controller, synonymous with nonlocking detection memory.

Memory Protect

Computer hardware which will prevent the accident or deliberate destruction of certain parts of memory.

Merge Control

Concept of entrance ramp metering which guides ramp vehicles into acceptable gaps in the freeway traffic stream.

Merge Detector

A detector used to sense the presence of vehicles in the primary merging area of the ramp and freeway mainline.

Metered Ramp By-Pass

Bypass lanes provided at ramp metering locations so that buses, van pools, and carpools avoid ramp queue delay.

Metering

Traffic control method or technique for regulating traffic flow.

Metering Rate

Number of vehicles allowed to enter a given section of a roadway per unit time.

Microcomputer

A programmable computer whose CPU is a microprocessor.

Microprocessing Unit (MPU)

The processor chip used in any microprocessor.

Microprocessor Optimized Vehicle Activation MOVA)

An advanced control strategy, developed in the United Kingdom. It provides self-optimized control of signal timing at isolated intersections with eight or fewer phases.

Microprogramming

(1) The technique of using a certain special set of computer instructions that consist only of basic elemental operations which the

programmer can combine into higher-level instructions as he/she chooses, and can then program using only the higher level instruction. (2) Machine language coding in which the coder builds his/her own machine instructions from the primitive basic instructions built into the hardware.

Microsecond

One millionth of a second.

Millisecond

One thousandth of a second.

Minimum Acceptable Gap

Smallest time headway between successive vehicles in a traffic stream into which another vehicle is willing, and able, to merge.

Minimum Green Interval

The shortest green time of a phase. If a time setting control is designated as minimum green, the green time shall not be less than that setting. For a fully-actuated controller, the first timed portion of the green interval. It is set considering the number of waiting vehicles between the approach detector and stopline.

Minnesota Guidestar

The ITS program for the state of Minnesota. It seeks to develop a statewide intelligent transportation system. Major Guidestar projects are: Genesis, an application of a personal communications device for ATIS applications; Travelink, evaluates effectiveness of enhanced transit information on influencing commuter mode choice and increasing HOV travel; ITMS, evaluates effectiveness of fully integrated traffic management and control in Twin Cities metropolitan area; Rural ITS, evaluates effectiveness of ITS applications an a rural environment.

MOBFLE5C

An EPA developed computer program that calculates emission factors for eight vehicle types based on calendar year, ambient temperature, average speed and engine operating temperature

Model 170 Controller

One of two types of most commonly installed and available intersection controller. Specifications jointly developed by California and New York. Specifications include sections on electronic modules, connectors, wiring, harnesses, and cabinet enclosures.

Model 2070 Advanced Transportation Controller

The next generation of traffic signal controller under development by California DOT. A microprocessor based controller using OS9 real-time operating system, with VERSA Module Eurocard (VME) backplane and Motorola 680X0 processor family.

Modem

A modulator/demodulator device that prepares data for transmission and accepts data at reception. Provides interface between computer and field equipment, such as the model 170 and NEMA controllers.

Modification Maintenance

Task that becomes necessary to fix a manufacturing design flaw or change needed to improve equipment characteristics.

Modulation

The process whereby information is superimposed on another signal for the purpose of transmitting the information over a communications link. The desired information is retrieved by a demodulation process.

Module

(1) ***Software* --** A program unit that is discrete and identifiable with respect to compiling, combining with other units, and loading, e.g., the input to, or output from, an assembler, compiler, linkage editor, or executive routine. (2) ***Hardware* --** An assembly of electronic or other equipment mounted in a single enclosure.

Monitor

A device that verifies the operations of a data processing system and indicates any significant departure from the norm.

MOST

A five-volume book set that explains signal timing and analysis techniques. Includes discussion of all major programs.

Motorist Aid Systems

A motorist aid system assists the detection of stranded motorists, offers means to communicate their needs, arid provide appropriate aid response. Types of systems are call boxes, cellular telephones, citizen band radio and CCTV systems.

Motorist Aid Telephone System

A telephone system with a handset that allows the person reporting to relay unique event information.

Motorist Call Boxes

A call box consists of a switch or toggle that signals the operating agency via phone line that am incident has occurred. The box may have message buttons to indicate the type of assistance required.

MOVA Detection

Detector configuration that requires two sets of loops for each approach of an isolated intersection that implements MOVA strategy.

Moving Head Disk

A mass storage device using a sensing head which moves over the storage medium.

Multi-Jurisdictional Traffic Management

The management of traffic and transportation systems across multiple agency jurisdictions with memorandums of understanding to effect cooperation.

MULTIBAND

Arterial timing program that tailors progression and bandwidth to traffic flow patterns on a link to link basis.

Multidrop Connection

The connection of more than two data receiver/transmitter stations to a single communications link. Special control signals must then be used to allow communication between the proper units. A multidrop connection is a topology that connects two or more receivers on the same channel (link). (See also ***Point-To-Point Connection**.)*

Multilevel Control

Form of traffic signal control which uses a hierarchical arrangement of control units.

Multipath Fading

Attenuation of an RF signal due to interference between a direct wave and a reflected wave. Multipath can introduce attenuation in excess of 30 dB.

Multiple Processor Configuration

Multicomputer control system consisting of two or more central processing units. Each CPU can perform a particular set of functions or can control part of the traffic signal system.

Multiplexed DC

A multiplex method which uses a combination of DC voltage amplitudes to transmit or receive messages.

Multiplexer (MUX)

A device which uses several communication channels at the same time, transmits and receives messages and controls the communications lines. This device may or may not be a stored program computer.

Multiplexing

The combining of several signals into one channel.

Multipoint Channels

Communications links (cable runs) which are wired in parallel and multiple sending/receiving stations. Every message to or from any incorporated sending/receiving station is transmitted over the same cable pair.

Multiprocessing

Ability of computer operating system to process more than one programmed task at the same time.

Multiprocessor

(1) A control configuration in which more than one CPU is used. (2) A computer with multiple arithmetic and logic units which can be programmed to run more than one task simultaneously.

Multiprogramming

A situation wherein two or more programs are simultaneously competing for the resources of the CPU.

N

Nanosecond

One billionth of a second.

National Ambient Air Quality Standards

The air pollution standard for the United States from all polluting sources. Vehicle related emissions are controlled as a part of this standard.

National Traffic Control / ITS Communication Protocol (NTCIP)

A proposed open standard protocol for communication between traffic controllers. Adoption of this standard by NEMA and manufacturers will open the traffic network to equipment interchangeability.

National Cooperative Highway Research Program (NCBRP)

An agency administered by the Transportation Research Board for conducting research in the various highway construction, design, and operation disciplines.

NEMA TS21992 Controller

One of two types of most commonly installed and available intersection controller. Adopted by electrical equipment manufacturers. Standard provides operational and electrical requirements for a pretimed and two full-actuated controllers. Type 1 actuated controller standard uses communication ports in place of MS connection. Type 2 actuated controller upgrades the 1983 NEMA TS1 standard.

Neon Sign

This sign uses noon tubing to form legend characters. The sign display area limits the number of allowable messages.

NETFLO Level I

This program is an event based urban network simulator of traffic operations. It is a macroscopic model that does not employ car-following logic. Vehicles move when events occur.

NETFLO Level II

This program was adapted from the TRANSYT flow model. Link specific statistical flow histograms are used to describe the platoon structure of the traffic flow on each network link.

NETSIM

A simulation program originally called UTCS-l.

Network Signal Control

Control techniques that are applicable to a signalized roadway grid network. Grid network imposes control constraints including common cycle lengths and closed loop slim of offsets that must be an integral number of cycle lengths.

Network System Control

A type of control applied to a central business district grid. Prevalent local control is pretimed and/or coordinated across all signals in network.

Noise

Random variations of one or more characteristics of any entity such as voltage, current, and data. Generally, any disturbance tending to interfere with the normal operation of a device or system.

Non-Locking Detection Memory

Controller feature that sets phases through loop occupancy control using large area presence detectors. Waiting calls are dropped when vehicle leaves detection zone.

Non-Restrictive Ramp Metering

A form of ramp metering that standardizes vehicle release rates in order to smooth ramp platoons and improve merge safety.

Non-congested

Absence of congestion, which is sometime arbitrarily defined as a function of traffic variables such as volume, speed, and density.

Non-Directional Detector

A detector capable of being actuated by vehicles traveling in either direction.

