Synthesis Study of Texas Signal Control Systems: Technical Report

Technical Report 0-6670-1

Cooperative Research Program

TEXAS A&M UNIVERSITY—KINGSVILLE
KINGSVILLE, TEXAS

TEXAS A&M TRANSPORTATION INSTITUTE
COLLEGE STATION, TEXAS

in cooperation with the
Federal Highway Administration and the
Texas Department of Transportation
http://tti.tamu.edu/documents/0-6670-1.pdf

1. Report No. FHWA/TX-13/0-6670-1	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle SYNTHESIS STUDY OF TEXAS SIGNAL CONTROL SYSTEMS: TECHNICAL REPORT		5. Report Date September 2012 Published: November 2012
		6. Performing Organization Code
7. Author(s) Dazhi Sun, Leslie Dodoo, Andres Rubio, Harsha Kalyan Penumala, Michael Pratt, and Srinivasa Sunkari		8. Performing Organization Report No. Report 0-6670-1
9. Performing Organization Name and Address Texas A&M University-Kingsville Kingsville, Texas 78363		10. Work Unit No. (TRAIS)
		11. Contract or Grant No. Project 0-6670
12. Sponsoring Agency Name and Address Texas Department of Transportation Research and Technology Implementation Office P.O. Box 5080 Austin, Texas 78763-5080		13. Type of Report and Period Covered Technical Report: September 2011–August 2012
		14. Sponsoring Agency Code

15. Supplementary Notes

Project performed in cooperation with the Texas Department of Transportation and the Federal Highway Administration.
Project Title: Synthesis Study of Texas Signal Control Systems
URL: http://tti.tamu.edu/documents/0-6670-1.pdf

16. Abstract:

In recent years, several versions of traffic control systems have been established across the United States and within the state of Texas. There is a growing need to identify the various versions of these systems that exist, including the system hardware components and communications. Such an effort will also help identify operational successes, deficiencies, cost effectiveness, and other attributes of the various traffic signal system components.

The research objective was to develop a synthesis of traffic control system practices that can be utilized by various Texas Department of Transportation districts in pursuance of improved traffic signal operations and reduction in traffic signal system inefficiency and related costs. The study showed that while most operating agencies are utilizing newer and more technologically adaptive systems to control traffic, some agencies still have outdated traffic control systems. The lack of personnel and training to effectively use these advancements is one of the main reasons that the advanced systems are not fully being utilized.

An average of 23 percent of all Texas agencies interviewed was equipped to transmit video from the field to their traffic management center. Increasing this percentage could facilitate the implementation of more advanced and effective traffic signal control, but would require the deployment of updated communications mediums. Inter-agency coordination was found to be lacking in most cases due to reasons such as non-uniform communications and controller equipment and communication between agency officials. Recommendations were made on how to achieve better inter-agency coordination and more effective use of signal systems across Texas.

17. Key Words	18. Distribution Statement
Signal Controllers, Traffic Signal Control Operations, Traffic Signal Communication, Vehicle Detection Applications, Signal Coordination	No restrictions. This document is available to the National Technical Information Service Alexandria, Virginia 22312 http://www.ntis.gov

19. Security Classif.(of this report)	20. Security Classif.(of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	92	

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

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Report 0-6670-1
Project 0-6670
Project Title: Synthesis Study of Texas Signal Control Systems

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Texas Department of Transportation
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Federal Highway Administration

September 2012
Published: November 2012

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DISCLAIMER

This research was performed in cooperation with the Texas Department of Transportation (TxDOT) and the Federal Highway Administration (FHWA). The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official view or policies of the FHWA or TxDOT. This report does not constitute a standard, specification, or regulation.

This report is not intended for construction, bidding, or permit purposes. The researcher in charge of this project was Dazhi Sun. The United States Government and the State of Texas do not endorse products or manufacturers. Trade or manufacturers' names appear herein solely because they are considered essential to the object of this report.

ACKNOWLEDGMENTS

The activities reported herein were performed by the Texas A&M University-Kingsville (TAMUK) and Texas A&M Transportation Institute as a part of project entitled *Synthesis Study of Texas Signal Control Systems*, which was sponsored by TxDOT. Dazhi Sun of TAMUK served as research supervisor, and Henry Wickes, P.E., of the Texas Department of Transportation, served as the project director. In addition to the project director, the authors wish to acknowledge other members of the Project Monitoring Committee (PMC), who provided assistance and guidance throughout the project activities. These PMC members were:

- Dan Maupin, TxDOT - Project Advisor.
- Leo Ramirez, TxDOT - Project Advisor.
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- Wade Odell, TxDOT, Research and Technology Implementation Office – Research Engineer.

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CHAPTER ONE – INTRODUCTION

BACKGROUND

The *2011 Urban Mobility Report* stated that congestion, aside from choking our nation's highways, is choking the economy. The report outlined that the annual delay for the average commuter increased from 14 hours in 1982 to 34 hours in 2010 (*1*). In 2006, the U.S. Department of Transportation estimated that America loses $200 billion a year due to freight bottlenecks and delayed deliveries. In addition, consumers lose 3.7 billion hours and 2.3 billion gallons of fuel sitting in traffic jams (*2*). It has been estimated that inadequate traffic signal timing accounts for an estimated 10 percent of all traffic delay—about 300 million vehicle-hours—on major roadways alone. A U.S. Department of Transportation (U.S. DOT) survey found that 47 percent of people believe delays caused by congestion are the top community concern (*3*). In recognition of the fact that congestion is a national problem, the U.S. DOT launched the *National Strategy to Reduce Congestion on America's Transportation Network*. One element of this strategy is to reduce congestion by promoting operational and technical improvements that will enable existing roadways to operate more efficiently (*2*).

Traffic Signal Control Systems have evolved to serve as a critical component of the traffic management infrastructure utilized to combat excessive delays on the roadways. Advancements in traffic signal control systems including communications systems—adaptive control systems, traffic-responsive systems, real-time data collection and analysis, and maintenance management systems—enable signal control systems to operate with greater efficiency (*3*).

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

Leading transportation professionals have long recognized the value designing signal timing to meet specific operational objectives, and the value of monitoring performance to meet changing travel demands that can affect efficiency. Appropriately designed, operated, and maintained traffic signals can (*4*):

- Provide for the smooth flow of traffic along streets and highways at defined speeds, thereby reducing congestion.
- Effectively manage the traffic-handling capacity of intersections to improve mobility through the use of appropriate layouts and control measures and regular reviews and updates to the operational parameters.
- Reduce vehicle stops and delays, thereby:
  - Lessening the negative impacts to air quality.
  - Reducing fuel consumption.

PROBLEM STATEMENT

Lately, various versions of traffic control systems have been introduced across the United States and within the state of Texas. There is a growing need to identify the various versions of these systems that exist, including the system hardware components, communications, and other associated practices. Such an effort will help identify operational successes, deficiencies, cost effectiveness, and other attributes of the various traffic signal system components.

OBJECTIVE

The literature review focused on broad traffic signal issues such as:

- Signal control and operations.
- Vehicle detection applications.
- Communications systems.
- Information technology support and training.
- Signal control performance monitoring.
- Interagency/cross jurisdictional coordination.

The survey of state departments of transportation and survey of Texas systems focused on the following traffic signal timing and design issues:

- Signal controller types and detection technologies in use.
- Signal maintenance practices (e.g., in-house).
- Signal operation types being used in coordinated signal systems (e.g., time-based coordination).

- Centralized system software type, and capabilities and challenges faced in relation to the type of centralized system software.
- Communication technologies in use for the following applications:
  - Connecting signal controllers to traffic management centers (TMCs).
  - Transmitting video footage from signalized intersections to TMCs.
- Support for signal timing and control efforts that is available from information technology (IT) departments and from training resources.
- Methods used to assess signal control performance.
- Methods used to coordinate traffic signal systems across jurisdictional boundaries.

Detailed information about these issues can yield insight into the potential for improvement in traffic signal timing. These improvements may include implementation of more sophisticated signal coordination strategies or ITS-based treatments, the achievement of more effective signal coordination between neighboring jurisdictions, and provision of resources to address gaps in support or training needs.

OVERVIEW OF METHODOLOGY

The following activities were undertaken as part of the research:

- A literature review to identify and obtain exhaustive information on current traffic signal control systems across the United States and relevant systems from international examples. Researchers utilized national research documents such as the Traffic Signal Control Systems Handbook and the Traffic Detector Handbook to help identify state of the practice in traffic signal systems across the country. Traditionally published and electronic sources outside of the nationally recognized documents were also reviewed.
- Two online surveys, the first comprising 14 questions administered to selected U.S. states and the second comprising 19 questions administered to Texas local agencies that have been found in the literature review to be leaders in traffic signal control systems and operations and all 25 TxDOT districts. The list of contacts was built based on the researchers' knowledge and experience, recommendations of the Project Monitoring Committee, and a review of media and agency reports documenting the implementation of traffic signal improvement projects. The two surveys are provided in their entirety in the appendices to this final report. The responses to each question are described in the

second part of this report. Efforts were made to reflect a range of area types (rural, mid-sized, and urban) in the group of contacts.

- In-person interviews conducted with selected local agencies and TxDOT districts to clarify and confirm some of the information obtained through the thorough literature review and online survey. These interviews helped researcher better understand and expand the responses provided online.

A total of 42 interviewees answered the online survey questions or agreed to be interviewed in person or by telephone. The agencies represented by these interviewees are listed in Table 1. Agencies Represented in Survey Responses.

ORGANIZATION OF SYNTHESIS

The results of the literature review, survey, and in-person interviews are categorized under separate chapters as follows:

- Traffic Signal Control and Operations.
- Vehicle Detection Applications.
- Communication Systems.
- Personnel Training and Information Technology Support.
- Signal Control and Performance Monitoring.
- Inter-Agency Coordination.

Table 1. Agencies Represented in Survey Responses.

