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SPECIAL ISSUE PAPERS

Traffic Control Systems Hardware

Driver Information and Motorist Aid Hardware

Advanced Systems Hardware

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Preface

LYLE SAXTON, MEMBER. IEEE

TEN YEARS ago the February 1970 issue of the, IEEE TRANSACTIONS ON VEHICULAR TECHNOLOGY was dedicated as a Special Issue on Highway Electronic Systems. That collection of 19 papers was an excellent treatment of the subject in the early 1970's. Recently, an International Symposium on Traffic Control Systems was held with the objective of bringing researchers and users together to review the state of the art. The symposium emphasized four broad areas, one of which was traffic control systems hardware. The collection of papers presented in this subject-emphasis area is the most current and comprehensive review presently available. As such, it seems quite appropriate that a Special Issue of this TRANSACTIONS be published.

The reader will find the format of this Special Issue organized around three general topics:

- traffic control systems hardware,
- driver information and motorist aid hardware,
- advanced systems hardware.

Each of these three subsections is preceeded by a resource or overview paper which was invited and authored by an expert in the field. The remainder of the papers resulted from a Call for Papers for the symposium and were grouped into these three subsections as appropriate.

It is interesting to review briefly the progress and changes in emphasis that have occurred during the past decade and to note their impact on possible future directions. Perhaps the first observation is that overall emphasis areas remain essentially the same. The 1970 issue dealt with such topics as vehicle detection, communications, route guidance, automatic vehicle identification and location, traffic control systems, and automated control. Ten years later, you will find this subsequent issue dealing with these same general areas and providing an updated status report.

A second observation is that, in general, the field acceptance and implementation of modern traffic control hardware and systems are proceeding moderately slowly. Perhaps this is to be expected when involved in a socioinstitutional area which is characterized by an immense number of miles of roadway and vehicles, multiplicity of independent operating agencies at the local and State level, and perennial shortness of funding which has been severely aggravated by inflation and petroleum shortages. Clearly, there is a need for decisionmakers to maintain considerable emphasis and funding on the research, development, and implementation of traffic control systems if the benefits of improved traffic control are to be realized.

A third observation in reviewing this Special Issue is the relationship of traffic systems technology to the broader state of the art of electronics and control. For example, the introduction of and advancements in microprocessors, digital computers, communications, and video processing technologies have fostered similar advances in traffic control systems or subsystems which utilize these elements. While this is not surprising, it does support the broad payoff of developments in these more basic areas. Similarly, it points out the need for knowledgeable people in the traffic control field that can rapidly recognize and apply the broader advances in electronics, control, and communications to the specific needs of the highway transportation system.

A final thought relates to the obvious global and strategic changes which have occurred since 1970. The 1960's have sometimes been referred to as the "golden years of R&D;" and, indeed, the perspective at the beginning of the 1970's was different from today. Gasoline was viewed as plentiful and comparitively inexpensive, highway speeds were higher, and vehicles were larger and more powerful. The motorist was generally concerned with getting "there" faster and with less congestion and frustration. As a result, R&D was oriented toward the reduction of congestion, improvements in driver safety and decisionmaking, plus improvements in driver comfort and convenience. The energy crisis, with its specific shortages of 1974 and 1979, is reshaping the highway system's needs and R&D emphasis areas. No longer is congestion reduction and improved traffic management just a desirable goal for the convenience of motorist-it is now becoming critical as a means of *maintaining* mobility while reducing fuel use. In fact, advanced system concepts such as the automated highway, which was once viewed primarily as a system for higher speed and motorist convenience, is now being examined as a possible means of maintaining future mobility by the use of guideway-derived electrical power and the virtual elimination of fuel-consuming stop-and-go congestion conditions. Traffic control systems will be an increasingly important factor in dealing with the energy shortage.

I believe you will find this issue timely, useful, and interesting.

Lyle Saxton (S' 58-M' 62-M' 68) was born in Vici, OK, on March 16, 1936. He received the B.S.E.E. degree from the University of Oklahoma in 1959.

He joined the Astro Electronics Division of RCA where he was engaged in image sensor design and development for spacecraft. In 1966 he joined the Goddard Space Flight Center of the National Aeronautics and Space Administration and was engaged in the advanced mission system design of the Earth Resources Technology Satellite. In 1968 he joined the Traffic Systems Division of the Offices of Research and Development, Federal Highway Administration. He is presently Chief of the Systems Development and Technology Group.

Mr. Saxton is a member of Tau Beta Pi and Eta Kappa Nu. He is a member of the Special Committee on Communications of the American Association of State Highway Officials and past Chairman of the Committee on Communications of the Transportation Research Board.

Manuscript received January 21, 1980.

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Traffic Control Systems Hardware

ARTHUR A. CIMENTO

Abstract-In the past ten years the technology of traffic control has experienced extensive change. Equipment which was once familiar to traffic engineers and maintenance personnel has been supplanted by the new breed of devices using solid-state digital circuitry, sophisticated multiplexing, and microprocessor logic. The changes in operational capability and technical performance of systems brought about by these advances have been widely acknowledged. However, the impact upon the user is only beginning to be realized, as traffic engineers learn to cope with such considerations as operator training, maintenance, reliability, updating, and expansion. The current developments in traffic control systems hardware and the experience that is starting to be collected with respect to their installation and use are discussed. Technical and nontechnical factors are discussed and future directions are predicted.

INTRODUCTION

THE DECADE of the 1970's witnessed the technological transformation of the traffic control community. Spurred by the pressures of increased demand for mobility, rising costs of providing new facilities, and growing concerns for fuel consumption, air pollution, and land usage. traffic managers sought to maximize the effectiveness of existing streets and highways through the application of technically sophisticated systems of traffic control. In North America alone, during the past 15 years, the number of urban communities using some form of computerized traffic control has increased from less than five to over one hundred and twenty-five (see Fig. 1). The number of intersections increased from less than 1000 to over 10000. Considering the fact that each intersection generally requires the installation of control hardware, sensors, and communications, not to mention an amortized share of a computational and operations facility, it is evident why this aspect of the traffic control field should be emphasized.

The historical development of traffic control may be viewed as in the top portion of Fig. 2. With the introduction and widespread use of traffic control devices in the early 1920's, the science of traffic engineering developed as traffic managers sought to utilize these devices in effective ways. Not surprisingly, the technology developed in a parallel and supportive manner (bottom portion of Fig. 2) with industry developing and providing the hardware used by traffic managers. As use of control devices continued, more effective techniques of control were conceived, and vehicle detection hardware and analog logic emerged on the scene in the 1950's. In the early 1960's the digital computer began to make its impact in the traffic systems field, and the period from 1960 to 1970 saw the application and feasibility of digital computer controlled traffic systems demonstrated in a number of cities around the world. As interest in these systems grew in the next five years, the emphasis in research focused on the algorithms of control and the software application packages adapted to existing control hardware. While hardware continued to develop with the use of solid-state devices and integrated circuits, the hardware design concepts clearly lagged behind the inventiveness of system designers.

At this critical point of acceptance and application of digital control systems, the need for equipment development once again takes on predominant importance. This importance is seen from two aspects:

- development of functionally interchangeable equipment and universally accepted design concepts for use in modern computer systems;
- the need for a concerted effort in the testing and quality assurance of hardware to improve the reliability and maintainability of such systems once installed in a city.

This paper will serve as an overview of traffic control systems hardware, examining current practices and shortcomings, and stimulating thinking of how and where to improve things in the future. This paper will not attempt to discuss specific design features of any manufacturer's equipment or alternative design approaches in each equipment area because these are best left to the individual preferences of manufacturers and users. Rather, this subject will be viewed from the standpoints of application in a system and suitability for the user. Conclusions are attempted from often inadequate data, and trends are generalized from often premature results to stimulate constructive controversy as a means of identifying areas where improvement and development can be rewarding. The basic purpose, then, can be summarized in the answers to three questions: What's new? What have we learned? Where do we go from here?

BACKGROUND/HISTORY

With few exceptions, most computerized traffic control systems installed in the early 1970's used the available standard hardware of the traffic industry. Interfacing this equipment with the digital computer was accomplished through the introduction of special input/output devices, signal adapters, or, in some cases, through modifications to the equipment itself. The wisdom of this approach has been amply demonstrated by systems installed five to ten years ago that continue to be operated and maintained at reasonable cost. These systems characteristically used electromechanical or solid-state controllers, simple dc relay communications over owned or

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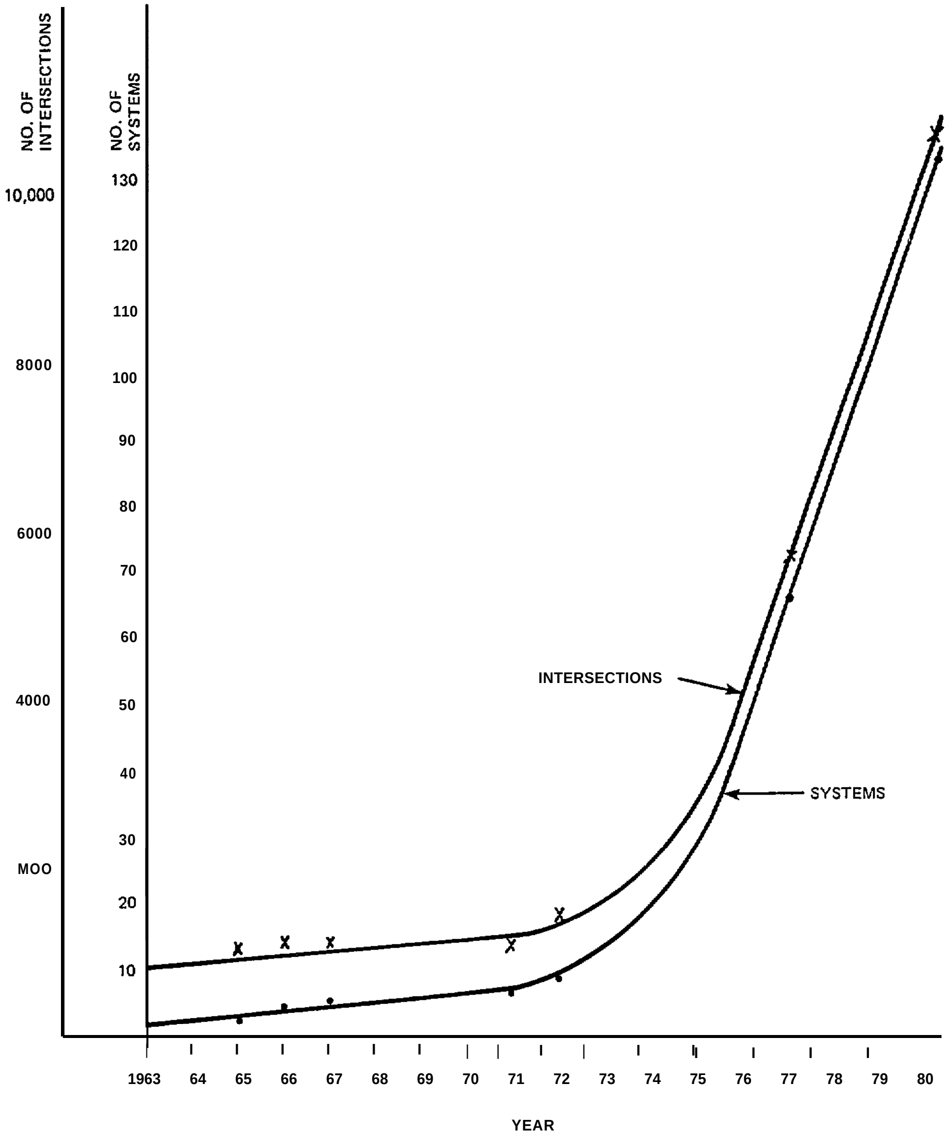


Fig. 1. Number of computerized traffic control systems and controlled intersections.

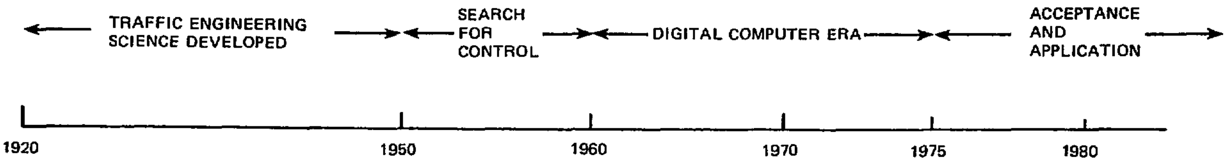
leased telephone lines, and one of the several state-of-the-art minicomputers operating with a field-supported operating software system. With the exception of the computer itself and the greater quantity of equipment employed, the traffic system operator could feel relatively comfortable in the familiarity of his hardware and the traditional sources of maintenance support. This is perhaps one reason for the response reported in a recent National Cooperative Highway Research Program (NCHRP) survey [I] where the functional traffic operation capability was identified as the most important system design goal, with reliability, maintainability, and operational management given only medium importance.

As system designs became more functionally complex and sophisticated, familiar equipment was replaced with new devices. The traditional analog circuitry of electronic devices was supplanted by digital circuitry. The simple dc communication techniques gave way to the more efficient multiplexing techniques of frequency division or time division. Data compression and preprocessing of field data added yet another complication. Controller hardware evolved from relatively inflexible pretimed devices to actuated and responsive devices and ultimately, to the “intelligent” devices having microprocessor logic and memory capabilities.

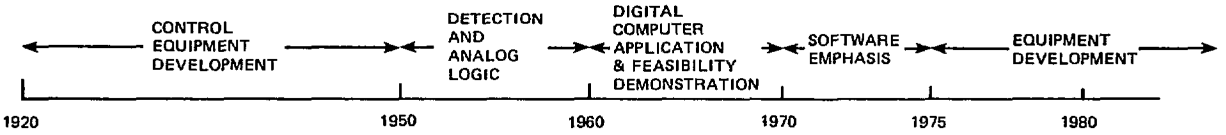
The increasing requirement for data communications in the more sophisticated systems and the increasing cost of installation or leasing brought challenging alternatives to the wire-cable transmission medium. Wide bandwidth media such as coaxial cable and fiber optics are feasible, practical, and, in many cases, economically advantageous. Even wireless communications using low-intensity lasers have become a practical reality with unique advantages in certain applications.

The very concepts of system design and architecture have undergone change. The virtues of a central processing structure with all data and functions coordinated through a central computer have to be reevaluated in comparison to the distributed hierarchical and network configurations made possible with the advent of the microcomputer.

The total cost of equipment for computerized traffic control systems is a significant portion of the cost of installation (refer to Table I). Further, the cost of maintenance (including



HISTORICAL DEVELOPMENT



TECHNOLOGICAL DEVELOPMENT

Fig. 2. Historical and technological development of traffic control.

TABLE I
COST OF TRAFFIC CONTROL SYSTEM EQUIPMENT

	SYSTEMS								
	A	B	C	D	E	F	G	H	I
Total Cost of Equipment as % of Cost of Installation	58.7	37.9	24.6	50.8	35.8	36.6	47.2	51.8	32.0
Number of Intersections	100	113	214	160	180	128	71	202	114

spares) is generally considered to be proportional to the capital cost and represents a recurring obligation for the traffic system operator.

Fig. 3 indicates the trend in cost (as a percentage of the total installation cost) for the major equipment subsystems from 1970 to the present. Where the basic technical approach has remained relatively stable (central computer system and detectors) and where the hardware has matured and suppliers have been able to produce in quantities, the general cost trend has been a decreasing one. By contrast, the changes in controller technology and communications have produced increasing trends. Starting with the early 1970's, the increased sophistication of this equipment has been accompanied by cost increases (very significantly in the signals and controller area). However, recent indications show a downward trend in relative costs as these areas stabilize. Note that, since the middle of the 1970's, the cost of the basic signal and control hardware has dominated the total cost of system equipment.

From this brief background the conditions affecting the future direction of research and application become apparent. They are as follows.

- The increasing sophistication of systems will result in the need for new, more complex, and less familiar equipment.
- The technical nature of this equipment will produce new, unfamiliar, and possibly impermanent suppliers.
- Keeping pace with new technology will require training and the development of new maintenance skills by the user agencies.
- Procurement of new equipment by user agencies will require new acceptance standards and multiple sources of supply.

CURRENT STATE-OF-THE-ART PRACTICES

Computerized traffic control systems are generally considered to include five major subsystems:

- detection or surveillance subsystem, which includes the basic vehicle sensor, and its related electronic signal processor;
- controller subsystem, which includes the local signal controller, auxiliary signal devices (such as conflict monitor, flasher, and load relays), wire termination panel, and cabinet enclosure;
- communications subsystem, which includes the communication medium and transmit and receive units (including multiplexing and error checking circuitry) at both the local and field data processing ends of a link;
- computer subsystem, which includes the central processor unit, core and bulk memory storage, and associated peripheral devices such as magnetic tape units, card reader, line printer, etc.;
- operator interface subsystem, which includes operator command and data entry devices (such as control panel,

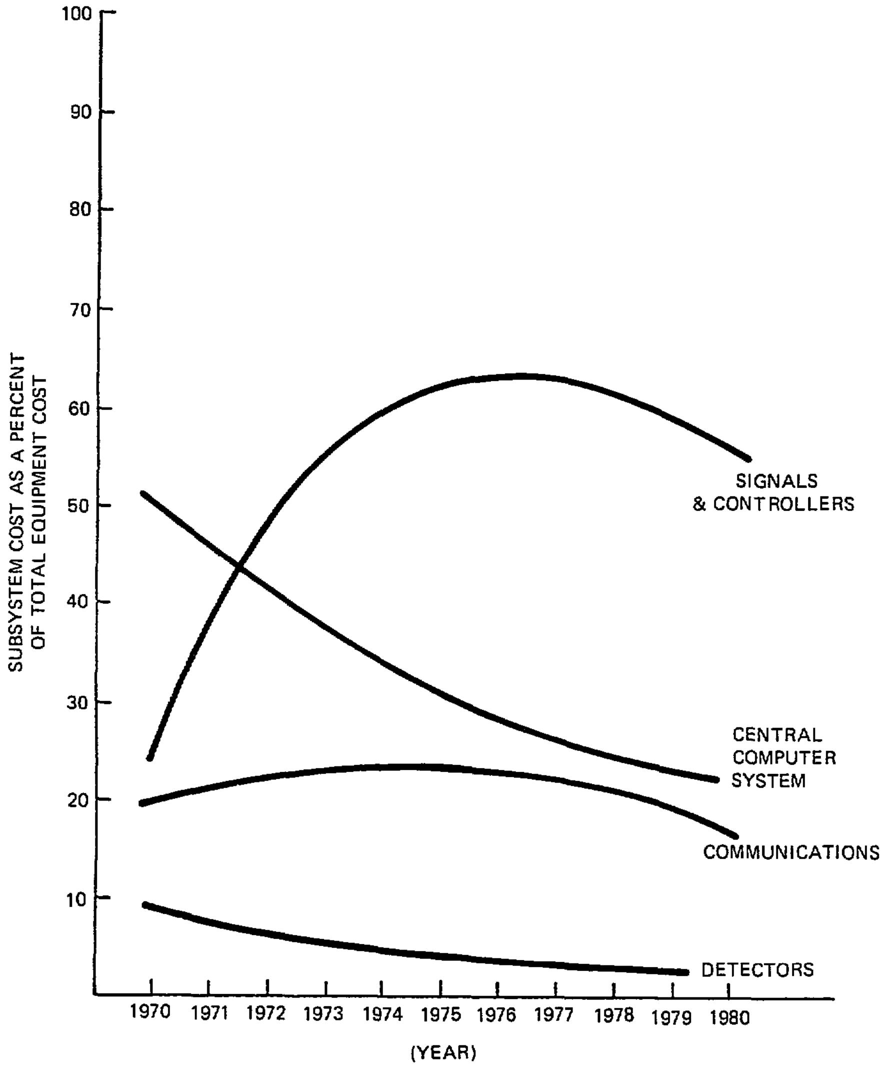


Fig. 3. Major equipment subsystem cost.

cathode-ray tube (CRT), teletypewriter (TTY) and display devices (CRT, map display).

All of the approximately 70 systems in active operation in the U.S. today have each of these subsystems in some degree. In fact, except for system size (number of intersections and detectors), there is little apparent physical difference between systems, despite the fact that they are the products of over ten different system suppliers. The most distinguishing difference among the systems is in the functional operating features included in their application software package.

It is not surprising that there are physical similarities if the following are considered.

- Most systems are designed around off-the-shelf equipment provided by a limited number of traditional manufacturers. Even special equipment indigenous to computerized systems (e.g., computers, displays) are furnished by relatively few suppliers.
- Most systems (until the relatively recent introduction of microprocessors) have employed the central processing architecture. Therefore, the distribution of elements between field and central is essentially fixed.
- The Federal Highway Administration's (FHWA's) research with the Urban Traffic Control System (UTCS) developed a number of implementation guidelines that were adopted in many systems.

The general history of these systems has been relatively successful, at least after the initial installation difficulties were overcome. Almost all systems demonstrated performance improvements in terms of benefits to motorists and greater effectiveness for the traffic operating agency. Where a cost-benefit analysis was performed, most demonstrated a recovery of initial capital investment in about three years of operation.

Summary of Operational Systems

Tables II and IV summarize the principal features of a representative sampling of urban and freeway computerized traffic control systems currently in operation in the U.S. Tables III and V are similar summaries of urban and freeway systems in other worldwide locations.

Equipment Evaluation Considerations

For each major subsystem identified previously, there are a number of alternatives currently in use. The choice of alter-

TABLE II
REPRESENTATIVE U.S. URBAN TRAFFIC CONTROL SYSTEMS

		NEW YORK CITY N Y	SOUTH BAY, L A COUNTY CALIF	BALTIMORE, MARYLAND	INGLEWOOD, CALIF	NEW ORLEANS, L A	COLUMBUS, OHIO	ATLANTA, GA	RALEIGH, N C	OMAHA NEB	METRO-DADE COUNTY, FLA	PHOENIX, ARIZ	TUCSON, ARIZ	GREENSBORO N C	HIGH POINT N C
	OPERATIONAL DATE	1969	1974	1978	1977	1977	1975	1973	1975	1977	1977/79	1976	1977	1975	1979
	NO OF INTERSECTIONS	1500	111	900	105	203	94	49	153	128	462	268	149	158	48
	SYSTEM ARCHITECTURE	CENTRAL	CENTRAL WITH PREPROCESSING	CENTRAL	CENTRAL	CENTRAL	CENTRAL	CENTRAL	CENTRAL	CENTRAL	CENTRAL	CENTRAL	CENTRAL	CENTRAL	CENTRAL
	CONTROLLER TYPE	SINGLE DIAL F T	—	MICRO PROCESSOR	DIAL, SS ACTUATED	SINGLE DIAL F T SS ACTUATED	MULTIPHASE SS	SS ACTUATED	2 DIAL PT, SS ACTUATED	EXISTING PRETIMED	SINGLE DIAL PT, SS ACTUATED	3 DIAL PT & ACTUATED	—	2φ-8φ SS	2φ 3φ SS
DETECTORS	NUMBER	1000	500	1000	83	278	253	70	110	162	394	175	355	600	75
	TYPE	SONIC	LOOP	MAGNETOMETER	LOOP	LOOP	LOOP	LOOP	LOOP	LOOP	LOOP	LOOP	LOOP	LOOP	LOOP
COMMUNICATIONS	MEDIUM	MULTI PR CABLE	MULTI PR CABLE	MULTI-PR CABLE	MULTI-PR CABLE	MULTI PR CABLE	COAX CABLE	MULTI PR CABLE	MULTI-PR CABLE	MULTI PR CABLE	MULTI-PR CABLE	MULTI PR CABLE	MULTI PR CABLE	MULTI PAIR	MULTI PAIR
	OWN/LEASE	LEASE	LEASE	OWN	OWNED	OWN/LEASE	OWN	OWN/LEASE	LEASE	OWN/LEASE	LEASE	LEASE & OWNED	LEASE & OWNED	OWNED	OWNED
	MULTIPLEX	D C	TDM	TDM	TDM	FDM	TDM	FDM	D C	TDM	TDM	TDM	TDM	TDM	TDM
COMPUTER SYSTEM	MFG MODEL	IBM 1800 (5)	—	MODCOMP IV (2)	MODCOMP II	INTERDATA 7 32	INTERDATA 70	INTERDATA 70	INTERDATA 70	INTERDATA 7 32	MODCOMP IV	MODCOMP II	MODCOMP II	HONEYWELL 716	HONEYWELL 716 (2)
	CORE SIZE	64KB COMP	64KB	312 KB	128 KB	256 KB	128 KB	64 KB	64 KB	196 KB	512 KB	96 KB	128 KB	128 KB	128 KB
	PERIPHERALS	STD COMP	—	STD COMP.	STD. COMP	STD COMP	STD COMP	STD COMP	STD COMP	STD COMP	STD COMP	STD COMP	—	STD COMP	STD COMP
OPERATOR INTERFACE	PRIME CONTROL	TTY CRT	—	—	—	CONT PANEL	CONT PANEL	CONT PANEL	TTY	CONT PANEL	CONT PANEL	CRT	—	TTY CRT	TTY/CRT
	DISPLAY	NO	DYNAMIC MAP	—	—	DYNAMIC MAP	DYNAMIC MAP	DYNAMIC MAP	DYNAMIC MAP	DYNAMIC MAP	DYNAMIC MAP	DYNAMIC MAP	—	DYNAMIC MAP	DYNAMIC MAP
	CONTROL SOFTWARE	SPECIAL	ON LINE OPTIMIZATION	—	1st GEN UTCS	UTCS FORTRAN	UTCS ASS'Y LANG	SUPPLIER DEV	SUPPLIER DEV	SUPPLIER DEV	UTCS FORTRAN	SUPPLIER DEV	SUPPLIER DEV	SUPPLIER DEV	SUPPLIER DEV
	SPECIAL FUNCTIONS	NONE	—	—	REVERSIBLE LANE	NONE	TV SURV	TRAFFIC DATA ACQUISITION REV. LANE CONT	FIRE PRE-EMPT	NONE	BRIDGE & FIRE PRE-EMPT BUS PRIORITY	—	—	CIC	OFF LINE TP GEN
	SYSTEM INSTALLER	CITY IBM	TRW	TRW	TRW DELEUW CATHER	SPERRY	SPERRY	SPERRY	SPERRY	SPERRY	SPERRY	COMPUTRAN	COMPUTRAN	HONEYWELL	HONEYWELL

TABLE III
REPRESENTATIVE NON-U.S. URBAN TRAFFIC CONTROL SYSTEMS

		TORONTO, CANADA	LONDON, ENGLAND	GLASGOW, SCOTLAND	LIVERPOOL, ENGLAND	HAMBURG, GERMANY	BERLIN, GERMANY	MADRID, SPAIN	BARCELONA, SPAIN	ZURICH, SWITZERLAND	LISBON, PORTUGAL	TOKYO, JAPAN	YOKAHAMA, JAPAN	SAPPORO JAPAN
	OPERATIONAL DATE	1963	—	—	—	—	—	—	—	—	—	—	—	—
	NO OF INTERSECTIONS	1000	1000	80	47	100	800	112	130	32	240	1377	365	175
	SYSTEM ARCHITECTURE	CENTRAL	CENTRAL	—	—	—	—	—	—	—	—	—	—	—
DETECTORS	NUMBER	500	1000	250	40	60	300	130	144	31	300	2088	680	422
	TYPE	LOOP	LOOP	PNEUMATIC	PNEUMATIC/ LOOP	LOOP	—	LOOP	LOOP	TROLLEY & LOOP	LOOP	SONIC	LOOP	—
COMMUNICATIONS	MEDIUM	MULTI PR CABLE	MULTI-PR CABLE	MULTI-PR CABLE	MULTI PR CABLE	MULTI PR CABLE	MULTI PR CABLE	MULTI-PR CABLE	MULTI PR CABLE	MULTI PR CABLE	MULTI-PR CABLE	MULTI PR CABLE	MULTI-PR CABLE	MULTI-PR CABLE
	OWN/LEASE	LEASED	LEASED	OWN	OWN	OWN	OWN	LEASED	LEASED	LEASED	LEASED	LEASED	LEASED	LEASED
	MULTIPLEX	—	FDM	—	—	—	D.C	—	—	—	—	—	FDM	—
	COMPUTER SYSTEM MFG MODEL	UNIVAC 1107/418	SIEMANS 306(2)	MARCONI	PLESSEY	SIEMANS-16000	SIEMANS-16000 (11)	ELLIOT 903	ELLIOT	SIEMANS 16000	ELLIOT	NEAC (15) MACC	—	—
OPERATOR INTERFACE	PRIME CONTROL	TTY/CRT	—	—	—	—	—	—	—	—	OPER CONSOLE	—	—	—
	DISPLAY	—	GRAPHIC CRT	—	—	—	—	—	DYNAMIC MAP	DYNAMIC MAP	DYNAMIC MAP	DYNAMIC MAP	GRAPHIC CRT	DYNAMIC MAP
	BACKUP CAPABILITY	BACKUP COMPUTER	LOCAL CONT.	LOCAL CONT.	LOCAL CONT.	LOCAL CONT.	BATTERY PACK	SUBMASTER CONTROL	LOCAL CONT.	—	SUBMASTER CONTROL	LOCAL CONT	—	—
	CONTROL SOFTWARE	TR-2 SIGART SIGRID	TOD PATTERN MATCH	—	—	DEMAND RESPONSIVE	—	—	—	—	—	—	—	—
	SPECIAL FUNCTIONS	—	—	—	QUEUE CONT. AT TUNNEL ENT.	TV SURV.	MESSAGE SIGN CONT.	—	—	TRAM PRIORITY	—	• TV SURV • RADIO BROADCAST	—	WEATHER SENSORS

TABLE IV
REPRESENTATIVE U.S. FREEWAY SURVEILLANCE CONTROL AND SYSTEMS

		VAN WYCK EXPRESSWAY N.Y.C., N Y.	SCANDI– DETROIT FWY SYSTEM DETROIT, MICH.	NEW JERSEY TURNPIKE NEW BRUNSWICK, N J	I-35W MINNEAPOLIS, MINN	IMIS LONG ISLAND CORRIDOR L I , N Y	SEATTLE FREEWAY SEATTLE, WASH.	PENN LINCOLN– PKWY. PITTSBURGH, PA.	NO. CENTRAL EXPWY. DALLAS, TEX.
	OPERATIONAL DATE	1980	1980	1975	1974	1983	1979	1978	1978
	LENGTH OF ROADWAY	6.4 km	104 km	58 km (dual) ≈ 116 km	27 4 km	169 km LIM.ACC 97 km SURF ST	–	–	16 km
CONTROL MODES	ENTRY SIGN	YES	–	YES	YES	–	–	–	YES
	RAMP CONTROL	YES	YES	–	YES	YES	YES	–	YES
	LANE CONTROL	–	–	–	HOV ON RAMPS	–	–	–	–
	DIVERSION	SERVICE ROAD	MESSAGE SIGN (FUTURE)	ALT BARRELS	YES	YES	–	–	YES
DETECTORS	NUMBER	236	1364	800	450	2500	300	–	317
	SPACING	536 M	536 M	600 M	800 M	800 M	800 M	800 M	800 M
	TYPE	LOOP	LOOP – MULTI CHANNEL	LOOP	LOOP	LOOP	LOOP	LOOP	SPECIAL BUS & LOOP
	MANUFACTURER	DECATUR	CANOGA	DECATUR	VARIOUS	TBD	–	–	–
COMMUNICATIONS	MEDIUM	COAX TV PLUS MULTI-PR CABLE	COAX TV PLUS MULTI-PR CABLE	MULTI-PR CABLE	MULTI-PR CABLE	MULTI-PR CABLE	MULTI-PR CABLE	MULTI-PR CABLE	MULTI-PR CABLE
	OWN/LEASE	OWN	OWN	OWN	OWN	OWN	OWN/LEASE	LEASE	LEASE
	MULTIPLEX	TDM	TDM	FDM	FDM	TDM	TDM	FDM	FDM
	MANUFACTURER	SAFETRANS	TOCOM	RFL	QUINDAR	TBD	–	–	–
COMPUTER SYSTEM	MFG/MODEL	DATA GENERAL ECLIPSE	INTERDATA (2)	DIGITAL ELEC. CORP. PDP	HONEYWELL 316	TBD	INTERDATA	–	–
	CORE SIZE	224 KB	256 KB	192 KB	64 KB	620 KB	–	–	–
	PERIPHERALS	STD. COMP.	STD. COMP.	STD. COMP.	STD. COMP.	STD. COMP.	STD. COMP.	–	–
OPERATOR INTERFACE	PRIME CONTROL	OPER. CONSOLE	CRT KEYBOARD	OPER. CONSOLE INTERACTIVE CRT	OPER. CONSOLE	OPER. CONSOLE	–	–	–
	DISPLAY	DYNAMIC MAP	GRAPHIC CRT	DYNAMIC MAP	DYNAMIC MAP	DYNAMIC MAP	–	–	–
	BACK-UP CAPABILITY	TIME-OF-DAY	–	MANUAL SIGN CONTROL	PRE-TIMED	LOCAL CONTROL	LOCAL CONTROL	–	–
	CONTROL SOFTWARE	SPECIAL	SPECIAL	SPECIAL	SPECIAL	CORRIDOR LOGIC	SPECIAL	–	–
	SPECIAL FUNCTIONS	• INCIDENT DET. • TV.SURV.	• MOTORIST AID • TV SURV.	• EMER. VEH. ROUTING • INCIDENT DET. • SPEED WARNING	• HAR, CB MONT. • TV SURV.	• MOTORIST AID HAR. • CIC, DIAL-UP AND MEDIA INFO.	• TV SURV. • DIAL-UP INFO	–	• MOTORIST AID HAR. • BPS ON RAMPS • ART SIG. COORD.