Non-recurrent Congestion

Type of congestion resulting from the occurrence of random or unpredictable events.

Notice of Award

The written notice to the contractor by the owner that the contractor is the successful bidder and that, upon compliance with certain contract requirements (e.g., furnishing bonds, etc.), the owner will execute and deliver an agreement to the contractor.

Number of Stops

Measure of effectiveness (MOE) of control systems which is an estimate of the number of vehicles stopped by traffic signals.

O

O&M

Operation and Maintenance.

Object Program

The machine language equivalent of a source program. The output of a language translator. A program that is ready to be loaded.

Occupancy

Percent of time that a point on roadway is occupied by a vehicle.

Occupancy Control

Traffic responsive control strategy whereby metering rates are selected on the basis of real-time occupancy measurements taken upstreain or downstream of the entrance ramp.

Offline

Descriptive of a system, peripheral equipment, or a process under control of the central processing unit. (See ***Offline***.*)*

Offset

The time relationship expressed in seconds or percent of cycle length, determined by the difference between a defined interval portion of the coordinated phase green and a system reference point.

Offset Selection

Choosing one of several possible offsets manually or automatically either by time-of-day or in response to some directional characteristic of traffic flow.

Online

Descriptive of a system, peripheral equipment, or a process under control of the central processing unit. (See ***Offline***.)

Online Arterial Control Systems

Control techniques designed for arterial highways and service roads. includes: DARTS; ACS; Actuated Controllers with Background Cycle; and Field Master Based Systems Signal.

Online Optimization

A method by which a process, i.e., traffic signal plan, is continually recomputed in real-time to seek the best obtainable set of operating conditions.

Online Signal Control Techniques

The algorithm embedded in the signal control system that control the signal arterial or network in real-time. Includes time-of-day and traffic responsive techniques.

Onboard Safety Monitoring

The user service that, monitors and records the safety status of a commercial vehicle and driver.

OPAC

The Optimized Policies for Adaptive Control; an adaptive traffic control technique.

OPAC Detection

Detector configuration used for isolated intersection control based on an OPAC strategy. Uses upstream detectors to project vehicle arrivals at downstream intersection.

Open Specifications

Specifications written so as to allow several manufacturers to bid on materials and equipment.

Open-Loop Signal System

A system that supervises the intersection controller functions but does not receive feedback station information.

Open-Loop System

Pertaining to a control system in which there is no self-correcting action or feedback as there is in a closed-loop system.

Operating System

Computer software that performs the function of organizing and controlling the overall execution of the application software.

Operation Code (Opcode)

The portion of a computer instruction which designates the operation to be performed such as: Add; Subtract; Input; Output; and Logical Operations.

Operational Delay

Time lost as a result of interference between components of traffic. Included are delays caused by traffic movements that interfere with stream flow, such as: parking and unparking vehicles; pedestrians; stalled vehicles; double parking; cross traffic; and merging/weaving maneuvers.

Optical Communications Interface Standard

The ANSI T1 standard (post-1988) is called synchronous optical network (SONET). Defined in terms of optical carrier type N (OC-n) with DS 3 equivalents. OC-3 specifies a bit rate of 155.52 Mbps.

Optical Dispersion

The spreading of the light pulses determine the information carrying capacity or bandwidth of the fiber. Dispersion limits the data transmission speed.

Optical Video Transmission

Video signals may be transmitted using fiber optics: (1) ***Baseband*** **--** Unmodulated video signals (2) ***Modulation*** **--** Extends the transmission range using AM or FM. (3) ***Multiplexed*** **--** Enables transmission of a number of video signals on the same fiber.

Optimization Programs

Programs that compute and evaluate the effects of various sets of signal timing on vehicle flow within a given network. These pro grams determine optimal timing plans and/or evaluate a given timing plan.

Optimized Policies for Adaptive Control (OPAC)

An advanced control strategy, developed at the University of Massachusetts. It provides self-optimized control at isolated intersections, annual coordination of adjacent traffic signals, and can serve as part of an interconnected system.

Optimum Density

Traffic flow density (or concentration) which corresponds to maximum volume of traffic flow on a particular roadway.

Optimum Speed

Traffic flow speed (vehicle movement) which corresponds to maximum volume of traffic flow on a particular roadway.

Origin-Destination Survey

Survey to determine the point of origin and the point of destination for a given vehicular trip

Out-of-Step

A term used to describe a condition when one or more of the controller assemblies are not in coordination with the control system.

Output

Data transferred from a computer's internal storage unit to an external storage device or output device.

Overheight Vehicle Control Systems

A control system that provides warning of over-height vehicles approaching transportation structures (i.e., bridges, tunnels). System consists of over-height vehicle detectors and warning message devices.

Overlap

A right-of-way indication that allows traffic movement when the right-of-way is being assigned to two or more traffic phases.

Overlay

In a computer, the technique of repeatedly using the same blocks of internal storage during different stages of a program; e.g., when one routine is no longer needed in internal storage, another routine can use the same storage area.

P

Parallel Transmission

All bits of the data byte or word are transgression considering various multiphase transmitted simultaneously. Used for short distance and fast data transfer. Requires a separate link for carrying each bit.

Parameter

(1) A quantity in mathematics that may be assigned any arbitrary value and that remains constant during some calculation. (2) A definable characteristic of an item, device, or system.

Parity

An error code that adds an additional bit to each data word. The sum of the 1s in the word and the extra bit must be odd or even as specified. At the receiver, the bits in each received character are checked to see that an odd (even) number of one bits per character is received in order to detect errors in the received data.

Passage Period

The time allowed for a vehicle to travel at a selected speed from the detector to the nearest point of conflicting traffic.

Progression Analysis and Signal System Evaluation Routine (PASSER)

An automated computer program for calculation of intersection signal timing plans.

PASSER II-90

Arterial timing program that optimizes progression considering various multiphase arterial signal operations.

PASSER III-90

A computer program designed to assist in the analysis of pretimed or traffic-responsive fixed sequence signalized diamond interchanges. Runs on IBM-compatible PCs.

PASSER IV

A computer program that evolved from MAXBAND. Optimizes signal timing in grid networks, based on maximizing platoon progression.

PATH Program

A program for development of ATMS, ATIS, and AVCS evaluation test beds in Orange County and San Francisco Bay areas of California. Organized by CALTRANS and the Institute of Transportation Studies at University of California at Berkeley.

Pattern

See ***Timing Plan*.**

Pattern Generation

See ***Plan Generation.***

Pattern Matching

See ***Plan Selection.***

Payment Bond

Bond guaranteeing contractor's payment for materials, equipment, labor and other items associated with the project.

Pedestrian (WALK) Interval

The interval used to initiate the assignment of pedestrian missing time

Pedestrian Clearance (DONT WALK) Interval

The interval that provides time for a pedestrian to leave the curb and travel to other curb before opposing vehicles receive a green indicator.

Pedestrian Crossing Detector

Vibrating plate device to indicate right of way for blind and/or deaf pedestrians.

Pedestrian Detector (Pushbutton)

A pole mounted momentary switch which, when activated by a pedestrian, causes a pulse which notes the demand by a pedestrian for the right-of-way.

Pedestrian Phase

A traffic phase allocated to pedestrian traffic which may provide a right-of-way indication either concurrently with one or more vehicular phases, or to the exclusion of all vehicular phases.

Pedestrian Signal Control

A type of midblock isolated control that is used when pedestrian crossing can not be accommodated at nearby intersections.

Pedestrian-Actuated Controller Assembly

A controller assembly in which intervals, such as pedestrian WALK and clearance intervals, can be added to or included in the controller cycle by the actuation of a pedestrian detector.

Performance Bond

Bond guaranteeing contractor's completion of the project.

Peripheral Equipment

Various units or machines that are used mainly for input-output in combination or conjunction with the computer but are not part of the computer itself.

Personal Portable Advanced Traveler Information System (FPATIS)

Hand-held devices that assist travelers with planning and execution of all modes of ground transportation. Functions include communication, database, location, and navigation.

Personalized Public Transit

This user service provides flexibly routed transit vehicles that offer more convenient service to customers.

Phase

The portion of a traffic cycle allocated to any single combination of one or more traffic movements simultaneously receiving the right-of-way during one or more intervals. (See ***Traffic Phase***.)