Agency	Contact Method
CalTrans District 6	Online survey
CalTrans District 8	Online Survey
CalTrans District 10	Online survey
CalTrans Sacramento	Online survey
New York State DOT Albany District	Online survey
New York State DOT	Online survey
GDOT District 4-Tifton	Online survey
GDOT District Cartersville	Online survey
NCDOT Division 2	Online survey
NCDOT Division 11	Online survey
TxDOT – Amarillo	Online survey
TxDOT – Atlanta	Online survey
TxDOT – Austin	Online survey
TxDOT – Beaumont	Online survey
TxDOT – Brownwood	Online survey
TxDOT – Bryan	In-person interview
TxDOT – Corpus Christi	In-person interview
TxDOT – Dallas District	Online survey
TxDOT – El Paso District	Online survey
TxDOT – Houston District	Telephone interview
TxDOT – Lubbock District	Online survey
TxDOT – Pharr District	Online survey
TxDOT – San Antonio District	In-person interview
TxDOT – San Angelo District	Online survey
TxDOT – Waco District	In-person interview
TxDOT – Yoakum District	Online survey
City of Beaumont, Texas	Online survey
City of Bryan, Texas	In-person interview
City of Cedar Park, Texas	Online survey
City of College Station, Texas	In-person interview
City of Corpus Christi, Texas	In-person interview
City of Frisco, Texas	Online survey
City of Grapevine, Texas	Online survey
City of Lewisville, Texas	Online survey
City of McAllen, Texas	Online survey
City of Missouri City, Texas	Telephone survey
City of North Richland Hills, Texas	Online survey
City of Richardson, Texas	Online survey
City of San Antonio, Texas	In-person interview
City of Sugar Land, Texas	Telephone survey
City of Tyler, Texas	Online survey
City of Waco, Texas	In-person interview

CHAPTER TWO – TRAFFIC SIGNAL CONTROL AND OPERATIONS

This chapter discusses traffic signal control practices primarily focusing on controller types and their mode of operation.

LITERATURE REVIEW

Impact of Traffic Control Systems

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

In typical urban areas, approximately two-thirds of all vehicle-miles of travel, and even a higher percentage of vehicle-hours of travel, take place on facilities controlled by traffic signals (*5*). To a major extent, therefore, the quality of traffic signal operation determines urban vehicular traffic flow quality. Thus, operational objectives of traffic control systems include making the best use of existing roadway and freeway network capacity and reducing trip times, without creating adverse environmental impacts (*6*).

Research and application have demonstrated the effectiveness of signal system improvements in reducing delays, stops, fuel consumption, emission of pollutants, and accidents. For instance, since 2003, the Denver Traffic Signal System Improvement Program (TSSIP) has assisted 16 operating agencies in upgrading efforts and has completed capital improvement projects for 55 arterial roadway sections. These projects improved operations for more than 1,100 traffic signals throughout the region and reduced delay by nearly 36,000 vehicle-hours per day, reduced fuel consumption by more than 15,000 gallons per day, and reduced air pollution emissions by more than 45,000 lb per day (*7*).

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

Traffic Signal Control Systems – Overview

The Federal Highway Administration (FHWA) published the third edition of the *Traffic Control Systems Handbook* in 2005 (*8*). The current edition updates signal system technology and broadens it into other methods for achieving surface street traffic management. Since the 1990s, surface street traffic control systems technology has seen significant advances in the following areas (*8*):

- Improved traffic signal controllers.
- Increased use of closed-circuit television (CCTV) and changeable message signs (CMS) on surface streets.
- Increased use of non-intrusive detectors.
- Improved transit priority strategies and equipment based on the use of GPS technology.
- Increased use of fiber optic cable for interconnection of traffic signal controllers and communication with other field devices.
- Increased use of standardized protocols to migrate data between intersection controllers and field master controllers or TMCs.

The traffic control system consists of hardware components including local controllers, detectors, changeable message signs, CCTV (in various forms), central computers, and field masters. Traffic signal systems also include the software that is used in traffic control systems. This includes real-time control software, optimization software, and simulation software. Control software developed for local controllers allows the controller to function by receiving detector inputs, processing status data, computing timing, and driving signal lamp load switches.

Traffic Signal Control Systems – Components

The typical traffic signal control system has various components that contribute to its functionality and operational objectives. These components are briefly described in the following section.

Traffic Signal Controllers

The evolution of traffic signal controllers parallels the evolution in related electronics industries. Signal controller unit hardware has evolved from the days of motor-driven dials and camshaft switching units to the adaptation of general-use microprocessors for a wide variety of intersection and special control applications (*8*).

Traffic signals can be classified according to operational type as pre-timed (or fixed time), fully-actuated, or semi-actuated/coordinated. Specific operational types are described in Table 2 and discussed in detail in the following paragraphs.

Pre-timed or Interval Controllers. Pre-timed controllers (interval controllers) allow the user to divide the cycle into any number of intervals, with the duration of each interval being set by the user. The cycle length equals the sum of the interval durations, and all intervals are timed sequentially. Pre-timed controllers work best for intersections with well-defined traffic patterns that do not vary greatly with time of day. One common application is the downtown area grid.

Actuated or Phase Controllers. Actuated controllers have a different approach to signal timing. The cycle is typically divided into phases, with each phase having pre-defined intervals—green, yellow, and red clearance for vehicle control; and walk and flashing don't walk if the phase serves pedestrians. The user specifies the duration of each of these intervals, or in the case of the green interval, the minimum and maximum duration. If the signal is coordinated, the user also specifies a split time for each phase and a start-of-cycle offset. This type of controller is particularly well suited to actuated control of normal intersections, especially those with protected left turn movements.

Table 2. Traffic Signal Control System Operations (*8*).

Categories	Main Characteristics	Control Technique	Method	Application
Isolated Intersection Control	Does not consider timing for adjacent signalized intersections	Fixed Time (Pre-timed)	Assigns right-of-way according to a pre-determined schedule	Intersection sufficiently isolated from adjacent signalized intersection so that arriving vehicles do not exhibit strong platooning characteristics. Intersection timing requirements inconsistent with remaining signal section
		Traffic Actuated	Adjusts green time according to real-time demand measured by detectors on one or more approaches	
Time Based Coordination (or Interconnected Control)	Coordinates based on common time synchronization	Pre-determined coordination	Computer programs used with average demand volumes for period to compute timing off line	Signals sufficiently closely spaced to require coordination
Traffic Responsive (or Adjusted) Control	Timing plans generated rapidly and automatically using system sensors	Changes split within a cycle. Changes cycle offset within a few minutes	Uses upstream sensor data to optimize objective function such as delay or controls to level of congestion	Where variations in day-to-day demand may vary significantly or where variations result from unusual traffic patterns or events
Traffic Adaptive Control	Phase change based on prediction from traffic measurement at each signalized approach	Uses predictive data change phase. Does not use explicitly defined signal cycles, splits, or offsets	Predicts vehicle flow at intersection from sensor data	Same as traffic responsive control. Also responds to random variations in traffic flow

Table 2 summarizes commonly- used traffic signal control system operational types. The operational type describes the degree to which adjacent signals are coordinated, and the degree to which the signal system can make adjustments to timing without programming from the responsible agency.

The National Electrical Manufacturers Association (NEMA) TS 2 standard specifies minimum functional standards for both interval and phase controllers (*9*). Most modern controllers meet most or all of these minimum requirements and most controllers also provide additional functionality not yet standardized (*8*). NEMA maintains the TS 2 standard for traffic signal controllers and related equipment. This standard defines functionality, interfaces (physical and logical), environmental endurance, electrical specifications, and some physical specifications, for the following components:

- Traffic signal controllers.
- Malfunction management units.
- Vehicle detectors.
- Load switches and bus interface units (BIU).
- Facilities for signal flashing and related control transfer.
- Cabinets.

A controller built to the physical requirements of the NEMA TS 2 standard is typically referred to as a NEMA controller. It is intended to operate in a NEMA cabinet meeting the NEMA TS 2 specifications, and can use either the A, B, C connectors (often called the TS 1 interface), or serial bus interface (often called the TS 2 serial interface) for cabinet inputs and outputs (*10*).

The Advanced Transportation Controller (ATC) family of standards is maintained by a consortium composed of NEMA, ITE, and AASHTO. Two standards are currently in place: the Advanced Transportation Controller 2070 (ATC 2070) and the Intelligent Transportation System (ITS) Cabinet for ATCs. The ATC 2070 standard is based on the Caltrans Model 2070 controller specification (*11*). Unlike the NEMA TS 2 standard, the ATC 2070 standard specifies every detail of the controller hardware and internal sub-components, but does not specify any application software functionality.

The states of California and New York jointly developed specifications that describe the Model 170 family of traffic control components (*8*). These standards cover the hardware for cabinets and all components, including the controller. As with the ATC standards, the Model 170 specifications do not specify software functionality. There are enhancements to the Model 170 controller which, although not standardized, provide another means of prolonging the life of the Model 170 family. The New York State Department of Transportation for instance, uses a similar controller, the Model 179, which uses a more powerful microprocessor. The Model 179 has not achieved the same acceptance as the Model 170 (*8*).

Traffic Signal Control System Operations

Over the years, traffic signals have evolved from single traffic signal controller to more complex systems with advanced capabilities. Improvements in control strategies and operations include the following (*8*):

- Greater information migration among adjacent and nearby traffic management centers.
- Increased coordination of signals across neighboring jurisdictions and traffic control systems.
- Increased use of adaptive traffic control systems.
- Improved coordination of surface street and freeway operations.
- Provision of traffic control systems with software that facilitates the automatic migration of signal timing plan data derived from signal timing programs into the traffic control system database.

Table 2 is adapted from the Traffic Signal Control System Handbook (*8*) and outlines all the various categories of traffic signal controller operations, their characteristics, control technique, method of operation and application. One of the more recent technological advances made in traffic signal control systems are the adaptive control systems (ACS).

Adaptive Control Systems. Adaptive traffic systems have been operating successfully in many countries since the early 1970s and the most widely deployed systems are the SCATS (Sydney Coordinated Adaptive Traffic System) and SCOOT (Split Cycle and Offset Optimization Technique). Other adaptive traffic systems found to have been deployed in the United States are:

- Los Angeles Department of Transportation Adaptive Traffic Control System (LA ATCS).
- Real Time Hierarchical Optimized Distributed Effective System (RHODES).
- ACS-Lite.
- Optimization Policies for Adaptive Control (OPAC).
- InSync, ATMS.now (formerly Streetwise by Naztec).
- Real Time Adaptive Control Logic (RTACL).
- QuicTrac Adaptive (by McCain).
- SPOT (Omaha, Nebraska).