TABLE V
REPRESENTATIVE NON-U.S. FREEWAY SURVEILLANCE AND CONTROL SYSTEMS

		Q.E.W. FWY TORONTO, CANADA	PARIS–ORLY CORRIDOR PARIS, FR.	PARIS–LE BOURGET CORRIDOR PARIS, FR.	RHEIN–MAIN CORRIDOR FRANKFURT, GER.	CORRIDOR TOLLWAY NAPLES, ITALY	TOKYO METRO. EXPRESSWAY CORRIDOR TOKYO, JAPAN	HAGUE-ROTTERDAM CORRIDOR NETHERLANDS	TEMPORARY CORRIDOR ZURICH, SWITZ.	LANGLEY–CHISWICK CORRIDOR UNITED KINGDOM
	OPERATIONAL DATE	1976	—	—	—	—	—	—	—	—
	LENGTH OF ROADWAY	—	12 Km	9 Km	30 Km	14 Km	100 Km	30 Km	11 Km	18 Km
CONTROL MODES	ENTRY SIGN	—	YES	—	YES	YES	YES	—	YES	YES
	RAMP CONTROL	YES	YES	YES	—	YES	YES	—	—	—
	LANE CONTROL	—	YES	YES	—	—	—	YES	YES	YES
	DIVERSION	—	—	—	YES	—	—	—	YES	YES
DETECTORS	NUMBER	60	283	—	—	502	—	—	—	—
	SPACING	800 M	—	—	—	125–250 M	600–1000 M	—	—	—
	TYPE	—	LOOP	LOOP/RADAR	LOOP	LOOP	LOOP	LOOP	LOOP	AXEL DET. & LOOP
COMMUNICATIONS	MEDIUM	COAX CABLE	—	—	RADIO	MULTI–PR CABLE	—	—	—	—
	OWN/LEASE	OWN	—	—	—	LEASE	—	—	—	—
	SPECIAL FUNCTIONS	• ARTERIAL SIG. CONTROL • TV SURV.	• BUS PRIORITY ON RAMPS • TRUCK PREF. • SURF. ST. SIGNAL COORD. • TV SURV.	• TV SURV. • SPEED WARNING SIGN CONT.	• TV SURV.	• SPEED WARNING SIGN CONT. • TUNNEL SIGN CONT. • WEATHER COND. WARNING	• SPEED WARNING MESSAGE SIGNS • WEATHER COND. WARNING • TV SURV.	• SPEED LIMIT SIGN CONT. • HAZARDOUS COND. WARNING	• SURF. ST. SIGNAL COORD. • SPEED LIMIT SIGN CONT.	• FOG WARNING SIGNS • SPEED LIMIT SIGN CONT. • TV SURV.

native equipment depends on considerations which must be weighed for each specific application. Generally, performance and cost are the predominating factors, but frequently one of the other considerations may be an overriding factor in the choice. The following characteristics, as applicable, should be considered in the selection of an equipment alternative.

- ***Performance:*** This is the ability of the equipment, by its design nature and functional capabilities, to meet the requirements of the system as specified.
- ***Reliability:*** This is a function of the equipment engineering design. It describes the designed-in ability of the equip ment to maintain its functional integrity and continue to perform without failure or degradation.
- ***Maintainability:*** An equipment requiring simple maintenance procedures would receive a higher score for this attribute than one which requires specially trained personnel, special test equipment, or frequent preventive maintenance.
- ***Ease of Installation:*** A higher value is placed on an equipment which permits simple installation procedures within reasonable physical confines. Compactness and economy of special installation equipment required are typically valued characteristics.
- ***Damage invulnerability:*** This is the equipment's ability to withstand malfunction due to causes not related to design, for example, vandalism, hostile physical environment, or rough handling.
- ***Ease of Procurement:*** This places a premium on the use of equipment available from multiple sources within reasonable schedule.
- ***Ease of Expansion:*** These are characteristics of an equipment that allow the expansion of a system or subsystem with a minimum of disruption and modification. Modular addition of components or simple extension of chassis parts are typically valued characteristics.
- ***Monitoring Capability:*** This is a measure of how well an equipment can be monitored for malfunction of performance.

A proper evaluation of the "best" equipment for a given application requires consideration of all these factors with appropriate weighting. Unfortunately, the task of ensuring the best choice of equipment is shared between the system designer (who develops the specifications) and the system installer (who furnishes the equipment). Since most of these attributes how each type of device fulfills the objectives of the eight considerations listed above.

CRITIQUE-WHAT HAVE WE LEARNED?

The rate of growth of computerized traffic control systems throughout the world in the past ten years is ample proof that we have learned much. From over 100 actively operating systems in existence, we have learned to install systems so that they perform in a relatively satisfactory manner. Formal evaluations of traffic control systems report benefits which show that we have learned to operate systems so as to improve traffic movement and vehicular safety. According to a large sample of opinions, we have learned that operating and maintaining computerized systems requires more resources than anyone originally anticipated.

However, very few specifics of the individual experiences of the various system users have been formally reported. A recent Institute of Transportation Engineers (ITE) survey [2] asked users to identify the biggest problem encountered in obtaining, installing, and/or operating their system. Twenty-five system users (with systems operational or being implemented) in the U.S. and Canada responded. The responses did not focus specifically on technical problems and, as shown in Fig. 4, were distributed among several categories. One evident conclusion among users is that communications is the single most troublesome element. This category, however, includes all communications-related difficulties, both with system hardware and leased line problems of both a technical and institutional nature. From a slightly different point of view, Fig. 5 illustrates the distribution of installation problems encountered by one system installer (Sperry Systems Management experience data) based on the experience with approximately 20 systems.

Difficulties encountered with specification interpretations and with controllers were significantly high. Communications also showed approximately the same ratio of problems. It should be noted, however, that controllers include the adapters and interfaces with the computer system, and distinguishing between these problems and communication system problems is often difficult.

To examine the situation more closely, two sources of data were available: the operational data collected and documented by the FHWA's UTCS system in Washington, DC, from November 1972 through July 1975; and the installation data collected from the Metro-DadeCounty system in Florida from April 1975 through October 1976. Fig. 6 compares the dis-

TABLE VI
CONTROLLER SUBSYSTEMS

	SOLID STATE ACTUATED	SOLID STATE PRE-TIMED	ELECTRO-MECHANICAL PRE-TIMED	MICROPROCESSOR (170TYPE)
MANUFACTURERS				
. L.F.E. TRAFF CONT.	YES	YES	—	
. CROUSE-HINDS	YES	YES	YES	YES
. SAFE TRANS	YES	YES	—	YES
. EAGLE SIGNAL	YES	YES	YES	YES
. ECONOLITE	YES	-	YES	—
. HONEYWELL	YES		—	YES
.MULTISONICS	YES			YES
• GAMMATRONIX	YES	YES		—
. DATA COMM. SYSTEMS	—	—	—	YES
RELATIVE USE IN SYSTEMS	HEAVY	MODERATE	HEAVY	LIGHT
APPROX. UNIT COST (SK) (INCL. INSTALLATION)	5-15	3-8	1-3	4-8
ADVANTAGES	NEMA STDS HAVE MADE MAINTENANCE AND INTERCHANGEABILITY EASY	SOLID STATE RELIABILITY	LOW COST-SIMPLE TO MAINTAIN - EASY TO ADAPT TO EXISTING SYSTEM	FLEXIBILITY THROUGH REPROGRAMMING
DISADVANTAGES	HIGHER COST - MAINTENANCE REQUIRES MOD. LEVEL OF SKILL	HIGHER COST THAN E-M EQUIVALENT - HIGHER LEVEL OF MAINT. SKILL	REQUIRES REGULAR MAINTENANCE DUE TO PARTS WEAR	REQUIRES SOFTWARE SUPPORT AND HIGH LEVEL OF MAINT. SKILL
RELATIVE COMPARISON				
. PERFORMANCE	G	G	G	G
. RELIABILITY	F	G	F	G
. MAINTAINABILITY	F	F	G	F
• EASE OF INSTALLATION	G	G	G	G
• OAMAGE INVULNERABILITY	NOISE AND SURGE SUSCEPTIBLE	NOISE AND SURGE SUSCEPTIBLE	G	NOISE AND SURGE SUSCEPTIBLE
. EASE OF PROCUREMENT	G	G	F	F
. EASE OF EXPANSION	P	F	G	G
. MONITORING CAPABILITY	G	G	F	G

G = GOOD F = FAIR P = POOR

cause it is a performance characteristic important to operating agencies. System and equipment specifications are increasingly calling for reliability demonstrations, and a quantitative measure of this characteristic is desirable. The concept of mean time between failures (MTBF) as a measure of reliability is in widespread use, particularly for military components. It is valid when a large sample of units is considered and when the product and operational maturity of the components are such that failures can be considered random in occurrence rather than attributable to a design defect.

Consider the failure history of two elements of the UTCS in Washington, DC (Figs. 7 and 8): the leased telephone line service and the loop detector electronic amplifiers. These particular historical data are good because they represent a long period (33 months) over which the fully installed complement of equipment was operated regularly and during which good records were kept. In both cases the characteristic improvement with time is apparent as is the period of time for the failure rates to stabilize to a level where they can be considered random. Based upon similar experience in other installations, it is possible to generalize a historical profile of failures for typical traffic control system hardware as in Fig. 9. Typically, the failure rate during factory acceptance testing decreases as deficiencies are correct and units delivered. As installation begins, the quantity of units in operation increases at the same time that field environment conditions are encountered, resulting in the gradual increase in failures. As the "infant mortality" failures are weeded out and system condi-

TABLE VII
DETECTION AND SURVEILLANCE SUBSYSTEMS

	INDUCTIVE LOOP	SONIC	MAGNETOMETER
MANUFACTURERS	DECATUR SARASOTA CANOGA (3M) SAFETRAN ICS STREETER AMET DBA SYSTEMS	GEN. RWY.SIG. AUTOMATIC SIGNAL	CANOGA (3M) AUTOMATIC SIGNAL
RELATIVE USE IN SYSTEMS	HEAVY	MODERATE	LIGHT
APPROX. UNIT COST (S) (INCL INSTALL)	500-1200	1000-1500	400-600
ADVANTAGES	• GOOD PERFORMANCE • RELIABLE WHERE STREET CONDITION IS GOOD • CAN BE USED IN VARIOUS CONFIGURATIONS	• EASY TO INSTALL IF POLES ARE AVAILABLE • NOT AFFECTED BY PAVEMENT CONDITION	. LOWER INSTALL COST . ADEQUATE FOR COUNTS. *CAN USE LONG LEAD-IN
DISADVANTAGES	• REQUIRES STREET INSTALLATION • DIFFICULT TO REPAIR	• TENDENCY TO DOUBLE COUNT • OCCUPANCY ACCURACY POOR • SUSCEPTIBLE TO VANDALISM	*DETECTION ZONE NOT WELL DEFINED
RELATIVE COMPARISON			
. PERFORMANCE	G	F	F
. RELIABILITY	G	F	F
. MAINTAINABILITY	G	F	F
• EASE OF INSTALLATION	F	F	F
• DAMAGE INVULNERABILITY	G	F	G
. EASE OF PROCUREMENT	G	F	F
. EASE OF EXPANSION	F	G	F
. MONITORING CAPABILITY	G	F	F

G = GOOD F = FAIR P = POOR

tions improve, the failures decrease again, finally stabilizing at a level indicative of the random failure performance of the particular equipment as designed. Although the specific time scale and relative magnitudes may vary with different equipment, the important point to note is that the peak failure period is often likely to occur during the system acceptance test and evaluation period. Also, a bona fide MTBF calculation cannot be made until a year or more following the normal test and evaluation period.

Since most of the equipment used in computerized traffic systems is electronic in nature, it is instructive to examine the component failure distribution of this equipment. Fig. 10 is a typical distribution of component failures for three typical electronic equipment used in a current system. These specific data, as well as similar results from other systems, indicate a predominance of failures resulting from the use of substandard or marginal electronic components (particularly integrated circuit chips) and mechanical connectors and sockets holding components of circuit boards.

Since reliability is such an important consideration, it is appropriate to consider other ways of rating the reliability of a computerized traffic control system. Because such a system can operate in different modes and failures can occur which do not prevent the system from continuing to operate, the concept of “intersection availability” is worth some attention. In a simple form, the availability of an intersection can be defined as the percentage of the time (based on component failure rates and equipment repair times) that an intersection is able to operate using the first generation responsive areawide control strategy (or some other acceptable mode). This model is useful because it

- describes reliability in terms perceived by the system user (the motorist),
- normalizes the system as to size, that is, a 25-intersection system can be compared to a 200-intersection system,
- allows systems with different architectures and equipment approaches to be readily compared.

TABLE VIII
COMMUNICATIONS SUBSYSTEMS (MULTIPAIR CABLE)

	TIME DIVISION MULTIPLEX	FREOUENCY DIVISION MULTIPLEX	DIRECT CURRENT RELAY
MANUFACTURERS	SONEX LARSE SAFETRAN	RFL OEI DATAMASTER	HONEYWELL AMF
RELATIVE USE IN SYSTEMS	FREQUENT USE IN RECENT YEARS	FREQUENT USE IN EARLIER SYSTEMS	LIMITED
APPROX. UNIT COST ($) (INCL INSTALLATION)	$1000 PER INTERSECTION	$500 PER CHANNEL	$100-$600 PER INTERSECTION
ADVANTAGES	. SIMPLE INTERFACE WITH COMPUTER . LESS SPACE FOR REQUIRED EQUIPMENT *MORE FLEXIBILITY FOR SPECIAL FUNCTIONS	.SIMPLER TO SERVICE *MINIMIZES NO. OF INTERSECTIONS LOST IF CENTRAL OFFICE EQUIPMENT FAILS . LESS SENSITIVE TO NOISE & LINE CHARACTERISTICS	• COMPATIBLE WITH EXISTING SWITCH GRADE TARIFF *LOW NOISE SENSITIVITY
DISADVANTAGES	. LOSS OF CENTRAL OFFICE EQUIPMENT CAUSES GROUPS OF INTERSECTION TO FAIL . MORE SENSITIVE TO TRANSMISSION LINE CHARACTERISTICS & NOISE	. SPACE REQUIREMENTS MAY BE HIGH FOR LARGE SYSTEMS . CONTROL OF ADDED FUNCTIONS REQUIRE A NEW CHANNEL	. MINIMAL MULTIPLEX CAPABILITY . SPACE REQUIREMENTS MAY BE EXCESSIVE . LIMITED FUNCTIONAL CAPABILITY
RELATIVE COMPARISON			
. PERFORMANCE	G	G	G
. RELIABILITY	G	G	G
. MAINTAINABILITY	F	G	G
. EASE OF INSTALLATION	G	G	G
. DAMAGE INVULNERABILITY	G	G	G
. EASE OF PROCUREMENT	G	G	F
. EASE OF EXPANSION	G	F	F
*MONITORING CAPABILITY	G	F	P

G = GOOD F = FAIR P = POOR

This concept was used in comparing systems using different communications approaches in a study recently completed for the FHWA [3] . Table X summarizes the comparison of candidates using this method.

When viewed in this manner, the small difference in reliability (or availability) among alternatives for a given architecture indicates that this would not be a major basis for selection, yet the significant difference in intersection downtime between architectures clearly indicates one of the major assets of a distributed network-type system. However, central systems have certain functional advantages apart from the reliability issue which may make them more advantageous in many cases. Also the particular comparison shown was based on current practices in central architecture design which can be improved by reducing the sensitivity to failures of critical elements (e.g., disk drives).

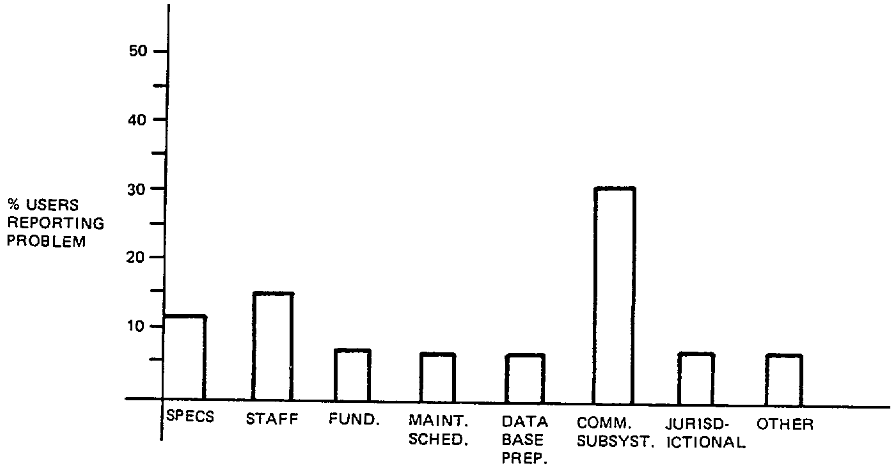
What has been learned is summarized in the following.

- Communications appears to be the single biggest problem area in the implementation and operation of computerized traffic control systems.
- The newer technologies (e.g., time division multiplexing (TDM), digital circuitry, microprocessors) are also the most susceptible to operating problems (line disturbances, ambient noise, lightning) and the most difficult to troubleshoot.

TABLE IX
COMPUTER SUBSYSTEMS

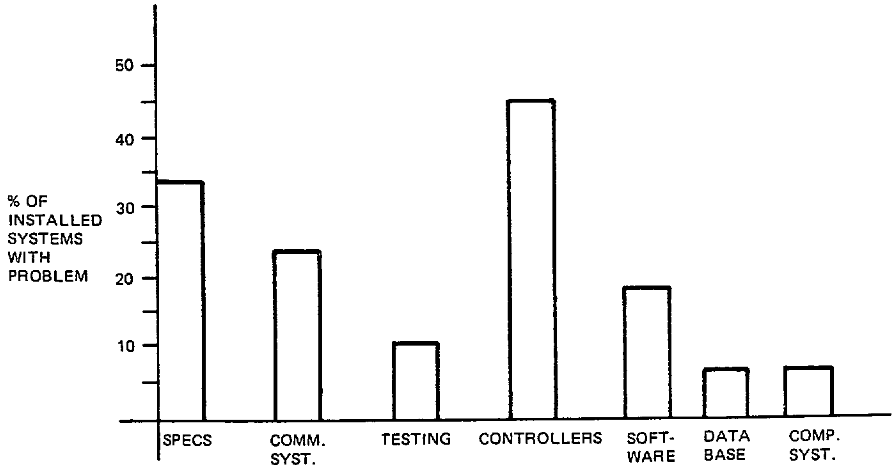
	CENTRAL	HIERARCHICAL	DISTRIBUTED
MANUFACTURERS	DATA GENERAL HONEYWELL INTERDATA MOD COMP DEC	DATA GENERAL HONEYWELL INTERDATA MOD COMP DEC	VARIOUS MICRO-PROCESSOR MFGS.
RELATIVE USE ON SYSTEMS	HIGH	LOW	LOW
APPROX UNIT COST ($K)	150-250	COST DEPENDS ON SIGNAL SYSTEM GEOMETRY	COST DEPENDS ON SIGNAL SYSTEM GEOMETRY
ADVANTAGES	• EASIER TO ADAPT TO DIFFERENT EQUIPMENT COMPLEMENTS AND SOFTWARE VARIATIONS. • EASIER TO CHANGE DATA BASE • MORE ADVANCED FUNCTIONS ARE POSSIBLE	• MAY REFLECT EITHER CENTRAL OR DISTRIBUTED CHARACTERISTICS DEPENDING ON SPECIFIC DESIGN	• DESENSITIZED TO CENTRAL COMPUTER FAILURE
DISADVANTAGES	• LOSS OF CENTRAL COMPUTER REQUIRES STANDBY CONTROL FOR ALL INTERSECTIONS	SEE ADVANTAGES ABOVE	• MORE DIFFICULT DATA BASE AND SOFTWARE CHANGES • LESS FLEXIBLE TO CHANGE SUBNETWORK STRUCTURE AND DETECTOR ASSIGNMENTS.
RELATIVE COMPARISON			
• PERFORMANCE	G	G	G
• RELIABILITY	F	G	G
• MAINTAINABILITY	G	G	F
• EASE OF INSTALLATION	G	G	F
• DAMAGE INVULNERABILITY	G	G	P
• EASE OF PROCUREMENT	G	G	F
• EASE OF EXPANSION	P	F	G
• MONITORING CAPABILITY	G	G	F

G = GOOD F = FAIR P = POOR



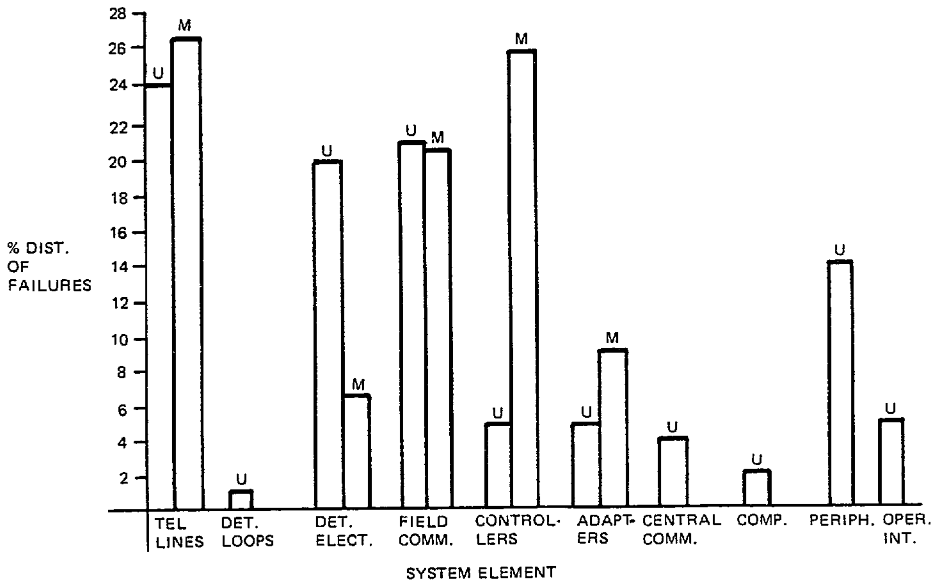
NOTE. FIGURE IS BASED ON ITE/CCSAC SURVEY WHICH HAD RESPONSES FROM 25 SYSTEM USERS

Fig. 4. Survey of major problems.



NOTE: BASED ON 18 SYSTEMS INSTALLED BY SPERRY SYSTEMS MANAGEMENT

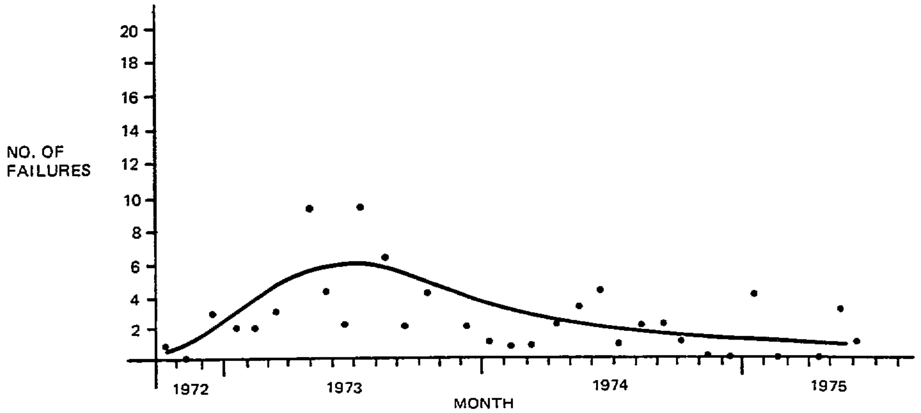
Fig. 5. Survey of installation problems.



NOTE. U = UTCS OPERATIONAL EXPERIENCE (11/72 - 7/75, 972 DAYS)

M = METRO-DADE OPERATIONAL EXPERIENCE (APPROX. 1 YEAR)

Fig. 6. Comparison of UTCS and Metro-Dade operational experience.



NOTE: 79 LINES TOTAL

Fig. 7. UTCS telephone line experience.

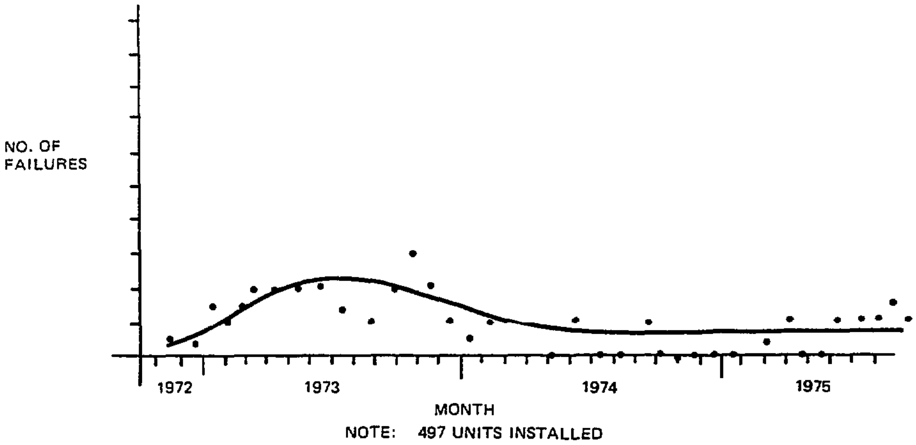


Fig. 8. UTCS detector amplifier experience.

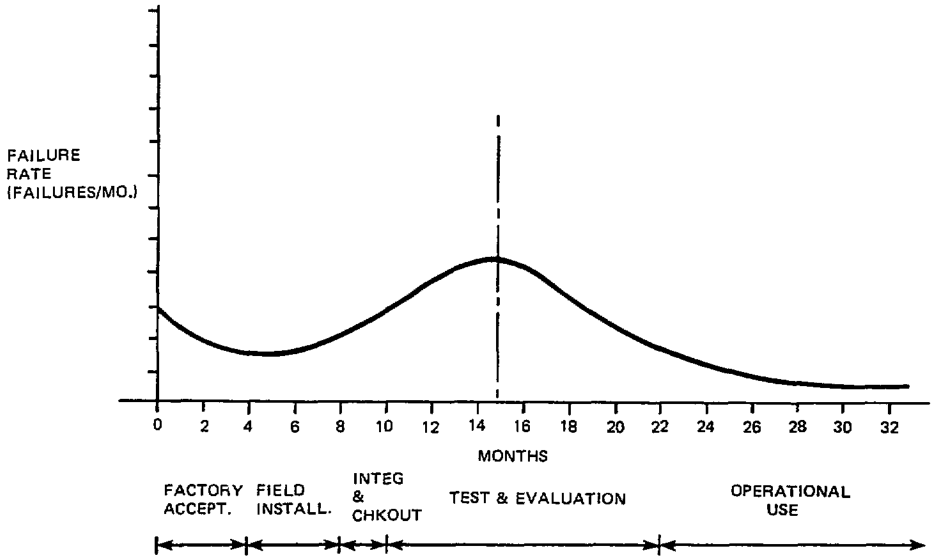


Fig. 9. Typical failure rate.

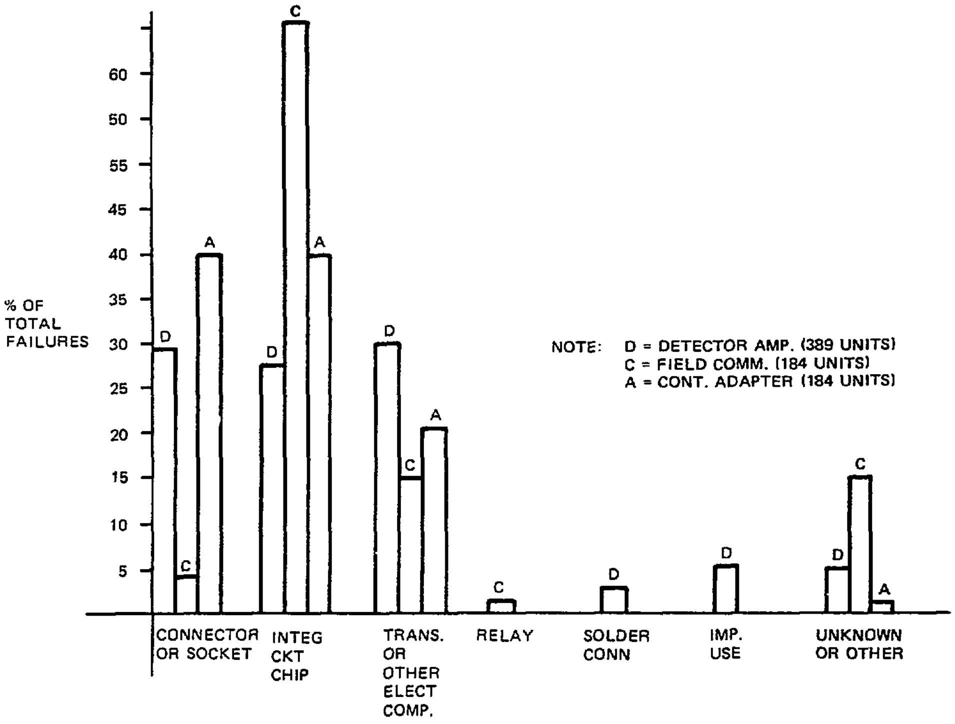


Fig. 10. Component failure distribution.