Phase Modulation (PM)

A technique to transmit information using signal phase. The *carrier* signal has its phase changed in accordance with the information to be transmitted. Can vary the phase of the carrier signal (relative to a constant phase reference signal) to represent binary signal values.

Phase Sequence

A predetermined order in which the phases of a cycle occur.

Phase Shift Keying (PSK)

A modulation method employed to transmit data. The technique of differentially coherent phase modulation is generally used as it eliminates the difficulty of deriving a reference phase. In such a system, each signal element is stored one element at a time and the phase change between successive elements provides system coherence and the desired reference.

Pickup Procedures

The orderly processes or operations which are performed to bring a controller assembly under control of the system master.

Pixel

The smallest area on the screen of a graphics CRT display that can be discretely displayed by the system. Pixel is an abbreviation of ***Picture Element***. More generally, can be the smallest discrete element of an image.

Plan Generation

The process of computing the traffic parameters forming a timing plan from accumulated traffic data and the area geometry.

Plan Matching

A technique used to select a timing plan based on comparing measured traffic data with stored data associated with a stored timing plan.

Plan Selection

Choosing one of several different timing plans, from a library of timing plans, either manually, or automatically as a function of time-of-day or traffic-responsively.

Plans, Specifications and Cost Estimates (PS&E)

The PS&E are the design documents, hardware/software specifications, and cost estimates suitable for competitive bid.

Point Detection

The detection of vehicles as they pass a specific point on the roadway. Detection by pressure and magnetometer detectors are typical examples. Frequently referred to as *small-area detection.*

Point-to-Point Interconnect

Simple topology where separate links are provided between receiver and transmitters.

Polar Loop

A form of direct-wire linkage wherein the ON/OFF conditions are represented by DC voltages of opposite polarities. (See ***DC Multiplexing***.)

POLIS

The European ITS field test Promoting operational Links with Integrated Services through RTI between European cities.

Polling System

A communications system that uses a systematic method, centrally controlled for permitting stations on a multipoint circuit to transmit without contending for the interconnect line.

Power Budget

The budget is the difference between the signal power transmitted into the channel and the signal power required for proper operation at the receiver after passing through the physical medium.

Power Fading

Attenuation of an RF signal due to absorption by water vapor causes a power loss at the receiver.

Powerhead Loop Detection

Detector configuration that has increased detection sensitivity for small-vehicles. Uses small internal loops of wire at stopline end of long loops.

Pre-Crash Restraint Deployment

This ITS user service anticipates an imminent collision and activates passenger safety systems before the collision occurs.

PreTrip Travel Information

The ITS user service that provides information for selecting the best transportation mode, departure time, and route.

Preemption

The transfer of the normal control of signals to a special signal control mode.

Preemption/Priority Systems

Preemption control of normal signal timing plans applies in the following situations: signals adjacent to railroad crossings; emergency vehicle priority movement and priority for transit vehicle. Preemption occurs on a single cycle basis.

Preemptive Devices

Provide priority for fire and emergency vehicles by detecting the vehicle and sending the preemption command to the controller.

Preliminary Traffic Engineering Analysis

An analysis that examines the present traffic situation in detail and identifies the problem to be addressed. Specific factors include: Controlled Area; Operating Characteristics; Transportation Characteristics; Existing System Resources; and System Objective.

Prequalification

The process by which prospective bidders must prove their financial and technical capabilities to implement the proposed system before their bid will be accepted.

Presence Detection

The sensing of a vehicle passing over a detector. True presence is when the pulse duration is equal to the actual time the vehicle remain in the detector field of influence.

Presence Detector

Traffic detector which is able to detect the presence or absence of a vehicle within its field of detection.

Presence Holding Time

The time that a detector system will continue to indicate the presence of a vehicle over one of its loops without adjusting to consider the vehicle in a new environment. Upon making this adjustment, the actuation is terminated.

Presence Loop Detector

An induction loop detector which is capable of detecting the presence of a standing or moving vehicle in any portion of the effective loop area.

Pressure Detector

A pavement installed device that is activated by vehicle weight.

Pretimed Controller Assembly

A controller assembly for the operation of traffic signals with predetermined fixed cycle length, fixed interval duration, and fixed interval sequence.

Pretimed Intersection Control

Assigns right-of-way according to a fixed predetermined schedule.

Preventive Maintenance

Task that includes work done at scheduled (PROM) intervals to minimize probability of failure.

Probe

(1) The sensor form that is commonly used with a magnetometer-type detector. (2) A vehicle in the traffic stream used for acquiring traffic flow data.

Process Control Computer

A computer whose primary purpose is to provide automation of continuous operations.

Processor Storage

A storage device which can hold data and instructions for immediate retrieval by the CPU. Each byte or word of a storage device is directly accessible. (Also called ***Memory*** or ***Internal Storage****.)*

Procurement Analysis

Evaluation and selection of procurement options based on specific needs of traffic agency and jurisdictions. Planning is necessary to smoothly transition from old to new control.

Program

A series of instructions or statements, in a form acceptable to a computer, prepared in order to achieve a certain result.

Programmable Read-Only Memory Presence

A device that stores data which cannot be alerted by computer instructions. Data is stored (commonly referred to as burned) into this device by an external electronic process. Some PROMs can be erased and programmed through special physical processes. (See ***EPROM****.)*

Progression

A term used to describe the progressive movement of traffic through several intersections within a control system without stopping.

Progressive Network Timing Plans

Control techniques based on establishing a progression timing along key network arterials. Techniques include: Single Alternate; Double Alternate; Quarter-Cycle; and Simultaneous Offset.

Project Evaluation and Review Technique (FERI)

A technique of project management which relates the interdependency of project tasks based cit time factors and ensures a timely and coordinated project completion.

Project Management

A management process that transforms a design into an installed system. Uses management tools such as: contract administration; project scheduling; construction management; work breakdown structure; defined and budgeted work packages; project design reviews and audits; and cost/progress status reports This process carries forward the implementation of the system design. Tasks include: procurement of subsystems and equipment; construction; training; debugging; documentation; acceptance testing; and turn-over to user.

PROMETHEUS

The Program for European Traffic with Highest Efficiency and Unprecedented Safety is a seven-year European program aimed to make vehicles safer, more economical, and less polluting.

Protected/Protective-Permissive/ Permissive

A type of control that provides left-turn phases only when needed. Left-turn phases can be protected or permissive or both when required by intersection conditions.

Public Transportation Management

This ITS user service provides for the automatic operation, planning, and management function of public transit systems.

Public Transportation Operations

The bundle of ITS user services including: public transportation management; en route transit information; personalized public transit; and public travel security.

Pull Box

A container that is placed underground with a removable cover flush within the ground line. Splices and conduit ends are located here.

Pulse Mode

The detector produces a short output pulse when detection occurs. The pulse lasts about 100 ms, even if the vehicle remains in the detection zone for a longer time.

Q

Quadrupole

A loop configuration that adds a longitudinal sawcut along the center of the rectangle, so that the wire can be installed in a figure-8 pattern, thereby producing four electromagnetic poles instead of the normal two. The design improves the sensitivity to small vehicles and also minimizes splashover.

Quarter-Cycle

A progressive timing technique applicable to one-way grids. Adjacent signals offset by one-quarter of cycle length.

Queue Detector

(1) A vehicle presence detector installed on the entrance ramp just downstream of the frontage road to detect queue spillback onto the frontage road. (2) Component of a traffic control system which senses the presence (or number) of vehicles waiting in a queue.

Queue Length

(1) Number of vehicles stopped in a lane behind the stopline at a traffic signal. (2) Number of vehicles that are stopped or moving in a line where the movement of each vehicle is constrained by that of the lead vehicle.

R

Radar/Microwave Detectors

Pole-mounted radar device that can sense speed and passage and/or presence, when activated by a vehicle passing through its RF field.

Radio Broadcast Data System (RBDS)

A commercial standard to implement an RDS system in the United States. Using RBDS, FM stations can transmit data to smart receivers.

Radio Communication

Radio Frequency (RF) transmission using any one of the following techniques: cellular networks; satellite transmission; packet radio; and spread spectrum radio.

Radio Data System (RDS) Traffic Message Channel (TMC)

A traffic information broadcasting system implemented in Europe. RDS provides for the transmission of a silent data channel on existing FM radio stations. It identifies radio data broadcasters and allows self-tuning receivers to automatically select the strongest signal carrying any particular program.