With over 272,000 traffic signals in the United States, less than 1 percent are operating adaptively. In contrast, while there appear to be no published statistics, it is estimated that possibly 50 percent of the signals in Australia operative adaptively, and the majority of coordination in larger cities is adaptive (*12*). Adaptive signal control systems improve the responsiveness of signal timing in rapidly changing traffic conditions. Various adaptive signal systems have demonstrated network performance enhancement from 5 percent to over 30 percent (*3*). ITS communication and sensor networks are the enabling technologies that allow adaptive signal control to be deployed. Traffic adaptive control systems feature sufficient surveillance capability to provide a detailed profile of traffic approaching an intersection. Since control decisions are made during each phase, no explicit cycle length is defined in the control algorithm.

Adaptive traffic control systems have been documented to provide success in their deployment. For instance, in an effort to control delays and improve operations along arterial streets, the Los Angeles Department of Transportation developed its own Adaptive Traffic Control System (ATCS) to adjust traffic signal timing in response to real-time traffic demands (*11*). A subsequent study showed that the ATCS reduced travel time by 12.7 percent, reduced average stops by 31 percent, and decrease average delays by 21.4 percent. Another study in two counties in Virginia revealed that the addition of an adaptive split feature was able to reduce delays by about 40 percent without impacting progression on the coordinated approaches (*13*).

SCATS. SCATS calculates cycle length, splits, and offsets cycle-by-cycle and dynamically changes the grouping of signals in as traffic changes. It has been successfully deployed on arterial roads, downtown grid networks, and at small groups of intersections (*12*).

SCOOT. SCOOT was originally designed to control dense urban networks, such as large towns and cities but it is also successful in small networks, especially for areas where traffic patterns are unpredictable. SCOOT continually calculates the required coordination pattern for a group of signals in real time and immediately implements the changes (*12*).

ATMS.now. ATMS.now modifies splits on cycle-by-cycle basis and selects cycle length and offsets from lookup tables on a user-specified time interval.

RHODES. RHODES, originally developed by researchers from the University of Arizona, is currently in use in Pinellas County, Florida. It has also been tested at several locations to enable further research. RHODES, unlike most adaptive applications, has its operation hinged on prevailing demand at an intersection and predictions of future arrivals at that same intersection. Thus, RHODES veers away from the usual cycle length, splits, and offset approach.

InSync. InSync was released by Rhythm Engineering in 2009 and has experienced pilot tests in several locations. InSync, similar to RHODES abandons the philosophy of cycle lengths and phases. It constantly evaluates whether a signal should remain in its prevailing state or move to a different state based on both its current demand at the intersection and predicted arrivals of platoons from other intersections (*12*).

ACS Lite. ACS Lite is a scaled-down version of the FHWA Adaptive Control Software (ACS) (*3*). It is designed to monitor and evaluate traffic conditions and provide refinements to signal timing on a cycle-by-cycle basis. ACS Lite is intended to be a low-cost solution that adjusts traffic signal timing for real-time traffic conditions in small- to medium-sized communities. It was designed specifically for the closed loop arterial traffic signal system, which is representative of 90 percent of the traffic signal systems in the United States.

Case Study-Gresham, Oregon (SCATS)

The Burnside corridor is a five-lane major arterial that carries approximately 38,000 ADT through a growing commercial and retail district of the city. It is the primary route through Gresham to Mt. Hood and other weekend destinations in Central Oregon, connecting I-84 and US-26. It also serves as a key freight route through Gresham (*12*).

The arterial was run without coordination until 1995, at which time a coordinated signal system was implemented. In 2005, the coordinated signal timing plan was updated. Travel time runs were collected at several time periods along the corridor for comparison. These were:

- In 1997, while the system was operating free (i.e., without coordination between signals).
- In 1998, under new time-of-day coordinated plans.
- In 2004, under free conditions.
- In 2004, with old time-of-day plans from 1998.

- In 2004, with new time-of-day plans.
- In 2007, with time-of-day plans from 2004.
- In 2007, while operating under the SCATS system.

The comparison of these results indicated that the effectiveness of the time-of-day plans degraded over time as volumes changed, leading to increased travel times and delay. Comparison of the SCATS adaptive system to the time-of day plans indicated an improvement for both directions of travel and for all times of day except the AM peak in the direction of heavier flow. This time period was more efficiently controlled using the time-of-day plan and was considered to be performing optimally at the time the SCATS system was implemented (*14*).

ONLINE AND IN-PERSON INTERVIEWS

Other State Departments of Transportation Survey

A total of 18 responses were collected through the online questionnaire. Out of those, only 10 had most questions filled out. There were four subjects that responded from the state of California, from CalTrans Districts 6, 8, and 10, and Sacramento. There were two subjects from New York State Department of Transportation, one from Albany district and the other an unknown district. There were two subjects from North Carolina Department of Transportation, from Divisions 2 and 11. Finally, the two remaining subjects were from Georgia Department of Transportation, Cartersville and Tifton Districts.

The interviewees were asked what type of controller they currently have in use. Sixty percent of the agencies reported to use NTCIP-compliant controllers of varying types, including TS1, TS2, 170, and 2070.

Five of the 10 agencies indicated that they had had no difficulties with their controllers. The remaining five reported problems such as operating software issues, signal firmware lacking NTCIP compliance, power supply unit super capacitor leakage, front panel resetting issues, and back panel light failure.

The interviewees were asked which type of maintenance they used (whether in-house or outsourced) and a follow-up question was asked about what factors influenced their selection type. All agencies had in-house maintenance but stated various reasons as to what influenced their choice. Thirty percent of the respondents (representing three agencies) reported to have considered cost in selecting the type of maintenance used. Two agencies reported to have available in-house maintenance technicians and as such swayed their selection in that direction. The rest of the agencies had reasons such as: mandated by the central office or head office; emergency response; and number of signals within district. The distribution of responses is shown in Figure 1.

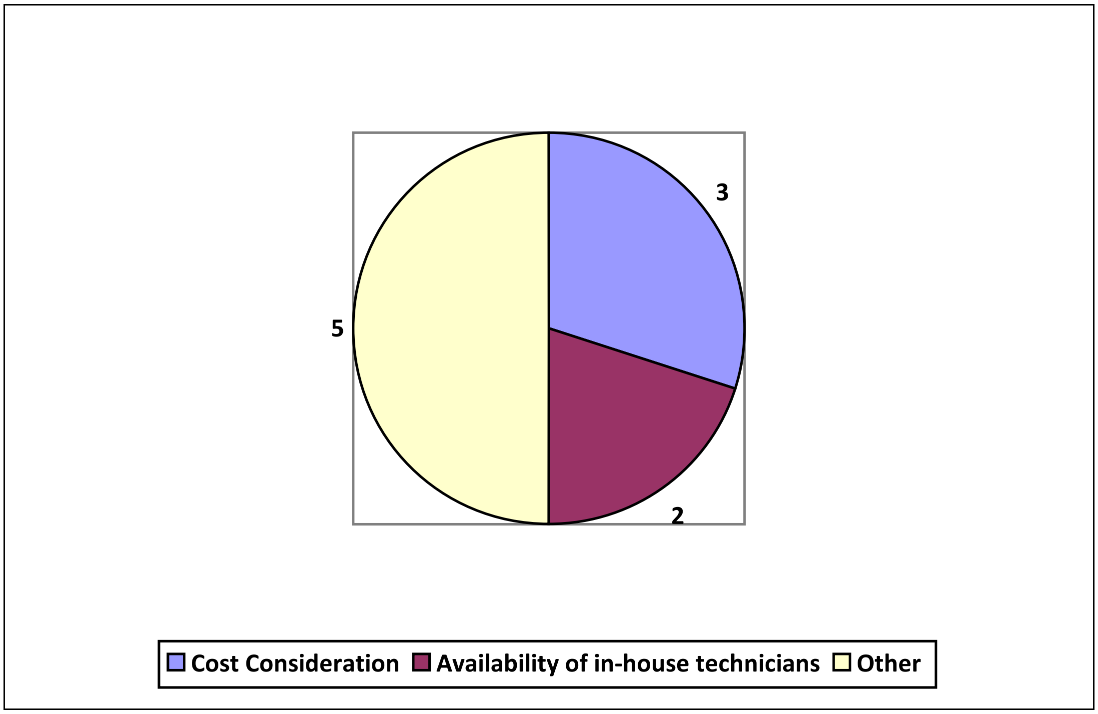

Figure 1. Factors Affecting Maintenance Type of Selection.

The interviewees were asked which type of centralized system software they used for rural and urban areas. Four out of the 10 interviewees used the same centralized system software for both urban and rural areas, which was CTNet. The remaining answers varied. One district used ACTRA for both, while the other used Naztec Streetwise. Another used Translink for both, and the remaining used Translink for rural and Translink, ICON, and Pyramids for urban areas.

Six of the 10 interviewees mentioned the capabilities and challenges faced with the type of centralized system software used. The responses are as follows:

- Centralized software contract will be a standardized product to be used statewide.
- In-house software with no video monitoring capability.
- Not updated for use with 2070.
- System frequently goes down for unknown reasons.

- Translink is utilized statewide.
- Developed in-house central system.
- Not properly supported by headquarters for upgrades and fixes to the code.
- Difficult to set up and numerous errors while operating.

The interviewees were asked what type of system they were currently using and also whether they had had experienced any security breach, for example a potential hacking. Four out of 10 have NTCIP compliant systems, and the remaining six have a proprietary system. None of the interviewees have experienced a security breach.

Six interviewees responded to the question that dealt with how the licensing agreements are set up to provide the most benefit to cost and if there were any limitations on the number of intersections or computers that could be used with the software. An interviewee answered that they used in-house software so there was no problem and no limitations. Another interviewee claimed that there is no licensing agreement and no limitations due to the fact that they owned the software. One interviewee responded that they had a 10-year maintenance contract with unlimited license, but could only create a 255 max drop. Another interviewee claimed to have a statewide license that everyone in the state can use without limitations. One interviewee answered that specifications were developed by state and vendor bids.

The interviewees were asked if their signal systems had been replaced to produce a better outcome and to provide the names of the old and new systems. Six out of the nine agencies reported to have changed their signal controllers. Changes made include: Traconix system to Type 2070; Type 170 to Type 2070; NEMA to Type 170, and TS2 to Type 2070.

According to some interviewees, the best time to replace older systems would be when equipment or components are out of date and no longer compatible with the latest technology.

There were different responses as to how to manage budgeting and financial challenges. One mentioned that they worked with what was allocated. Another worked with headquarters functional managers to prioritize. An interviewee stated that they would usually set up projects to upgrade an entire system and submit for state funding. One in particular answered that they expect their communication costs to increase with future deployments of wireless modems, so headquarters will need to provide funding for those costs.