TABLE X
COMPARISON OF INTERSECTION AVAILABILITY

	Central Architecture[a]				Network Architecture[b]	
	FDM w/ Owned Cable	TDM w/ Owned Cable	TDM w/ Fiber Optics	TDM w/ COAX	TDM w/ Owned Cable	TDM w/ Air Path Optics
Intersection Availability (Fraction of Time)	.997349	.997353	.996689	.996689	.999729	.999439
Intersection Downtime/yr (in hours)	23.1	23.0	28.9	28.9	2.3	4.9

[a] Based on use of electromechanical controllers.
[b] Based on use of microprocessor controllers.

- The major sources of equipment problems are apparently caused by the use of low-grade components (not suitable to the environment) and insufficient quality control. Users should realize, though, that better quality control will result in higher costs.
- Computerized traffic control systems require a reasonable commitment in maintenance and operating support. This includes adequate spares and an equipment servicing routine.
- Good record-keeping procedures are more essential than with previous systems and equipment, as a necessary aid in systematic troubleshooting and effective system unkeep.

FUTURE DIRECTION-WHERE DO WE GO FROM HERE?

While there has been much technological change in the traffic industry over the past ten years, perhaps the most significant transformation has been in the receptivity of traffic engineers to new and changing ideas. The once traditionally conservative traffic manager is willing and capable of using the new and innovative ideas continuously being developed. Having adopted a progressive attitude, the future direction of traffic control may be expected to advance as rapidly as the techniques, equipment, and application concepts unfold from any area, be it in the military and space development laboratories, the government and university research agencies, or the industrial facilities of manufacturers and suppliers. To illustrate briefly, consider a few of the new technological developments and trends that the next ten years will probably see.

Vehicle Detection

A Federal Highway Administration report [4] presents an excellent summary of the state-of-the-art in vehicle detection. As noted in that report, the inductive loop detector is currently the most popular and widely used in traffic control systems. With installation practices and procedures improving continuously, this detector is likely to remain in widespread use in the future with a variety of loop configurations being adopted for improved performance in given applications.

Government-sponsored research in the last several years, however, has resulted in several new detection concepts including the radio frequency traffic sensor, the magnetic gradient vehicle detector, the self-powered vehicle detector, the wide area detection system, and the passive bus detector.

The radio frequency traffic sensor was investigated by New York State's Department of Transportation to develop a more accurate replacement for the road tube as a vehicle counting detector. It consisted of a battery-powered roadway sensor, approximately 25.4 cm (10 in) in diameter and 3.8 cm (1.5 in) high, and a roadside receiver/decoder. Although an engineering model was developed and tested, the development of this unit, was suspended.

The magnetic gradient vehicle detector (MGVD) was developed by the FHWA as an alternative to the inductive loop detector and to overcome some of its problems. An MGVD consists of a transducer that is approximately 2.1 m (7 ft) long but only 3.8 by 1.3 cm (1.5 by 0.5 in) in cross section and easily insertable in a roadway slot. A number of prototype units were built for the FHWA and testing is being continued by various governmental agencies.

The self-powered vehicle detector is a promising device to reduce in-street installation costs since it requires no lead-in but operates with a radio transmission link between the detector and roadside electronic receiver. The detector is a cylinder measuring 11.4 cm (4.5 in) in diameter by 36.8 cm (14.5 in) in length and powered by a self-contained battery with a projected life of one year. Development of this device is being continued in the FHWA, and 20 prototype units have been fabricated and will be distributed to a number of states for in-field operational experience. The FHWA plans to have an additional 100 units built by several manufacturers to establish multiple sources for this device.

The wide area detection system is a television detector which covers a roadway zone of about 106.8-152.5 m (350-500 ft) in length. The detector can provide volume, occupancy, and individual vehicle speed on a lane basis, and will operate in conjunction with a local microcomputer. The feasibility of this device is presently undergoing demonstration, and a prototype unit is planned. This type of detector could lead to the development of new strategies of control based on the measurement of parameters or characteristics of traffic flow hitherto not readily measurable in the field.

The passive bus detector is a special purpose detector intended for use in bus priority or preemption systems. It makes use of a standard vehicle detector loop from which a microprocessor-based detector package can identify a bus by the use of signature processing techniques. The FHWA has several prototype units built and is investigating the possible demonstration in conjunction with the Urban Mass Transportation Administration (UMTA).

Communications

A recently completed FHWA study examined all applicable techniques to provide communications for urban traffic control systems. Although wire cable (whether underground or aerial and whether leased or owned) will continue to be used to a large extent, newer techniques have proven to be both less expensive and technically superior in many ways. Three communication techniques expected to become more prevalent in the next ten years are coaxial cable, fiber optics, and air-path optical.

A traffic control communication system employing coaxial cable as the transmission medium consists of coaxial cable and repeater amplifiers arranged as a network connecting a control-center communication unit with transceivers at each intersection. The cable and amplifiers have a wide radio-frequency bandwidth (5-300 MHz) which can handle the traffic control communications requirement of any city and can also provide up to 30 television channels at the same time. Using the appro-griate filters and amplifiers at the repeater amplifier positions, the cable can carry signals in both directions simultaneously by dividing the total bandwidth into two parts, one for signals toward the intersections and one for signals from the intersections (a form of frequency division multiplexing).

The equipment and installation costs of coaxial cable networks are similar to those of twisted wire pair networks for pole-mounted, direct burial, and underground construction. Additional costs are required for the line (repeater) amplifiers plus their power sources and cabinets. Coaxial cable cost is similar to twisted pair costs for the smaller diameter 1.0 cm (0.4 in) coaxial cable, but additional costs are present with the larger diameter 1.3 cm (0.5 in) or 1.9 cm (0.8 in) coaxial cable because the cable rigidity may present installation difficulties, particularly for conduit installations. Some cost advantage over twisted pair networks results from the fact that twisted pairs require extensive design and installation efforts to identify, splice, or connect each wire at every intersection. Coaxial cable networks require only that a single coaxial cable and a trunk-line tap be installed at each intersection, thus eliminating much of the design, documentation, and installation costs. Cost of transceivers at the intersection is generally comparable to that of twisted pair time division multiplexing (TDM) units, but the front-end computer and programming cost is usually higher than that of typical twisted pair central communication units.

If an existing or planned cable TV installation encompasses an appreciable part of the traffic control network, a portion of the cable spectrum may be leased from the community antenna television (CATV) operator, thus substituting a monthly leasing cost for cable installation cost.

A fiber optics data link is functionally the same as a data link using wires or coaxial cable, except that the transmitter module converts electronic signals into optical signals. The fiber optics transmission medium is an optical waveguide, which in the case of a single-fiber data channel, is analogous to a coaxial cable or, more accurately, a cylindrical waveguide.

The glass fibers are coated glass or plastic having a different refractive index from the glass in the fibers. When these elements are properly designed, light rays entering one of these clad fibers will be reflected off the fiber walls and will propagate along the inside of the fiber without escaping until they reach the end. Continuous fibers can be made as long as several kilometers and can be interconnected by specially designed connecters where necessary.

Unlike electrical cables, junctions with fiber optics need not make intimate contact. Radial alignment at cable junctions is usually required to be within 1-5 mils, depending on fiber optics, or bundle diameter, and this tolerance is readily achieved through the use of standard matched connectors or couplings.

The cost of fiber optics system installation is essentially the same as for wire pair cables and coaxial cable. High data-rate fiber optics cables, however, are smaller and lighter and, therefore, they are somewhat easier to handle and occupy less space in a conduit. Since conduit installation cost is the dominant cost factor, the overall cost difference between a fiber optics and coaxial cable installation may be insignificant. Maintenance costs should be similar to those for other forms of cable communications.

Energy in the optical spectrum (usually visible or near infrared) may be used for the transmission of data through the atmosphere. This type of transmission has become practical in recent years through the development of low-cost injection laser diodes for transmission and light-sensitive diodes for reception. By using a laser in the transmitter of an optical data link, much greater range and/or signal-to-noise ratio at the receiver can be achieved compared to using nonchoerent light sources of comparable input power.

Equipment for traffic control communications consists of pole-mounted optical transceivers (single or multiple heads) at each intersection facing their upstream and downstream counterparts at adjacent controlled intersections, plus a microcomputer at each intersection for processing the data. Each bidirectional transceiver acts as a repeater for data being transmitted in both directions and also communicates with the microcomputer in the controller cabinet via a short cable.

An air-path optical system is feasible where the intersections to be controlled are physically located such that line-of-sight paths exist at all intersections. Two wire pairs (leased or owned) may be used for links which do not have unobstructed line-of-sight paths, since the data rates used with this technique may be made compatible with voiceband transmission media and equipment.

Signal Hardware

Signal hardware is probably the most standardized equipment in the traffic control industry. Standards for traffic signals published by the ITE have been long established and accepted by both user and manufacturer, and define color, light output, message size, lens diffusion patterns, and almost every characteristic of these devices. In spite of this standardization, a variety of new concepts are entering even this part of the equipment spectrum.

- ***Lenses*** : Lexan polycarbonate plastics are now available as replacements for glass. This material is very resistant to breakage and meets the enviornmental and optical requirements of signal hardware.
- ***Heads:*** Signal heads made entirely of Lexan polycarbonate are now offered by several manufacturers. These heads are lighter than the aluminum die-cast counterparts and have colors molded-in rather than painted-on for easier maintenance.
- ***Dimming:*** In response to changing ambient light levels, individual signal heads or entire intersection signalization can be dimmed to conserve energy.
- ***Programmed Visibility:*** Signal displays which tend to confuse motorists can be improved by the use of focused indicators which direct light along a narrow cone visible only to the motorist intended.
- ***Turn Arrows:*** Signal heads that can display a green arrow followed by a yellow in the same housing permit a reduction in overall signal height.
- ***Fiber Optics*** Fiber optic bundles are being used to illumi-

nate pedestrian signal messages making it simpler to fabricate units in smaller housings.

Microprocessors

Whether an integral part of a system equipment (e.g., a microprocessor controller or a communication interface unit) or an element of the data processing structure, the microprocessor will become an increasingly dominant type of hardware in traffic control systems of the next decade. As part of a controller, the microprocessor affords a wide range of applicability without the need for special purpose modifications (e.g., two to eight phases, overlaps, dual ring, fully actuated, preemption skip phase, and so forth) and provides an intelligent local control when operated independently as an intended mode of operation or as a fall-back mode.

However, microprocessors will have their greatest impact in their broader use as elements of distributed or hierarchical system structures. Because systems will be able to be configured as modular elements with relatively easy expansion capability, the concept of systems adaptable to various size cities may, in fact, become a practical reality.

There is, however, one big specter that looms over this electronic paradise. If there is no direction or universal acceptance of these new concepts of traffic control and some degree of functional standardization, it is likely that the desire for uniqueness and inventiveness will result in many different designs to do the same thing. That, in itself, would not be too serious if the users and operators of systems could be assured that their unique and peculiar equipment would always be supportable, maintainable, and replaceable at reasonable cost. Toward this end it appears essential that a functional standardization concept be considered for the new breed of distributed systems of the future.

One such concept has been described by Pinnell and Wilshire [5]. In this concept four levels of signal control units are defined as follows:

- ***Level 1, Intersection Control Unit (ICU):*** essentially the local controller with backup capability to provide intersection control;
- ***Level 2, System Control Unit*** (SCU): a receiving and processing unit which could operate on detector data and provide control commands to several ICU's;
- ***Level 3, Regional Control Unit*** (RCU): a master level unit that would supervise and control SCU's or ICU's;
- ***Level 4, Command/Control Unit (CCU):*** the central level of control which provides the operator interface, display and reporting, and overall monitoring functions.

Without restricting the innovativeness of manufacturers, functional interchangeability of units could be provided by a commonly accepted definition of each unit as to function and interfaces.

These, then, are only a few of the trends and issues which the future portends for the technology of traffic control. What about the institutional factors which will influence future practices? For one thing, traffic engineers are becoming more technically sophisticated and will look for more capabilities in their systems. Traffic managers will require more and better staffing, and the education and training of personnel will be an important consideration. An unfortunate consequence of good training is a high turnover rate as well-qualified people find it easier to sell their capabilities in the marketplace.

The increasing numbers and complexity of equipment will intensify the need for maintenance. Electronic equipment will predominate in use, and maintenance personnel will be required to develop more troubleshooting skills.

The nature of the systems and equipment will be such that many new suppliers will enter the field and many will leave. The situation is not likely to stablilize as long as the technology is advancing. Thus the need for multiple sources becomes more acute.

In this era of rapid technical growth, the need for more and continued information from the federal government will increase. Traffic mangers, system users, as well as designers and consultants will need the kind of evaluated data and nationwide experiences that can only be collected and disseminated by the federal agencies.

Along with this, there will be a continued and intensified need for government-sponsored research and development. This will become increasingly important as the technology accelerates and designers and users grow anxious to apply new ideas without making an adequate analysis and evaluation.

SUMMARY AND CONCLUSIONS

This paper sought to touch upon the issues, both current and future, involving traffic control systems hardware. If this broad subject can be summarized at all, it would contain the following four points.

1) Personal automobile use and vehicular traffic are here to stay at least through the end of the century. It is still a cost-effective, convenient, and reliable mode of transportation. Even impending rising fuel costs and shortages will probably not significantly impact this trend. It has already been clearly shown that higher costs can and will be sustained by motorists, and true shortages will only have a transient effect while spurring the research for gasoline substitutes. Therefore, we can expect to see the continued use and growth of computerized traffic control as traffic managers rely more on this tool to make efficient use of their streets and freeways.

2) The field of computerized traffic control has advanced greatly in the past decade. There are over 100 computerized systems in use in this country today with over 10 000 intersections being controlled automatically and effectively on a daily basis. The past ten years have seen large technological changes in the hardware used in these systems, particularly in the extensive use of solid-state electronics, the gradual transition from electromechanical and analog equipment to digital devices, and in the rapid application of microprocessors.

3) Rapid technological changes can pose problems in a traditionally conservative field where public pressures and governmental constraints abound. Changing technology brings with it the need for more education and training, more staff personnel, more progressive attitudes, and better procurement practices. At the same time, users may lose the traditional sources of technical support from long-established suppliers of equipment. Higher levels of skill will be required to operate, main-

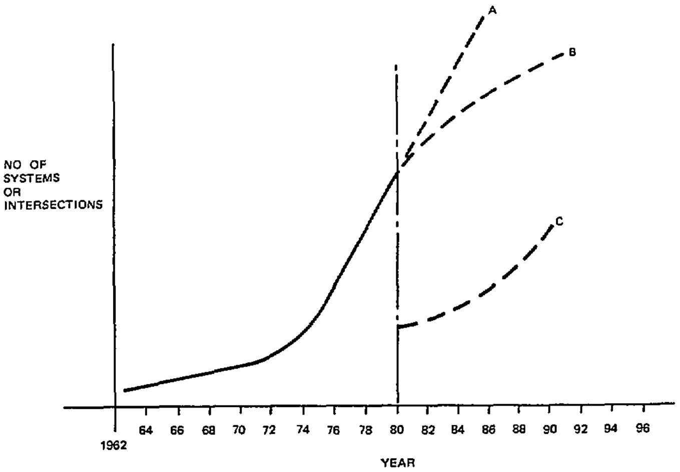


Fig. 11. Projected growth of traffic control systems.

tain, and effectively use the more sophisticated systems, and retaining qualified personnel will be increasingly difficult. And, by its nature, technological advancement is accompanied by obsolescence. New developments spur the desire to keep up, improve, and enhance; and equipment and techniques that were new one day are unattractive or even unsupportable in a short time.

4) While changes are expected to affect all elements of traffic control systems, the most significant will probably occur in the areas of communications, data processing, and controllers. Changes in communications technology will require a better understanding by users of the transmission hardware and functions and, together with controllers, will be the two areas in which most maintenance impacts are likely to occur. Advances in data processing will continue and have a significant effect on system configurations of the future, but changes in computer architecture and processing capabilities will largely be unnoticed by the user unless the system computer is used for off-line or background functions.

The growth of computerized traffic control systems over the past ten years is history, the trend for the next ten years is only conjecture. Continued growth at the same rate (curve A of Fig. 11) is possible but problematical as the number of applications warranting systems becomes fulfilled. This would indicate a continuing growth trend but at a somewhat reduced rate (curve B of Fig. 11). However, by the mid 1980's a substantial number of systems will have been in operation for ten years or more, and a market for replacement, upgrading, and modernization of systems is likely to occur (curve C of Fig. 11). This assumes systems of this type continue to produce benefits and are supportable with reasonable resources by traffic operators. The challenge to provide this growth and continued acceptance of such systems is, in one way or another, upon us all. The accomplishments of the past ten years should be evidence enough that the challenge of the future can be met with equal success.

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The Northeast New Jersey Route Guidance System (RGS): Case Study of a Distributed System

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Abstract-**The general trend in the computer industry today is moving from centralized toward distributed processing. The same trend is impacting the traffic-control field and is being fueled by the availability of low-priced microprocessors in a general environment of increasing communications costs. The Northeast New Jersey Route Guidance System (RGS), now in the final design phase, serves as an example to illustrate the reasons behind this current trend. One of the major decisions facing the traffic-control system designer concerns the selection of the communications system to be used between a central control base and the remote controllers/processors. Whereas in the past it was possible to separate communications system design decisions from control design decisions, such separation is no longer possible. A portion of the decision is outlined by which a 1972 recommendation for central control, made as part of a surveillance-and-control system feasibility study, was modified to distributed control in 1977, during the preliminary design phase of that project. Five communication alternatives, analyzed for use in the RGS, are described. Two of the five alternatives, requiring the least expensive communication-media leasing costs, entoil distributed rather than central control.**

PROJECT BACKGROUND

Introduction

THE NEW JERSEY Department of Transportation (NJDOT) has organized the Northeast New Jersey Route Guidance System (RGS) project to protect public investment in major highways of the northeast New Jersey area. A feasibility study, performed in 1972, investigated the potential of northeastern New Jersey for the diversion of traffic around the sites of incidents that blocked or impeded traffic use of major roadways. These incidents have frequently caused costly traffic delays and secondary accidents. The study defined and set priorities for viable diversion corridors that were determined to be economically and institutionally feasible. In 1976, Edwards and Kelcey, Inc., was selected by NJDOT to design stage I of the project. The system should be in operation by 1983.

In general, the purpose of an RGS is to increase travel efficiency by

- better use of existing roadways (transportation systems management),
- reduction of secondary accidents,
- reduction of fuel consumption,
- decrease in total vehicle emissions as a step toward meeting the objectives of the Clean Air Act Amendments of 1977,
- reduction of traffic spillover from jammed highways onto local streets.

Scope

The initial studies investigated highways of Bergen, Essex, Hudson, Middlesex, Morris, Passaic, Somerset, and Union counties. Within the northeast New Jersey area, 12 travel corridors were investigated. Of these, five were selected as having the highest priority and were organized into a design project. This is the current project under discussion and will be referred to as "stage I."

Stage I Corridors

The corridors included in the first stage of the project are as follows:

- ***corridor A,*** including diversions among Routes NJ-4, 1.80, and US-46 between the George Washington Bridge on the east and Route NJ-l 7 on the west;
- ***corridor E,*** including diversions among Routes US-I, 9 (in the southern portion of the corridor these routes divide into Routes US-1 and US-9), Garden State Parkway, and the New Jersey Turnpike between the Raritan River area to Routes 1, 78;
- ***corridor F,*** including diversions among the Garden State Parkway/Route I-280 and Routes NJ-3, 21 in the southbound direction between Clifton (junction of Garden State Parkway and Route NJ-3) and downtown Newark;
- ***corridor J,*** including diversions among Routes I-95 and US-46 between the New Jersey side of the George Washington Bridge and the northern terminus of the New Jersey Turnpike;
- ***corridor M,*** including diversions among Route US-9 and the Garden State Parkway, across the Raritan River, between Garden State Parkway interchanges #123 and #129.

The above corridors are shown in Fig. 1.

Planned System Operation

The roadways of the corridors will be instrumented by placement of induction-loop vehicle detectors at approximately one-half mile intervals. These detectors will sense the movement or stoppage of traffic by measuring lane occupancy. The detector stations will be served by a communication subsystem transmitting the data to the RGS computer. The **computer** will analyze the data to determine if interruptions

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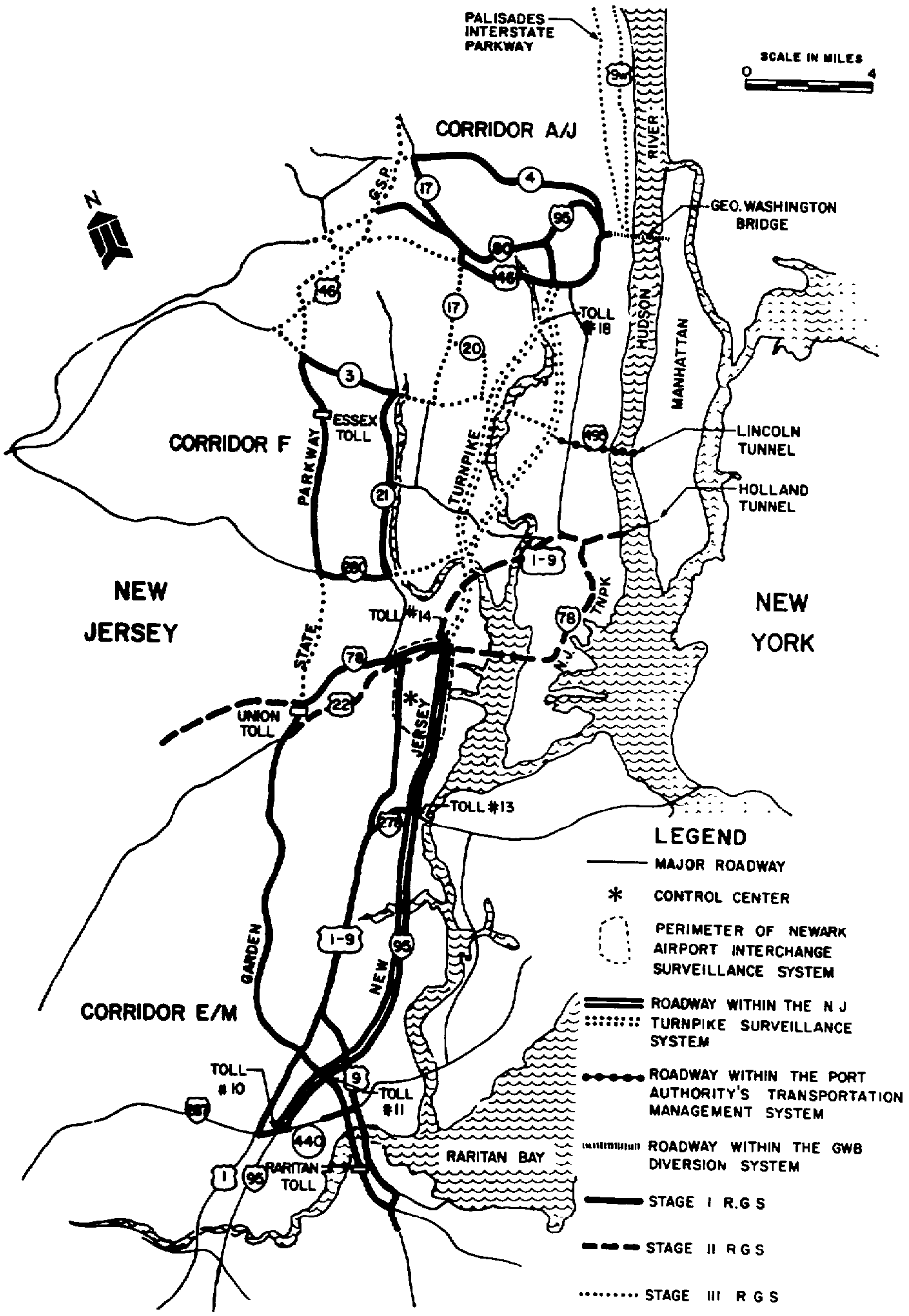

Fig. 1. Northeast New Jersey Route Guidance System (RGS).

to normal flow occur. An incident detection algorithm, such as the modified California algorithm [1], will be used by the RGS computer to identify possible incident locations. The computer will assess the capability of alternate routes to accept the divertible traffic volume and will advise whether diversion is or is not feasible. If the diversion is accepted, variable message signs at strategic points in the road system will advise traffic of alternate roadways bypassing the incident site. Concurrently, the State Police will be notified of the existence of the incident. When normal traffic flows are reestablished following clearance of the roadway, the signs will be turned off and the diversion terminated.

MICROCOMPUTERS AND COMMUNICATIONS

Microcomputers and Distributed Processing

The capabilities of the microcomputer have been available in higher priced minicomputers for approximately two decades. It is the decreasing cost of microprocessors and other microcomputer circuits that is fueling the current trend toward distributed processing. This trend is particularly evident in systems that must utilize communication media whose costs are significant and increasing.

A major part of surveillance-and-control system design consists of the synthesis of a communication system linking the central-control room with widely dispersed loop-detector amplifiers and variable message (VM) sign controllers. Whereas in the past it was possible to separate the design of the control system from the design of the communication system, such separation is no longer desirable. Various communication-system options are available to the system designer. Some of these options require field "intelligence" that can be provided by a series of field microcomputers, off-loading both the communication medium and the central computer.

In the case of the RGS, the communication system must transfer data between 1857 loop detectors, 120 VM sign controllers, and the RGS computer. The incident detection algorithm will be using detector data aggregated over 60-s intervals at each detecting-station lane. Thus field microcomputers can be used to aggregate the required data and transmit them to the central-control location once per minute. The various tasks performed by each microcomputer can be divided into the following functional areas:

- communication with central control,
- communication with local sign controllers,
- sampling loop-detector outputs,
- processing surveillance data,
- diagnosing own operation,
- diagnosing communication validity,
- diagnosing loop-detector failures,
- providing local sign control when communications fail.

All microcomputers are identical with the exception of an externally pluggable memory module containing unique data such as station address, local VM sign data, and local loop configuration.

For the purpose of this paper, systems using field microcomputers to aggregate detector data and to control communication tasks will be defined as "distributed-processing systems." All other systems will be defined as "central-processing systems."

Communication-Media Constraints

Each of the communication options analyzed for use in the RGS consists of a methodology that attempts to maximize the utility of leased voice-grade (Bell 3002 type) telephone circuits. There are two major constraints imposed by these circuits:

- a bandwidth[1] of about 3000 H,
- a limit of the number of connection points.

Two basic types of voice-grade circuits are available:

- two-wire circuits,
- four-wire circuits.

Signals on a two-wire circuit share the same physical path regardless of the direction of the communicated data. Signals on a four-wire circuit follow a separate physical path in each direction.

The Bell System [3] recommends the following limits on the number of connection points to each circuit:

- six points to a two-wire circuit,
- sixteen points to a four-wire circuit or to a single-direction two-wire circuit.

Though a larger number of connection points per circuit is sometimes possible, some Bell companies will not guarantee the quality of the leased communication circuits unless their recommendations are followed.

The following discussion of the communication options is divided into two major option groups:

- central-processing communication options,
- distributed-processing communication options.

CENTRALPROCESSING COMMUNICATION OPTIONS

Traditional Frequency-Division Multiplexing[2] [3] *(FDM) Arrangement*

This method of communication-medium sharing was proposed in 1972 for use in the RGS. The use of FDM divides each voice grade circuit into 16 to 24 independent channels, each sufficient for the purposes of transmitting loop-closure data. FDM requires one transmitter and one receiver for each loop-detector amplifier. The layout of such FDM communication systems is shown in Fig. 2. VM signs requiring two-way communications may occupy two channels on the circuit. The front-end communication processor shown in Fig. 2 is necessitated by the requirement to off-load the RGS computer, which must sample each loop at a rate of about 30 samples/s. The scale of the RGS precludes such sampling by the RGS computer and requires sampling and some data concentration to be done by a front-end communication processor (normally computer-based). FDM was the traditional multiplexing method in the past and is gradually being abandoned in favor of other methods for various reasons including:

- the need for one transmitter and one receiver for each loop-detector amplifier,
- the inefficient use of circuit bandwidth.

Traditional Time-Division Multiplexing (TDM) Arrangement

This multiplexing technique, sometimes used in conjunction with FDM, divides each communication circuit into a number of channels by time segments. TDM is most prevalent in recent surveillance systems that lack field intelligence. It should be noted that some data reduction capabilities are normally implemented within field TDM units, enabling relatively efficient use of circuit bandwidth. The layout of the TDM network required for the RGS is shown in Fig. 3. The TDM system depicted is limited to six loop-detector

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[1] A measure of the capacity of the communication circuit (see McNamara [2]).

[2] The division of a circuit into two or more channels.

[3] For more information, see McNamara [2].

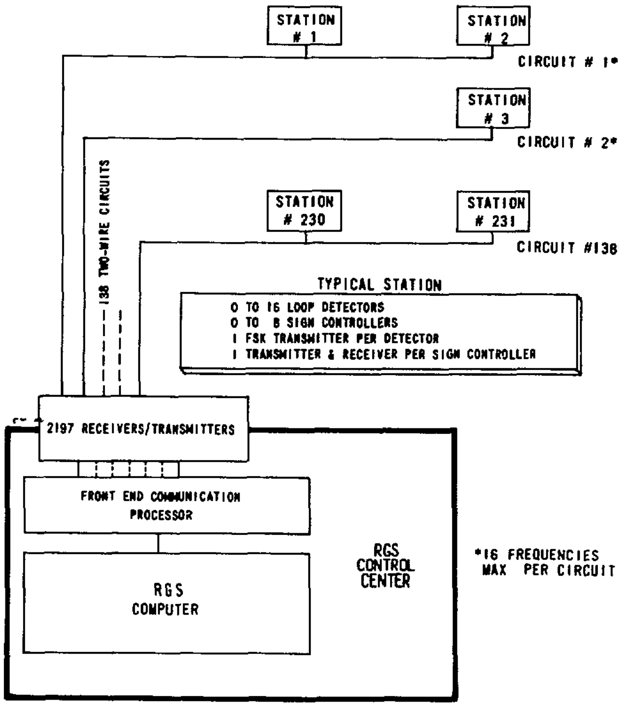

Fig. 2. Central processing: traditional FDM arrangement.

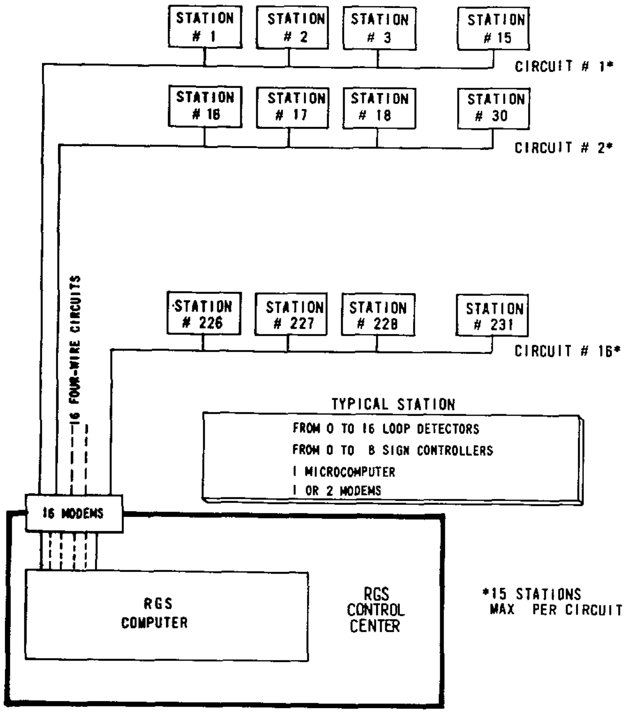

Fig. 4. Distributed processing: multipoint polled arrangement.