Radio-Frequency Detector

A vehicle detector consisting of a loop of wire embedded in the roadway that is tuned to receive a preselected radio frequency from a transmitter normally located on a vehicle.

Ramp Control

Regulation, warning, or guidance of traffic at points of access to or egress (exit) from a freeway.

Ramp Metering

The most widely used form of freeway traffic control. It regulates the number of vehicles entering the freeway over a given time interval so that demand does not exceed capacity.

Ramp Metering Signal

Traffic signal which directs entrance ramp vehicles to stop and permits them to proceed in accordance with metering rates determined by the type of entrance ramp control being used.

Ramp Storage

The roadway available for storage of vehicles queued and waiting for service at the entrance ramp meter.

Random Access

The process of obtaining information from, or placing information into, storage where the time required for such access is independent of the location of the information.

Random Access Memory (RAM)

A storage device with both read and write capabilities which will allow random access to stored data.

RDS-TMC

The European ITS field test for Radio Data System-Traffic Management Channel.

Read-Only Memory (ROM)

A storage device programmed during manufacturing that cannot be changed. Synonymous with non-erasable storage and read-only storage.

Real-Time Clock

A clock which indicates the passage of actual time-of-day rather than a clock set by the computer to measure an arbitrary interval of time.

Real-Time Control

The processing of information or data in a sufficiently rapid manner so that the results of the processing are available in time to control the process being monitored.

Real-Time Operating System (RTOS)

A computer program that controls the operation of a computer so that it performs its control function in a timely manner. (See ***Real-Time Control*** and ***Operating System***.)

Real-Time System (RTS)

A computer system wherein a computation is performed during the actual time that the related physical process occurs, so that results of the computation can be used in controlling the physical process.

Real-Time, Traffic-Responsive Control System.

Traffic control system which evaluates and selects control actions continuously on the basis of current measures of traffic conditions.

Recall

An operational mode for an actuated controller unit whereby a phase, either vehicle or pedestrian, is displayed each cycle whether or not demand exists. Usually a temporary or emergency situation.

Receiver

A part of the communications system which accepts and translates (decodes) signals into commands or data functions.

Recurrent Congestion

A type of congestion which is routinely expected at predictable locations during specific time periods.

Red Clearance Interval

Follows the yellow change interval. Both terminating phase and conflicting phase display red.

Register

A data processing device used for the temporary storage of one or more words to facilitate arithmetic, logical, or transfer operations.

Regulatory Signs

Signs that inform motorists of traffic laws and regulations and the applicability of legal requirements.

Relay

An electromagnetic switching device, having multiple electrical contacts, energized by electrical current through its coil. It is used to complete electrical circuits.

Reliability

The quality of a traffic control system to maintain acceptable system operations with minimum system downtime, minimum maintenance cost, and built-in test for equipment failure.

Remedial Hardware Maintenance Task

Task that results from malfunctions and equipment failures. Includes emergency repair activity to restore operation.

Remote Terminal

An input/output device physically removed from the central facility but connected by means of a communication link.

Removable Disk Pack

A set of magnetic disks used in a processing device for reading and writing which can be interchanged with other disk packs. Common to moving head disk units.

Repeater

A device used in a communication channel to amplify and/or reshape signals.

Request for Proposal (RFP)

A written document inviting prospective bidders to submit a project proposal.

Reserved Freeway Lanes

Freeway lanes reserved for HOV use have two configurations: (1) ***Concurrent Flow*** **-** Reserve lanes in the same direction as peak *flow. (2)* ***Contraflow*** **-** Reserve lanes on the opposite side of the median where HOV moves against the flow of traffic.

Reset

The action in an intersection controller which causes the control to begin its cycle at a new position in time in relation to reference. Resetting a control assures a desired offset between intersections in a progression system at all times.

Response Services

The types of roadway patrols available for at-the-scene incident response. Includes service patrol, and police patrol.

Responsive Mode

A system operation wherein the selection of signal timing plans is based on current traffic data as input by vehicle and pedestrian detectors.

Rest-In-Red

A controller designed to display red to all movements, in the absence of any traffic demand.

Restrictive Ramp Metering

A form of ramp metering that provides sufficient flow control to maintain non-congested freeway flow.

Reverse Offsets

The technique used for calculation of signal timings when the roadway link is saturated. A reverse progression is implemented in order to clear the downstream queue.

Reversible Lane

A term used to describe a traffic lane upon which the direction of the flow of traffic may be varied during different periods of the day.

Reversible Lane Control

A strategy used to change freeway directional capacities to accommodate peak directional traffic demands. Useful when directional splits are at least 70/30 percent.

Ride Matching and Reservation

The ITS user service that provides real-time ride Matching information and reservations to users at their locations.

Road Transport Informatics

The Intelligent Transportation System of Europe. Controlled through the Commission of European Communities (CEC).

Road/Automobile Communication System (RACS)

A Japanese driver information project sponsored by the Public Works Research Institute of the Ministry of Construction (MC), Highway Industry Development Organization, and private interests. System consists of vehicles with dead reckoning navigation systems and a roadway network of beacons.

Roadside Radio

Type of driver information system by which messages are conveyed to motorists from local transmitters beside the roadway to radio receivers in their vehicles.

Rotating Drum Sign

This sign contains I to 4 multifaced. rotating drums, each containing 2 to 6 message faces. Each drum face has one line of a fixed message. The faces can be mixed and matched to form many messages.

Rotating-Tape Sign

A sign which has a number of messages on a tape or film, and which is mechanically capable of selecting and rotating a given message so that it can be viewed. Also referred to as rotating-film, windowshade, or scroll sign. (See ***Scroll Sign***.)

Route Guidance

This ITS user service provides motorists with simple instructions on how to best reach their destinations.

Route Preemption

Emergency vehicles have preplanned routes that are incorporated into the signal system. Signal control on an emergency basis can be modified at EMS, fire, or police headquarters.

Routine Maintenance

Those work items that must be done regularly to ensure that traffic signal equipment will continue to operate.

RTTRACS (Real Time Traffic Adaptive Control System)

FHWA project to develop a traffic-responsive system control algorithm suitable for an ITS environment by 1997.

Rural ITS

A Minnesota Guidestar project evaluating rural ITS through operational tests; each examines ITS applications in a rural setting.

S

Sampling Detector

Any type of vehicle detector used to obtain representative traffic flow information.

Sampling Period

The length of time between each sample of a sensor. (Equal to 1/***Sampling Rate***.)

Sampling Process

The process by which a measurement is made. A measurement is made when a presence detector is sampled to determine its state. The finite time between samples generates an error in pulse duration which propagates into speed and other variables.

Sampling Rate

The rate at which measurements of physical quantifies are made. The number of times each second that the computer senses the status of a data sensor such as a loop detector.

Saturated Flow Conditions

A saturated flow condition develops in a network when traffic demand exceeds link capacity for a sustained period. Characterized by long queues that reach between intersections.

Scanning System

A system which senses the status of multiple points, such as detectors, and/or transmits commands to multiple points such as controller units in a predetermined sequence and time schedule.

SCATS

A real-time Sydney Coordinated Adaptive Traffic System (SCATS) developed by the Roads and Traffic Authority (RTA) of New South Wales, Australia. It uses two levels of control. Strategic control determines timing plans for areas and sub-areas based on average traffic conditions. Tactical control applies at the individual intersection.

Scheduled Control

A strategy for selecting ramp metering rates as a function of occupancy.

SCOOT

A real-time Split, Cycle and Offset Optimization Technique (SCOOT) developed by the Transport and Road Research Laboratory (TRRL) in Great Britain. It computes the cyclic flow profile for every traffic link every four seconds. It projects these profiles down-stream using the TRANSYT dispersion model.

Scroll Sign

The scroll sign contains a tape or film, rotated to properly position a desired message in the display window. The sign contains a set of stored standard messages.

Search

A software procedure for the examination of a set of items for one or more having a given property.

Second-Generation Control (2-GC)

Online timing plan generation wherein timing plans are updated periodically. This type of control program is based on a background cycle but provides for online real-time computation of timing plans. It uses a model to predict near-term changes in traffic demand. These predictions are then used in an optimization program to develop the timing plan.

Safety Readiness

This ITS user service provides warnings about the condition of the driver, the vehicle and the roadway.