Seven interviewees stated that their systems are made up of different types of mixed equipment. Some of their main concerns or problems are the lack of adaptive control; ease of use; compatibility, programming, and operating differences for technicians to know; and minor software issues.

Generally, the interviewees indicated that they prefer to perform their controller maintenance in-house. Hence, their choice of controller type and software type is influenced by their technicians' capabilities and knowledge. There is a general preference for maintaining uniformity among the hardware and software components in use, but this preference is weighed against the need to upgrade to obtain enhanced capabilities.

Texas Surveys

Traffic Signal Controllers

The interviewees were asked how many traffic signals existed within their jurisdiction. The responses ranged from 20 to 1,301 signals. For classification purposes, the following three system size categories were devised: < 100 signals, 101–350 signals, and > 350 signals. Figure 2 shows the distribution of signal counts within these categories.

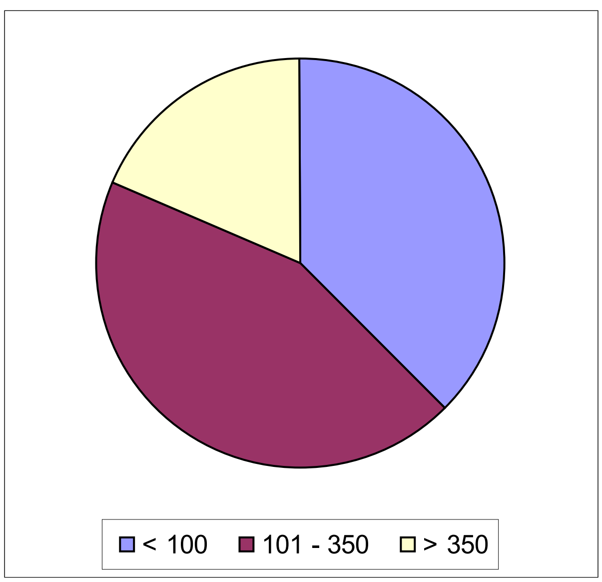

Figure 2. Signal Count Distribution.

Figure 3 shows the distribution of controller types being used by the interviewees. Almost all of the interviewees indicated that their agencies use TS2 controllers, and many of the agencies also use TS1 controllers. There were no notable differences between the responses from TxDOT practitioners and city practitioners.

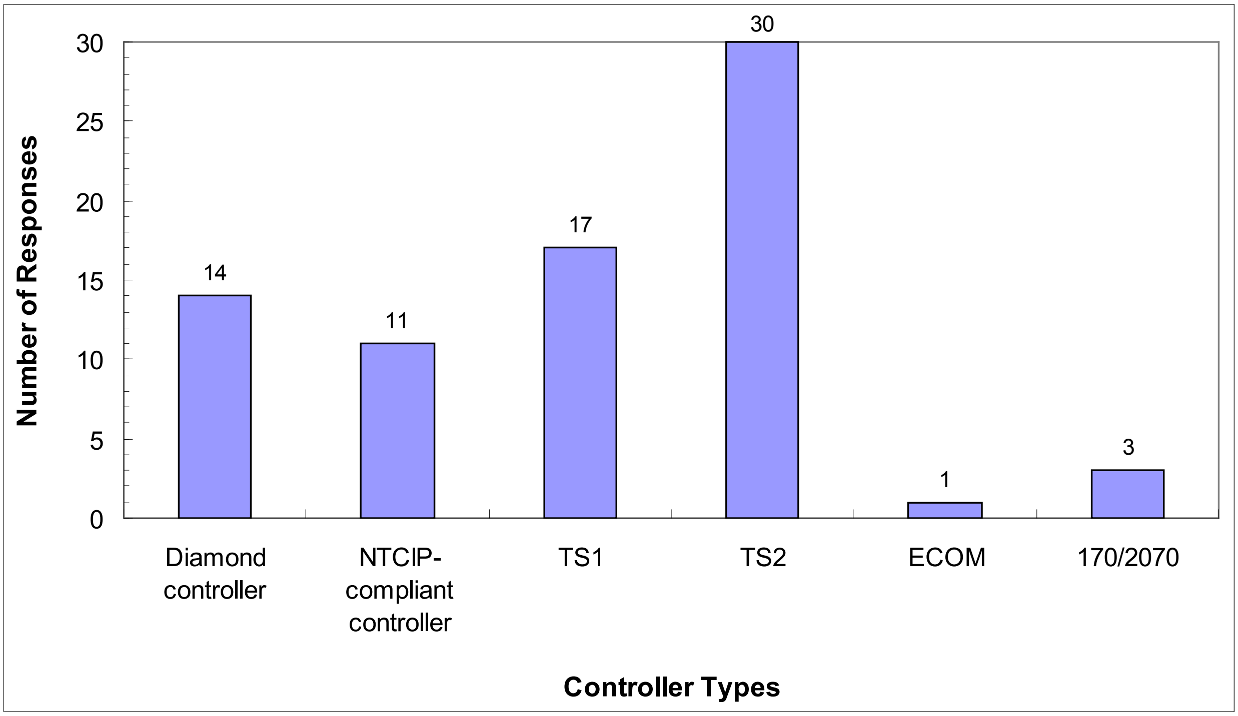

Figure 3. Controller Types in Use.

Generally, the interviewees indicated that their choice of controller type is guided by the following factors:

- Standards, specifications, and agency policies in place at the time of purchase.
- Cabinet capacity and size constraints.
- Desire for consistency in hardware and software within the jurisdiction.
- Need for special capabilities in site-specific cases (e.g., the 2070 controller can run the Detection-Control System [D-CS] algorithm).
- Historical legacy—existing controllers are often kept in service as long as they function.

Several interviewees noted that maintenance tasks are more easily handled by the technicians if fewer types of controllers are used in the field. It is also easier to keep spare parts available if there is more uniformity in controller type within the jurisdiction. As a result, they are reluctant to switch to different controller types or allow a mix of types to be used.

Traffic Signal Control Operations

The interviewees were asked what type of signal coordination, if any, that they were using. They were given the five choices that are defined in Table 2 earlier presented in the literature review. Figure 4 shows the distribution of their responses.

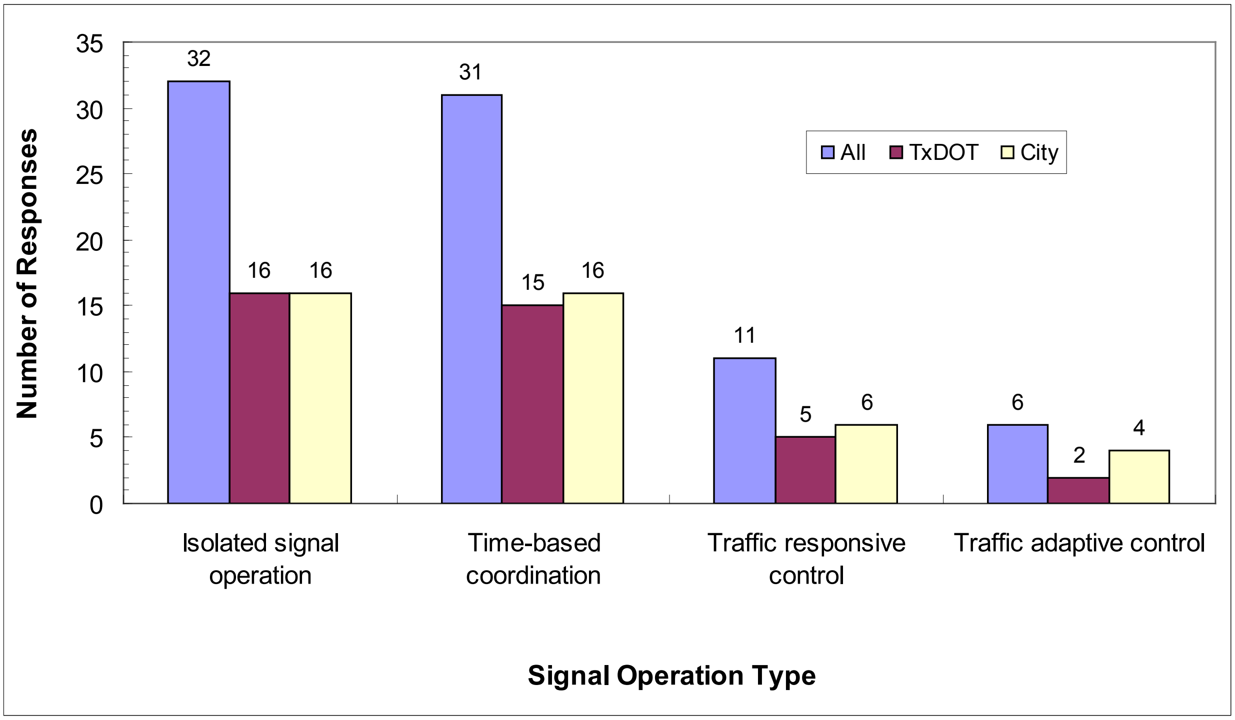

Figure 4. Traffic Signal Operation Types in Use.

Isolated signal operation and time-based coordination are the two most-commonly-used signal operation types. All interviewees indicated that their jurisdiction uses isolated signal operation, and all but one of the interviewees indicated that their jurisdiction used time-based coordination. The other two choices (traffic responsive and traffic adaptive control) were relatively rare, and they were used more often in city-operated signal systems than TxDOT-operated signal systems.

STATE OF THE PRACTICE AND CONCLUSIONS

The surveys and in-person interviews indicate that traffic signal control has the following concerns:

- Agencies are moving away from old systems to newer systems since new systems provide additional functionalities.
- In-house maintenance is preferred to outsourcing since the former is relatively cheap and most agencies have in-house technicians who perform routine maintenance.
- The choice of controller type depends on compatibility and ease of use, especially in reference to the type of controllers already in use. Continued use of the same software (perhaps with upgraded versions) will allow for easy migration and management.
- Control operations employed were invariably coordinated with the minimum being the time-based coordination. Adaptive systems are being utilized but require more education and investment.

CHAPTER THREE – VEHICLE DETECTION TECHNOLOGIES

This chapter describes vehicle detection applications laying more emphasis on the major detection applications being utilized by most agencies.

LITERATURE REVIEW

Vehicle detection and surveillance technologies are an integral part of Intelligent Transportation Systems (ITS), since they gather all or part of the data that are used in ITS. New vehicle detection and surveillance technologies are constantly being developed, and existing technologies improved, to provide speed monitoring, traffic counting, presence detection, headway measurement, vehicle classification, and weigh-in-motion data (*15*).