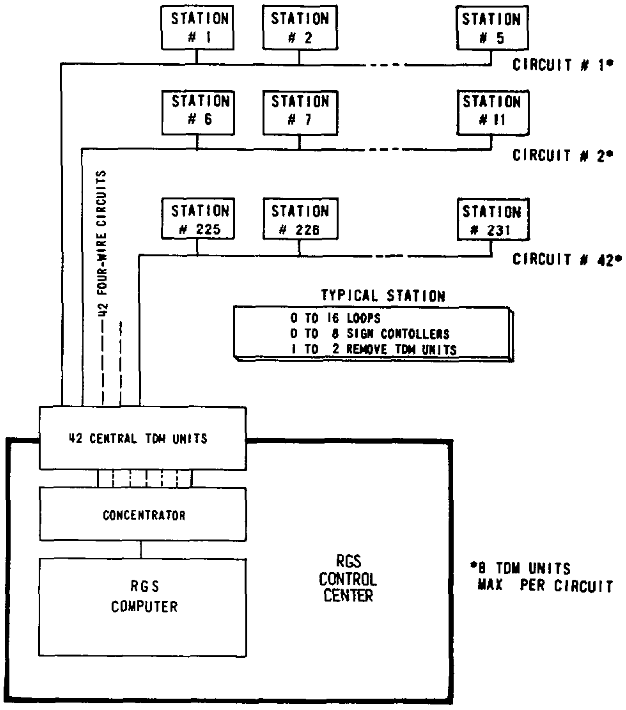

Fig. 3. Central processing: traditional TDM arrangement.

amplifiers per TDM unit, and eight TDM units per four-wire circuit.

DISTRIBUTED-PROCESSING COMMUNICATION OPTIONS

Multipoint Polled Arrangement

In this arrangement up to 15 microcomputers are connected to each four-wire circuit by means of standard 1200 bit/s asynchronous frequency shift keying (FSK) modems.[3] Each microcomputer responds to a unique station address when polled by the RGS computer. The layout of such a multipoint polled arrangement is shown in Fig. 4. Since each microcomputer aggregates data from up to 16 loop amplifiers, each circuit can be used for transmitting data from up to 16 X 15 loop amplifiers. However, the average number of loop detectors at any microcomputer location is only eight.

DSASS Arrangement

Dataphone Select-A-Station Service (DSASS) has been designed by the Bell System in response to a need they preceived in the security services industry. DSASS provides a means for electronically switching leased telephone lines to provide an exclusive path from a central customer location and a remote site. DSASS equipment must be leased from the telephone company. One selector central unit (SCU) is installed in the customer's-central-control location to communicate with each primary data station selector (DSS), which is located on telephone company premises, local or remote. Each DSS has 128 ports that can be linked to the central-computer port on demand. Secondary DSS units (normally remote) can be used through any port of a primary DSS unit for addressability of up to 128 X 128 ports. DSASS can be used advantageously, in systems that do not use the full bandwidth of each circuit, as a means to increase the number of points that can be connected to each circuit beyond the six or 16 previously mentioned and as a means of reducing the number of long-haul lines that must be leased. DSASS requires a modem and a phone-company-supplied channel service unit (CSU) at each field station. The layout

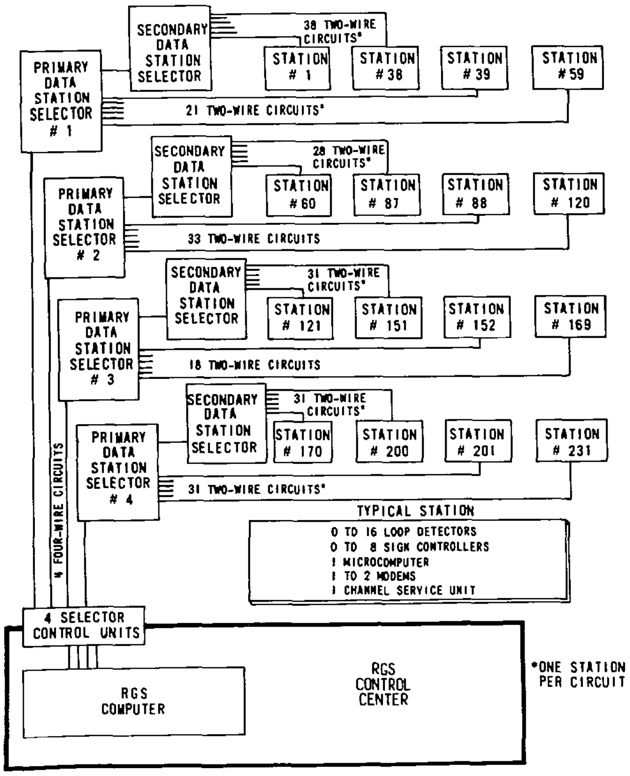

Fig. 5. Distributed processing: DSASS arrangement.

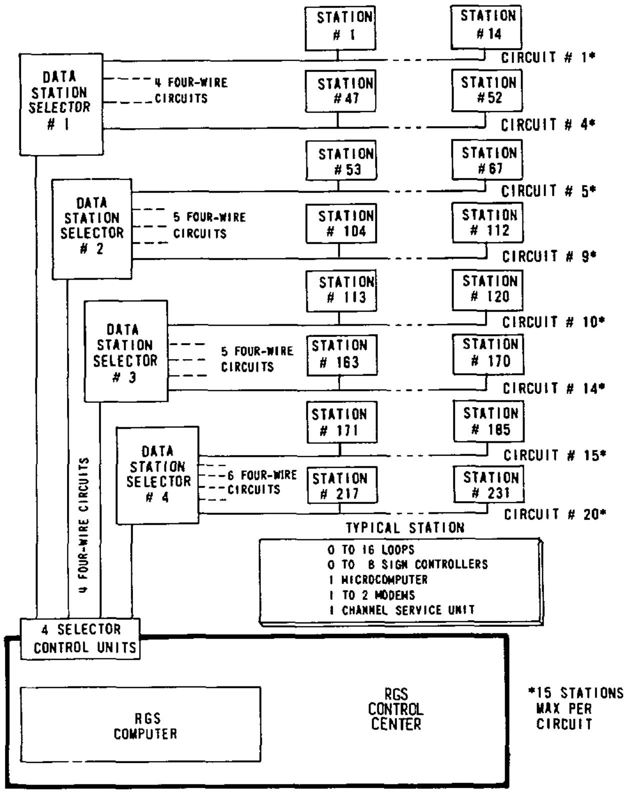

Fig. 6. Distributed processing: modified DSASS arrangement.

of the DSASS arrangement required for the RGS is shown in Fig. 5. The need for four separate four-wire circuits entering the control center is based on bandwidth requirements. The DSASS arrangement shown enables the addressing of each remote station through a DSS, since each is uniquely connected to a DSS port. The function for which DSASS is contemplated for use in the RGS can also be achieved by remote concentrators[3] or regenerative repeaters. However, DSS units are located on phone company premises and are serviced by phone company personnel.

Modified DSASS Arrangement

In the modified DSASS arrangement, DSS units are used to switch among ports that are connected to multipoint circuits. Once connected to each such port, the RGS computer may poll each station on the circuit as in the multipoint polled arrangement. The DSS units are used to reduce the number of long-haul leased lines and the number of RGS computer ports used. The layout of the modified DSASS arrangement is shown in Fig. 6.

COMMUNICATION-MEDIA LEASING COSTS

An analysis of the leasing costs associated with each communication option was performed, using the most recent tariff (published rates) approved by the New Jersey Public Commission. The lease costs of required phone company equipment (such as SCU's, DSS's, and CSU's) were included as part of the media-leasing costs. The costs of leasing the media required by each communication option are given in Table I.

TABLE I
LEASED-MEDIA COSTS (1979)

Communication Option	Monthly ($)	Yearly ($)
1. Traditional FDM Arrangement	$ 8,665	$ 103,980
2. Traditional TDM Arrangement	5,430	65,160
3. Multipoint Polled Arrangement	3,325	39,900
4. DSASS Arrangement	5,665	67,980
5. Modified DSASS Arrangement	3,340	40,080

CONCLUSION

On the basis of communication-media leasing costs, the multipoint polled arrangement and the modified DSASS arrangement stand out as the least expensive communication alternatives. The latter has the added advantage of reducing the number of leased lines entering the control center to four. This benefit is offset somewhat by the added risk implied, since the failure of one circuit can result in the loss of communications with 25 percent of the system.

Not surprisingly, both options belong to the distributed-processing group. A separate analysis of the initial hardware and engineering costs involved has shown that the distributed-processing options are also cheaper to implement than the central-processing options discussed. A decision on the choice between the multipoint polled arrangement and the modified DSASS arrangement will be made later this year.

ACKNOWLEDGMENT AND DISCLAIMER

This paper was prepared in cooperation with the New Jersey Department of Transportation and the U.S. Department of Transportation, Federal Highway Administration. The contents of this paper reflect the views of the authors who are responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the State of New Jersey or the Federal Highway Administration. This paper does not constitute a standard, specification, or regulation.

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The Sydney Coordinated Adaptive Traffic (SCAT) System Philosophy and Benefits

A. G. SIMS AND K. W. DOBINSON

Abstract-**Sydney, Australia, just as many major cities in the world, has seen traffic movement become more and more congested despite capital expenditure on road construction and widening, on public transport systems, and on traffic management measures. SCAT, the coordinated adaptive traffic signal system, now being installed in Sydney, offers a substantial improvement to movement on arterial roads at low cost thereby enabling usage of the arterial road network to be optimized. An initial trial on a length of arterial road showed advantages in journey time over optimized fixed-time signal coordination of 35-39 percent in peak periods. SCAT is unique in that it consists entirely of computers and is totally adaptive to traffic demand. Its communication network provides extremely powerful yet flexible management of the system. The system, the system philosophy, and the benefits it is expected to yield are described. The benefits are not only in reduced delay, improved flow, and decreased congestion, but also in reduced accidents, lesser usage of petroleum resources, decreased air pollution, and improved residential amenity.**

THE SYDNEY TRANSPORT SCENE

TRAFFIC on most arterial roads in Sydney, Australia, is at or near capacity on the many radial routes which extend for 30 km from the central business district (CBD). Even a minor disruption, such as a broken-down vehicle, causes a serious disruption to traffic flow, with the resultant congestion affecting many kilometers of the route. This traffic congestion which extends through most of the daylight hours, in addition to its time-consuming delay to people and goods movement, wastes the scarce petroleum resources, increases air pollution, and causes traffic to be diverted to residential streets, reducing residential amenity.

Public transport offers little opportunity for relief as usage in peak periods has been optimized: 78 percent of commuters travel to the CBD by train, bus, or ferry [1]. Due to urban sprawl, there is insufficient movement elsewhere in Sydney to justify a train system, while few oppportunities exist for the expansion of bus services. Because of a

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cutback in funds for urban arterial roads, Sydney cannot look forward to a comprehensive freeway system, as in American cities, to ease the situation in the short term. At the same time, traffic management measures such as clearways, priority roads, bus and transit lanes, median closures, turn bans, and the like, have for the most part been taken up to increase the capacity of existing arteries.

This leaves the intersections en route as the ultimate constraint. SCAT, through the comprehensive coordination of traffic signals, offers a breakthrough of this intersection constraint so that usage of the entire arterial road network may be optimized at all times.

Flow rates, particularly in peak periods, fluctuate over a wide range extending from free flow to congested conditions. At the same time, peaks vary in length and traffic will change routes to adapt to route blockages. Congestion extends beyond peak periods due to capacity reduction from nonrestrictive curbside parking on many arterials. The problem is further exacerbated by the vagaries of weather and the consequent attraction of the beaches, and by major sporting events. Thus a real-time dynamic system of the SCAT type offers the only effective means of overall coordination of the traffic signal network.

THE PHILOSOPHY OF SCAT

The System

SCAT is the signalized urban traffic control (UTC) system now being introduced in Sydney. It is exceptional in that it consists entirely of computers and it is totally adaptive to traffic demand.

SCAT comprises one central supervisory PDP 11/34 minicomputer at the control center, 11 remote regional minicomputers (ten PDP 11/34 and one PDP 11/40), and over 1000 microcomputer traffic signal controllers distributed throughout the 1500 km2 of the Sydney metropolitan area. The central computer also supervises duplicate PDP 1 l/40 computers which control the 150 slave traffic signal controllers in the Sydney CBD. The distribution of the regional computers, which is determined by the economics of communication, is shown in Fig. 1. Each regional computer maintains autonomous control of its region.

Communication is via rented telephone lines except for the Sydney CBD which is connected via dedicated cable. The interrelationship of the computers is shown in Fig. 2.

The Intersection Computer

The microcomputer intelligence at the traffic signal site is utilized to process strategic data collected from traffic detectors, make tactical decisions on signal operation, and assess detector malfunction. It also incorporates a software method of cableless link coordination (with 11 plans) through synchronous clocks; this provides a fall-back mode of operation that enhances total system security without the need for dual computer systems.

The Regional Computer

Each regional computer controls up to 200 sets of signals as interactive or noninteractive systems as illustrated in Fig. 3. These computers are the heart of the SCAT system. They implement the real-time operation of the signals by analysis of the detector information preprocessed by the microcomputers.

The software and data base are entirely core-resident for reliability. However, disk units are used for the storage of

- the regional computer program and data for reloading purposes,
- a copy of the data for reloading each microcomputer,
- miscellaneous data collected for off-line analysis purposes.

The Supervisory Computer

The supervisory computer does not automatically influence traffic operation but has the following functions:

- outputs traffic and equipment status for fault rectification,
- stores specified traffic data for short term or permanent record,
- maintains core image of each regional computer and reloads the regional computer if required,
- allows central control to monitor system, subsystem, or intersection, alter control parameters, manually override dynamic functions, or plot time-distance diagrams.

The Communication System

To realize the full potential of the distributed intelligence system based on microcomputers, a compatible communication system was required. The local microcomputers dramatically reduce the time demand on the communication channels and on the regional computer, because they perform all the repetitive high-speed functions. They preprocess data and only require information transfers at decision points which may occur at intervals between 1 and 120 s; this is in sharp contrast to traditional hardware systems where data transfers are required at intervals between 20 and 100 ms.

This ability to transfer preprocessed data from local controllers in digital form and the ability to load local computers with control parameters as digital values from the regional computer required that the communication protocol resemble conventional computer-to-computer technology. This communication system, although using conventional 300-bit/s frequency-shift keying (FSK) hardware, is therefore completely software controlled. A sample of communication codes used is given in Table I.

The system is very flexible, powerful, and expandable, and yields unprecedented monitoring and management possibilities. A system operator can remotely check any local controller in fine detail at the regional site or at the central control; its exact state can be seen, all times and plans can be monitored, and all detector states and demands can be viewed; in fact, any memory location in the local controller can be monitored by a system operator. Data can also be referred back to the regional or central master for logging or mass storage. This monitoring capability makes the local controller

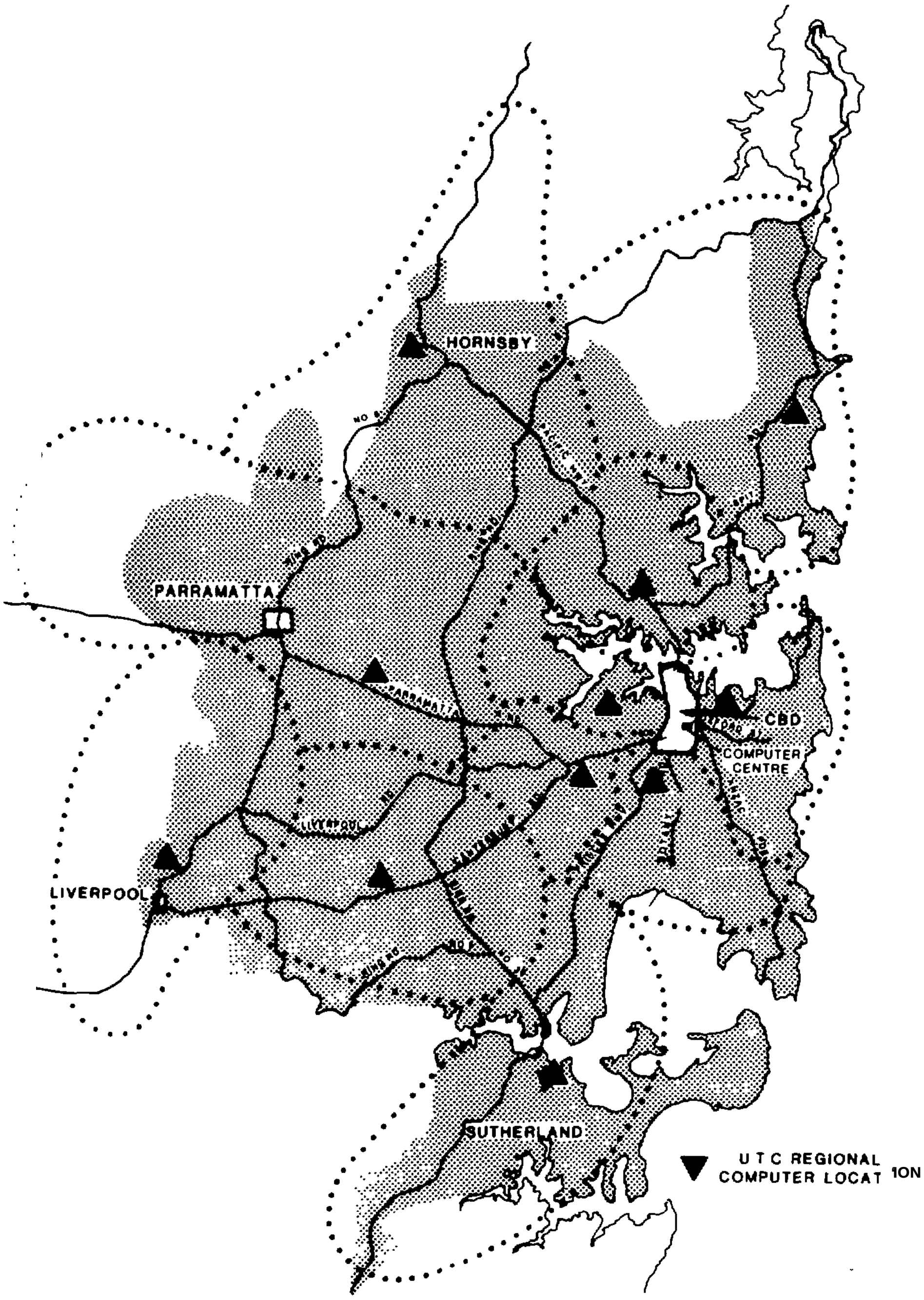

Fig. 1. Sydney regional computer locations.

"transparent" and enables remote fault diagnosis to take place. The system operator also has the capability to change local controller times, fall-back plans, phase sequences, special facilities, and controller operating modes. If desired, the operator can manually remote-operate a controller while continuously monitoring its performance. Selected controller and detector parameters are continuously monitored by the central master and operate alarms when a failure occurs.

Hence the communications system is a major factor in providing a system of high availability that gives extremely powerful management and diagnostic capability. This is apart from traffic benefits due to its contribution to signal coordination. In fact, the SCAT system provides a city-wide street-side data network with distributed intelligence and spare data capacity for subsequent use in public transport priority, vehicle locations, route management, etc.

System Operation

The normal mode of coordination is real-time adjustment of cycle, split, and offset in response to detected variations in demand and capacity. Maximum freedom consistent with good coordination is given to local controllers to act in the traffic-actuated mode. The system is designed to autocalibrate itself on the basis of data received, to minimize the need for manual calibration and adjustment, and to reduce the amount and criticality of preprepared data.

For control purposes, the total system is divided into a large number of comparatively small subsystems varying from

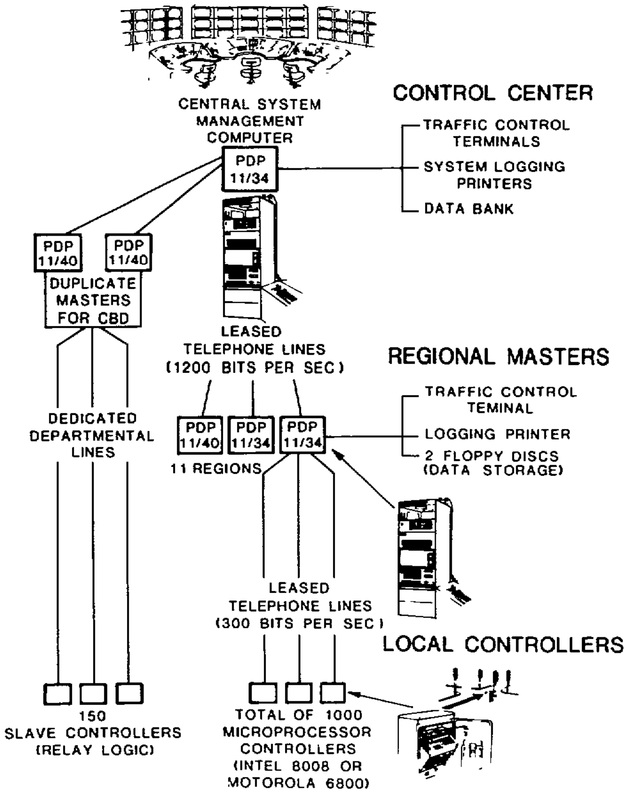

Fig. 2. SCAT computer hierachy.

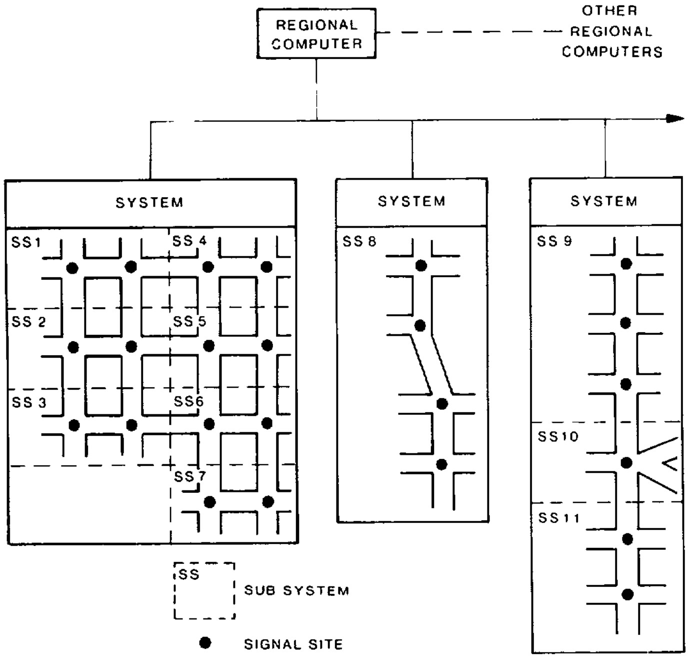

Fig. 3. Regional computer control of systems and subsystems.

TABLE I
SAMPLE OF COMMUNICATION CODES

Mnemonic	Code	No. of Bytes	Message Group	Function
Regional Master to Local Controller Command Codes				
CLPn	02n	1	1	Call Phase n
RST	020	1	2	Request Controller Status
RDM	054	2	2	Request Demand Status
SSF	040	3	3	Set Special Facilities
RSF	041	2	3	Read Special Faciltiies
STS	100	3	4	Store Time Setting in RAM
RTSn	10n	2	4	Read Time Setting in one of several Modes defined by n
SPD	110	3	4	Store Plan Data
RPD	111	2	4	Read Plan Data
SPC	112	3	4	Set Plan Change Schedule
RPC	113	2	4	Read Plan Change Schedule
SCT	004	3	4	Set Clock Time
RCT	005	2	4	Read Clock Time
BVO	044	3	4	Begin Volume and Occupancy Counts
FVO	045	3	4	Finish Volume and Occupancy Counts
RDA	051	2	4	Read Detector Alarms
RMEn	12n	2	4	Read Memory Location in Page n
RMC	116	2	4	Read Memory Checksum
Local Controller to Regional Master Reply Codes				
SST	020	2	2	System Status
CSTn	02n	3	2	Controller Status on Termination Command
DMS	054	2	2	Demand Status
SFS	040	3	3	Special Facilities Set
TBF	100	3	4	Time Setting Buffer Full
TSSn	10n	3	4	Time Setting Set for Mode n
PDS	110	3	4	Plan Data Set
PCS	112	3	4	Plan Change Schedule
CTS	004	3	4	Clock Time Set
VOB	044	3	4	Volume and Occupancy Counts Begun
VOCOn	14n	3	4	Volume and Occupancy of Detector n + 1 for detectors 1-8
VOC1n	15n	3	4	Volume and Occupancy of Detector n + 9 for detectors 9-16
DAS	050	3	4	Detector Alarm Status
MECn	12n	3	4	Memory Contents of Page n
CSM	115	3	4	Checksum of Memory

one to ten intersections (see Fig. 3). This system configuration is in software. As far as possible, the subsystems are chosen to be traffic entities, and for many traffic conditions they will run without relation to each other. As traffic conditions demand, the subsystems "marry" with adjacent subsystems to form a number of larger systems or one large system. This marriage of subsystems is calculated in much the same way as are the interrelationships between intersections within a subsystem. Thus there is a hierarchy of control that is distinct from a hardware hierarchy.

The data for each subsystem specify minimum, maximum, and geometrically optimum cycle length. Four background plans are also stored in the data base for each subsystem. Cycle length and the appropriate plan are selected independently of each other to meet the traffic demand. For this purpose, a number of detectors in the subsystem area are defined as strategic detectors; these are stop-line detectors at key intersections. Various system factors are calculated from the strategic detector data which are used to decide whether the current cycle and plan should remain or be changed.

For linking subsystems together there are four linking plans for each subsystem which define the conditons for marriage with other subsystems, and which use strategic data in much the same way as subsystem plans. When a number of subsystems are linked together, the cycle time becomes that of the linked subsystem with the longest cycle time. The combination of subsystem plans, link plans between subsystems, variable cycle length, and variation of offsets provides an infinite number of operating plans.

Strategic options are available which provide for the operation to be minimum delay, minimum stops, or maximum throughput. These may be either permanent options or can dynamically change at threshold levels of traffic activity.

During normal operation of the system, the regional computer notifies each local controller of a fall-back mode, which can be "lamps off," "flashing," "isolated," or "cableless link" operation. The cableless link operation is the normal fall-back mode as it provides an effective linking system without the

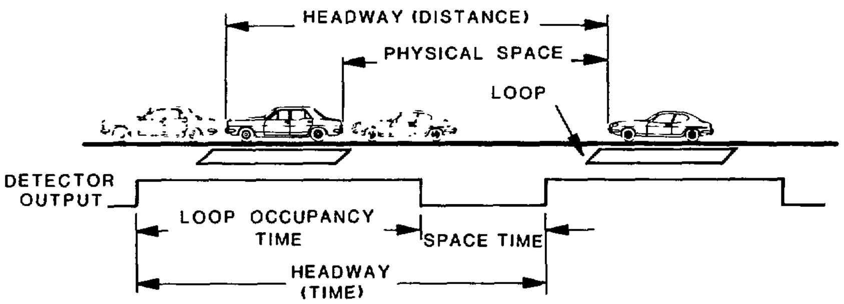

Fig. 4. Relationship between headway, occupancy, and space between vehicles.

need for a master through an in-built software cableless link program.

Traffic Information Processing

In a real-time system it is vital that the detector data used in the algorithms be unambiguous, and that it enable more parameters to be ascertained than is possible from volume and headway. It should also be recognized that the primary cause of delay in a system is the phase split and cycle length of intersections: unless these are first optimized, any benefits from coordination are unattainable.

If demand/capacity is optimized, then coordination provides the means to realize that capacity, as well as reducing delay and stops, by ensuring that platoons will not be fragmented by the asynchronous operation of adjacent signals. The capacity of any traffic lane is not constant, because the ability to flow at saturation varies due to many factors such as weather, time of day, parking, pedestrian friction, downstream conditions, and type of vehicles.

Simple volume and headway information cannot show the difference between these variations and changes in actual demand, and can lead to gross errors in operation. The data from presence detectors can be evaluated to obtain the information essential to describe all the flow parameters, but the detector locations must be in close proximity to the intersection so that high correlation exists between the signal timing and the measurements. In other words, the information will only directly relate to the intersection's capacity if the measurements are made when the traffic should be moving at saturation flow with a green signal. Remote detector locations do not provide this direct correlation, and assumptions on intersection capacities must be made.

In the detector data base the highest flow rate recorded is stored for calibration purposes. As well as the flow rate, the occupancy that occcurred when the flow rate was attained is also recorded. Numerous checks are made to discard erroneous data. This provides the following data relating to maximum flow as reference data:

1) headway (time),
2) loop occupancy time,
3) space time between vehicles,
4) speed.

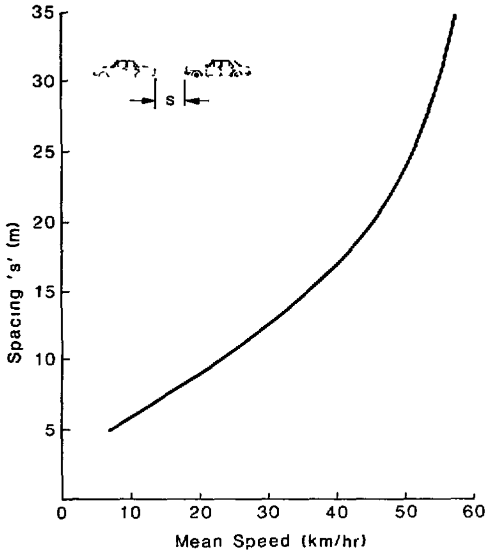

Fig. 5. Speed-spacing relationship [3].

It is assumed that maximum flow will occur when only cars are present and therefore, as loop length and the length of cars are known, then speed can be calculated approximately. The relationship between these first three parameters is illustrated in Fig. 4.

These data are compared against the cyclic data in the various algorithms to determine traffic flow status. The speed/spacing relationship defined by Wardrop [2] and shown in Fig. 5 is used to determine whether speed, and hence saturation flow has varied; i.e., if the actual average space time is less than the reference space time, then speed is less than optimum and flow rate has decreased.

The space time uniquely defines the actual flow conditions as illustrated in Fig. 6. By using the reference speed, the amount of change can be approximated. Neither headway nor occupancy time are appropriate for this purpose because they can vary, as illustrated in Figs. 6 and 7.

Where the flow has decreased due to lower speeds, then, if the decrease is within practical limits, it can be assumed that this is the saturation flow of the lane due to intersection factors. If the decrease is excessive it must be assumed that it is due to downstream conditions.

If the actual average space time is larger than the reference data, this is interpreted as a reduction in demand. For all cycles where flow continues for the whole of a phase in a lane, it is possible to calculate the average vehicle length by means of the measured occupancy, the previously calculated speed, and the reference occupancy. This information would be included in the algorithm for the selection of phase splits and is particularly valuable for including a passive bus priority.