Secondary Controller Assembly

A controller assembly which operates traffic signals under the supervision of a master controller assembly. (Sometimes called a ***Slave***.)

Section

A group of signalized intersections which are interconnected and have some time relationship among them.

Self-powered Vehicle Detection

An inroad detection device, currently in development, that does not require lead-in or interconnecting cables. Uses internal battery and RF link.

Self-Tracking Detector

A loop detector unit, not necessarily self-tuning, that includes electronics that compensate for environmental drift.

Self-Tuning Loop Detector Unit

One that is capable of adapting its operation to the resonant frequency of the loop and lead-in wire without any manual adjustment required. The term applies particularly to the startup of the detector's operation, upon turn-on. (Compare ***Self-Tracking Detector***)

Semiactuated Traffic Controller Assembly

A type of traffic-actuated controller assembly in which means are provided for traffic actuation on one or more, but not all, approaches to an intersection.

Sensitivity

As it relates to a loop system, the change in total induction of a system caused by a minimum vehicle at one loop, expressed as a percentage of the total inductance. As it relates to a detector, is the minimum inductance change in percent required at the input terminals, to cause the detector to actuate.

Sensor (System and Local)

Traffic detection devices (detectors) that permit the system master or a local controller to obtain information as to the traffic flow characteristics in the area of the sensor. (See Detector.) NEMA limits the meaning of sensor to the sensing element of a detector.

Separated Facilities

Positive separation of HOV and conventional traffic use techniques ranging from buffer lanes without physical barriers to parallel physical barriers.

Serial Port Standards

Standards prepared by Electronics Industry Association. Most common is RS 232 with a data rate up to 19200 bits/second. Other standards are RS 422, RS 423, and RS 449.

Serial Transmission

Each bit of the data byte or word is transmitted in sequence over a single channel. Used for long distance where cost is a factor.

Service Patrol

A patrol which provides assistance to those motorists in need of routine aid, such as: fuel; oil; water; tire change; and minor mechanical repairs at the roadside.

Shield

A conductive material surrounding the pair of lead-in wires of a loop-detector installation, so that outside electrical interference will not induce noise onto them.

Shock Wave

Boundary, moving upstream of an incident, between the region of traffic flow affected by the incident and that region of traffic flow not affected by the incident (i.e., congested versus non-congested).

Shuttered Fiber Optic Signs

These signs are constructed of fiber optic cable bundles and guide light energy from a point source to pixels on the sign face. Pixel shutters mounted behind the sign face control emission of light from each pixel. Proper shuttering controls the formation of characters.

Sign Controllers

Sign controllers monitor and control the sign display elements. Types of control are: remote automatic; onsite automatic; remote manual; onsite manual; fixed-time automatic; fixed time remote manual; and fixed-time onsite manual.

Signal Control Strategy

The method of controlling an intersection so as to enhance the flow of traffic. Examples of control strategies are pretimed and actuated control. (Also see ***Actuated Controller Assembly, Pretimed Controller Assembly,*** and ***Full-Actuated Controller Assembly.)***

Signal Indication

The illumination of a signal lens (or an equivalent device) whereby the movement of vehicular or pedestrian traffic is controlled.

Signal Modulation

Transforms the signal into a form suitable for the transmission system and media. Binary data requires two types of modulated signals.

Signal Priority Systems

Priority control at signalized intersections are typically used for reduction of transit delay. Conditional signal priority for transit vehicles can be implemented through: phase/green extension; phase early start or red truncation; red interrupt or special phase; phase suppression or skipping; and window stretching.

Signal Timing

The amount of time allocated to each interval/function in a signal cycle.

Signal Timing Plan Priority

Signal timing plans can be generated that favor minimization of transit vehicle delay. For example, TRANSYT incorporates this feature in its optimization routine.

Signal-Related Special Control

Categories of control that include: HOV priority systems; preemption/priority systems; directional lane control; television control monitoring; and overheight vehicle control systems.

Signal-to-Noise Ratio (SNR)

A measure of the quality of a communications channel that relates the received signal strength to the strength of the unwanted signals (noise) that combine with the desired signal during transmission.

Simplex Channel

A one-way communications channel. One end of the channel is always the transmitter and the other end is always the receiver.

Simulation

A pseudo-experimental analysis of a system by means of mathematical or physical models that operates in a time-sequential manner similar to the system itself.

Simultaneous Offsets

A progressive timing technique used for long cycle lengths and congested conditions. All signals on the major street turn green at same time.

Single Alternate

A progressive timing technique based on alternating half-cycle offsets at each intersection.

Single Entry

A fully-actuated operating mode in a dual-ring in which a phase in one ring can be selected and timed alone when there is no demand for service in a non-conflicting phase or a parallel ring.

Single Point Freeway Interchange Operation

A freeway interchange controller design that provides a basic six movement operation. Useful when the distance between ramp connections (frontage roads) are between 250 and 400 ft (400 and 650 km).

Single Entry Metering

Method of entrance ramp control which permits only one vehicle to enter the freeway per ramp metering signal cycle.

Single-Message Sign

Sign which is capable of transmitting only one message to the driver.

Single-Reset System

Reset system of direct interconnection of local controller units which provides only one offset.

Single-Ring Controller Unit

A controller unit that contains two to four sequentially timed and individually selected conflicting phases arranged to occur in an established order.

Sinusoidal

A waveform having the shape of the mathematically defined sine wave. This wave shape is commonly used in defining frequency-related parameters in communications systems.

Skip Phasing

The ability of a controller unit to omit a phase in the absence of demand on that phase or as directed by a master control.

Slow-Vehicle Detector

Component of a merge control system which senses the presence of a slow-moving vehicle on the entrance ramp between the ramp metering signal and the merge detector.

Small-Area Point Detector

A detector intended to detect vehicles at a spot location upstream of the stopline. They may detect more than one lane. The 6 ft (1.8 in) loop detector is a prominent example. Also, included are ultrasonic and radar units, whose detection areas may be as long as 20 to 30 ft (6 to 9 in), because the length of time the moving vehicle is in the detection zone is not used in the intersection control logic.

Small Scale Integration (SSI)

In integrated circuitry, a chip with fewer than 100 logic elements.

Small-Area Detectors

Devices that detect vehicle passage at spot locations. Also called short-loop, point or passage detectors.

Smart Corridor System

An example of an Integrated Traffic Management System (ITMS) for a major traffic corridor located in Southern California between Santa Monica and downtown Los Angeles. It is 14 miles (22.5 kilometers) long and contains the Santa Monica Freeway and five arteriales. Implemented by CALTRANS.

Smoothed Data Value

A point or value representing the trend of discrete data. This value is found by using a filtering equation which is an iterative process. (Also see ***Filtering Equation.)***

Smoothing Filter

A sampled data filter that operates on the time series of data samples to extract the non-random trend component.

Society of Automotive Engineers (SAE)

This organization plays a leading role in development of ITS standards, in particular the vehicle and vehicle interface. Serves as Secretariat for the ISO technical committee 204.

SOCRATES

The European ITS field test for the System of Cellular Radio for Traffic Efficiency and Safety.

Software

Various computer programs to facilitate the efficient operation of the system. Software items include: assemblers; generators; subroutines; libraries; compilers; operating system; and application programs.

Software Generations

A family of software routines related to each other in that each generation is a modification/upgrade of the preceding routine. All generations have the same name and are distinguished from each other by their generation numbers (first, second, third) and their successive dates of creation.

Software Maintenance

Those tasks required to correct errors remaining in computer programs after they are placed in operation, as well as making other program modifications to meet the demands of changing system needs.

Sonic Detector (Active)

Pole-mounted device that transmits/receives ultrasonic pulses to provide vehicle presence.

Some Detector (Passive)

Mounted acoustic device that listens to vehicle generated noise to establish presence and passage. May provide vehicle type based on noise spectrum.

Source Program

A program written in a nonmachine language such as FORTRAN or C. The program becomes the input to a language translator.

Space Mean Speed

The average of speeds of vehicles within a given space or section of roadway at a given instant; also, average speed of a specified group of vehicles based on their average travel time over a section of roadway.

Special Conditions

That portion of the contract documents which provides further explanation of general conditions or relates a general condition to a specific requirement associated with a project.

Special Event Plan

A timing plan stored in memory which is activated to compensate for unusual traffic flow caused by a special event (such as a football game)

Specialized Intersection Control

Categories of control that include isolated intersection control; arterial intersection control; closed network (CBD) control; and areawide system control.