Vehicle detectors are used only for actuated signals. There are generally two kinds of vehicle detection sensors: *intrusive* and *non-intrusive*.

Intrusive Detector Technology

An intrusive detector is embedded in the pavement of the roadway or subgrade of the roadway, or taped or otherwise attached to the surface of the roadway. Examples of intrusive detectors include inductive loop detectors (which require saw cuts in the pavement); weigh-in-motion sensors (which are embedded in the pavement); magnetometers (which may be embedded or placed underneath a paved roadway or bridge structure); and tape switches, microloops, pneumatic road tubes, and piezoelectric cables, which are mounted on the roadway surface.

The operation of most of these detectors is well-understood as they represent applications of known technologies to traffic surveillance. The drawbacks to their use include disruption of traffic for installation and repair, failures associated with installations in poor road surfaces, and use of substandard installation procedures. Resurfacing of roadways and utility repair can also create the need to reinstall these types of sensors.

Non-intrusive Detector Technology

Non-intrusive detectors are typically mounted above the surface of the roadway itself or alongside the roadway and offset from the nearest traffic lane by some distance. Examples of non-intrusive detectors are video-image vehicle detection system (VIVDS) cameras that are mounted on traffic signal mast arms, poles, or on structures that span the roadway; microwave radar sensors mounted adjacent to the roadway or over the lanes to be monitored; ultrasonic, passive infrared, and laser radar sensors normally mounted over the lanes to be monitored (can also be mounted adjacent to the roadway); and passive acoustic sensors mounted adjacent to the roadway.

Recent evaluations have shown that modern non-intrusive detectors produce data that meet the requirements of many current freeway and surface street applications. Figure 5 displays an example of a sensor that combines passive infrared with Doppler microwave radar. The passive infrared-Doppler microwave radar sensor is designed for presence and queue detection, vehicle counting, speed measurement, and length classification (*15*).

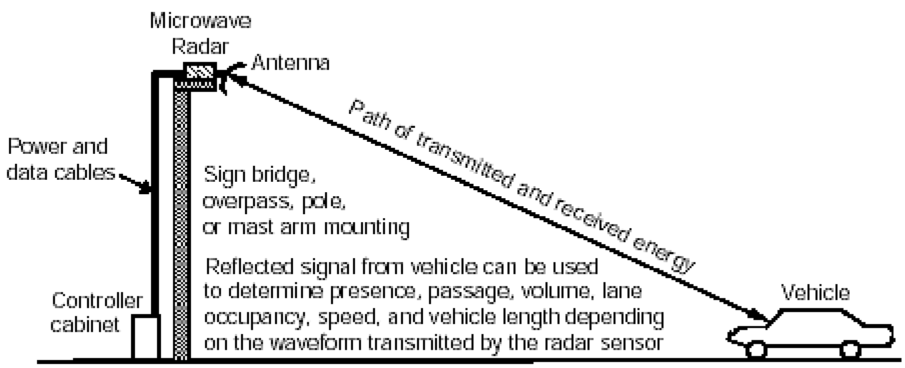

Figure 5. Microwave Radar Operation (*15*).

Types of Detector Applications

Several detector applications exist with traffic signal control system(s). They are generally grouped into presence detection and velocity measurement applications. Each detector application requires a particular level of sensitivity that will allow for adequate information to be obtained from the detector. Some of the common vehicle detector applications include: stop-bar detection, multi-lane intersection control, dilemma zone detection (and other advance detection), queue detection, freeway traffic management and incident detection systems, ramp metering, off ramp queue control and signal control actuation, work zone and temporary intersection control, permanent and mobile traffic counting stations, and enforcing of speed and red light violation.

The need for monitoring and reporting of freeway and arterial traffic conditions have increased with the growing implementation of both traffic management and traveler information systems. Travel time is perhaps the key quantitative parameter for ITS surveillance systems. Partners for Advanced Transportation Technology (PATH) researchers in California are applying advanced technology to improve traffic surveillance systems. Methods under development include the following (*17*):

- Automated Travel Time Measurement Using Vehicle Lengths from Loop Detectors.
- Using Vehicle Induction Signatures to Estimate Travel Time.
- Laser-based Travel Time Estimation.
- Video-based Vehicle Signature Analysis and Tracking.
- Image Sensing with Low Visibility.
- Probe Vehicle Surveillance.

Detector Technology Comparison

The merits and demerits of each type of detector technology are outlined in Table 3. Table 4 lists the typical characteristics for each type of detector technology.

Table 3. Strengths and Weaknesses of Sensor Technologies (*17*).

Technology	Strengths	Weaknesses
Inductive Loop	• Flexible design to satisfy large variety of applications. • Mature, well-understood technology. • Provides basic traffic parameters, e.g., volume, presence, occupancy, speed, headway, and gap. High-frequency excitation models provide classification data.	• Installation requires pavement cut. • Decreases pavement life. • Installation and maintenance require lane closure. • Wire loops subject to stresses of traffic and temperature. • Multiple detectors usually required to instrument a change.
Magnetometer (two-axis fluxgate magnetometer)	• Less susceptible than loops to stresses of traffic. • Some models transmit data over wireless RF link.	• Installation requires pavement cut. • Decreases pavement life. • Installation and maintenance require lane closure. • Some models have small detection zones. • Battery life is limited.
Magnetic (Induction or search coil magnetometer)	• Can be used where loops are not feasible (e.g., on bridge decks). • Some models installed under roadway without need for pavement cuts. • Less susceptible than loops to stresses of traffic.	• Installation requires pavement cut or tunneling under roadway. • Cannot detect stopped vehicles.

Microwave Radar	• Generally insensitive to inclement weather. • Direct measurement of speed. • Multiple lane operation available.	• Antenna beamwidth and transmitted waveform must be suitable for application. • Doppler sensors cannot detect stopped vehicles.
Infrared	• Active sensor transmits multiple beams for accurate measurement of vehicle position, speed, and class. • Multizone passive sensors measure speed. • Multilane operation available.	• Operation of active sensor may be affected by fog when visibility is less 20 ft or blowing snow is present. • Passive sensor may have reduced sensitivity to vehicles in its field of view in rain and fog.
Ultrasonic	• Multilane operation available.	• Some environmental conditions such as temperature change and extreme air turbulence can affect performance. Temperature compensation is built into some models. • Large pulse repetition periods may degrade occupancy measurement on freeways with vehicles traveling at moderate to high speeds.
Acoustic	• Passive detection. • Insensitive to precipitation. • Multilane operation available.	• Cold temperatures have been reported as affecting data accuracy. • Specific models are recommended with slow moving vehicles in stop and go traffic.
VIVDS	• Monitors multiple lanes and multiple zones/lane. • Easy to add and modify detection zones. • Rich array of data available. • Provides wide-area detection when information gathered at one camera location can be linked to another.	• Inclement weather, shadows, vehicle projection into adjacent lanes, occlusion, day-to-night transition, vehicle road contrast, and water, salt grime, icicles, and cobwebs on camera lens can affect performance. • Requires 50- to 60-ft camera mounting height (in a side mounting configuration) for optimum presence detection and speed measurement. • Some models susceptible to camera motion caused by strong winds. • Generally cost-effective only if many detection zones are required within the field of view of the camera.

Table 4. Traffic Sensor Output Data, Bandwidth and Cost (*17*).

Technology	Output Data					Multiple Lane, Multiple Detection Zone Data	Communication Bandwidth	Sensor Purchase Cost[1] (each in 1999 $)
	Count	Presence	Speed	Occupancy	Classification			
Inductive Loop	X	X	X	X[2]	X[3]		Low to moderate	Low[9] ($500 to $800)
Magnetometer (Two-axis fuxgate)	X	X	X[2]	X			Low	Moderate[9] ($1,100 to $6,300)
Magnetic (Induction or search coil)	X		X[2]	X			Low	Low to moderate[9] ($385 to $2000)
Microwave radar	X	X[4]	X	X[4]	X[4]	X[4]	Moderate	Low to moderate ($700 to $3300)
Infrared	X	X	X[5]	X	X[6]	X[6]	Low to moderate	Low to high (Passive: $700 to $1,200) (Active: $6,500 to $14,000)
Ultrasonic	X	X		X			Low	Low to moderate (Pulse model: $600 to $1,900)
Acoustic Array	X	X	X	X		X[7]	Low to moderate	Moderate ($3, 100 to $8,100)
VIVDS	X	X	X	X	X	X	Low to high[8]	Moderate to high ($5, 000 to $26,000)

Notes:

1. Installation, maintenance, repair costs must also be included to arrive at the true cost of a sensor technology.
2. Speed can be measured using two sensors a known distance apart or by knowing or assuming the length of the detection zone and the vehicle.
3. With specialized electronics unit containing embedded firmware that classifies vehicles.
4. From microwave sensors that transmit the power waveform and have appropriate signal processing.
5. With multi-detection zone passive or active mode infrared sensors.
6. With active mode infrared sensor.
7. Models with appropriate beam forming and signal processing.
8. Depends on whether higher-bandwidth raw data, lower-bandwidth processed data, or video imagery is transmitted to the TMC.
9. Includes underground sensor and local receiver electronics. Receiver options are available for multiple sensor, multiple lane coverage.

ONLINE SURVEYS AND IN-PERSON INTERVIEWS

Texas Surveys

The Texas interviewees were asked what types of vehicle detectors are used in their jurisdiction. Figure 6 shows the distribution of their responses.