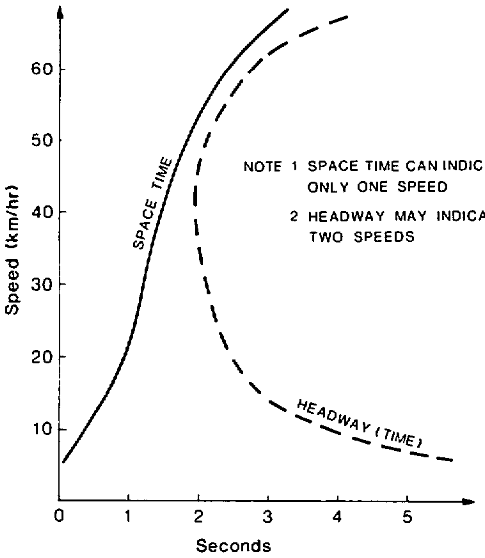

Fig. 6. Space time and headway variation with speed.

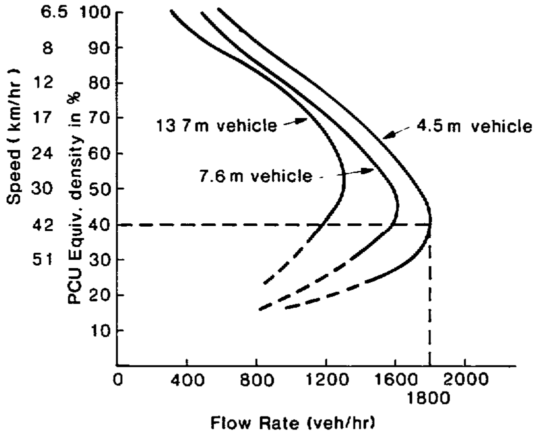

Fig. 7. Variation of vehicle speed and passenger car unit equivalent density with flow rate using 4.5-m long detector zone [4].

THE COST OF SCAT

The total computer configuration enables a system to be developed which incorporates advanced concepts at low cost and which is capable of future amendment without obsolescence. The cableless link fall-back mode saves computer duplication which not only reduces computer costs by 50 percent but avoids the undesirable complexities of dual systems.

Component costs are as follows.

Local controller	$ 6000 (US$6600)
Regional computer: cabin, computer, and peripherals	$ 50 000 (US$55 000)
Total capital cost for coordination of 1000 sets of signals excluding replacement controllers (this represents about 10 percent of the total signal installation cost)	$2.8 million (US$3.1 million)
Annual rental of telephone lines	$36/km (US$40/km)
Annual rental of telephone lines for 1000 sets of signals	$200 000 (US$220 000).

THE BENEFITS OF SCAT

SCAT offers many community benefits through reduction in travel time, accident reduction, saving in fuel consumption, and reduced air pollution.

Travel Time

Moore [4], in a study of a trial of SCAT in late 1974 on Princes Highway, Newtown, 2.6 km of a Sydney arterial, indicated reductions in travel times compared with optimized fixed-time, using the Greater London Council's (GLC's) combination method of signal coordination, of

- 39.5 percent in the morning peak period,
- 14.5 percent in the main business hours between peaks,
- 32.8 percent in the evening peak period.

Vehicles traversed 8.8 X 10^9 km in Sydney in 1977, of which 3.1 X 10^9 km were on arterials that will be covered by SCAT control. Relating the work of Moore to these latter arterials, the estimated savings by SCAT control, compared to the optimized fixed-time coordination of signals, are 40 X 10^6 km vehicle hours per annum. The latter figure represents an annual savings of $150 million (US$165 million), using an average value of $3.75 (US$4.12) per hour for driver and vehicle time. (This figure was derived from the $2.30 per hour in 1973-1974 derived by Bayley and Both [5] and updated to 1979). Translated into motorists' terms, the saving in delay represents 12 min for the average 13-km trip (42 min under optimized fixed-time) in the journey to work on Sydney roads.

Accidents

In 1977-1978, 113 people died and 5800 were injured in a total of 13 225 accidents on arterial roads in Sydney that are planned for SCAT control. Moore and Lowrie [6] showed that signal coordination on arterial roads as compared with isolated operation reduced accidents by 20 percent, with right-angle collisions and pedestrian accidents being the most significant reduction.

Applying the above study to the accident data for 1977-1978, it was estimated that SCAT's accident reduction would save over 1000 injury accidents per annum. Using the average costing of Bayley and Both [5] for accidents, updated to 1979, of $130 000 (US$143 000) per fatality, $5 400 (US$5900) per injury accident, and $800 (US$880) per property damage accident, this represents a community saving of $8.3 million (US$9.1 million) per annum.

Fuel Consumption

Moore [4] indicated that 20-48 percent of stops would be saved by signal coordination as compared with isolated operation, with peak periods representing the higher figures. Johnston *et al.* [7] indicated that, for each stop eliminated in travel on an arterial road, 1/40th of a liter of fuel is saved.

By applying these data to the arterial roads to be covered by SCAT, a savings of 37 million liters per annum can be projected, or seven percent of the 525 million liters of fuel used in travel on arterials in Sydney. This is 1.5 percent of the total fuel consumption for the Sydney metropolitan area. At the present retail price this is a savings of $9 million (US$10 million) annually. To the average motorist this means a savings of two liters per week in the journey to work or a saving of $25 (US$27.5) per annum for work journeys.

Air Pollution

The Sydney Area Transportation Study (SATS) [1] indicated that 360 km, or 15 percent, of the developed area of Sydney exceeded the World Health Organization (WHO) eight-hour average goal of 9 ppm of carbon monoxide (CO) in 1971. 90 percent of the CO emission is from motor vehicles. By the installation of SCAT, the improvements in average speed estimated by Moore [4] over optimized fixed-time coordination represents 25 percent overall. This corresponds to an 18 percent decrease in CO emitted by arterial road traffic [8].

Considering emissions from other sources and nonarterial road traffic, the net reduction in CO adjacent to SCAT-controlled arterials is estimated at 13 percent. With the highest emission of CO adjacent to arterials, the expected decrease in the area of Sydney exceeding the WHO level is 60 km^2, i.e., a 16-percent reduction. This represents a seven-percent reduction in CO release in the Sydney metropolitan area as against optimized fixed-time coordination.

Hydrocarbon emissions are not improved to the same degree. Only 65 percent of the hydrocarbons arise from motor vehicles. SATS [1] indicated that 35 percent of the Sydney area exceeded the WHO goal of 0.24 ppm in 1971.

The 25-percent improved speed of travel with SCAT over optimized fixed-time coordination represents a 12-percent decrease in hydrocarbon emissions [8]. It is estimated that this will reduce the total atmospheric concentration of hydrocarbons in the Sydney region by two percent. The greatest benefit will be alongside arterial roads, but overall it will not make a significant reduction in the area above the WHO goal.

The increase in average vehicle speeds from SCAT does not decrease emissions of nitrogen oxides; in fact, the 15-percent expected increase would increase nitrogen oxides emitted by vehicles on arterials by 30 percent [8]. This is estimated to increase the area of Sydney which exceeded the three-hour average goal of 0.1 ppm in 1971 from the six percent determined by SATS to nine percent. This increase is not critical from a health viewpoint, but can be significant in the formation of photochemical smog.

Photochemical smog is a problem in Sydney. Ozone is the measure of photochemical smog, being one of its constituent components together with nitrogen dioxide, peroxyacetyl nitrate, and oxidants. Ozone levels are rising as illustrated in Fig. 8 for the monitoring station at Lidcombe in the western suburbs of Sydney [9].

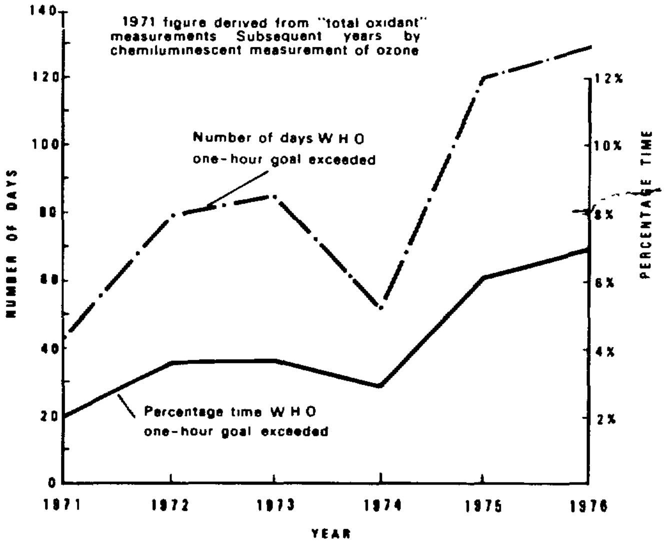

Fig. 8. Ozone concentration, Lidcombe [9].

The effect of SCAT on photochemical smog is complex, as it is derived from combinations of oxides of nitrogen and hydrocarbons which are affected differently. The predicted reduction in hydrocarbons by SCAT will reduce the formation rate. However, the probable attraction of additional traffic to the arterials by the improved flow conditions will increase concentrations of emissions along these routes, particularly of nitrogen oxides, causing increased local smog concentrations. The net resultant immediate change in photochemical smog due to SCAT is estimated as minimal. However, as vehicle emission controls reduce hydrocarbon levels, the improved travel speeds will become progressively more effective in reducing oxidant formation and as a consequence the photochemical smog.

Other Benefits

The improved flow on the arterials resulting from SCAT will attract traffic from residential streets which are presently used as bypasses, with a consequent improvement in residential amenity through reduced air pollution, reduced traffic noise, reduced accidents, and reduced physical intrusion by vehicles.

Traffic volume data collection and analysis is being included as an integral part of the SCAT scheme. This replaces automatic and manual collection of these data which are required for road planning and design with substantial cost savings. SCAT offers a greater volume of original data which improve the accuracy level of all data. Storage is in mathematical model form to obviate the need for large computer core storage. SCAT also offers a simple low-cost travel-time data monitoring system for assessing the effects of road proposals. This is to be added to the system.

SCAT OFFERS A FUTURE

SCAT offers a totally adaptive UTC coordinated network signal system of high intelligence at low cost. It offers substantial savings in delay to motorists, principally on arterial roads, and particularly during peak periods. Its peripheral benefits in substantial accident reduction, major savings in fuel consumption, reduced air pollution, and improved residential amenity cannot be overlooked at this time of grave concern in these areas. It offers options for data collection, traffic volume, and travel time data, and for the introduction of variable message signing, reversal flow of lanes, and who knows what else—all at minimal additional cost. SCAT is the UTC signal system for the 1980s.

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Hampton Roads Traffic Surveillance and Control System

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***Abstract*-A surveillance and control system was designed and implemented for the Hampton Roads Bridge-Tunnel Crossing connecting Hampton and Norfolk, VA. The facility is a part of the Interstate 64 subsystem and consists of two bridges at each end connected by two two-lane tunnels. This system has been operating successfully since November 15, 1977. The system provides the means for improving vehicular throughput and reducing congestion, improving the management of vehicle incidents and facility operations, improving motorist information, improving environmental conditions, and improving traffic data collection. A control room situated in one of the four tunnel ventilation buildings is the nucleus of the traffic management activities. The system enables vehicle flow control of tunnel access; incident detection, incident verification, and incident operations management; automatic response to environmental and overheight problems; hardware monitoring of the signs, signals, and vehicle detectors; execution of major traffic operations on the faculty upon operator request; and daily reporting and logging of system events. Vehicle data are collected and accumulated by the system and are used for reporting and for performing incident detection and access control.**

INTRODUCTION

THE Hampton Roads Traffic Surveillance and Control System was designed and developed for the bridge-tunnel facility connecting Interstate Route 64 between Hampton and Norfolk, VA. The system is fully integrated and combines five major components: traffic control, safety surveillance, environmental surveillance, communications, and equipment status. Within the system these components provide for

- maximum vehicular throughput and reducing congestion,
- improving the management of vehicle incidents and facility operations,
- improving motorist safety and information,
- improving environmental conditions, and
- improving traffic data collection.

The system was designed in conjunction with construction of a second tunnel for relieving traffic congestion on the 9.8 km (6.1 m) of eastbound and westbound roadways of Route I-64 between Willoughby Spit in Norfolk and Hampton, VA. As depicted in Fig. 1, the facility consists of dual two-lane tunnels and trestle-type bridges which connect the tunnels to the mainland. The tunnel portals and ventilation fan buildings are

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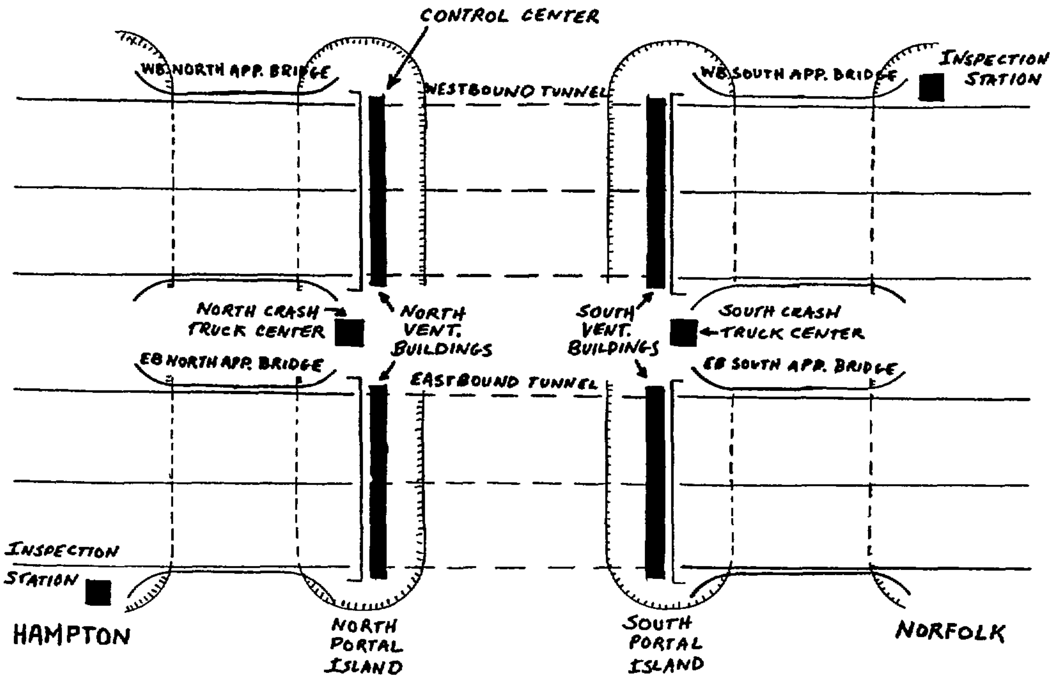


Fig. 1. Hampton Roads Bridge-Tunnel Facility.

situated on two islands. The agency responsible for operating the system is the Virginia Department of Highways and Transportation Tunnel and Toll Facilities, and staffing is provided on a 24-h seven-day a week basis.

Prior to implementation of the system and new tunnel, the facility handled approximately 24 000 vehicles per day in both directions and had an incident rate of 70 occurrences daily. Traffic control was maintained using manually operated traffic signals, stationary signing, police foot patrol on the tunnel sidewalk, and a manual incident management system.

The design of the surveillance and control for the new system involves the use of 75 variable message signs, 137 traffic signals, automated access control of the tunnels, 76 vehicle loop detectors, ice and fog detectors, carbon monoxide (CO) and haze detectors, overheight vehicle detectors, closed-circuit television, and ventilation fan and electrical power distribution controls. A control room located in the Westbound Tunnel North Ventilation Building is the nucleus of the traffic management and roadway operations activities. Supervision and control of the various system elements are maintained in this room using a control console, a control and map board display, and two digital minicomputers. These computers are used for primary and backup operations.

SYSTEM CONFIGURATION

The major components of the Hampton Roads Surveillance and Control System include both hardware and software. These elements are designed to provide an integrated operating system for the facility.

System Hardware

The system hardware consists of traffic control signing, an overheight vehicle detection system, a vehicle detection system, an environmental detection system, a closed-circuit television (CCTV) surveillance system, and central control equipment.

Signing: The various energized signs and signals on the facility are individually controllable from the control room using the operator control panel and the computers on a time-division multiplexed communications link. These devices consist of the matrix-type changeable speed limit signs, rotating drum variable message signs, scroll variable message signs, blankout signs, traffic signals, and lane-use signals. The warning and regulatory messages displayed by the signs indicate

- changes in travel lane,
- median crossover,
- lane designation and closures,
- vehicle inspection,
- ice and fog conditions,
- speed limit changes,
- traffic movement and channelization, and
- tunnel passing prohibition.

Overheight Detection System: The overheight detection equipment illustrated in Fig. 2 is designed for sensing moving overheight vehicles approaching the bridges and tunnels. Audible and visual alarms are triggered to alert the drivers of such vehicles to stop at the inspection station located at bridge approaches for a positive vehicle height check. At the instant of detection both inspection station and central control room personnel are alerted by annunciator alarms and by a computer warning message, respectively, that an overheight vehicle is on the facility. In addition, the inspection stations are equipped with a manual override push button for activating these alarms.

For both eastbound and westbound directions, primary and secondary overheight photoelectric-sensing devices project steady beams of light across the roadway at a height slightly under the actual tunnel clearance. When this light beam is broken at the primary detector, alarms are activated for alerting motorists and inspection station and central control room

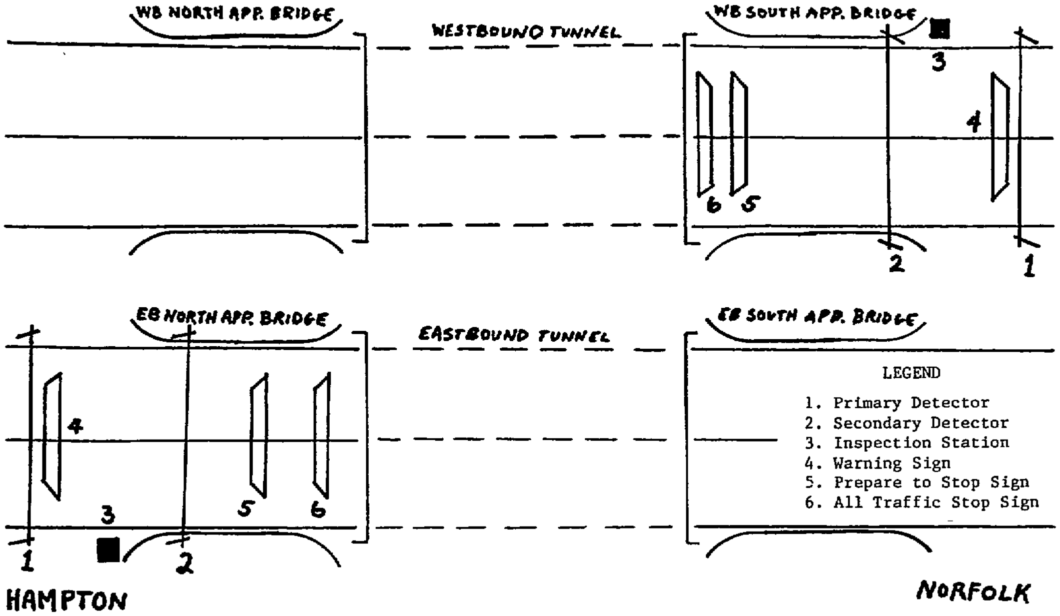


Fig. 2. Overheight detection system.

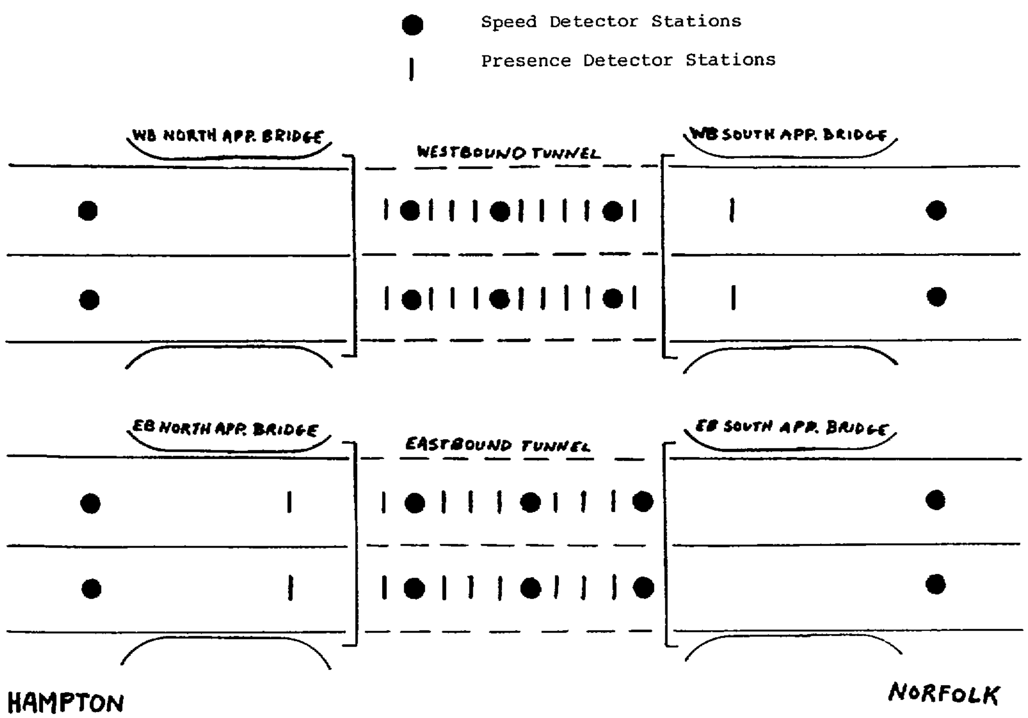


Fig. 3. Vehicle detection systems.

personnel. In the event that an overheight vehicle fails to stop for inspection, the secondary detector will be triggered, and emergency alarms will be initiated in the inspection station, the emergency crash truck garage, and the central control room. Furthermore, this detector will activate a computer controlled shutdown of the roadway to apprehend the violator by automatically lowering speed limits, displaying warning messages on the variable signs, and transitioning the lane-use signals to the red full-stop condition.

Vehicle Detection System: Vehicle presence and speed detectors of the induction-loop type are located in each lane of the facility (Fig. 3). Vehicle presence detector stations consist of a single loop detector (1.8 m [6 ft] square) spaced at approximately 183 m (600 ft) intervals within the tunnels. The speed detector stations are a pair of loops spaced 7.6 m (25 ft) apart located at the boundaries of the facility and at each of the three grade levels of the tunnels.

The computer monitors each loop detector 40 times per second on a frequency-division multiplexed communication link for calculating vehicle volume, occupancy, and speed on the facility. The vehicle occupancy accumulated by the vehicle presence stations is used by the system for detecting vehicle incidents in the tunnel. Vehicle speed and volume are monitored for providing access control to the tunnels.

Environment Detection System: The components of the environment detection system include ice detection, fog detec-

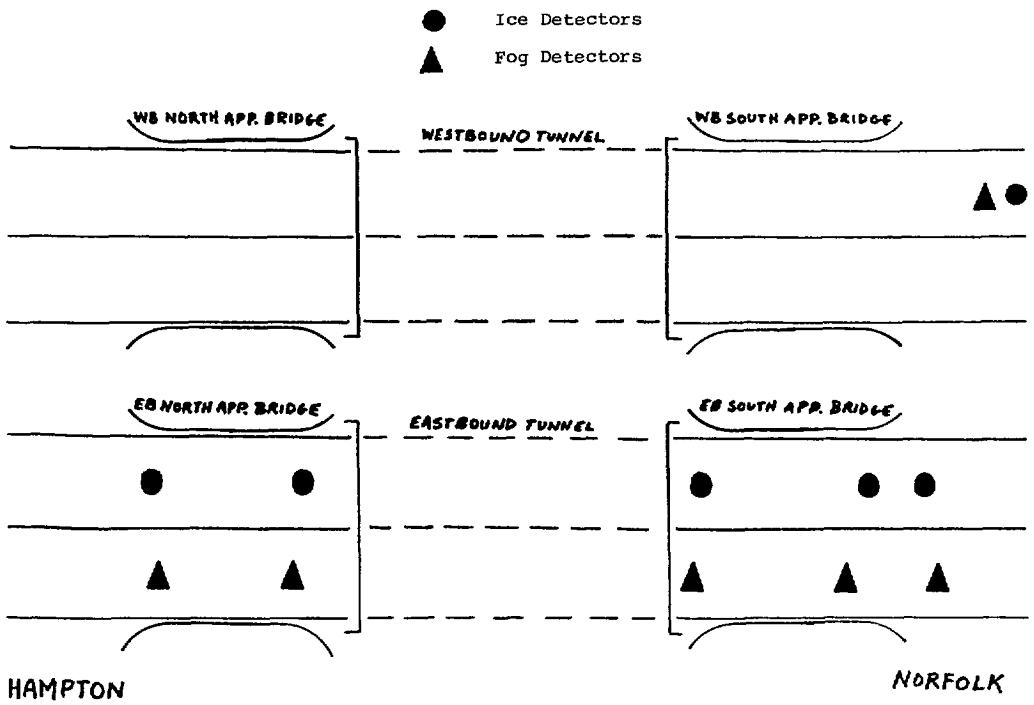


Fig. 4. Ice/fog detection system.

tion, carbon monoxide detection, haze detection, and wind detection. As illustrated in Fig. 4, ice and fog detection is provided on the bridges of the facility. Each of the sensors automatically activates audible alarms on the annunciator panel of the central control board. On activation of an ice or fog alarm, the central control operator may initiate a computer program for automatically reducing speed limits on the facility and displaying ice or fog warning signs.

Carbon monoxide and haze detectors are located within the tunnels for reducing the effects of automotive emission and increasing motorist visibility and air quality. Each of the detectors is monitored by a chart recorder on the central control board in the central control room. When the levels of CO or haze exceed allowable limits an audible alarm is sounded in the control room and the operator will select and activate the proper number and speeds of the tunnel ventilation fans to improve the environment conditions in the tunnel.

Surface winds are measured from a sensor on the roof of the Westbound North Ventilation Building and are indicated in continuous drum recorders in the central control room. When the winds are such as to constitute hazards for mobile homes, campers, truck-trailers, and light vehicles, the operator may reduce the facility speed limits, activate lane-use signals to shift the traffic to downwind lanes, or prevent vehicles from entering the facility.

CCTV System: In addition to the vehicle detection system, a closed-circuit television system is utilized for monitoring traffic flow on the facility. The CCTV cameras provide for verification of an incident determined by the loop detectors by giving visual affirmation of the roadway condition.

The CCTV system consists of TV cameras mounted on the sidewalk side walls of the tunnels and on 30.5 m (100 ft) towers located on the tunnel portal islands and on the Willoughby Spit shore, providing traffic surveillance on the bridges (Fig. 5). The cameras transmit video pictures of the facility traffic conditions by means of cables or microwave antennas to monitors located on the central control board and on the control console.

The fixed focus cameras in the tunnel face oncoming traffic and are located at each presence detector station to view traffic for approximately 183 m (600 ft). Full-tilt, 350° pan, and zoom lens cameras are mounted on the towers. The cameras located on the South Portal Island and Willoughby Spit Towers transmit the TV signals via a microwave antenna to receiver dishes located on the tower on the North Portal Island, where the signals from all cameras are transmitted to monitors on the central control console via coaxial cable.

Central Control Equipment: The facility control center is located in the North Portal Island Westbound Tunnel Ventilation Building. Management of the system is conducted at this location via a central control board display, a control console and operator panel, and two digital computers. Environmental surveillance systems are also located in this center. The components of the control room are depicted in Fig. 6.

The central control board display consists of two sections. The upper section contains a traffic display panel, recorders for CO and haze detection, alarm communications for electrical and fan malfunctions, alarm annunciators for ice and fog detectors, and 24 CCTV monitors for monitoring tunnel traffic. On the traffic display panel there are indicators for each of the energized signs and signals on the facility, each of the presence and speed detector stations, and each of the tunnel CCTV monitors. The computer is linked to the traffic panel and displays the actual sign message on the sign and signal indicators, and the level of the facility traffic congestion is displayed on the detector indicators. The lower section consists of the controls and status indicators for all of the electrical and mechanical equipment for operating the facility.

The components of the control console and operator panel are a sign and signal escutcheon control panel, a video terminal

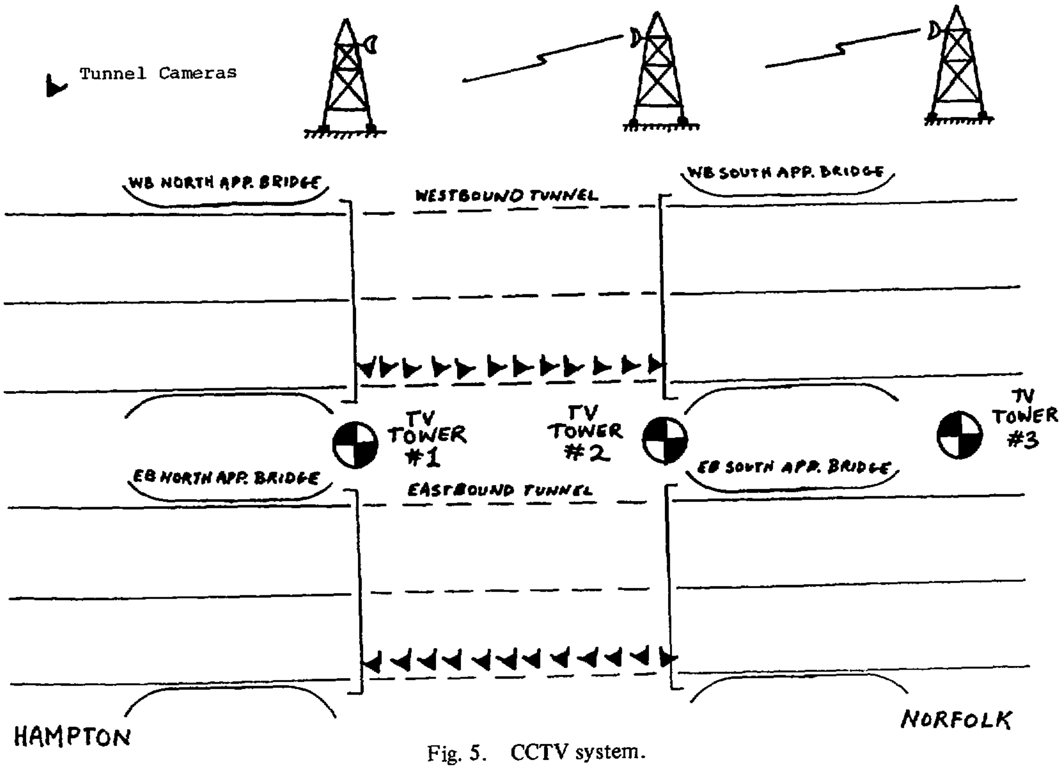


Fig. 5. CCTV system.