Specifications

Written documents describing minimum requirements for items of work, materials, equipment, etc.

Speed

Distance traveled by a vehicle per unit time.

Splashover

An unwanted actuation caused by a vehicle in a lane adjacent to that in which the detector is located.

Split

The percentage of a cycle length allocated to each of the various phases in a single cycle.

Split Selection

The process by which a split is selected or calculated by the computer based on a measurement and comparison of directional demand as detected by system sensors or predetermined by time-of-day clock.

Spread Spectrum Radio

A technique that spreads the signal over a wide frequency range at the transmitter, then compresses to original frequency at the receiver. Used in conjunction with code division multiplexing, separate channels do not require unique transmitter and receiver modules. Can transmit data and compressed video.

Standby Mode

An operational status of a local controller assembly or system which is not under central computer control but is capable of responding to central computer control.

Standby System

Local control components which operate the intersection signals upon failure of the communication link to the computer or when the intersection is in standby mode.

Standby Transition

The act of changing to or from a standby mode. (See ***Drop Procedures*** and ***Pickup Procedures****.)*

Starting Delay

A delay experienced in initiating the movement of queued traffic from a stop to a maximum flow rate through a signalized intersection.

Startup Assistance

A contractor support service to assist the operating agency bring the system online. Includes supply of initial spares and repair of equipment and reviewing operational proficiency.

Statewide Signal Optimization Squad (SSOS)

A North Carolina traffic signal improvement program.

Static Signs

A single message is conveyed by a static sign. They are most useful at road locations where the same driver response is desired all the time.

Stops

The number of vehicles that stop. Used as a measure of effectiveness to assess the effectiveness of a timing pattern. A computer controlled system goal is to minimize stops.

Store

The procedure by which one or more bytes of data are transferred from the CPU to processor storage.

Stored Plan

A timing plan in computer storage (memory).

Strategic Plans

Approaches that use predetermined timing plans and then call them into use by time-of-day or traffic responsively as measured by traffic detectors. (Contrasted with ***Tactical.***)

Street Equipment

That equipment or hardware which is located *on the street*, such as an intersection controller assembly, signal heads, and detectors.

Stretch Detector (Extended Call Detector)

A detector with a carryover output. It holds or stretches the call of a vehicle for a period of seconds that has been set on an adjustable timer incorporated into the detector. It can be designed to begin the timing of that period when the vehicle enters the detection area, or when it leaves. The latter option is more common.

Submaster Controller Assembly

A controller assembly which receives commands from a master controller assembly and effects changes in timing plans to secondary controller assemblies.

Subnetwork

Subdivision of a section.

Subnetwork Control

A control technique in which a signal system consisting of numerous signalized intersections is subdivided into two or more subnetworks for control purposes.

Subroutine

(1) The sequence of machine instructions that complete a defined function or program. (2) A program that defines desired operations and which may be included in another program to produce the desired operations.

Subroutine Library

A collection of subroutines.

Super Smart Vehicle System (SSVS)

The Japanese project developing systems to assist drivers with automated lateral control, in-vehicle display of vehicle and traffic flow, active roadside lighting, and in-vehicle dynamic signing.

Supervisor

Software routine that controls and schedules the other software routines.

Supervisory Local Controller

A control device ranging from a time-base coordination unit to a remote master controller that determines or alters interval duration and/or maintains timing relationships in a group of local controllers.

Supply Strategies

The TSM strategies that focus on changing the quality of vehicular flow. Supply actions include: arterial signal coordination; incident management; parking prohibition; and turn controls.

Surveillance

The monitoring of traffic performance and control system operation.

Sync Pulse

A pulse generated from a central point that provides a common time-base to all coordinated traffic controller units and which is used to provide a smooth flow of traffic through coordinated intersections.

Synchronization

In communications, the process by which a transmitter and a receiver coordinate their operation so as to properly identify the bits and characters that make up a digitally transmitted message.

Synchronous Controller Unit

A controller unit in which the timing mechanism is controlled by and dependent on a suitable frequency standard such as the frequency of the alternating current source.

Synchronous Transmission

The data characters are transmitted at a fixed rate, with transmitter and receiver synchronized with no start or stop bits. Timing is derived through synchronizing characters at the beginning of each message or block of data. This technique is a more efficient transfer.

System

An array of components (hardware, software, interfaces) designed to achieve specific transportation objectives.

System Acceptance Tests

A contractor support service to develop, conduct and sign off on successful completion of the test plan. Acceptance testing includes: equipment checkout tests; system electrical tests; computer software tests; subsystem operations tests; and final system acceptance tests.

System Feasibility Study

The study that establishes the concept or preliminary design of a traffic system. It establishes the framework for detailed design and specifications for both the system and communication network. It also discusses capital, maintenance and operating costs, and staffing requirements.

System Implementation

Implementation of a traffic system includes the following phases: System Feasibility Study; Generation of Plans, Specifications and Cost Estimates (PS&E); and System Procurement, Installation and Acceptance Test.

System Management

A deliverable service by a contractor to direct, coordinate, review, monitor, and control the system design and implementation.

System Manager Approach

This approach uses a prime contractor to be responsible under an engineering services contract for: system design; PS&E preparation; system integration; documentation; and training. The system manager does not supply the system hardware or software components. Separate contractors provide these items.

System Modifications and Updates

Operations task that determines the need for system upgrades. Upgrades could include: control strategy and timing plans; operating and control software; and new control features and system capabilities (i.e., ATIS, ETTM, AVI).

System Monitoring/Intervention

Operations task to verify proper operation of traffic field equipment and when necessary manually override signal tuning and metering plans.

System Performance Evaluation

The determination of the relative merits of system improvements.

System Selection Process

The specific decision process that leads to a rational selection of a traffic system. The four sequential steps with feedback are: define system requirements; identify alternative systems; evaluate alternative systems; and select desired approach.

System Shutdown

(1) Emergency system shutdown involves the failsafe turning off of some or all system components due to power failure or equipment failures. (2) Planned system shutdown consists of turning off some or all system components by manual or automatic means, usually for maintenance or offline tasks.

System Speed (or Average Overall Travel Speed)

The ratio of total travel to total travel time.

System Staffing

The organization required to operate and maintain the system. Staff skills include knowledge of traffic operations, systems integration, equipment maintenance, and repair.

System Start Up Analysis

System start up concerns the planning necessary to smoothly transition from old to new control. It includes traffic management during construction, timing plans, database preparations, and acceptance testing.

System Status

A display or printout of the operational condition of each monitored unit in the system.

Systems Approach

The process or combination of tasks that ends in the operation of a traffic system. In developing a traffic control system, these tasks include problem identification, feasibility analysis, system evaluation and selection, system design, installation, operation, and maintenance.

T

Table

An array of data each item of which may be unambiguously identified by one or more subscripts.

Tariff

The published rate for a particular commercial service of a common carrier.

Technical Specifications

The document that describes the specific requirements for material, equipment, installation, test, and operation of the planned system.

Telemarketing Call-In System

One type of driver information system which provides traffic information upon request via telephone to be used for pretrip planning.

Terrestrial Microwave Links

Microwave links provide point-to-point (line-of-sight) between transmitting and receiving antennas. In traffic control, used for trunk lines carrying both voice and data. Requires FCC license. Can transmit voice, data, and compressed video.

Texas Traffic Light Synchronization Program

A Texas traffic signal improvement program that has demonstrated through reductions in fuel consumption, delay, and steps, the benefits of applying signal optimization on an intersection and network basis.

Third-Generation Control (3-GC)

Online timing-plan generation wherein timing plans are updated on a cycle-by-cycle basis or some comparable time frequency. The requirement for a constant or background cycle is eliminated. Generally discarded concept. Replaced by ***adaptive systems.*** (See ***RT-TRACS**.)*

Threshold

A present level or value of a parameter which indicates that a change of activity will occur if the current value is above or below this level.

Through-Band

The area between a pair of parallel speed lines which delineate a progressive movement on a time-space diagram.

Throughput

A MOE expressed in terms of Total Travel divided by Total Travel Time for a given set of traffic conditions with a given time interval. Throughput connotes traffic being put in at one end and taken out the other.

Time Division Multiplexing (TDM)

This technique sends a number of signals over a single channel by time, dividing the channel into a number of time slots and assigning each signal its own time slot.