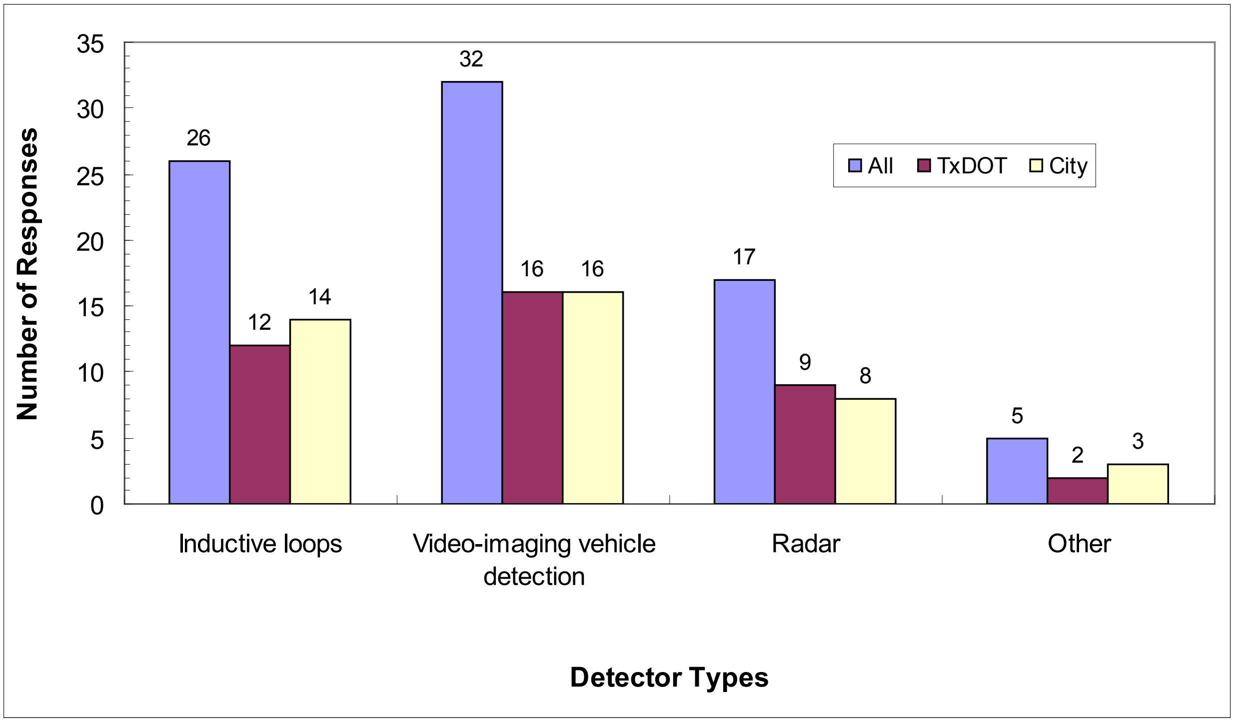

Figure 6. Detector Types in Use.

The two most common detector types are inductive loops and VIVDS, in terms of both number of jurisdictions and number of sites. Radar is the third most commonly-used detector type and has seen considerable growth in usage over the past several years. The other detector types chosen by the interviewees included the following:

- Sensys wireless detector also known as hockey puck detector (used by two cities).
- Infrared camera (used by two cities).
- Microwave detector (used by two TxDOT districts).
- Combination video/radar camera (used by one city).
- Single fisheye camera (used by one city).

The interviewees were asked their reasons for using the various detector types. Their responses are summarized in the following paragraphs.

Inductive Loops

There are numerous inductive loop installations throughout the state, but new installations of loops are now uncommon. The interviewees generally stated that they continue to use their existing loops as long as they function, but often replace them with VIVDS when they fail. Loop failure is often caused by age, pavement distress or milling, and high truck traffic volumes. One interviewee indicated that his jurisdiction seldom installs new loops because local contractors that provide this service are no longer available. Loops are generally still regarded as the preferred detector type for high-speed advance detection applications, though the newer radar devices are seeing growing acceptance for this application.

Video-Imaging Vehicle Detection

VIVDS are now the most commonly-installed detector types, for both new installations and replacement of existing inductive loops that have failed. The interviewees generally preferred VIVDS because the technology is non-intrusive, does not require altering the pavement, and can be adjusted easily when the positions of lanes are shifted (e.g., in work zones or when turn bays are added). However, the installation of VIVDS as a replacement for loops is not always feasible, as it requires space both in the conduits and in the cabinet. Additionally, VIVDS can be problematic at sites with excessive sun glare, fog, water mist (in coastal areas), or dust. Several interviewees noted that they had problems at sites where an intersection approach's vertical alignment made it impossible to obtain reliable detection zones in the camera's field of view while avoiding having the horizon in view. At these sites, there are certain times of the year that the sun will be directly visible during the morning or evening peak period, causing detection failures during the busiest traffic periods.

Radar

Radar sensors are now the third most commonly-used detection technology. These sensors are mounted on signal mast arms or poles, but operate with a different principle than VIVDS. While VIVDS technology monitors a defined detection zone and registers a call when visible characteristics like color, brightness, and contrast change, radar monitors and tracks moving objects continuously. Hence, it is regarded as suitable for high-speed advance detection applications, and it also overcomes the challenges that VIVDS technology has with sun glare, fog, mist, and dust.

Other Detector Types

Sensys wireless detectors (also referred to as hockey puck inductive sensors, infrared cameras, combination video/radar cameras, and single fisheye cameras were the other types of detectors used by agencies interviewed. The discussion on these detectors will be expatiated in the following case study.

Case Study – Selecting Vehicle Detection Technology

In one mid-sized Texas city, a wide variety of vehicle detection technologies are used, including the following:

- Inductive loops.
- VIVDS.
- Radar.
- Sensys wireless detector (hockey puck).
- Infrared camera.
- Combination video/radar camera.
- Single fisheye camera.

Generally, the city traffic department seeks to obtain the needed detection capabilities while minimizing the need to install new cables and cabinet hardware. Hence, when an existing vehicle detection system (e.g., VIVDS) is upgraded to a newer technology (e.g., infrared camera), the new technology is desirably chosen from among options that use the same type of cabling as the old technology. The possibility of using wireless communication devices to connect the detectors to the controller cabinet is considered when possible because it reduces the need to install cables and possibly power supplies. However, wireless communication is not feasible in locations where a significant amount of wireless communication traffic already exists (e.g., near a hospital). Additionally, the space requirements for new cabling and cabinet hardware are checked against the space available in the conduits and the cabinet. The city traffic department also weighs the costs of the various detection technology options.

The city's main technology choice is VIVDS, and it still has numerous inductive loop installations that were installed in the past. The rest of the technologies are used for site-specific reasons. The city's reasons for using the various technology choices are discussed in the following paragraphs.

Inductive Loops

The city continues to maintain many inductive loop installations that were installed in the past. Existing loop installations are kept in service as long as they continue to function, but they are not commonly chosen for new installations. However, the city does still replace single loops that have failed in cases where the rest of the loops at the intersection are still functioning and the failed loop can be replaced easily. The city traffic department has found that inductive loops last longer in concrete pavement than in asphalt pavement. The periodic grinding and resurfacing of asphalt pavement also frequently causes loop failures.

VIVDS

The city started using VIVDS 15–20 years ago, and VIVDS is now the city's primary choice for vehicle detection. VIVDS is the least expensive of the non-intrusive detection technologies. The city traffic department does have to clean the camera lenses occasionally, particularly at intersections with notable truck volumes where diesel exhaust creates smudges on the lenses. Fortunately, the city is not located in a coastal area, so there is no exposure to salt water mist. The city has found VIVDS to be problematic in conditions of fog, sunlight glare, and night. In the latter case, the detection zones must be drawn such that they will observe headlight glare rather than the vehicles themselves.

Radar

The city uses radar mounted at the intersection for stop line detection applications. The device can be mounted on a pole or a mast arm. Radar is expensive but more reliable than VIVDS. Radar is not affected by sunlight glare, and it is less susceptible to errors from wind vibration, compared to VIVDS. Hence, the city uses radar at sites where sunlight glare and wind vibration cause errors in VIVDS performance. The city has also used radar in parts of the city where older-style traffic signal poles and mast arms are used to create an aesthetic vintage appearance. In these settings, a VIVDS camera looks conspicuously out of place. Radar vehicle detectors use Ethernet cable, so if radar is chosen to replace an existing VIVDS installation, new cabling must be installed in addition to the detectors and the cabinet hardware.

The city also uses side-fire radar devices for advance detection at a few sites. These devices are installed roadside a few hundred feet upstream of the stop line.

Sensys Wireless Detector

Sensys wireless detectors are buried in the pavement, with a device located laterally in the middle of each lane. The city used Sensys wireless detectors on some intersection approaches that are brick-paved, out of a desire to preserve aesthetics by using detection technologies that are invisible. The detectors were installed by removing a half of a brick at each installation location, placing the device in the ground, and replacing the removed half-brick with a mixture of epoxy and crushed brick material that had the same color as the surrounding bricks.

Infrared

The city experienced problems with a VIVDS installation on an intersection approach that experienced significant sun glare. The problematic approach is the westbound approach, which experiences high traffic volumes during the morning peak period. The terrain required the VIVDS camera to be aimed such that the horizon was in view. As a result, sun glare would cause the camera iris to close during the morning peak period in certain portions of the year, resulting in a loss of detection capabilities. At this site, the VIVDS camera was replaced with an infrared camera because infrared is not negatively affected by sun glare. Infrared cameras detect heat from vehicles' engine blocks, exhaust, and brakes. Additionally, infrared cameras use the same type of cabling as VIVDS cameras.

The city traffic department is not certain how well the infrared camera technology will work when electric vehicles become more prolific. Electric vehicles do not generate exhaust, and their motors do not generate a significant amount of heat like conventional engine blocks. Electric vehicles' brakes generate heat, but brakes represent a much smaller visual target than engine blocks.

Combination Video/Radar Camera

The city has used a combination video/radar camera in adaptive control systems where some intersection approaches have high speeds and require advance detection. The video detection function is used for stop line detection, and the radar function is used for advance detection. The radar function is believed to be reliable for advance detection when mounted at the intersection. In contrast, VIVDS technology cannot be used reliably for advance detection unless an additional camera is mounted several hundred feet upstream of the stop bar on each high-speed intersection approach. Another benefit is that the combination video/radar camera can be installed easily to replace a VIVDS camera because both camera types use the same type of coaxial cable.

Single Fisheye Camera

The single fisheye camera is mounted in a dome and looks similar to a pan-tilt-zoom (PTZ) camera. The single fisheye camera has the ability to monitor the entire intersection from a single mounting location at a corner of the intersection. The raw images obtained from this type of camera appear distorted, so the camera's software flattens the image to allow the user to define detection zones.

The city uses the single fisheye camera at one intersection that has significant width, high truck volumes, and dual left-turn lanes on several approaches. The intersection's signal displays are mounted on span wires, eliminating the option of mast-arm mounting for VIVDS cameras. Each approach would require two VIVDS cameras to minimize view occlusion problems resulting from the trucks and the dual left-turn lanes. Alternatively, one radar device could be mounted on each intersection approach, but this option would require the installation of more Ethernet cabling. The city traffic department determined that the unique combination of challenges at the intersection justified the use of the single fisheye camera, despite its cost and the need to learn how to use a specialized device that may only be used at one site.