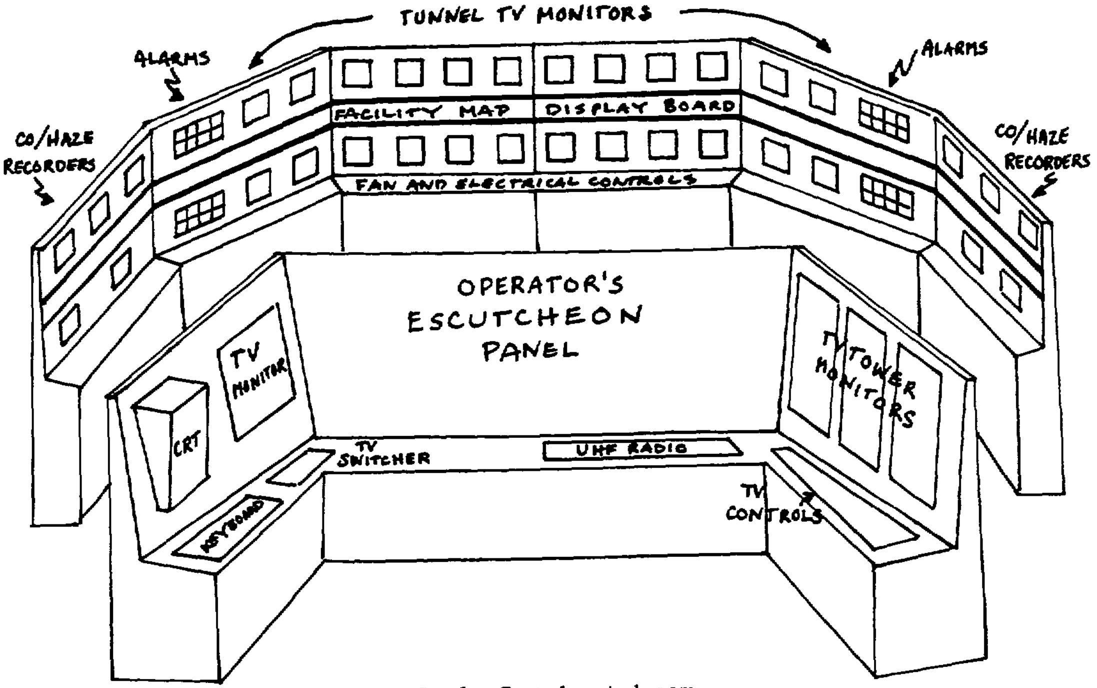


Fig. 6. Central control room.

for access to the computer, a CCTV master monitor with controls for transferring the video signals from the tunnel cameras, three CCTV monitors with controls for viewing the pictures transmitted from tower cameras, a digital clock for computer timing, and sound-powered telephones and an ultrahigh frequency (UHF) radio for communicating with facility operations and maintenance personnel. The escutcheon panel, which contains a control push button and indicator lamps for each sign and signal on the facility, controls the displays on these devices via computer programming over a time-division multiplexing communications link. The traffic operator commands sign or signal display changes by pressing appropriate panel push buttons. The computer samples the panel four times per second and transmits the desired commands to the field equipment. On the panel indicators, actual sign and signal status or failure conditions are displayed by the computer. In addition, there is a verification and reset push button on the escutcheon panel for incident management. The computer video terminal provides a means for the operator to initiate computer routines which automatically transition the signs and signals to predetermined messages for handling such traffic maneuvers as lane closures, tunnel closures, and speed reductions for hazardous environmental conditions.

The two digital minicomputers are used for primary and backup operations. The primary computer is a 128 kbyte machine, and it supports all the surveillance and control functions of the system. This computer monitors the vehicle detectors for detecting incidents and controlling tunnel flow access controls, monitors the signs and signals via the control console and traffic display panel, performs automatic traffic operations maneuvers, and reports and logs all daily traffic system events. In the event of a primary computer failure the backup computer automatically switches into control. Under backup operation only the control and monitor of the signs and signals are provided.

Also located in the central control room are the central communications cabinets. This equipment is used for supporting the time-division multiplex and frequency-division multiplex communication link between the computer and the signs, signals, and detectors.

System Software

Computer programs have been developed to monitor and control the system hardware, evaluate and compute traffic flow measures, provide for an operator-machine interface, and report and log traffic data and system events (Fig. 7).

Monitor and Control Software: The monitor and control software interfaces the control hardware equipment to the computer surveillance and control programs. The monitoring and commanding of the signs and signals, of the overheight-vehicle detection equipment, and of the ice and fog detectors is performed by this software twice per second over the time-division multiplexed communication link. In addition, the panel push buttons are monitored for operator commands, and equipment status information is put out to the panel indicators and map display twice per second. This software also accommodates the sampling of each loop detector forty times per second over the frequency-division multiplexed communications link for calculation of vehicle occupancy, speed, and volume with high resolution.

All of the data received from this equipment are checked by software for errors in transmission and validity. In addition, when a signal or sign display change has been commanded, the software follows the transitioning of the device to ensure that the proper status has been achieved.

Evaluation and Computational Software: The evaluation and computational software is designed to compute the vehicle flow measurements of occupancy, speed, and volume from the detector data accumulated by the monitor and control software. These measurements are used for detecting incidents, controlling access of tunnels, and performing detector failure checks. This software also logs incidents, equipment failures, overheight violations, and system events.

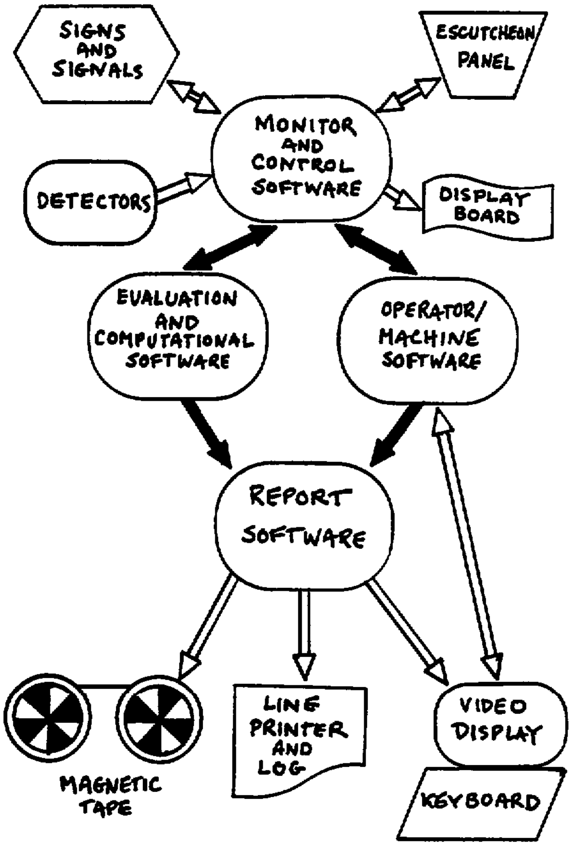
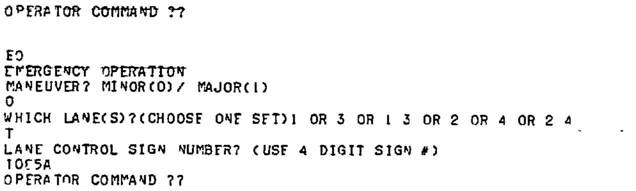


Fig. 7. Software components



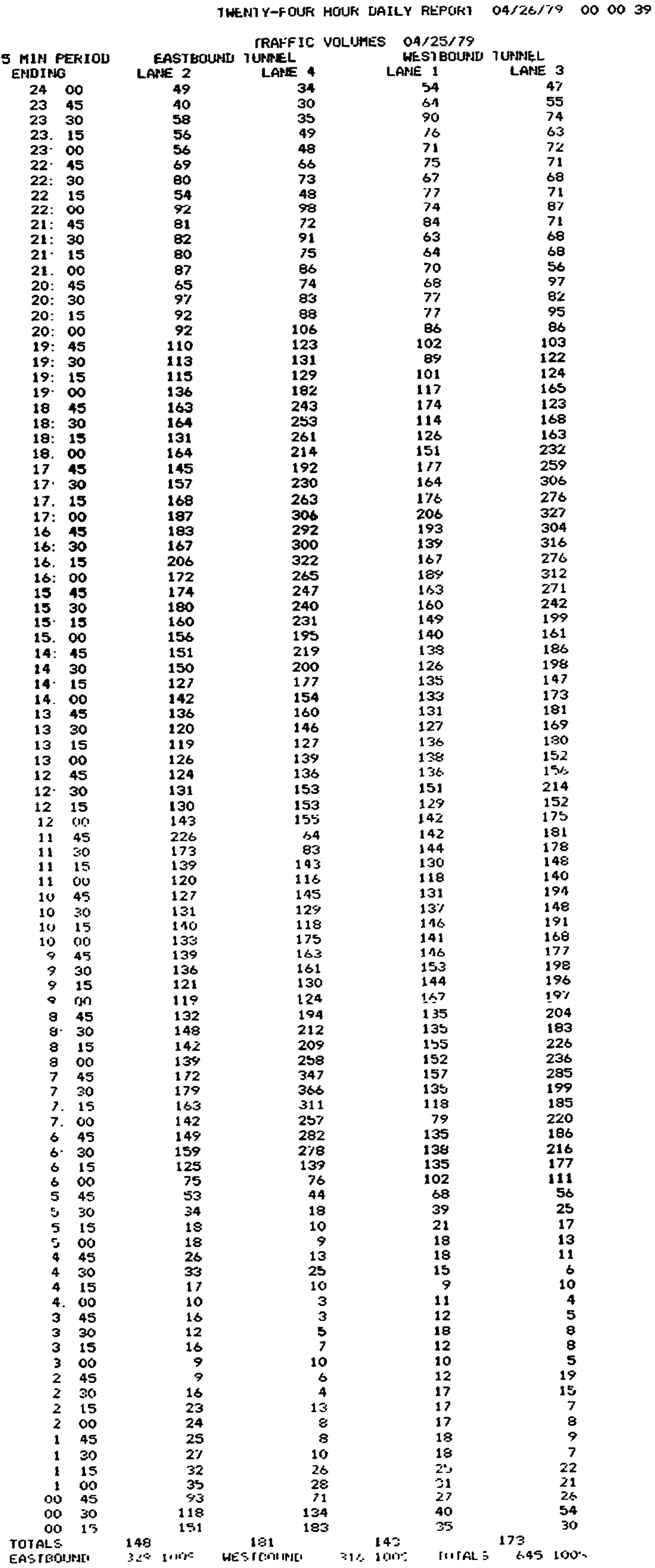
```
OPERATOR COMMAND ??


EO
EMERGENCY OPERATION
MANEUVER? MINOR(O)/ MAJOR(1)
O
WHICH LANE(S)?(CHOOSE ONE SET)1 OR 3 OR 1 3 OR 2 OR 4 OR 2 4
T
LANE CONTROL SIGN NUMBER? (USE 4 DIGIT SIGN #)
1005A
OPERATOR COMMAND ??
```

Fig. 8. Computer reports—emergency operations routine.

Operator/Machine Software: The operator/machine software was designed to accommodate operator initiation of special programs which automatically command the signs and signals on the facility for handling traffic and operation maneuvers such as lane closures, tunnel closures, and emergency operations via the video terminal. This software is interfaced with the command and monitor software to achieve direct control of each sign and signal. In addition, this software accommodates on-line updating of all system parameters and sign and signal displays for the special traffic maneuver programs to achieve real-time adjustment of system operation. An example of the emergency operation routine is presented in Fig. 8.

Report Software: The report software produces records of actual system operation and performance. The detector and sign status reports are produced on demand by the operator and summarize the status conditions of the equipment. On a periodic basis, the 15-min report and detector surveillance test provides information on the system performance measures of speed, volume, and occupancy for selected or all detector stations. The daily report, which is compiled at midnight, tabulates all the daily events and includes a summary of the 15-min traffic volumes for each lane on the facility. The daily report is presented in Fig. 9.



```
                          TWENTY-FOUR HOUR DAILY REPORT  04/26/79  00 00 39

                                  TRAFFIC VOLUMES  04/25/79
15 MIN PERIOD     EASTBOUND TUNNEL              WESTBOUND TUNNEL
  ENDING          LANE 2       LANE 4          LANE 1       LANE 3
   24   00          49           34              54           47
   23   45          40           30              64           55
   23   30          58           35              90           74
   23.  15          56           49              76           63
   23·  00          56           48              71           72
   22·  45          69           66              75           71
   22:  30          80           73              67           68
   22   15          54           48              77           71
   22:  00          92           98              74           87
   21:  45          81           72              84           71
   21:  30          82           91              63           68
   21·  15          80           75              64           68
   21.  00          87           86              70           56
   20:  45          65           74              68           97
   20:  30          97           83              77           82
   20:  15          92           88              77           95
   20:  00          92          106              86           86
   19:  45         110          123             102          103
   19:  30         113          131              89          122
   19:  15         115          129             101          124
   19·  00         136          182             117          165
   18   45         163          243             174          123
   18:  30         164          253             114          168
   18:  15         131          261             126          163
   18.  00         164          214             151          232
   17   45         145          192             177          259
   17·  30         157          230             164          306
   17.  15         168          263             176          276
   17:  00         187          306             206          327
   16   45         183          292             193          304
   16:  30         167          300             139          316
   16.  15         206          322             167          276
   16:  00         172          265             189          312
   15   45         174          247             163          271
   15   30         180          240             160          242
   15·  15         160          231             149          199
   15.  00         156          195             140          161
   14:  45         151          219             138          186
   14   30         150          200             126          198
   14·  15         127          177             135          147
   14.  00         142          154             133          173
   13   45         136          160             131          181
   13   30         120          146             127          169
   13   15         119          127             136          180
   13   00         126          139             138          152
   12   45         124          136             136          156
   12·  30         131          153             151          214
   12   15         130          153             129          152
   12   00         143          155             142          175
   11   45         226           64             142          181
   11   30         173           83             144          178
   11   15         139          143             130          148
   11   00         120          116             118          140
   10   45         127          145             131          194
   10   30         131          129             137          148
   10   15         140          118             146          191
   10   00         133          175             141          168
    9   45         139          163             146          177
    9   30         136          161             153          198
    9   15         121          130             144          196
    9   00         119          124             167          197
    8   45         132          194             135          204
    8·  30         148          212             135          183
    8   15         142          209             155          226
    8   00         139          258             152          236
    7   45         172          347             157          285
    7   30         179          366             135          199
    7.  15         163          311             118          185
    7.  00         142          257              79          220
    6   45         149          282             135          186
    6·  30         159          278             138          216
    6   15         125          139             135          177
    6   00          75           76             102          111
    5   45          53           44              68           56
    5   30          34           18              39           25
    5   15          18           10              21           17
    5   00          18            9              18           13
    4   45          26           13              18           11
    4   30          33           25              15            6
    4   15          17           10               9           10
    4.  00          10            3              11            4
    3   45          16            3              12            5
    3   30          12            5              18            8
    3   15          16            7              12            8
    3   00           9           10              10            5
    2   45           9            6              12           19
    2   30          16            4              17           15
    2   15          23           13              17            7
    2   00          24            8              17            8
    1   45          25            8              18            9
    1   30          27           10              18            7
    1   15          32           26              25           22
    1   00          35           28              31           21
   00   45          93           71              27           26
   00   30         118          134              40           54
   00   15         151          183              35           30
TOTALS         148          181          143          173
EASTBOUND      329 100%    WESTBOUND     316 100%    TOTALS   645 100%
```

(a)

Fig. 9. 24-h report. (a) Computer reports—24-h traffic volumes. (b) Communications and detector failure summary. (c) Operation and environmental logs summaries. (d) Overheight, detector, and sign log summaries. (Continued on next page.)

```
                    TWENTY-FOUR HOUR DAILY REPORT  04/26/79  00:00:39

                                          COMMUNICATION ERROR COUNT
DEVICE ID     ERROR COUNT     DEVICE ID     ERROR COUNT    DEVICE ID     ERROR COUNT     DEVICE ID     ERROR COUNT
2106                    6     2114                    1    1027                    2     1041                   13
5057                12439     2020                   10    2108                    1     4020                   11
4108                    1     4110                    1    4022                   11     1029                    3
1033                   13     1135                    1    3029                    3     3033                   12
3135                    1     3137                    1    3035                   13     3031                    3
6096                 5509     4100              ALL DAY
```

```
                        TWENTY-FOUR HOUR DAILY REPORT  04/26/79  00·00 39

                                          DETECTOR  PERCENTAGE  TIME  DOWN

  DETECTOR        TIME OFF  DETECTOR        TIME OFF  DETECTOR        TIME OFF  DETECTOR        TIME OFF
        21               2        35              24        36              24        39             100
        59             100
```

(b)

```
      TWENTY-FOUR HOUR DAILY REPORT  04/26/79  00 00 39

        OPERATION   LOG

   DATE  AND  TIME           OPERATION       REMARKS
04/25/79  00 07 39                           OVRHT WB
04/25/79  00 12 01                   3       RENORMRD
04/25/79  00 24 53                1109       MINOR EO
04/25/79  00 29 49                   3       RENORMRD
04/25/79  02 36 00                1143       MINOR EO
04/25/79  02 40 54                   3       RENORMRD
04/25/79  03 50 14                1043       MINOR EO
04/25/79  04 06 24                   3       RENORMRD
04/25/79  04 57 03                  13       RENORMRD
04/25/79  05 34 56                  24       RENORMRD
04/25/79  06·22 45                  13       RENORMRD
04/25/79  06 22 51                  24       RENORMRD
04/25/79  06·47 43                1109       MINOR EO
04/25/79  06 53 38                  13       RENORMRD
04/25/79  07.25 26                2086       MINOR EO
04/25/79  07.26.17                  24       RENORMRD
04/25/79  11:16 31                   4       SN LN L1
04/25/79  11·45 02                  24       RENORMRD
04/25/79  15 49 27                           OVRHT EB
04/25/79  15 50 37                  24       RENORMRD
04/25/79  16 25 37                1113       MINOR EO
04/25/79  16 37 18                  13       RENORMRD
04/25/79  18:06·42                2086       MINOR EO
04/25/79  18 10 55                  24       RENORMRD
04/25/79  18·37 11                3101       MINOR EO
04/25/79  18 41 18                  13       RENORMRD
04/25/79  19 08 44                           OVRHT EB
04/25/79  19 10 35                  24       RENORMRD
```

```
                           TWENTY-FOUR HOUR DAILY REPORT  04/26/79  00·00:39

                            ENVIRONMENTAL LOG

                     DATE  AND  TIME          STATION       REMARKS
NO EVENTS OCCURRED
```

(c)

```
      TWENTY-FOUR HOUR DAILY REPORT  04/26/79  00 00·39

  OVERHEIGHT VIOLATION LOG
  DATE  AND  TIME            STATION       REMARKS
04/25/79  00 07 39                 7       SECOND
04/25/79  04 04 31                 4       FIRST
04/25/79  05 41 28                 4       FIRST
04/25/79  11 05 48                 1       FIRST
04/25/79  12.14 20                 1       FIRST
04/25/79  13 25·12                 4       FIRST
04/25/79  13 39 57                 4       FIRST
04/25/79  15 22.43                 4       FIRST
04/25/79  15 49 27                 6       SECOND
04/25/79  19 08 44                 6       SECOND
04/25/79  20 24.20                 4       FIRST
04/25/79  21 31:52                 4       FIRST
```

```
      TWENTY-FOUR HOUR DAILY REPORT  04/26/79  00 00 39

          DETECTOR  LOG
  DATE  AND  TIME           DETECTOR     CONDITION
04/25/79  03:42 48                21       CLOSED
```

```
      TWENTY-FOUR HOUR DAILY REPORT  04/26/79  00 00 39

  SIGN AND COMMUNICATIONS LOG
  DATE  AND  TIME            DEVICE        FAILURE
04/25/79  08·25 58              6096       SIGN ERR
04/25/79  12.57.58              5057       SIGN ERR
04/25/79  12·59 07              6096       SIGN ERR
04/25/79  13.26 45              6096       SIGN ERR
04/25/79  13 28 36              6096       SIGN ERR
04/25/79  13·31 27              6096       SIGN ERR
04/25/79  13 34 37              6096       SIGN ERR
```

(d)

Fig. 9. *Continued.*

TABLE I

A. TUNNEL ACCESS CONTROL SCROLL SIGN DISPLAYS

Normal Display	STAY IN LANE
Control Display	PAUSE HERE THEN CC
Restriction Display	STOP
Renormalization Display -	RESUME SPEED

B. TUNNEL ACCESS CONTROL DECISION RULES

	Transition	Decision	Remarks
1.	Normal to Control Display	Tunnel volume increases to 1300 vph OR Tunnel speed decreases to 40km/h (25 mph)	Tunnel traffic flow degrades from stable to unstable flow.
2.	Control to Restriction Display	Tunnel volume increases to 1400 vph OR Tunnel speed decreases to 16km/h (10 mph)	Tunnel traffic flow degrades from unstable to forced flow.
3.	Restriction to Control Display	Tunnel volume decreases to 1350 vph AND Tunnel speed increases to 32km/n (20 mph) OR Five minutes of elapsed time in restriction display	Tunnel traffic flow improves from forced flow and is operating within restricted stable flow.
4.	Control to Renormalization Display	Tunnel volume decreases to 1150 vph AND Tunnel speed measures to 48km/n (30 mph)	Tunnel traffic flow improves from restricted flow and is operating within stable flow.
5.	Remormalization to Normal Display	Tunnel Queue Occupancy decreases to 20 percent	Bridge traffic flow is operating within stable flow.

SYSTEMOPERATION

The system is an integrated combination of hardware and software and has been designed to perform the functions necessary to operate a surveillance and control system for the tunnel-bridge complex. These functions are categorized as automatic, semiautomatic, and manual control operations.

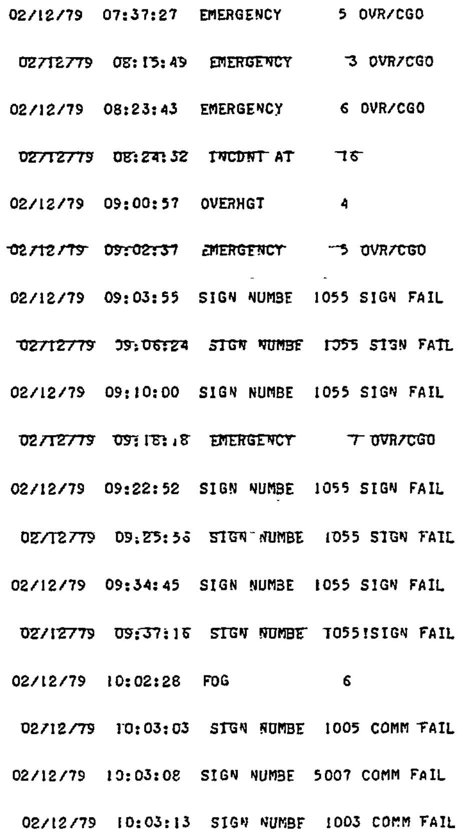
Automatic Control Functions

The automatic functions of the system consist of the access control of the tunnel, overheight detection, and hardware failure monitoring. The system provides automatic control of access to each tunnel by comparing the volume and speed accumulated at the speed detector stations in the three grade levels of the tunnel against preset thresholds. The system determines whether to adjust or display control and warning messages on scroll signs located at the tunnel approaches. The decision logic for the access control algorithm is based on the algorithm developed for the Lincoln Tunnel in New York City [1] and is presented in Table I. From this table we can see that the algorithm closely follows the level of traffic flow to initially control and possibly restrict motorist access to the tunnel. The algorithm logic is designed to be conservative since flow must improve significantly before a positive control action is taken. Each of the algorithm thresholds may be adjusted on-line to provide responsive tuning.

As previously described, the computer monitors the overheight equipment, logs all violations, and automatically initiates a controlled shutdown of the lanes where the overheight vehicle was detected.

Each of the signs and signals are monitored continuously for failures to respond due to the malfunctioning of the communications link or the energized sign equipment. When either of these failures are determined the software illuminates the failure indicator on the sign push button on the escutcheon panel, and a failure message is logged on the system console for diagnostic purposes. The operator has the ability to clear the failure indication by attempting to command the sign or signal using the escutcheon panel. If the failed device is operating properly, the failure indication will be extinguished and the normal operations will be resumed. If the failure persists, the failure indication will be relit and a new failure message will be put out.

The vehicle loop detectors are continuously checked for proper operation. The software monitors the detectors for excessive spurious detector activations (detector chatter), continuous loop activations (a closed loop), and no loop activations (an open loop). When any of these occurrences are determined,a detector failure message is logged on the system console and the detector indicator on the display map is extinguished. The system continuously monitors detector operation and will automatically clear the failure indication when proper operation is restored for a I-min period. A message log is shown in Fig. 10.



```
02/12/79  07:37:27  EMERGENCY       5 OVR/CGO
 02/12/79  08:15:49  EMERGENCY       3 OVR/CGO
02/12/79  08:23:43  EMERGENCY       6 OVR/CGO
 02/12/79  08:24:32  INCDNT AT      16
02/12/79  09:00:57  OVERHGT         4
02/12/79  09:02:37  EMERGENCY       5 OVR/CGO
02/12/79  09:03:55  SIGN NUMBE  1055 SIGN FAIL
 02/12/79  09:06:24  SIGN NUMBE  1055 SIGN FAIL
02/12/79  09:10:00  SIGN NUMBE  1055 SIGN FAIL
 02/12/79  09:16:18  EMERGENCY       7 OVR/CGO
02/12/79  09:22:52  SIGN NUMBE  1055 SIGN FAIL
 02/12/79  09:25:56  SIGN NUMBE  1055 SIGN FAIL
02/12/79  09:34:45  SIGN NUMBE  1055 SIGN FAIL
 02/12/79  09:37:16  SIGN NUMBE  1055!SIGN FAIL
02/12/79  10:02:28  FOG             6
 02/12/79  10:03:03  SIGN NUMBE  1005 COMM FAIL
02/12/79  10:03:08  SIGN NUMBE  5007 COMM FAIL
 02/12/79  10:03:13  SIGN NUMBF  1003 COMM FAIL
```

Fig. 10. Computer reports–events log.

Semiautomatic Control Functions

The semiautomatic functions of the system include incident management for the tunnels, environment surveillance, and traffic maneuver operations. These functions are established by automatic system detection of adverse traffic operating conditions, operator verification of these conditions, and operator initation of special sign and signal control displays for aiding and warning motorists.

The incident management system for the tunnels on the facility consists of the following three elements:

- automatic detection of incidents,
- visual verification of incidents, and
- preset automatic response routines for handling incidents.

The detection of incidents is accomplished using an algorithm based on the modified California incident detection algorithm [2]. Occupancy is calculated for each detector station in the tunnel. When the occupancy at a station is significantly higher than the occupancy at the next downstream station, an incident is assumed to have occurred and the operator is alerted by alarm. An incident message is logged on the system console indicating the station upstream to the incident, the detector indicators corresponding to the stations closest to the incident on display map are flashed, and an indicator associated to the CCTV monitor nearest to the incident is illuminated. Upon receiving this alarm, the operator is able to verify visually the incident using the CCTV monitors. In addition, the CCTV cameras located on the towers are used to verify incidents located on the bridges and the approach roadways.

If the operator verifies that an actual incident has occurred a special computer routine is implemented to change automatically the sign and signal displays for closing down the portion of the roadway affected by the incident and warning oncoming motorists. The operator indicates this routine by using the video terminal operator/machine interface or by pressing the incident verification push button on the escutceheon panel. In addition, a UHF radio message is transmitted to the appropriate crash truck shelter for issuing emergency vehicle aid to the disabled motorist. If a false incident alarm has occurred the operator resets normal operation by pressing the incident reset push button on the escutcheon panel.

The computer system monitors the ice and fog surveillance equipment and automatically puts out a message on the system log when these conditions are detected. In the event that these conditions constitute hazards for motorists, the operator may initiate special routines using the video terminal operator/machine interface to display hazard warning signs and reduce speeds automatically.

When the air quality in the tunnel becomes poor, the operator may activate additional tunnel ventilation fans or increase the fan operating speed. Air circulation in each tunnel is controlled by a full transverse ventilation system consisting of eight two-speed supply fans and eight two-speed exhaust fans. Using the fan controls the operator may select, on the lower section of the control board, the proper number of speeds of the fans to improve air circulation in the tunnel.

All traffic maneuvers and tunnel operations may be performed using the video terminal operator/machine interface routines. These routines, which are easily requested by the operator, automatically implement sign and signal displays for the following:

- emergency operations,
- single-lane operations,
- single-tunnel operations,
- return to normal dual-tunnel operations,
- ice/fog operation, and
- return to normal roadway operations.

Manual Control Functions

All sign and signal displays may be individually altered using the operator escutcheon panel. This control is maintained during primary and backup operations. The operator selects the desired sign displays by pressing the individual sign push button and the associated sign command. The system issues the command and then illuminates the desired display on the panel push button indicator for the sign. When the actual sign display matches the desired command the appropriate map indicator for the sign is displayed.

The electrical and fan equipment are controlled using the switches and indicators on the lower section of the control board. Power for the tunnels is obtained from two independent substations of the Virginia Electric and Power Company located on the Hampton and Norfolk sides of the facility. The power is switched using the board controls to assure continuous operation in the event of power outages from either station.

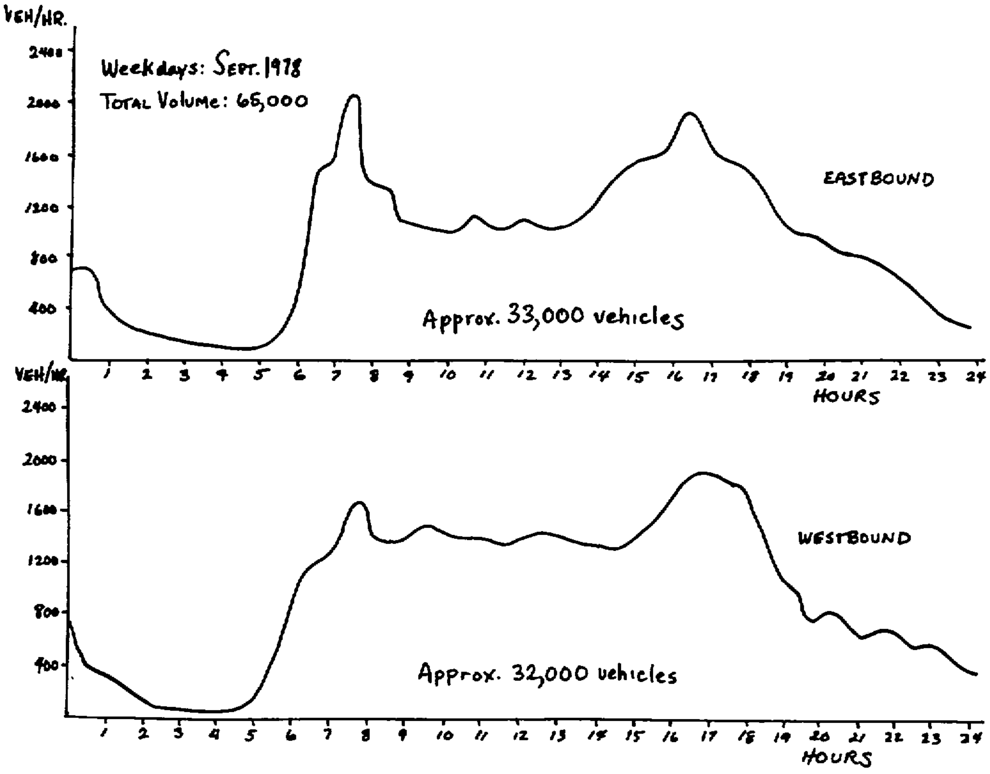


Fig. 11. Typical traffic volume profile.