Time Headway

The time separation between vehicles approaching an intersection, measured from front of vehicle to front of vehicle.

Time Mean Speed

The average of speeds of all vehicles or a specified class of vehicles at a specific point on a roadway during a specified period of time; also called average spot speed.

Time Share

The use of a device for two or more purposes during the same overall time interval, accomplished by interspersing component actions in time.

Time-Base Signal Coordination

A controller coordination technique that changes timing plans on an internal time basis.

Time-Based Coordination (TBC) Control

TBC control permits system operation of pretimed and traffic actuated local controllers without communication links or master control units. TBC can be implemented in all NEMA TS2 and Model 170 controllers, and some TSI controllers.

Time-of-Day Operation (TOD)

Signal timing plans selected according to time-of-day.

Time-Space Diagram

A graphical technique for calculating the progressive signal timing pattern based on street geometrics and traffic flow variables. The timing pattern is defined by green band, band speed, and bandwidth.

Timing Key

The device placed in a dial unit to effect a change in signal indication or check for coordination.

Timing Plan

A set of cycle length, splits, and offsets within a section of signals. The particular timing for each intersection may vary with time-of-day within the plan.

Timing Plan Elements

The components of a timing plan that include cycle length, splits, and offsets.

Timing Strategy

Procedure used to determine signal timing.

Total Travel

A MOE expressed in vehicle-miles (kilometers). It is the product of the total number of vehicles using the roadway during a given time interval and average trip length of vehicles.

Total Travel Time

A MOE expressed in vehicle-hours. It is the product of total number of vehicles using a roadway during a given time interval and the average vehicle travel time.

Trace Routine

A routine that provides a historical record of specified events in the execution of a program. Used primarily in debugging programs.

TRAF-NETSIM

This microscopic network simulation program is an interval-based, microscopic stochastic computer model that simulates the operational performance of a signalized network. Model based on UTCS-l traffic control model employing car-following logic.

Traffic Actuated Intersection Control

Assigns right-of-way and determines cycle length and phase, based on detection of traffic on the various approaches.

Traffic control

Regulation, warning, and guidance of traffic for the purpose of improving the safety and efficiency of traffic flow. This ITS user service manages the movement of traffic on streets and highways.

Traffic Control System Benefits

The improvements that result from use of a traffic control system. Includes reduction in accidents, travel time, delay, stops and increases in average speeds and flows. These in tam reduce fuel consumption, vehicle emissions, and user costs.

Traffic Control Systems Handbook

The handbook published by Federal Highway Administration to present basic technology used in planning, designing, and implementing traffic monitoring and control systems for urban street and freeway applications. Currently in its third edition (1996), it is a compendium of applicable technology, concepts and practice in the traffic control field.

Traffic Control Variables

Control variables are measurements of certain parameters that describe traffic conditions. Variables commonly used for street control are: vehicle presence*;* flow rate; occupancy; density; speed; headway; and queue length.

Traffic Corridor

A system of roadways that consists of a major limited access highway, parallel arterials and crossing highways, and surface streets.

Traffic Data Components

A time series of traffic data consists of two components, nonrandom and random. The random component records non-deterministic variations in data value from cycle to cycle. The nonrandom component records deterministic variations in basic service demand.

Traffic Delay

A MOE expressed in hours. On roadways it is defined as the increase in travel time beyond a value corresponding to a baseline speed. For intersections, it is defined as the time lost by the stopped vehicles.

Traffic Detector

(1) A device located in or near the roadway, which is acted upon directly by a vehicle to create a usable pulse to an intersection control device. (2) A device that can be used singly or in combination to measure traffic variables such as presence, volume, speed, and occupancy.

Traffic Generators/Attractors

Major activity centers, such as parking garages, shopping centers, etc., which generate or attract traffic.

Traffic Maintenance Management

An effective maintenance program includes: accurate record keeping; configuration; and documentation of timing plans; database; and equipment/software manuals. Daily updating is required.

Traffic Management and Control Structure

Traffic systems operate as closed-loop feedback processes. Basic functions to be performed are: traffic monitoring; decision-making; control execution, and performance verification and evaluation.

Traffic Management System

Operates as a real-time system that produces, within boundaries, a consistent, efficient allocation of traffic resources to service roadway traffic and motorist traveler demands.

Traffic Network Study Tool (TRANSYT)

A widely used and accepted offline optimization program for signal network timing plan generation. Developed by the United Kingdom Transport and Road Research Laboratory (TRRL). It can both evaluate existing timing and optimize new plans. Uses a platoon dispersion model. Widely used in the United States.

Traffic Operations

The response to existing and anticipated future traffic demands and incidents.

Traffic Operations Center (TOC)

A TOC is the central facility for the control, monitoring and management of the traffic signal, freeway and corridor control systems within its jurisdiction. A TOC consists of an operations room, computer and communications room, maintenance room, CCTV, large screen map displays, and workstations.

Traffic Operations Routine

Traffic operations require tasks be performed on a daily basis. These include: maintain daily control log; maintain event log: maintain ledger of timing plan modifications; daily summary reports of traffic conditions; maintain integrity of system databases and software; and maintain daily log of equipment failures and system operating status.

Traffic Phase

Those right-of-way, change, and clearance intervals in a cycle assigned to any independent movement(s) of traffic.

Traffic Responsive Integrated (Freeway Ramps)

A strategy based on real-time measurements, determination of freeway section operating point, and determination of maximum ramp metering rates for uncongested conditions.

Traffic Responsive Isolated (Freeway Ramps)

A strategy based on selecting metering rates on basis of real-time measurements, usually occupancy based.

Traffic-Responsive Signal Control

The feature of an open or closed-loop field master controller that changes intersection signal timing based on information from system detectors.

Traffic Signal Phases

Traffic phases reduce conflicts between traffic movements at signalized intersections.

Traffic Signal Systems

Traffic systems that control a group of arterials or surface street networks through coordinated traffic signals. There are two types of traffic signal systems: arterial and closed grid network systems.

Traffic Signal Timing Variables

Variables that control the phasing at a traffic signal. Include cycle length, phase interval, split, and offset.

Traffic Simulation (Corridors)

The modeling of a traffic freeway, network, and signal system to predict performance of the system. Classes of traffic simulation models are the FREQ model; the FRESIM model; the INTEGRATION; the MACK; and FREFLO models.

Traffic System Evaluation

Evaluation assesses performance levels of the operations and maintenance functions. Includes effects on safety and flow quality of systems, and control strategies. Before and after MOEs are required.

Traffic-Responsive System

A system in which a master controller either selects or computes signal timing based on the real-time demands of traffic as sensed by vehicle detectors.

Training

A deliverable service of courses and instructions to train the system operators and staff. Includes operation and maintenance courses.

Transceiver

A communications device used both to transmit and receive information. A transmitter I receiver on common chassis.

Transducer

A device that is actuated by power from one system, and that supplies power in any other form to a second system.

Transfer Rate

The speed at which data may be read from or written to the device.

Transition

The process whereby the system master and the local intersection controller units change from one program to another.

Transmission

The electrical transfer of a signal, message, or data from one point to another.

Transmission Modes

The direction of data over a channel. Simplex is flow in one direction only. Half-duplex is flow in either direction sequentially. Full duplex is flow in each direction simultaneously.

Transportable Signs

A transportable CMS displays real-time information at any location where predictable special events will occur and to manage traffic when unpredictable major incidents occur. Mobility provides for end of queue management. They can be mounted on, trucks or trailers,

Transportation Improvement Programs

The programs developed by Metropolitan Planning Organizations (MPOs) to implement the goals of ISTEA and ITS Strategic Plan.

Transportation Systems Management (TSM)

A philosophy for planning, programming, implementing, and operating, that focuses on improving the efficiency and effectiveness of the transportation system.

TRANSYT

An offline traffic signal timing optimization program developed in England.

TRANSYT-7F

An Americanized form of the original program, TRANSYT-7F was developed under Federal Highway Administration sponsorship.

TravTek

A state-of-the-art example of ADIS system. Operational field test conducted in Orlando, FL with 100 rental vehicles.

Travel and Transportation Management

The bundle of user services including: en-route driver information; route guidance; traveler service information; traffic control; incident management; emissions testing; and mitigation.