STATE OF THE PRACTICE AND CONCLUSIONS

Vehicle detection and surveillance applications are required for traffic actuation to be achieved.

- Agencies are moving away from intrusive vehicle detection and surveillance applications such as inductive loops to video-imaging applications due to the relative benefits video-imaging applications have over inductive loops.
- Newer and various types of vehicle detection applications are being explored since accurate vehicle detection culminates into better traffic flow management.
- Factors influencing the choice of detection technology include installation cost (including both the detector itself and the necessary wiring and control components), site-specific constraints (e.g., view occlusion, sun glare, and pavement condition), and the existence of adequate space in the conduits and the cabinet for the various components.

CHAPTER FOUR – COMMUNICATION SYSTEMS

This chapter covers communication systems being employed by agencies to effectively manage the ever-increasing traffic situations they face.

LITERATURE REVIEW

Communications is the lifeline of advanced signal systems. If signals cannot communicate, a real-time traffic control system cannot be provided. The success of signal coordination efforts rely on system features that provide communication. The communication devices and protocols are intended for use at traffic signals that require remote operation, coordination, or monitoring.

Signal controller may use the protocol to communicate with another controller, with a field master, or with a remote computer (*18*). Serial communications ports are often used for establishing a link to a master control unit or computer. Such connections may be permanent to a remote master or computer, or temporary to a laptop computer used by field personnel. Ethernet is increasingly being used instead of serial communications. A special serial port may be used to communicate with in-cabinet equipment in the case of a serial-bus cabinet.

The functionality and characteristics of a modern signal controller are determined by software more than hardware. The same controller may operate quite differently when programmed with a different software package. Different standards have evolved for modern traffic signal controllers, including those developed by the National Electrical Manufacturers Association (NEMA) TS 2, and Caltrans, New York DOT, and FHWA (Model 170).

Today, many types of communication mediums are utilized for various signal systems, including the following (*19*):

- Twisted Pair.
- Telephone Line.
- Fiber Optic.
- Microwave.
- Coaxial Cable.

- Satellite.
- Wireless.

Many engineers would argue that one communication medium is the best, or better than some of the others. Each communication medium has its own advantages and disadvantages. Which medium is best depends upon the purpose of the communications system and the desired end results. In actual fact, most systems are a hybrid—that is, two or more communications mediums are combined to result in an efficient communication network infrastructure. There are many traffic signal systems that combine a twisted copper pair infrastructure with wireless links to serve part of the system. The decision to create this type of system may have been based on economics—that is, to combine the use of several existing systems and minimize the need to install new hardware (*20*).

Twisted Pair

This is the ordinary copper wire that is used to provide telephone services to homes and businesses. The twisted consists of two insulated copper wires twisted round one another. Twisting prevents opposing electrical currents traveling along the wire to interfere with each other.

Communications signals sent over copper wire are primarily direct electrical current, which is modulated to represent a frequency. Foreign electrical currents near the communication wire can introduce interference and noise.

There are two types of twisted pair cables used for most in-building situations today:

- Category 3 Unshielded Twisted Pair (UTP), also known as Cat 3.
- Category 5 UTP (Cat 5).

Most new installations today use the Cat 5 twisted pair.

Coaxial Cable

Coaxial cable is a primary type of copper cable used by cable TV companies for signal distribution between the community antenna and user homes and businesses. It was once the primary medium for Ethernet and other types of local area networks. Coaxial cable is called coaxial because it includes one physical channel (the copper core) that carries the signal surrounded by (after a layer insulation) by another concentric physical channel (a metallic foil or braid), and an outer cover or sheath, all running along the same axis (*20*).

Some traffic departments originally deployed coaxial cables to provide communications between the field controllers and the central controller in an automated traffic signal system. The coaxial cable was also the preferred medium for early implementation of video incident management systems used in ITS. The introduction of fiber optics has rendered the use of coaxial cable for video incident management systems outdated.

The connection of Closed Circuit Television (CCTV) cameras to monitors and video switches, however, is often still achieved through the use of coaxial cables. The ever-reducing cost of technology affects the cost of fiber optics and has thus resulted in camera manufacturers installing fiber optic transceivers in the camera. By doing this, interference from electrical systems is curtailed and a secure video transmission network is created.

Fiber Optic Cable

Fiber optic refers to the medium and technology associated with the transmission of information as light impulses along a strand of glass. A fiber optic strand carries much more information than conventional copper wire and is far less subject to electromagnetic interference.

Wireless

Communication system designers prefer to use wireless technology over wireline technology because of reduce infrastructure cost and complexities. The construction of telephone line poles or cable trenches is eliminated; instead, a few strategically positioned radio towers need to be installed.

There are four general types of wireless (radio) communication systems:

- Cellular telephone.
- Basic 2-way radio.
- Point-to-point.
- Wi-Fi (Wireless Fidelity) and recently, Wi-Max.

Wi-Fi systems are becoming increasingly ubiquitous in their deployment and a part of most telecommunication deployment strategies. Wi-Fi systems are Ethernet based and allow for a seamless transition from wireless to wireline (*20*). Wi-Fi and Wi-MAX networks can be set up to operate at different frequencies. Each frequency has its own advantages and disadvantages. The primary frequencies for Wi-Fi networks are 900 megahertz (MHz), 2.4 gigahertz (GHz), 4.9 gigahertz (reserved for public safety), and 5.8 GHz. Wi-Max operates at 2.5 GHz in the United States (*21*).

CASE STUDY – THREE-TIER WIRELESS COMMUNICATION NETWORK IN SUGAR LAND (*21*)

The City of Sugar Land is constructing a wireless communication network to connect to the city's traffic signals and some other traffic control devices. This network will allow the city employees to monitor and adjust traffic signal timing, view images from closed circuit television (CCTV) cameras, and provide access for other city employees working remotely in the field such as police officers, building inspectors, and public works employees. During the evaluation process, this project was merged with a project being developed by the IT department to provide additional bandwidth and user capabilities for other city departments such as Public Utilities and Parks and Recreation.

The City of Sugar Land, located in eastern Fort Bend County, is approximately 20 miles southwest of downtown Houston. Sugar Land is one of the fastest growing cities in Texas, with Census 2000 figures ranking Sugar Land number 1 in growth in the Houston metro area and number 1 among the state's 45 largest cities. The city's estimated July 2011 population was 81,700 (*22*). Sugar Land's city limits encompass approximately 34 square miles.

The city currently operates and maintains 72 traffic signals divided into 11 different signal subsystems. There are approximately 20 more traffic signals that are currently operated by other agencies in the extra-territorial jurisdiction, which will become the responsibility of the City of Sugar Land when the areas are annexed over the next 10 years.

Sugar Land has a Traffic Management Center (TMC), which is located at the Public Works building on Gillingham Lane. The TMC monitors the 11 subsystems with 10 broadband Integrated Services Digital Network (ISDN) lines. The subsystems communicate with the individual subsystems through spread spectrum radios, twisted pair copper communications cable, or fiber optic cable. The ISDN lines are leased from the telephone company for $100 per month for each connection. The TMC utilizes software named ATMS.now (ATMS is an acronym for Advanced Traffic Management System) to monitor and control the traffic signals. The software and the traffic signal controllers are produced by Naztec, Incorporated. The traffic signal control units are currently configured to communicate at baud rates of 19.2 KB/s. The city intends to upgrade the communications system and field hardware to provide communications in the 10 to 1,000 MB/s range.

The objective of the three-tier wireless communication network project is to create a comprehensive, citywide system with sufficient bandwidth and sustainability to provide communication to all existing and proposed traffic signals in the City of Sugar Land as well as other departments. The city determined that the 4.9 GHz frequency would be most advantageous. The city plans to establish a fiber optic system in the future.

A wireless backbone was designed using eight elevated sites. These elevated sites consisted of water towers, existing buildings, and one new self-supporting tower. The wireless backbone will use 11 GHz microwave point-to-point radios. The wireless backbone will tie to the existing city network at City Hall and Fire Station #2 (via fiber optic connections). In the event that additional bandwidth is needed prior to the completion of the fiber optic system, additional point-to-point and point-to-multipoint radios can be added to the system.

The elevated sites will communicate with the individual traffic signals using 4.9 Ghz point-to-multipoint radios. All traffic signals within the city will be included in the network. Approximately half of the traffic signals will include CCTV cameras and Wireless Access Points (WAP). The WAP, operating at 2.4 GHz, will allow staff to log into the city network from the field and reduce the number of employees requiring aircards and the associated expense. The remaining intersections will have some combination of signal controller communication and possibly CCTV cameras. Nine older signal controllers and cabinets are being replaced with TS2 Ethernet controllers. In addition, 35 TS2 signal controllers are having the faceplates replaced to give them Ethernet capability. This will allow the signal controllers to interface with the switch and ultimately the 4.9 GHz radio system.

The project was funded through an Advanced Funding Agreement (AFA) between the City of Sugar Land and the Texas Department of Transportation through Congestion Mitigation and Air Quality (CMAQ) funds.

CASE STUDY – CITY OF IRVING, TEXAS (*20*)

Background

Irving, Texas, a community of about 200,000 residents, is part of the Dallas-Fort Worth Metro Area. The Traffic and Transportation department is responsible for the operation and maintenance of the traffic signal system-a system with 175 signalized intersections. Most operate on a time-of-day signal plan, and a few are closed-loop. The current system uses several versions of the NEMA traffic signal controller, and there is no centralized control. The department relies on telephone callers to report problems and dispatches technicians to investigate and perform repairs. The City of Irving is seeking to update its current traffic signal system to provide for centralized control and problem location. The traffic department is proposing to replace the variety of signal controllers with the 2070 type.

The update calls for the total replacement (over time) of the NEMA type controllers, addition of CCTV cameras, traveler information signs, and centralized control of all traffic signals. Central control would provide immediate notification of signal problems and allow for dynamic re-timing of signals to account for special events or significant traffic incidents. The use of CCTV cameras would provide real-time viewing of congestion problems and support temporary re-timing plans.

Proposed Update

An overall development plan with the objectives of standardizing on one controller type, one software system, one cabinet type, and centralized signal control was created. The construction of a private fiber optic communications network was considered. Transportation Equity Act for the 21st Century (TEA-21) funding was requested and granted but the level of funding was substantially less than what was needed. The city looked for alternate communication mediums to support their plan. The use of leased telecommunication services from local carriers was considered but subsequently rejected because the overall cost exceeded funding levels, available bandwidth was insufficient to handle the individual (3MB) video feeds required for the system, and the city did not want to incur a monthly recurring expense.