CURRENT OPERATIONS

The Surveillance and Control System has been in complete operation since November 15, 1977. Since the installation of the system and construction of the second tunnel, traffic operations and procedures have been adjusted to reflect the always increasing and changing traffic flows on the facility. This section outlines the current traffic operations on the facility.

Traffic Volumes and Accidents/Stoppages on the Facility

Current traffic volumes on the facility average 62 000 vehicles daily. A volume profile of a typical day is presented in Fig. 11. In the peak season, daily traffic volumes climb to 80 000 vehicles. This yields a 160 percent increase in average daily traffic and peak daily traffic. Stoppages have increased on the average by 100 per month. However, actual vehicle accidents have decreased by an average of one accident per month (almost 12 percent).

Although traffic volumes have greatly increased, the number of accidents and stoppages per average daily volume has decreased by 70 percent (Table II). During the peak summer months the actual number of stoppages is less than the number prior to system operation since the long backups are no longer experienced.

In addition, the nature of the accidents experienced on the facility has changed. In the past, rear-end collisions were the most common during stoppages or backups. This type of accident now occurs less frequently since the traffic control system warns the motorist well in advance of the congestion ahead and provides time for lane changing or stopping. Presently, most of the accidents are single-vehicle accidents occurring late at night, often involving tired or intoxicated drivers.

TABLE II
COMPARISON OF ADT AND INCIDENTS SINCE SYSTEM IMPLEMENTATION

	1975	1978
Yearly ADT	23,794	62,190
Peak Daily Volume	36,000	80,600
Stoppages Per Month	175	275
Accidents Per Month	8.5	7.5

Incident Management

The system provides detection of actual vehicle stoppages and very slow moving vehicles in the tunnel. Certain of these slow moving vehicles, such as oversize trucks and cranes, require special escort through the tunnel at off-peak hours of the day. Tracking of the slow moving vehicles is essential, since they may break down or cause other stoppages, and warnings to approaching motorists must be accommodated. On some occasions during periods of heavy traffic and hot weather there are as many as five stoppages in one tunnel at the same time, the majority of them being caused by the one initial stoppage.

Traffic Maneuvers

The traffic operations maneuvers performed by the video terminal operator/machine routines are very effective and easy to change for various traffic conditions. These routines are used extensively and allow the operators to set up traffic controls in a fraction of the time required normally. Two advantages of these plans are that they insure that all the signs and signals are set to the proper message every time regardless of who is setting up the operation, and since each operation is logged on the system console reference may be made to the condition of the roadway signs and signals during the day. These records have not been used in any court actions; however, the police have used this information for their reports.

Automatic Access Control

As previously described, the access control of the tunnel was initially designed to regulate the flow of traffic through the tunnel with the messages "PAUSE HERE THEN GO" and "STOP" on the scroll signs at the entrances to the tunnels. With traffic entering the tunnels from a high-speed Interstate approach roadway, these messages were confusing to the motorist and were a potential cause of accidents. Until the algorithm thresholds are adjusted properly for this facility, the messages "TRAFFIC CONGESTION AHEAD" and "PREPARE TO STOP," respectively, were substituted. Currently, the algorithm is being tuned to reflect the actual traffic conditions at the high-speed approaches.

CCTV System

The CCTV system has proven to be one of the most useful tools of the traffic control system. By providing the operator with a full view of the actual scene of trouble, lengthy and sometimes confusing radio conversations are eliminated. The CCTV system allows quick verification of any incident detection alarms and allows the operators to locate the trouble accurately.

The tower cameras located on the portal islands and Willoughby shore provide the operators with a complete view of the facility. The ability to zoom out great distances is especially useful when troubles occur far out on the approach bridge or when operators try to distinguish which approaching vehicle tripped the secondary mainline overheight detectors. In addition this allows a view of the top side of the vehicles for spotting objects which the inspection station personnel are not able to see.

UHF Radio System

The UHF two-way radio system allows complete communication between all personnel regardless of their location on the facility (bridge, island, tunnel, etc.). Since all of the patrol personnel have portable radios, this allows the operators to direct all operation via radio anywhere and anytime on the project.

Overheight Detection System

The overheight detection system is a most critical and important component of the traffic control system. The reliability of the system is determined by the correct adjustment of the overheight detectors. Currently the overheight violations per month amount to 20-30 vehicles, and approximately 80-100 are stopped at the inspection stations prior to approaching the facility. This system can detect objects as small as 89 mm (3.5 in) at speeds as high as 88.5 km/h (55 mi/h). All detectors are currently set for a height of 4.166 m (13 ft 8 in) to 4.172 m (13 ft 8 1/4 in). The actual clearances are 4.3 18 m (14 ft 2 in) for the westbound tunnel and 5.629 m (16 ft 6 in) for the eastbound tunnel.

Environmental Monitoring

The ice and fog monitoring equipment used in the system have not carried as much importance as other equipment, such as the overheight detectors. This is mostly due to the fact that the facility is staffed 24 h a day with personnel located throughout the facility to observe such problems. Although environmental monitoring is not considered critical, the environmental signing is used greatly during inclement weather.

Equipment Maintenance

To test motorist response the lane-use controls on the bridges were replaced with 30.5 cm (12 in) horizontally mounted traffic signal heads using 150 W bulbs. Since the new signals were installed, obedience of the signals has doubled. Listed below are estimated percents of maintenance effort required for the various equipment types.

Equipment Type		Percent of Time Required for Maintenance
Scroll		30
Speed		20
Drum		5
Lane control signal heads		1
Blank outs		2
Communications equipment (cmu)		5
Control board and console		5
Computer and peripheral equipment		5
Environmental detection equipment		10
Loop detection equipment		3
Overheight detection equipment		10
CCTV		5
	Total	100

SUMMARY

The Hampton Roads Surveillance and Control System has greatly improved the safety of traveling public on the bridge-tunnel facility. The system provides for maintaining traffic operations for efficient and effective use for motorists and operating personnel, and has been designed to be adjusted continually to reflect the changing traffic flows on the facility. The closed-circuit television system, in conjunction with the computer controlled surveillance equipment for vehicle detection and environmental detection, significantly adds to the safety of the facility by allowing better coordination of operation by viewing actual events.

ACKNOWLEDGMENT

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Signal Systems Without Cables

FRANK T. HARTLEY AND EDWARD F. CLEARY, MEMBER. IEEE

***Abstract*-A method is presented for achieving many of the benefits of linking isolated signalized intersections into systems without incurring the costs of either cable installation or leased communication channels. The method may be considered an interim step where traffic responsive systems are planned or as the final solution in situations where responsive systems are not warranted. The method employs a microprocessor together with an accurate clock whose stability is based on electrical service frequency under normal conditions and on a quartz crystal and battery under power failure conditions. The traffic advantages include all those- attributed to systemization but not those of traffic responsive operation. Other advantages include the initial cost, well below that of cable installation, and an excellent record of reliability and low maintenance costs. Development of similar devices in the U.S. is reviewed briefly with a Limited amount of cost comparison against the Australian unit. The equipment described offers a quicker and less costly means for setting up multiprogrammed signal systems either on an interim or permanent basis. The technology is within the current state of the art and should be applicable in many areas, particularly for arterial commuter routes where signal spacing is much greater than in central business district (CBD) situations.**

INTRODUCTION

EVERYONE is familiar with the green-yellow-red sequences of traffic signals. The control of traffic relies heavily on an almost instinctive response when a green-to-yellow transition occurs. This transition is effected by an intersection controller; with vehicle-actuated equipment the duration of each phase may be influenced by the presence of waiting vehicles and the number of vehicles with the right of way. It is less well known that during peak travel periods in heavily trafficked areas there is frequently a large number of vehicles present and, therefore, the otherwise effective vehicle responsive sequence regresses to a fixed cycle system.

Any road system has a limited capacity to carry traffic; this can sometimes be increased in a number of ways other than widening the road to provide more lanes which is usually very expensive and often politically impossible. However, if the traffic can be moved more quickly from source to destination, the capacity of the road is increased, just as more water will pass through a fixed size pipe if the speed of flow is increased.

The objective then becomes to increase the speed of flow of the traffic on the road. A number of tools are available to the traffic engineer to help in achieving this objective. One of the tools is to eliminate the major cause of delay by eliminating the intersections, i.e., build a freeway. Obviously, this approach is not practicable in the majority of cases, so the compromising begins. The causes of delay are attacked, turning movements are provided with special lanes or prohibited where this is not possible. Medians are built to reduce the side friction by reducing the unrestricted entry points to the road. Finally, the operation of the intersections is made as efficient as possible through the use of vehicle-actuated control and/or systems.

The history of systems is almost as old as the history of traffic signals. The need to establish a constant relationship of the timing of consecutive traffic signals on a particular route became obvious as soon as there were two or more signals within close proximity of each other. The earliest attempts involved cable linking the traffic controllers. There was no choice, for the controllers were driven by induction motors whose speed was a function of the voltage which drove them. The controllers either operated on a "run and dwell" principle or were equipped with a bucking coil which kept them running at a more or less constant speed.

Technology was advancing even then, and the synchronous

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motor was applied to traffic signal controllers. The first cableless linking was achieved: a 60-s cycle remained a 60-s cycle as long as the power frequency was constant, and the time relationship between all signals in a system remained constant as long as there were no power interruptions. In today's language such systems would be classed as labor intensive, for any widespread power outage required a visit to each controller in the system to reset the time relationship (offset) manually. Furthermore, only one offset could be established and maintained.

The need for more programs led back to cable linked systems, although there was a brief period when a radio was utilized as the linking medium. Many types of systems have been developed and applied, all of which offered multiple programs and a multiplicity of ways in which to choose the most appropriate program. Traffic engineers were not satisfied; there were and are many complaints of too much cost and questionable benefits. In addition, new problems arose that were not susceptible to solution by the systems now in use, or the solutions were to costly.

Technology was again on the move, driven in part by traffic engineers trying to find more cost effective equipment to solve their problems. A great deal of work was done in Great Britain on methods of linking without installing cable. Some of the early work involved the transmission of control intelligence through the power network which supplied the energy to operate the signal. This approach was abandoned and a new one launched utilizing the power line frequency as a time base, a very stable time base comparable to the synchronous motor driven clock.

Several years ago, the Department of Main Roads, New South Wales, Australia (DMR, N.S.W.), designed a cableless linking unit called the mains actuated synchronous control of traffic (MASCOTT). This unit included a matrix of switches which could be used to set up a plan (and plan change schedules) for a particular intersection. When the Road Traffic and Safety Authority (RoSTA) of the State of Victoria decided to employ cableless linking they found that the cost of the MASCOT units had escalated and that some of their components were not available; some redesign was therefore required. At this point the possibility of using a microprocessor was considered and it quickly became clear that a more powerful unit could be produced at a significantly lower cost.

The primary function of the linking unit is to guide an intersection controller in accordance with prestored plans. Facilities for setting up and changing plans are a secondary function.

The objectives of this paper are to examine the features, cost, and traffic management capabilities of the ITERRA cableless linking system and then to compare the ITERRA with other equipment which has since become available. The ITERRA is believed to be the first device which embodies microprocessors in a practical cableless linking application.

THE ITERRA SOLUTION

A Traffic Plan

A single traffic plan covers a period of time and a set of related intersections such that the flow of vehicles through those intersections is essentially the same during the entire period. A chart can be ruled off with lines spaced in proportion to the distance between the intersections, as in Fig. 1. Any given speed may then be represented by a sloping line and the arrival time at each intersection of a vehicle proceeding at that speed can be read directly from the chart. The plan length and the length of constituent phases determines the remainder of the plan. Note that the plan starts and ends simultaneously at all intersections but the phase times are offset by varying amounts from the beginning of the plan. The plan is repeated continuously until replaced by the start of a new plan.

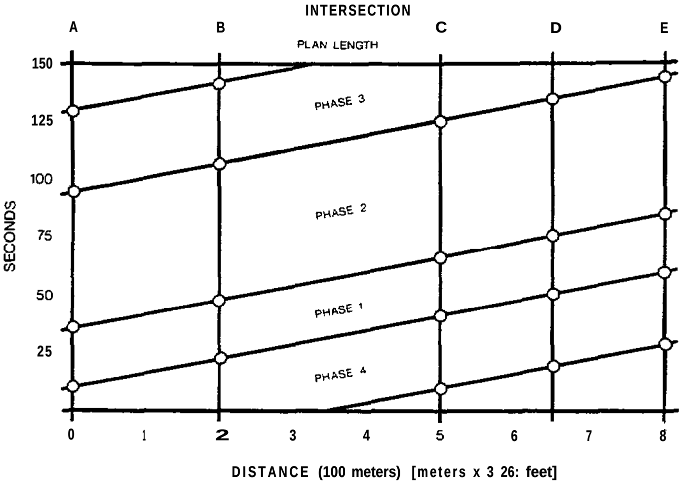

Fig. 1. Traffic plan chart.

While the traffic flow may be the same Monday through Thursday, flow on Fridays and on the weekends is likely to be different. Late shopping or other regular events can also affect the pattern. Therefore, it is desirable to specify the combination of days to which the plan applies.

Linking Unit Functions

The linking unit is designed to work with any vehicle-actuated or fixed cycle intersection controller. The traffic plans are stored in random access memory within the unit with the start times separated from the other plan data so that one plan can be used to cover several periods. Up to eight plans and 16 start times can be stored. The day combination is stored with the start time as seven separate bits so that any one of the 128 possible day combinations can be expressed. The linking unit maintains a day counter and a time of day clock in seconds, minutes, and hours. Every second the unit starts a new cycle or phase. Every minute it checks for time to start a new plan, and every 24 h it updates the day counter.

Time Maintenance

The clock operates from the supply or power line frequency with a backup battery-driven crystal oscillator for power failure periods. The supply frequency is highly accurate over a 24-h period, though it will run behind in peak demand periods and catch up during off-peak hours. Time is set into the supervisor unit with a 1-s accuracy and transferred to the linking unit with an accuracy of one-fiftieth of a second (50 Hz).

The battery is kept charged from the power circuit and will operate the oscillator, seconds counter, and random access memory for at least 48 h, after power failure. The second counter (with a capacity of 72 h) counts the seconds for the duration of each power failure, and this count is used to update the real-time clock when power is restored.

It should be noted that it is not important that time be absolutely correct but only that it be the same at related intersections. The supervisory unit provides this accuracy by establishing a constant zero time base and transferring this datum to each ITERRA when setting them.

Auxiliary Features

A facility which is selecting traffic plans by time reference must incorporate some means of accommodating the time shifts involved in changing to and from daylight saving time. Similarly, there is a need to accommodate other irregular events such as public holidays and special sporting features.

Often controller operation requirements change through the day and from day to day. Signalled right-turn movements may operate only with tidal traffic flow; turning movements may be banned or a pedestrian controller may be turned off. Thus there is a need for a variety of plan dependent output latches.

Daylight Saving Time: Along with the internal time register, a flag is kept to indicate whether that time is daylight saving time or standard time and whether it should be changed at the next transition from day 7 to day 1. Twice each year, up to a week in advance, someone must visit each intersection to set up or delete this flag to cause the change between standard time and daylight saving time.

Special Days: Along with the plan time there is a byte that indicates to which days a plan time applies. The eighth bit in this byte is used to designate that this time plan applies to special days. Any one or more days must be marked as special days up to seven days in advance. When a day marked special (i.e., "day 8" specified) arrives only the plan times designated for special days will apply.

Output Latches: Along with each plan number an output code may be specified. This output code is decoded and, if appropriate, is presented as a continuous signal on the appropriate output line or lines. There are six such output lines, the state of which is maintained for the operational period of the plan.

Environment

The linking unit is designed to work directly with vehicle-actuated controllers incorporating flexible progression facilities. However, outputs suitable for the more general intersection controllers can be obtained by adding an interface relay board.

The two major environmental hazards are heat and dust. All components in the unit are rated for a temperature of at least 85°C. The unit is mounted inside the intersection controller housing. The units are coated with a plastic membrane to prevent interference from any dust particles.

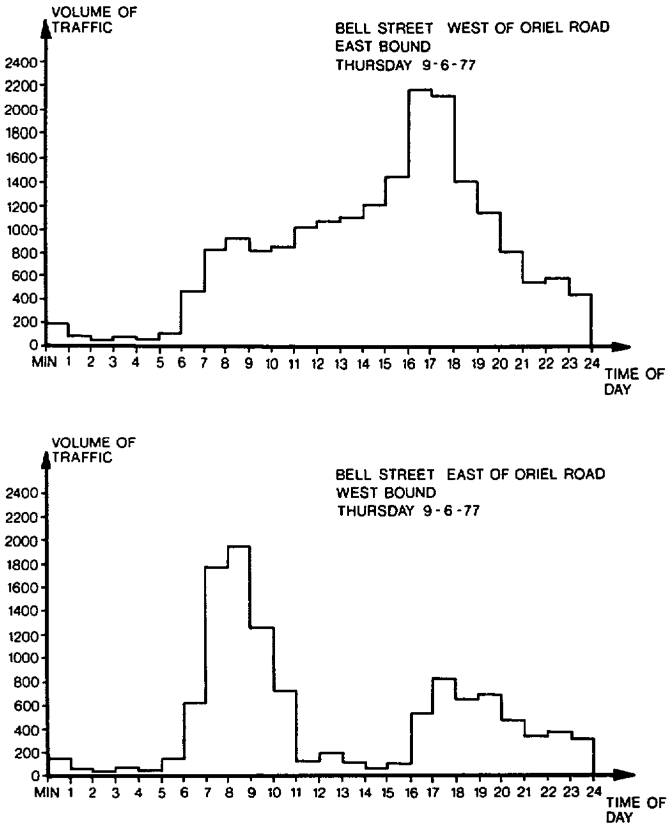

Fig. 2. Variation of traffic flow with the time of day.

TRAFFIC CONSTRAINTS OF FIXED TIME COORDINATION

To keep the phase or movement sequences of any series of traffic signalized intersections in synchronism, they must all operate such that the cumulative time required to service all movements (and inter-green times) at each intersection is the same. This time duration is called the cycle length. Each signalized intersection has its own preferred cycle length which is required to service the traffic flows on conflicting approaches. As the conflicting traffic flows at different intersections are generally at variance, the preferred cycle lengths for a series of signalized intersections will likewise vary. The intersection requiring the longest cycle time must then determine the cycle length of the synchronized series (unless large queues are tolerable) and the remaining intersections are thus required to run a cycle length of longer duration than preferred.

A universal cycle length is the first constraint placed on a coordinated series of signals over their isolated operation. In Fig. 2 a typical example of the variation of traffic flow with time of day is presented. Such fluctuations in traffic flow can be reflected as fluctuations in the preferred cycle length for each intersection. Where only one cycle length is available, traffic requirements will not be accommodated most of the time. Such mismatches between demand and service cause increases in delay and aggravate congestion. The severity of the constraints can be reduced by deploying several different plans, each matched more closely to particular traffic conditions.

The benefit of such multiple plans must be balanced against both the cost of their generation and the cost of a plan selection scheme. Resolving this cost utility of multiple plans and their selection is the second constraint placed on coordinating a series of signals.

Traffic signals interrupt and compact groups of vehicles which, after being given the right of way, disperse as they proceed down a road at a rate related to driver behavior, road conditions, and ease of overtaking. Fig. 3 illustrates the compaction of vehicles into platoons and their dispersion as they proceed down the road.

The closer signalized intersections are spaced and the more constrained are drivers on a road, the less dispersed are the vehicle platoons. Adverse timed arrivals of vehicles at a coordinated intersection are also exacerbated by traffic turning into the main street from upstream-controlled or uncontrolled intersections. Coordination of a series of signals is only possible where there is a marked periodicity (clustering) in vehicle arrivals from neighboring intersections. In fact, if vehicles are fully dispersed so that their arrival rate at an intersection is constant over a complete cycle, then there is no advantage in providing the right of way at a specific time. Dispersion of vehicle platoons is the third constraint placed on coordinating a series of signals.

Intersection layout is a physical constraint on a traffic system. Intersection separation and required offset times are related through vehicle traffic speeds. Heavy turning movements and multiple direction coordination complicate the choice of a designed progression speed which at best is itself constrained by congestion or statutory limits. The requirement for reasonably constant progression speeds over fixed and possibly nonsymmetrically spaced intersection networks is the fourth constraint on coordinating a series of signals.

Resolution of the conflict between traffic vying for the right of way has been described as being handled by the proportional segmentation of cycle length. It is sometimes desirable that particular classes of vehicles be given preferential treatment over the general traffic mix.

Such classes of vehicles might be emergency vehicles, public transport vehicles (buses or trams), and perhaps commercial vehicles. Emergency vehicles, by virtue of this classification, usually veto the requirements of all road users and are thus a special case. Passive assistance can, however, be afforded to public transport vehicles and/or commercial vehicles if their effective progression speeds between intersections are different from the general traffic mix and coordination is designed around their more specific requirements. Dynamic assistance can also be given to a specific class of vehicle, provided it is uniquely identifiable, by the manipulation of a flexible progression mode of operation. This scheduling of preferential treatment may be the fifth constraint to synchronizing a series of intersection controllers.

TRAFFIC MANAGEMENT CONSIDERATIONS

The implied assumption underlying any traffic regulation is that the network is not saturated. By improving general traffic mobility, through coordination or any other means, more traffic is attracted to a route. Congestion increases, perhaps even to saturation level, and in a traffic management sense the net effect is unstable and self defeating.

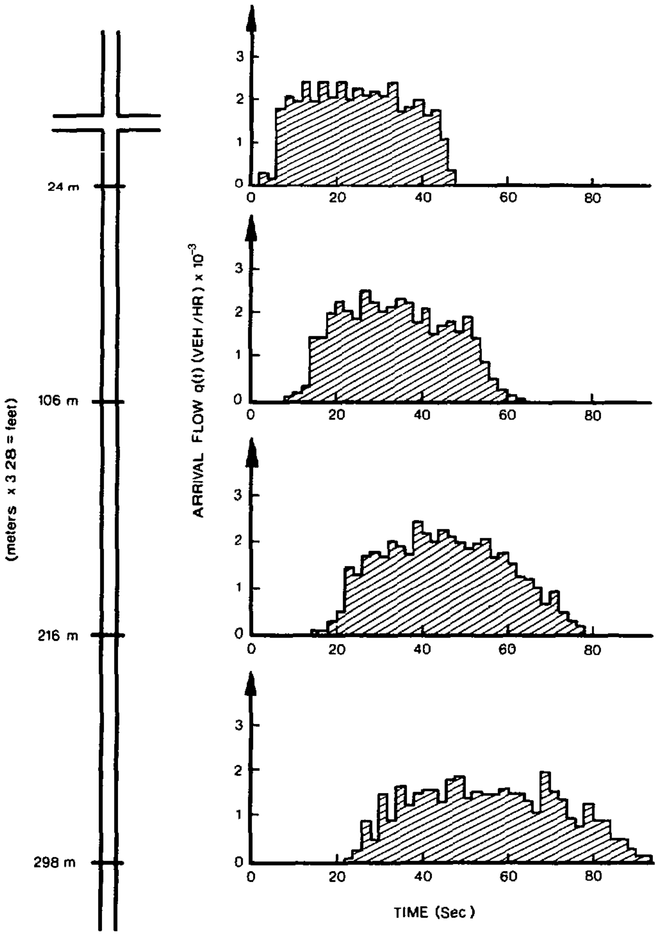

Fig. 3. Platoon dispersion.

If, alternatively, the improved capacity for a network obtained by coordination is not passed on to general traffic but applied to the preferential treatment of public vehicles, such a conflict is avoided. In such a case, general traffic is afforded the same mobility it had prior to coordination (or less by design). Thus driver routes remain unchanged while public vehicles have improved mobility and perhaps the potential of attracting more passengers. Hence the existing congestion level is maintained, the system is stable and, if anything, the tendency of drawing passengers to more mobile public vehicles will be beneficial in reducing private vehicle volumes and produce a net increase in general vehicle mobility.

APPLICABILITY OF MULTIPLE PLANS AND THEIR SELECTION BY TIME

The traffic regulation afforded by fixed time intersection controllers is degraded markedly as the actual traffic densities on the various approaches deviate from the expected traffic densities for which the stage duration (signal phases) and cycle length were determined. As platoon dispersion and progression rate are both functions of traffic density, the staging of offsets for a coordinated series of signal controllers will also be in error in relation to the deviation between design and actual traffic density levels.

The large variation in traffic density depicted in Fig. 2 clearly illustrates the futility of deploying only a single plan for coordination. If smaller and smaller time intervals are used over which a particular coordination plan is required to operate, then less discrepancy will exist between actual traffic density and the capacity of the coordinated network to accommodate it.

If the relationship between traffic density and time of day is consistent from day to day and/or week to week and the variance in traffic density is not great compared with the average value for the design interval, then time is a sufficient and a most convenient criterion on which to select plans. It is a convenient criterion because accurate time can be kept at isolated sites without the need for any cabling, any real time vehicle detection (strategic or at isolated intersections), and any equipment or technique for selecting the optimum preset plan to regulate existing traffic.

High traffic demand means variability in density is low, as is the potential for platoon dispersion. Generally, arterial roads carry predictable tidal traffic at high density levels and are thus potential candidates for cableless linking systems. Light traffic demand generally means that variability in density is high, as is the dispersion of vehicle platoons. Isolated intersection vehicle-actuated control is the most suitable means of handling the light, variable, and dispersed traffic experienced on arterial roads in the late evening and early morning.

Coordination of plans and isolated intersection vehicle-actuated operation, selection by time, provides a considerable part of the potential traffic management benefits of more elaborate traffic responsive systems. It is thus a most appropriate first stage in implementing signal coordination systems.

COSTS

ITERRA

It was stated earlier that a microprocessor cableless linking facility could provide a more powerful unit at lower cost than a hard-wired unit. A major factor in achieving this cost reduction was the separation of the facility for setting up or changing plans from that of the linking units [1] . By splitting these two roles into separate systems a much smaller number of supervisor units could be built, even at higher unit cost, with a resultant saving.

The production costs of the linking unit were almost one-third the costs of an integrated unit produced in equal numbers, and one integrated unit would have cost about ten percent more than the supervisor unit in equal quantities. For even small ratios of linking units to supervisors the savings available from role splitting are very dramatic.

In comparison with the MASCOT, estimated to cost about $2000, this ITERRA unit sells for about $800 plus supervisor units as required. Maintenance costs are also reduced by role splitting, because only the very reliable linking unit is used in the field and it is easily replaced. Also, no one can tamper with the plans set up in a linking unit without a supervisor unit.

General

Transportation consultants require about $1500 per intersection to collect traffic data and develop three separate coordination plans. However, such plans (generated by the traffic network study tool (TRANSYT) [3] or equivalent methods) are required with any fixed time coordination scheme and therefore can be considered as a fixed cost.

The ITERRA linking units can be directly coupled to controllers, configured for flexible progression, for a hardware cost of $800 and an installation cost of about $100. Other vehicle-actuated and fixed time controllers require an interface unit costing $160. Thus for a cost of about $1000, existing intersection and pedestrian controllers can be incorporated into multiplan fixed-time coordinated networks. For arterial routes and heavily trafficked networks, the major benefits obtainable from vehicle responsive coordination are derived from a cableless coordination scheme. Quotations from conventional traffic systems suppliers for vehicle responsive coordination of several arterial routes in a large metropolitan area were more than 1000 percent greater than those associated with an ITERRA based cableless linking system.

The major disadvantage of cableless coordination is the monitoring necessary to ensure that none of the equipment is malfunctioning and that the plans in use remain appropriate. These disadvantages can be overcome, in part, by good maintenance practices, particularly a good operational maintenance program on the part of the traffic engineering staff.

The cited disadvantages are in part the reason that cableless linking is a first stage in traffic management and leads, at a rate that can be afforded, to “vehicle responsive” coordination.

CONTINUING DEVELOPMENTS

The concept of cableless linking has not exactly taken the world by storm, but there are unmistakeable signs that it has arrived. In Australia, for example, most traffic signal controller manufacturers were developing units designed to be a plug-in controller module and hence an integral part of the controller. Some development in the U.S. appears to be directed along the same lines, although the units now available are of the stand-alone type. The microprocessor-based controllers are particularly susceptible to the plug-in module approach and these designs are sufficiently new to permit modification to accommodate the linking units as modules.

Where the linking unit is included as part of the original microprocessor controller design, there are opportunities for significant cost savings. For example, the controller’s display, memory, and power supply can all play dual roles by serving both the controller and the linking unit. As the evolution of the microprocessor continues, the units become more flexible and more powerful. The newer units now include a clock as part of the microprocessor rather than a unit on another chip. One manufacturer was able to redesign one model of his traffic signal controllers to use only ten major integrated circuit chips rather than the 30 required before the advent of the new microprocessors.

Another interesting application note is the use of the linking unit as part of a distributed multilevel system (DMLS)

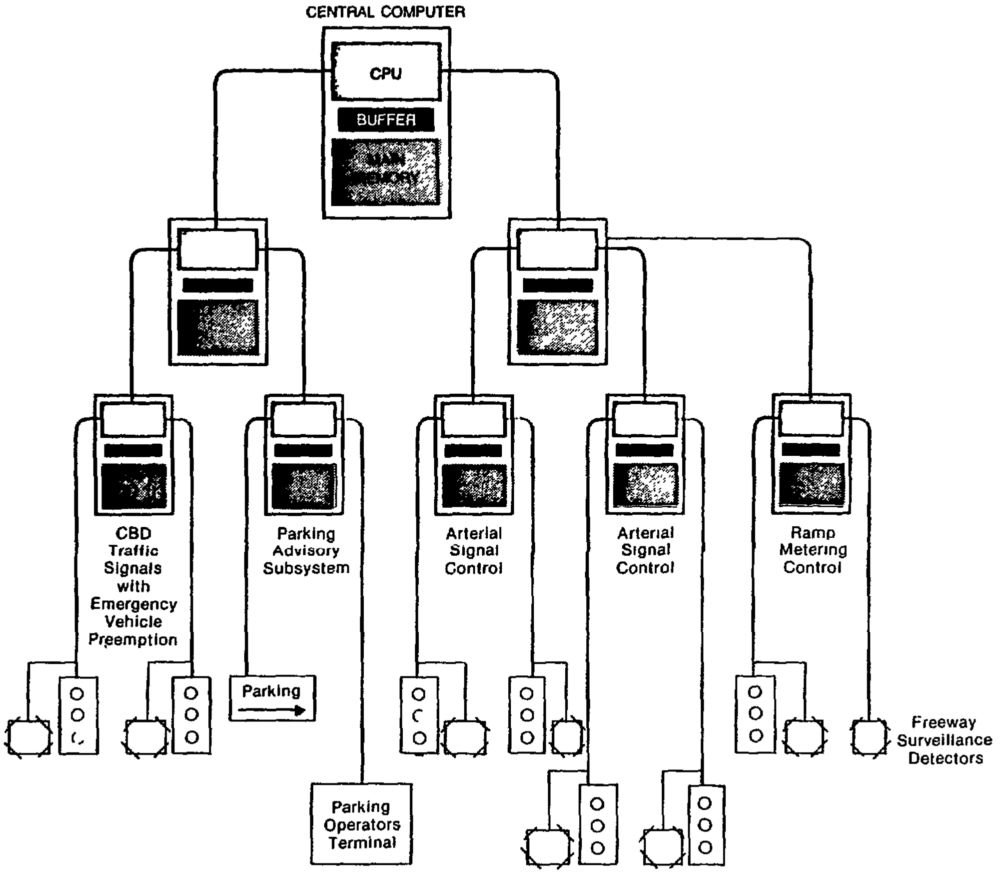

Fig. 4. Distributed multilevel systems (DMLS) hierarchical structure.

traffic control system. The hierarchical structure shown in Fig. 4 is an example of such a system. The linking unit would be housed with or built into the local controller. The role of the linking unit would be to receive, store, and utilize for control purposes data transmitted from a supervisory computer. Second, the linking unit would function as a fallback supervisor for the local intersection controller, providing plan changes based on time of day criteria during periods when the central computer was off-line or when a communications link failure occurred.