Travel Demand Management

The bundle of ITS user services including: pre-trip travel information; ride matching and reservation; and demand management and operations.

Traveler information Systems

Systems including both hardware and software that advise motorists of roadway conditions so that the motorist can take appropriate action to respond to the condition. Providing the motorist with this information enhances the efficiency and safety of traffic operations.

Traveler Services Information

This ITS user service provides a business directory or yellow pages of traveler/motorist related services.

Travelink

A Minnesota Guidestar project evaluating effectiveness of enhanced transit information directed to commuter mode choice and HOV travel.

Triple-Reset System

Reset system of direct interconnection of local controller units which provides three off-sets.

TRRL

The Transportation Road Research Laboratory. It is the equivalent of FHWA in Great Britain. It developed the SCOOT computer based traffic control system. This system implemented the concept of adaptive control.

Truth Table

A mathematical concept which can be used to represent the relationship between events.

Shows the result of a given logical expression for some combination of input values.

Turbulent Flow

See ***Unstable flow***.

Twisted Wire Pairs

Cable is provided in standard pair quantities: 6, 12, 18, 25, 50, 75, 100, 150, 200, 300, 400, 600, 1,200 and in wire gauges 19, 22, 24 and 26 AWG. Twisted pairs reduce electrical interference by cancellation.

Two-Abreast Metering

A form of platoon metering which releases two vehicles side by side per ramp metering signal cycle.

Two-Step Procurement

This approach uses a prequalification of the competing contractors in order to ensure only qualified contractors bid the second step, project installation.

U

Ultra Violet Erasable Programmable Read Only Memory (UVEPROM)

An EPROM that is erased and reprogrammed using ultra violet light.

Unconditioned Line

A voice-grade private line data channel (such as the 3002-type channel) without compensation to minimize attenuation in the audiofrequency band. (See ***Voice-Grade Line***.)

Universal Traffic Management Society (UTMS)

Organization sponsored by Japanese National Police, coordinates development of a new Traffic Management System.

Unstable Flow

The operating condition where a small increase in demand (flow) can be expected to be accompanied by a large decrease in speed leading to high densities and internal friction. This type of high-density operation cannot persist, and it leads inevitably to congested flow.

Updating System Timing

Operations task to determine new timing plans and strategies. Requires extensive field data collection and use of PC-based signal timing optimization programs (i.e., PASSER and TRANSYT).

Upstream

The roadway portion which is positioned toward the source of approaching traffic from the point of reference.

Upstream Occupancy Control

A ramp metering control strategy that uses real-time occupancy measurements taken upstream of the entrance ramp, to select a metering rate for the next control period.

Urban Traffic Control System (UTCS)

A widely deployed real-time traffic responsive control system originally developed by the Federal Highway Administration (FHWA) and prototyped in the Washington, DC network. Uses a signature matching algorithm to select a timing plan that minimizes matching error. The architecture of these systems has changed over the years to accommodate newer technologies including local area networks, open architecture computer and communication equipment, and microprocessors with real-time operating Systems at the intersections.

Urban Traffic Control System (UTCS) Project

A milestone in the development of computer-controlled traffic control systems. Sponsored by FHWA, it was installed in Washington, DC. Completed in 1972, it contained 512 vehicle detectors and controlled signal timing at 113 intersections. It supported extensive traffic control research.

User Service Bundles

A collection of ITS user services that have common characteristics and can be deployed in a coordinated manner.

UTCS 11/2 Generation Control

An enhancement to the original UTCS that incorporates an automatic timing plan generator. The generator uses data collected by the system, provides offline analysis and synthesis, and automated loading of new plans into the traffic system.

UTCS Software

Two software packages that add new functions to the original UTCS software product. Termed Extended UTCS and Enhanced UTCS software, they provide features including: NEMA controller interfaces; improved database management; signal state feedback; and display capabilities.

Utility Measure

A proxy value used as a measure of the benefit, or utility, of a traffic control system.

Utility-Cost Analysis

A specific evaluation technique that assigns a relative ranking to each requirement and a rating as to how well a system satisfies that requirement. The utility value for that system with respect to that requirement is the multiplication of these factors. The sum across all requirements is the system utility. The Utility-Cost factor is formed when Utility is divided by system cost including design, installation, and 0 & M costs. Analyzes the ability of a traffic control system to perform its function in comparison to its cost.

V

Variable Initial Interval

A controller unit design feature which adjusts the duration of initial interval for the number of vehicles in the queue.

Variable Speed Limit Signs

Signs often used by turnpikes and other toll facilities, warning motorists to reduce speed due to weather conditions, construction, and incident management.

Variable-Sequence Phasing

The control option that changes the sequence of phases on a cycle-to-cycle basis.

Variable-Speed Control

Concept of mainline control which limits the speed of traffic on a freeway in accordance with prevailing traffic conditions.

Vehicle Display

Equipment for displaying information to drivers; mounted within the vehicle.

Vehicle Extension

The amount of time, in seconds, that a green interval is extended for each vehicle actuation on a traffic-actuated controller assembly.

Vehicle Information and Control Systems (VICS)

The Japanese project that combines the best of RACS and AMTICS. Proposed to include a digital microcellular radio system that provides two-way data road vehicle communications and location information.

Vehicle Intersection Delay

The vehicle delay that results from stopped time delay (time waiting during red) and total delay (stopped time delay plus stop and startup delay).

Vehicle Location Technologies

Technologies used with ADIS and ATIS systems that provide vehicle location referenced to a geographical coordinate system. Technologies include: dead reckoning; global positioning systems; map matching; digital map; and proximity beacons.

Vehicle or Pedestrian Recall

A feature on a traffic-actuated controller unit which will allow the selection of any phase to which the unit will automatically return after it has served the other phases.

Vehicle Presence

Presence or absence of a vehicle at a point on the roadway.

Vehicle Road and Traffic Intelligence Society (VERTIS)

The Japanese ITS organization organized by government to promote cooperation between public and private organizations and provide liaison to foreign ITS organizations.

Vehicle Detector System

A system for indicating the presence or passage of vehicle. (See ***Defector System.***)

Vehicle/Road Intelligence (VeRI)

Organization sponsored by Japanese Society of Automotive Engineers to promote cooperation with other Japanese ITS groups.

Verify

To determine whether a transcription of data or other operation has been accomplished accurately.

VERSA Module Eurocard (VME)

A standardized bus back plane.

Vertical Antenna HAR Systems

A HAR system that uses a whip antenna or several antennas spaced along the highway and electronically interconnected. The signal radiates in all directions, forming a circular transmission zone.

Very Large Scale Integration (VLS1)

In integrated circuitry, a silicon chip with 100,000 or more logic elements.

Video Display Terminal

Used by some manufacturers to designate the combination of the CRT display with a keyboard.

Video Image Processing System

Mounted video camera device with associated processing hardware and imaging software to provide speed, presence, and passage measurement. Can be used for wide-area detection.

Vision Enhancement for Crash Avoidance

The ITS user service that improves the driver's ability to see the roadway and objects on or along the roadway.

Voice-Grade Lines

A channel suitable for transmission of speech, digital, or analog data, or facsimile, generally with a frequency range of about 300 - 3,000 Hz.

Volatile Memory

A storage medium in which information is destroyed when power is removed.

Volume

The number of vehicles passing a given point per unit of time.

Volume-Density Controller Unit

A type of actuated controller unit which has added initial and gap-reduction noting features.

W

Warning Signs

Signs that inform motorists of existing or potentially /hazardous conditions on or near the roadway.

Webster Delay Equation

The mathematical expression for average delay per vehicle at an isolated intersection approach based on signal settings and traffic variables.

Weighted Sensor Data

A channel having a bandwidth greater than that of a voice-grade channel. Wideband channels having bandwidths from 50,000 Hz to over one million Hz (a video channel) are available.

WHICH

An automated computer program for calculation of intersection signal timing Plans for either pretimed or actuated signals.

Word

A, group of consecutive bits which occupy one processor memory location and most frequently (but not always) are used in a standard computer instruction or operand.

Word Length

(1) The number of bits in a computer word. In a given computer, the number may be constant or variable. (2) The number of usable storage bits in a computer word.

Yellow Change Interval

The interval following green that alerts motorists to imminent phase termination.

Yield

A command which permits transfer of the right-of-way.

Yield Controller Command

is used to de-energize the hold command and begin the termination of the active phase.

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