Other Devices

Information is currently available on two devices being manufactured in the U.S. One is called a time base coordination unit (TBCU) while the other is designated an intersection management system (IMS); both are microprocessor-based cableless linking units.

The TBCU is a product of Eagle Signal and probably represents a transfer of technology from Australia to the U.S. It is not known whether any of these units are in actual service other than on a test basis. According to the published specifications [2] the TBCU is capable of storing nine different plans, any one of which can be selected up to 150 times during a seven-day week. This sounds very much like the ITERRA specification.

The IMS is a product of 3M (Fig. 5), and again it is not known whether any of the units are actually in service. This unit boasts a yearly clock, which is to say, an infinite clock.

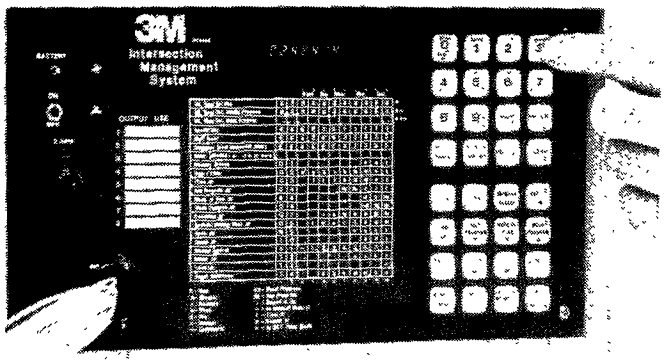

Fig. 5. Intersection management system (courtesy of 3M Company.

According to the published specifications [4] it can implement

- up to 99 plan changes per day,
- 16 day plans,
- 200 day plan events (turning on school signals, No Left Turn signs, etc.),
- five week plans,
- one year plan,
- 30 exception days to the year plan (holidays, special events, etc.).

At least one other U.S. manufacturer is known to be developing a cableless linking unit in conjunction with a keyboard entry microprocessor controller. It is understood that the plan storage will be a part of the controller and the linking unit will be a simple plug-in module whose principal function will be a seven-day or one-year clock. The exact installed price of the U.S. units is not known, but the TBCU and IMS are believed to be in the $1000 to $2000 range.

CONCLUSION

The traffic constraints caused by fixed cycle coordination of a series of traffic signals have been discussed. The ITERRA linking unit features have been expounded, along with an explanation of how their development provides a most effective and flexible coordination facility.

Known U.S. units have been compared with the ITERRA, based on published specifications, and were found to be directed to the same objective. There is reason to believe that parallel development is occurring in other parts of the world, particularly in Great Britain. The most significant point made is that, by providing the major part of the potential benefit of vehicle responsive coordination systems at a fraction of the cost, cableless coordination is the most responsible first stage in traffic management.

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Frank T. Hartley received the F.R.M.I.T. and MSc. degrees and M.I.E. and M.A.C.S.

He conducted engineering research and worked in commission engineering and process control for 12 years. For the following two years, as a Control Systems Engineer for the Road Traffic and Safety Authority, for whom he helped develop the ITERRA, he vanguarded the move toward area traffic control and traffic management. Concurrently, over the past live years, he has lectured in system engineering at RMIT, in addition to developing specialized computer equipment and working as an independent consultant. He is now the Director of Locus Systems Engineering in Melbourne. Victoria, Australia.

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On-Line Vehicle Classification

J. J. REIJMERS

Abstract—**For various applications it is useful to automatically divide vehicles passing a point into several categories. For the method described two inductive loop detectors were used in each lane. The shape of the bottom of a passing car can be assessed by examining the detector's analog signal. This signal, called the "signature," is sampled and fed into a digital computer, which calculates the vehicle's length and some shape factors. The passing vehicles can be separated into five categories: 1) passenger car, 2) delivery van, 3) truck, 4) truck–trailer, and 5) truck–semitrailer. To develop and optimize the method, a "learning set" of 1400 signatures was obtained from known vehicles. To investigate the effectiveness of the method, a "test set" of 950 signatures was gathered. By the use of the classifiers which were found with the above procedure, an on-line program in assembler code was written for a PDP-11/20 minicomputer. The determination of the class can be carried out in approximately 500 μs after a vehicle passes the detector. A trial with the on-line system gave very satisfactory results.**

INTRODUCTION

SINCE THE FOUNDING of the Automatic Traffic Systems Laboratory (ATSL) in 1969, vehicle detection has been a continuing research project. As a result of this research, we found that the inductive loop detector, with its loop under the road surface, is relatively reliable and requires little maintenance. In the usual setup, this detector gives a digital signal that indicates the presence of a vehicle over the inductive loop. If we place two loops at a short distance from each other, we can calculate the speed and length of each passing car with the two available digital signals, although the accuracy of this method leaves much to be desired.

Fig. 1 shows the configuration of the measuring points that are installed on motorways in The Netherlands. In the following formulas times are expressed in milliseconds (ms) and distances in meters (m). The speed and length of the passing vehicle are calculated by using the formulas

$$v = \frac{2500}{t_2 - t_1} \quad \text{m/s} \qquad (1)$$

$$L = \frac{t_3 - t_1}{1000}\, v - 1.5 = \frac{t_3 - t_1}{t_2 - t_1}\, 2.5 - 1.5 \quad \text{m.} \qquad (2)$$

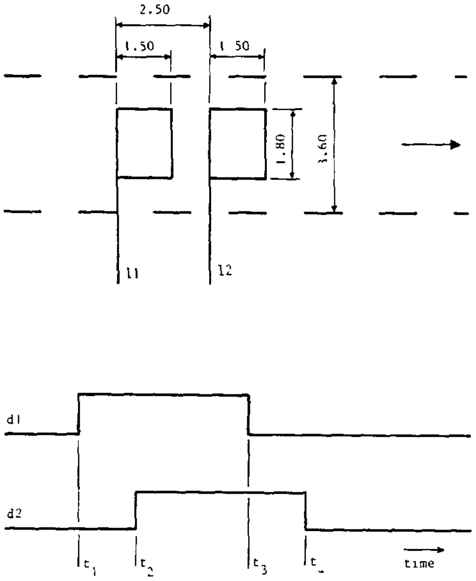

Fig. 1. Standard measuring point.

The length of the car can be used to recognize that car at the next measuring point. For the automatic incident detection system, which is under development at the ATSL, it is important that a vehicle which passes by a measuring point can be recognized at the next point. This is necessary to define and control the adjustment of the system. Unfortunately, this calculation of length is not sufficiently accurate, for errors up to 20 percent can occur. Therefore, a method has been developed to obtain more information from an ordinary loop detector. The digital output signal is not suitable for this purpose, so we paid attention to the analog output signal. This signal, which is not yet present at every standard detector, gives information on the influence exerted on the loop detector by the metal of the passing vehicle. The magnitude of this signal depends on the percentage of the loop which is covered by metal and the distance between the metal and the loop.

Observations of the signal by means of an oscilloscope showed clearly that the shape of this signal gave indications about the type of car that was passing. Fig. 2 gives an overview of the five types chosen for the classification system with the signals to match. This signal is called the "signature" of the car. Especially with trucks and truck combinations, the characteristic parts of the vehicles such as axles and towbars can be recognized. It is obvious that the detector "sees" only the bottom of the vehicle, so that the top of the car, the load, etc., cannot be examined. Some existing systems for vehicle classification use axle detectors, but these are placed on the road surface and are thus submitted to excessive wear [1], [2].

THE CLASSIFICATION METHOD

To separate the five classes, some characteristics of the signature are taken into account.

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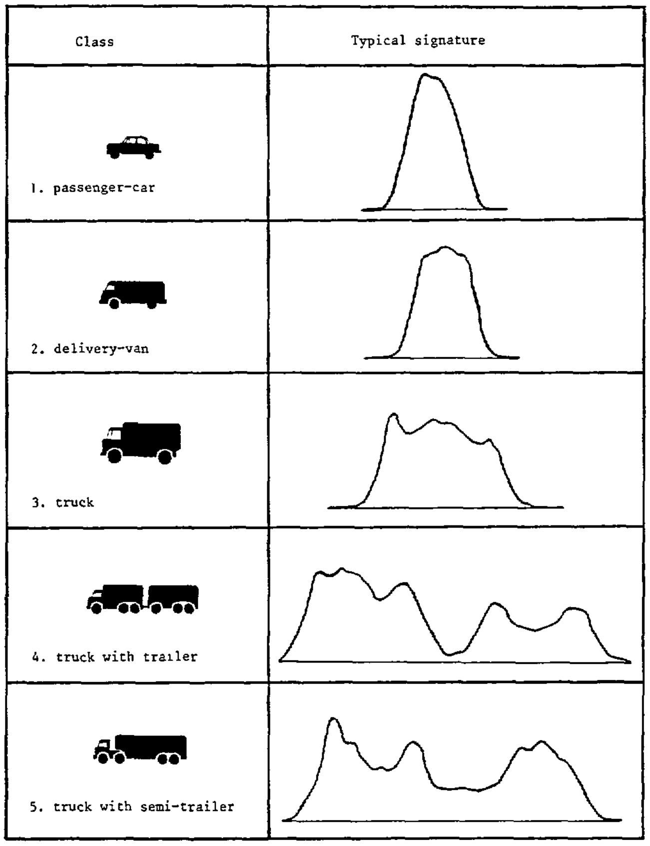


Fig. 2. The five classes.

Length of the Signature

The first and main signature characteristic is its length. This length, unfortunately, depends not only on the length of the passing vehicle, but also on its speed. Because the measuring point has two detectors, we can measure the speed from the time $t_2 - t_1$ (Fig. 1). The time length of the signature is

$$t_s = \frac{L+1.5}{v} 10^3 = \frac{L+1.5}{2.5} (t_2 - t_1). \tag{3}$$

The time $t_2 - t_1$ is known, so the time t_s can be normalized to a speed $v^* = 25$ m/s by using the following formula ($t_2^* - t_1^* = 100$ ms):

$$t_s^* = \frac{100}{t_2 - t_1} t_s = 40\,(L+1.5). \tag{4}$$

In this way the length of the vehicle can be obtained from the length of its signature. This length is used to recognize trucks (class 3). A vehicle belongs to class 3 if

$$352 \leqq t_s^* \leqq 512. \tag{5}$$

Top of the Signature

The second characteristic which is used for the distinction between passenger cars (class 1) and delivery vans (class 2) is the "flatness" of the top of the signature. The magnitude of the signature for delivery vans is also often less than that for passenger cars.

However, then the problem arises that the magnitude depends on the lateral position of the vehicle, so that the signature of a car that is driving partially outside its lane is lower than normal. The magnitude also depends on the loading and spring action of the car. Therefore, in the classification system first the mean value of the signature is calculated to relate the maximum of the signature to this mean value. The separation between passenger cars and delivery vans is obtained by first calculating the ratio of the maximum to the mean and then seeing if this value exceeds a certain boundary value. In that case the vehicle is a passenger car; otherwise, it is a delivery van. The boundary value depends on the length of the passing vehicle.

Minimum of the Signature

The third characteristic which is used for separating a truck-trailer (class 4) from a truck-semitrailer (class 5) is the minimum value of the signature that appears approximately in the middle of the signature. In the case of a truck-trailer this minimum is very low because the towbar between the two parts of the vehicle has very little metal and is not very close to the loop.

Now the mean value of the signature is also calculated to compare the minimum with this mean value. The minimum used is the absolute minimum between 25 and 75 percent of the signature, to eliminate the local minimums that sometimes occur on the trailing slope of the signature. After localizing the minimum the ratio of minimum to mean is calculated. If this value does not exceed a given boundary value, the vehicle is a truck-trailer; otherwise, it is a truck-semitrailer. The boundary value here is also dependent on the length of the vehicle.

DEVELOPMENT OF THE METHOD

The system described here has been developed after the investigation of a large number of vehicle signatures. The class to which each signature belonged was known. The signatures were gathered near the motorway, and each signature was completed with a code that indicated the type of vehicle measured. The category was determined by an observer who only registered the signatures of cars that could easily be classified. The distinction between passenger cars and delivery vans was sometimes difficult for the observer as well as for the classification system. Also, the distinction between delivery vans and small trucks was in some instances arbitrary.

Comprehensive measurements were carried out for the development and the optimization of the classification system. The first series was the so-called "learning set." The separation parameters were optimized by using this learning set. The set contained over 1400 cars, divided into the different classes.

After the first optimization a second series of measurements was carried out, forming the so-called "test set." With this test set the parameters found were checked, and the results indeed corresponded to the results of the learning set. These two sets are referred to as the "off-line measurements."

THE EQUIPMENT

The inductive loop detectors used are part of a measuring system also used by the Ministry of Transportation. The detectors are positioned on the A 13 motorway between The Hague and Rotterdam, and are connected with the laboratory computer room by means of a multipair telephone cable. The detectors are manufactured by Kurt Weisz, type Prodata DFA 73. This detector has an output in which the analog signal, the signature, is available. The signal is superimposed on a dc voltage, which must be eliminated first. To make the signature suitable for a digital computer, the signal is sampled with a sample time of 16 ms and, after that, converted from analog to an 8-bit binary value (1 byte). The data from one vehicle come in as follows (Fig. 3):

- header = 377_8
- code: the class of the vehicle (only relevant for off-line measurements);
- offset: the dc voltage at time t_1;
- $t_2 - t_1$: the time that determines the speed of the car (unit = 1 ms, so $v > 36$ km/h (22 mi/h);
- samples.

For the off-line measurements (visual) the data are recorded on punched tape for processing by the computer. For on-line measurements the data are fed directly into the computer.

THE CLASSIFICATION PROGRAM

If the classification system is going to be a part of a larger incident detection system or some other real-time system, it is important that the results be available as quickly as possible, and also that the program not require too much memory space. Therefore, the program is written in assembler language Macro-11 for the minicomputer PDP-11/20. During the collection of the samples some data are processed in order to save calculation time:

- the sum of all samples Σs_i,
- the number of samples $n = \Sigma i$,
- the maximum of the incoming samples.

The collection of samples and times is controlled by the digital signals from the two detectors (Fig. 3). The classification starts at time t_4. The length of the vehicle must be determined first. This length can be calculated from the number of collected samples. This number n is normalized to the already mentioned speed $v^* = 25$ m/s:

$$n^* = \frac{100}{t_2 - t_1}\, n. \qquad (6)$$

The sample time is 16 ms and the normalized speed is 25 m/s, so one sample of the normalized number of samples corresponds to a length of 0.4 m. The length of the car plus the length of the loop is

$$L + 1.5 = 0.4 n^* \quad \text{m.} \qquad (7)$$

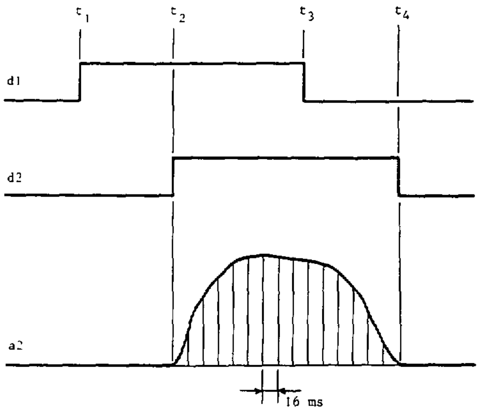


Fig. 3. Incoming data.

Trucks

If $22 \leqslant n^* \leqslant 32$, the vehicle comes under the category of trucks (class 3).

Passenger Cars and Delivery Vans

When $n^* < 22$, the value maximum/mean has to be calculated, i.e., max $(n/\Sigma s_i)$. All terms are present, so this calculation can be carried out immediately. Now the value found must be compared with the boundary value in order to classify the vehicle into class 1 or class 2. For each n^* from 10 to 22 the boundary value can be found in a table.

Truck Combinations

When $n^* > 32$, the value minimum/mean has to be calculated, i.e., min $(n/\Sigma s_i)$. The minimum is not present and has to be determined. The program now searches for the absolute minimum between $1/4\ n$ and $3/4\ n$. When the minimum is found, the calculation is carried out, and the value is compared with the boundary value in order to classify the vehicle into class 4 or class 5. For each n^* from 32 to 60 the boundary values can be found in a table.

Fig. 4 shows the flow diagram of the classification system.

THE OUTPUT RESULTS OF THE CLASSIFICATION PROGRAM

The already described part of the program is the nucleus of the system. If the classification system is part of a bigger system, only this part is used. During development and as a separate system, several kinds of outputs are used.

Lamps

First, five lamps are connected, which indicate the class of the passing vehicle.

Printed Output

Next, a number of data of the passing vehicle can be printed out:

- sequence number,
- class determined by the program,
- length,
- speed,

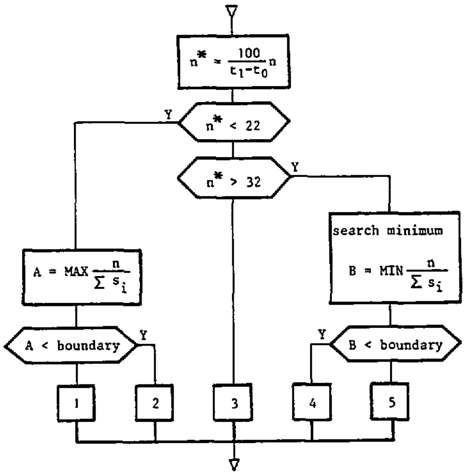


Fig. 4. Flow diagram.

- class according to human observer (only in off-line process).

Plotted Output

Third, and this was very important for the development of the system, there is the feature which provides the graphic display of the classification by means of a plotter (Fig. 5). The horizontal axis displays the normalized number of samples n^*, which is a measure for the length of the vehicle. The ordinates $n^* = 22^-$ and $n^* = 32^+$ divide the plane into three parts.

In the left partition lies the domain of the class 1 vehicles (passenger cars) and class 2 vehicles (delivery vans). The vertical axis displays the value of $A = 128$ (maximum/mean). For every vehicle of this length the system calculates n^* and A, and every vehicle is represented by a point in this left partition.

The line drawn from left to right is the best possible line dividing class 1 and class 2. If the point representing a vehicle is above the line, then the vehicle is considered to be in class 1, below the line in class 2.

In the off-line learning process the class determined by a human observer is known, and now the points representing passenger cars are displayed as crosses, while those representing delivery vans are displayed as squares. A faulty classification is immediately visible as a cross lying under the dividing line or a square above it.

Passenger cars and delivery vans with a length greater than $n^* = 21$ come under the class of trucks. Trucks are displayed in the middel partition $22 \leqslant n^* \leqslant 32$. Now the maximum value of the signature is displayed along the vertical axis. At the moment, this value is not used for classification purposes. The trucks are displayed as triangles. A faulty classification is visible as triangles lying outside the middle partition or crosses and squares within.

The right partition is the domain of the truck-trailer (class 4) and the truck-semitrailer (class 5). The vertical axis displays the value of $B = 256$ (minimum/mean). Through this partition the dividing line is drawn between class 4 and class 5 vehicles. Points under the dividing line are considered class 4 vehicles, those above as class 5. In the off-line process the class determined by human observers is displayed as a square for class 4 or a cross for class 5. Faulty classifications are now immediately visible.

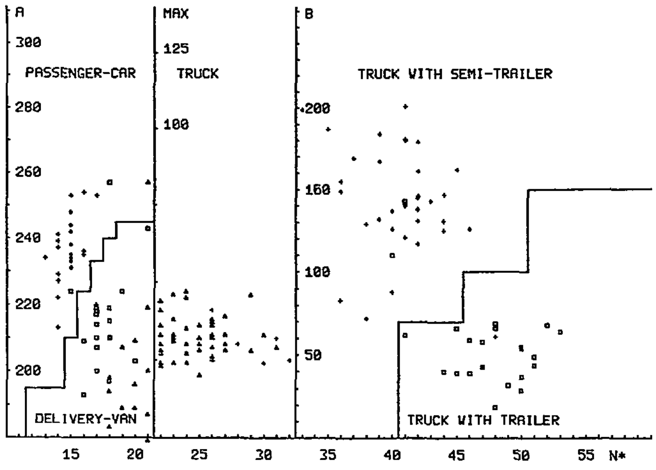
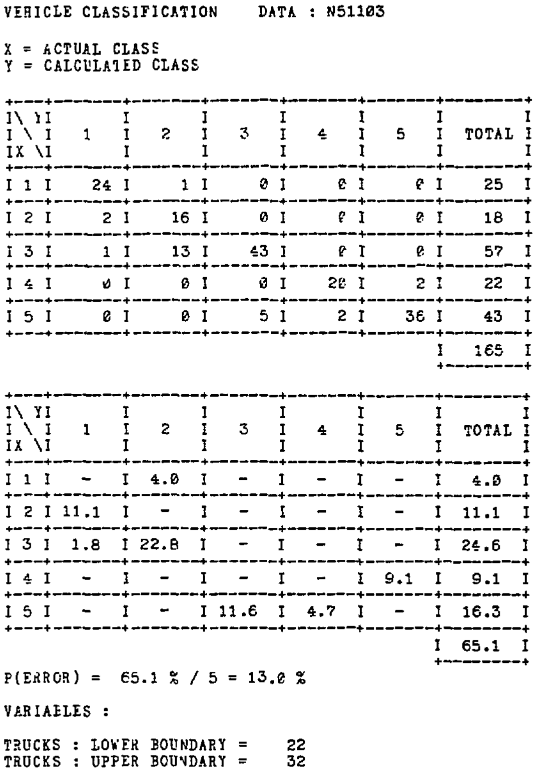


Fig. 5. Plotted output (example).



```
VEHICLE CLASSIFICATION    DATA : N51103

X = ACTUAL CLASS
Y = CALCULATED CLASS

+---+-------+-------+-------+-------+-------+--------+
I\ YI       I       I       I       I       I        I
I \ I   1   I   2   I   3   I   4   I   5   I  TOTAL I
IX \I       I       I       I       I       I        I
+---+-------+-------+-------+-------+-------+--------+
I 1 I    24 I     1 I     0 I     0 I     0 I    25  I
+---+-------+-------+-------+-------+-------+--------+
I 2 I     2 I    16 I     0 I     0 I     0 I    18  I
+---+-------+-------+-------+-------+-------+--------+
I 3 I     1 I    13 I    43 I     0 I     0 I    57  I
+---+-------+-------+-------+-------+-------+--------+
I 4 I     0 I     0 I     0 I    20 I     2 I    22  I
+---+-------+-------+-------+-------+-------+--------+
I 5 I     0 I     0 I     5 I     2 I    36 I    43  I
+---+-------+-------+-------+-------+-------+--------+
                                            I   165  I
                                            +--------+

+---+-------+-------+-------+-------+-------+--------+
I\ YI       I       I       I       I       I        I
I \ I   1   I   2   I   3   I   4   I   5   I  TOTAL I
IX \I       I       I       I       I       I        I
+---+-------+-------+-------+-------+-------+--------+
I 1 I   -   I  4.0  I   -   I   -   I   -   I   4.0  I
+---+-------+-------+-------+-------+-------+--------+
I 2 I 11.1  I   -   I   -   I   -   I   -   I  11.1  I
+---+-------+-------+-------+-------+-------+--------+
I 3 I  1.8  I 22.8  I   -   I   -   I   -   I  24.6  I
+---+-------+-------+-------+-------+-------+--------+
I 4 I   -   I   -   I   -   I   -   I  9.1  I   9.1  I
+---+-------+-------+-------+-------+-------+--------+
I 5 I   -   I   -   I 11.6  I  4.7  I   -   I  16.3  I
+---+-------+-------+-------+-------+-------+--------+
                                            I  65.1  I
                                            +--------+
P(ERROR) =  65.1 % / 5 = 13.0 %

VARIABLES :

TRUCKS : LOWER BOUNDARY =    22
TRUCKS : UPPER BOUNDARY =    32
```

Fig. 6. Error matrix (example).

Error Matrix

Finally, there is a printed output giving a survey of the errors made in the off-line process (Fig. 6). The first matrix shows the number of errors, while the second displays the percentage. Below that, the mean error percentage is printed out.

OPTIMIZATION OF THE PARAMETERS

The parameters used for the separation of the five classes are optimized with the learning set. To keep the program as fast as possible, the calculations for the separation are very

```
VEHICLE CLASSIFICATION    DATA : LEARN

X = ACTUAL CLASS
Y = CALCULATED CLASS


+---+--------+--------+--------+--------+--------+---------+
I\ YI        I        I        I        I        I         I
I \ I   1    I   2    I   3    I   4    I   5    I  TOTAL  I
IX \I        I        I        I        I        I         I
+---+--------+--------+--------+--------+--------+---------+
I 1 I    584 I     29 I      0 I      0 I      0 I   613   I
+---+--------+--------+--------+--------+--------+---------+
I 2 I     20 I    140 I      1 I      0 I      0 I   161   I
+---+--------+--------+--------+--------+--------+---------+
I 3 I      3 I     29 I    352 I      0 I      6 I   390   I
+---+--------+--------+--------+--------+--------+---------+
I 4 I      0 I      0 I      1 I    121 I      2 I   124   I
+---+--------+--------+--------+--------+--------+---------+
I 5 I      0 I      0 I      4 I      7 I    195 I   206   I
+---+--------+--------+--------+--------+--------+---------+
                                                 I  1494   I
                                                 +---------+


+---+--------+--------+--------+--------+--------+---------+
I\ YI        I        I        I        I        I         I
I \ I   1    I   2    I   3    I   4    I   5    I  TOTAL  I
IX \I        I        I        I        I        I         I
+---+--------+--------+--------+--------+--------+---------+
I 1 I   -    I  4.7   I   -    I   -    I   -    I   4.7   I
+---+--------+--------+--------+--------+--------+---------+
I 2 I 12.4   I   -    I  .6    I   -    I   -    I  13.0   I
+---+--------+--------+--------+--------+--------+---------+
I 3 I  .8    I  7.4   I   -    I   -    I  1.5   I   9.7   I
+---+--------+--------+--------+--------+--------+---------+
I 4 I   -    I   -    I  .8    I   -    I  1.6   I   2.4   I
+---+--------+--------+--------+--------+--------+---------+
I 5 I   -    I   -    I  1.9   I  3.4   I   -    I   5.3   I
+---+--------+--------+--------+--------+--------+---------+
                                                 I  35.1   I
                                                 +---------+

P(ERROR) =  35.1 % / 5 =  7.0 %

VARIABLES :

TRUCKS : LOWER BOUNDARY =    22
TRUCKS : UPPER BOUNDARY =    32
```

Fig. 7. Error matrix of learning set.

```
VEHICLE CLASSIFICATION    DATA : TEST

X = ACTUAL CLASS
Y = CALCULATED CLASS


+---+--------+--------+--------+--------+--------+---------+
I\ YI        I        I        I        I        I         I
I \ I   1    I   2    I   3    I   4    I   5    I  TOTAL  I
IX \I        I        I        I        I        I         I
+---+--------+--------+--------+--------+--------+---------+
I 1 I    372 I     20 I      0 I      0 I      0 I   392   I
+---+--------+--------+--------+--------+--------+---------+
I 2 I     10 I     66 I      0 I      0 I      0 I    76   I
+---+--------+--------+--------+--------+--------+---------+
I 3 I      3 I     14 I    243 I      0 I      6 I   266   I
+---+--------+--------+--------+--------+--------+---------+
I 4 I      0 I      0 I      0 I     69 I      0 I    69   I
+---+--------+--------+--------+--------+--------+---------+
I 5 I      0 I      0 I      0 I      6 I    128 I   134   I
+---+--------+--------+--------+--------+--------+---------+
                                                 I   937   I
                                                 +---------+


+---+--------+--------+--------+--------+--------+---------+
I\ YI        I        I        I        I        I         I
I \ I   1    I   2    I   3    I   4    I   5    I  TOTAL  I
IX \I        I        I        I        I        I         I
+---+--------+--------+--------+--------+--------+---------+
I 1 I   -    I  5.1   I   -    I   -    I   -    I   5.1   I
+---+--------+--------+--------+--------+--------+---------+
I 2 I 13.2   I   -    I   -    I   -    I   -    I  13.2   I
+---+--------+--------+--------+--------+--------+---------+
I 3 I  1.1   I  5.3   I   -    I   -    I  2.3   I   8.7   I
+---+--------+--------+--------+--------+--------+---------+
I 4 I   -    I   -    I   -    I   -    I   -    I    -    I
+---+--------+--------+--------+--------+--------+---------+
I 5 I   -    I   -    I   -    I  4.5   I   -    I   4.5   I
+---+--------+--------+--------+--------+--------+---------+
                                                 I  31.5   I
                                                 +---------+

P(ERROR) =  31.5 % / 5 =  6.3 %

VARIABLES :

TRUCKS : LOWER BOUNDARY =    22
TRUCKS : UPPER BOUNDARY =    32
```

Fig. 8. Error matrix of test set.

simple. In addition, the number of vehicles in the learning set (1400) is too small to develop a complicated separation system, because each point of the dividing line is defined by only a few cars.

Distinguishing between class 1 and class 2 caused many errors, so that much attention has been paid to this separation system. Unfortunately, each change in the separation system produced a more difficult calculation, while the number of errors did not decrease. This latter symptom could be due to the large sample time (16 ms) and the inaccuracy of the samples (8 bit). Further research should prove whether a more accurate sampling system gives any improvement. The errors as a result of the learning set are shown in Fig. 7 and the results of the test set in Fig. 8.

SPEED OF OPERATION

The program with all the possibilities of output is too slow for a real-time environment. Providing for all tables and output buffers takes a lot of time, but the slowness of the plotter and the lineprinter determines the speed of the classification system. When the system is used as a part of a bigger system, for instance an incident detection system, only the nucleus of the program is maintained.

The interrupt routine that is started each time a sample is entered has a run time of 70 μs. At time t_4 the classification starts. The process time is about 100-750 μs, depending on the length of the vehicle.

SOME REMARKS

The system that has been developed offers a fast separation into a limited number of classes and can be easily implemented in a mini- or microcomputer. Perhaps a reduction in the number of errors can be achieved by increasing the sample frequency and the number of bits per sample. Then the dividing criterion can be refined, but only at the cost of speed and memory usage. Problems will arise, especially in 8-bit microcomputers.

An extension of the number of classes is possible, but this also leads to a lower speed, while only a limited number of vehicles will end up in the new classes. Some other classes could be bus, passenger car with trailer, etc.

In optimizing the separation, all errors are treated equally. It is possible to attach a weight factor to each error, so that some errors are taken into account more then others. The total percentage is then found with the formula

$$P_{\text{tot}} = \sum a_i p_i. \tag{8}$$

Before this method is implemented, the consequences of each possible error should be considered in order to define a significant weight factor. It was not done for this system.

The complete program has been tested with an on-line measurement. A video camera was pointed to the road and the passing vehicles were visible on a video monitor. The