The city investigated wireless systems and discovered that they could provide total coverage at a substantially reduced cost compared the fiber optic medium's cost and leased telecommunication networks. Requirements for the system included:

- Broadband capability to support video.
- Point-to-multipoint to support centralized control.
- Ability to add locations with minimal system disruption (scalable).
- Ability to add locations with easy to configure communications hardware.
- Communication system reliability.
- Overall initial system costs kept within budgeted levels.

Additionally, the Irving Traffic Department wanted to provide:

- CCTV cameras with pan-tilt-zoom.
- Changeable message signs.
- Dynamic lane assignment.
- Video incident detection.
- Additional advanced traffic management features.
- Real-time traveler information.

The city has made a significant investment in a wireless infrastructure to support operational agencies and services. They currently use 5.8 GHz microwave (Wi-Fi 802.11a), 24/23 GHz microwave, and 18 GHz microwave. A group of experienced, licensed radio technicians are on staff to maintain and operate the radio networks.

Considering several different wireless network topologies, the city sought a design that would provide the necessary bandwidth, secure transmission, and high availability (99.999 percent). The typical point-to-point-to-point (multi-drop) design used for most traffic signal wireless communication systems did not prove to be adequate for a system that would ultimately be required support more than 70 CCTV cameras and almost 200 signalized intersections. The city's Communication and Electronics Department investigated a wireless system designed to provide broadband internet access. They found a product that is compliant with the IEEE 802.16 and 802.16a standard. The 802.16a standard provides for a significant reduction in the potential for interference from other radio systems on the same or adjacent channels. The IEEE 802.16 was developed as the "Air Interface for Fixed Broadband Wireless Systems." This standard describes wide area wireless networks (WAN) and is designed to provide coverage in terms of miles while the IEEE 802.11 wireless standard series was developed for local area wireless network (LAN) coverage with coverage distances measured in terms of feet.

ONLINE SURVEYS AND IN-PERSON INTERVIEWS

Other State Departments of Transportation

The interviewees were asked what type of communication mediums they used for rural and urban areas. The responses received from the agencies varied based on the area type (rural versus urban cities) being served by the communication system. For rural areas the answers included dial-up, wireless modems, Digital Subscriber Line (DSL) if available, General Packet Radio Service (GPRS), wireless radio, and fiber. For urban areas, the answers included wireless Ethernet, fiber, dial-up, DSL, GPRS, wireless modems, and wireless radio. Figure 7 illustrates the variation of communication mediums with type of agency setting (rural or urban).

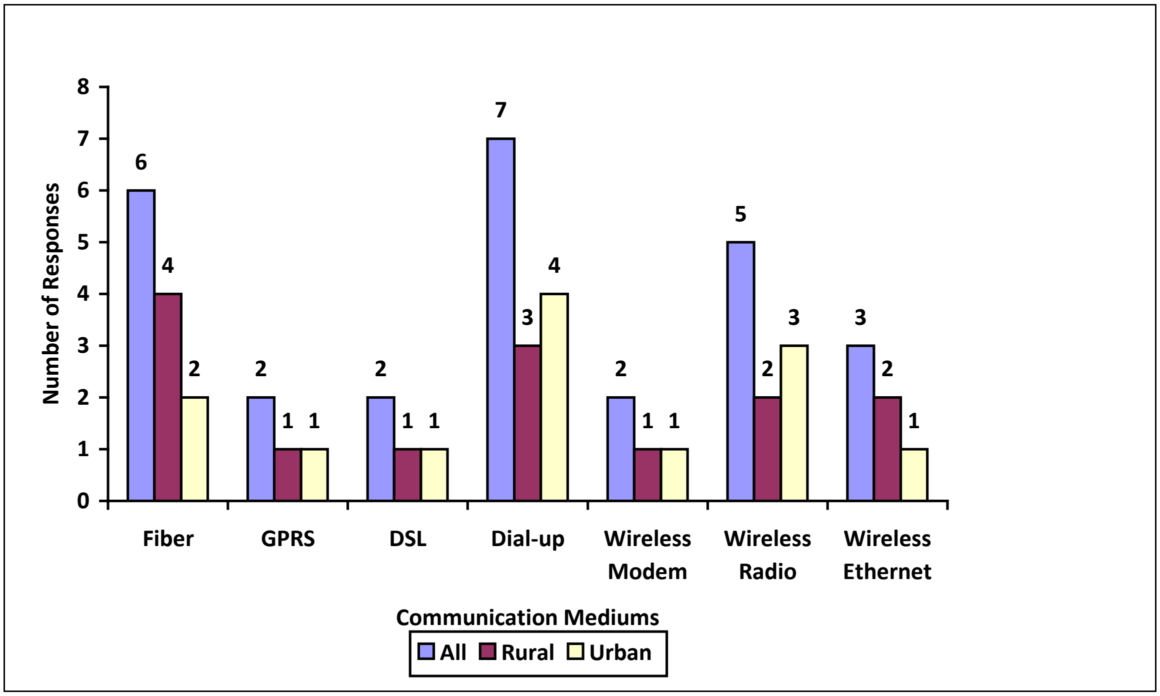

Figure 7. Communication Mediums in Use.

The interviewees were also asked what network challenges they faced, if any. The responses are as follows:

- Distance between intersections.
- Moving toward implementing a wireless Ethernet system, but it would require a point-to-point system structure that will present some difficulties when implementing.
- The state uses a Master-Slave configuration so the transition will be time consuming and expensive.
- Signals are weak, so unlimited data transfer is not available.
- Telco availability.
- Cost and lack of fiber.
- Coverage of service providers is limited.
- Dropped connections due to low signal strength.
- Not all rural areas have fiber, so in some cases dial-up or radio must be used.
- The use of dial up between office and controller prevents real time communication, which disables the capability to stream video or anything of that nature.

Texas Surveys

The interviewees were asked what types of communication mediums, if any, they use to connect their signal controllers to their TMC. Figure 8 shows the distribution of their responses.

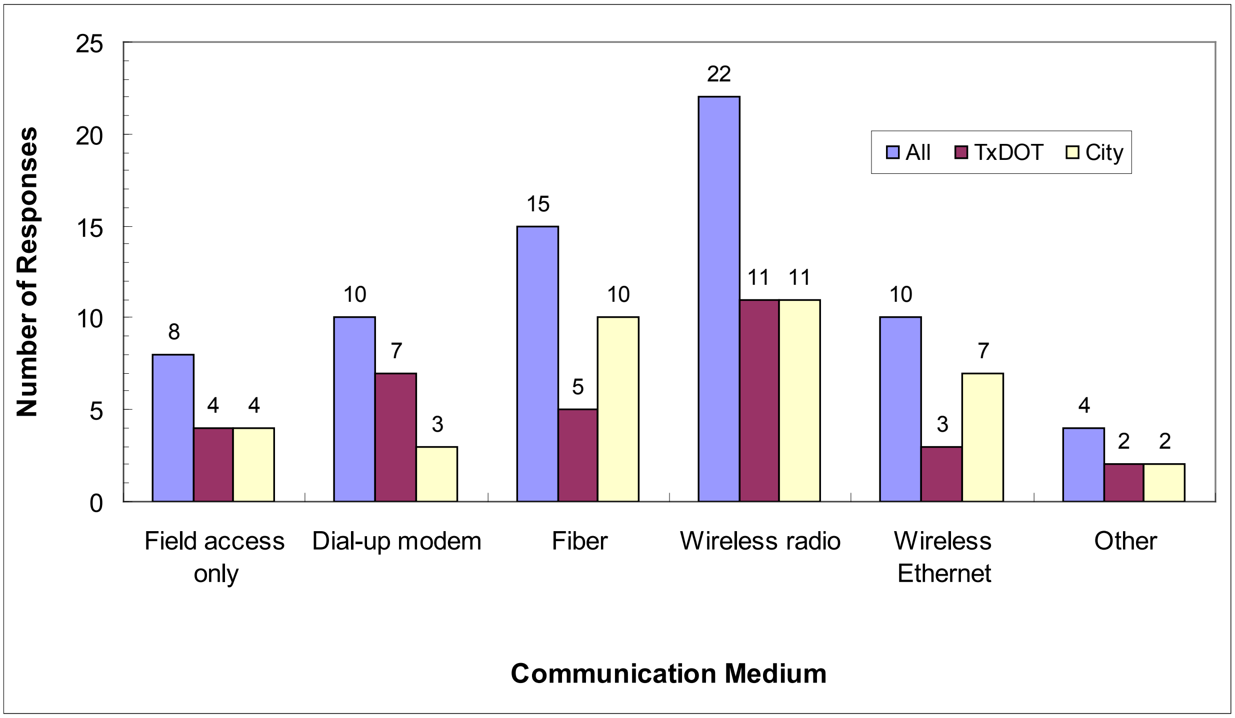

Figure 8. Communication Mediums in Use.

For both TxDOT districts and city agencies, wireless radio is the most commonly-used communication medium. The next most common medium is fiber, which is seeing increasing use especially in cities. Fiber in many cases may be present in segments and the remaining links completed by other mediums, most notably wireless radio or Ethernet. The mediums specified in the other category were digital subscriber line (DSL), cable modem, wired Ethernet, frequency shift key (FSK) hard wire serial (1200 baud), and copper wire. Each of these mediums was specified by one interviewee.

The interviewees were asked what percentage of their signalized intersections are equipped to transmit video back to their TMC. Across all interviewees, the average percentage was 23 percent, and the average percentages for TxDOT districts and city agencies were 6 percent and 40 percent, respectively. When these percentages are combined with the signal counts provided in response to the first question, the number of signalized intersections with video-transmitting capabilities can be estimated. This estimate reveals that there are 1022 signalized intersections within the represented agencies that are equipped to transmit video to the TMC. Of these intersections, 299 are operated by TxDOT and 723 are operated by cities.

The interviewees were also asked about their experiences with video transmission. Figure 9 shows the distribution of video transmission mediums specified by the interviewees. Fiber is the most commonly-used video transmission medium, followed by wireless Ethernet and wireless radio. The other specified mediums included dial-up modem (specified by two interviewees), DSL (specified by one interviewee), and cable modem (specified by one interviewee).

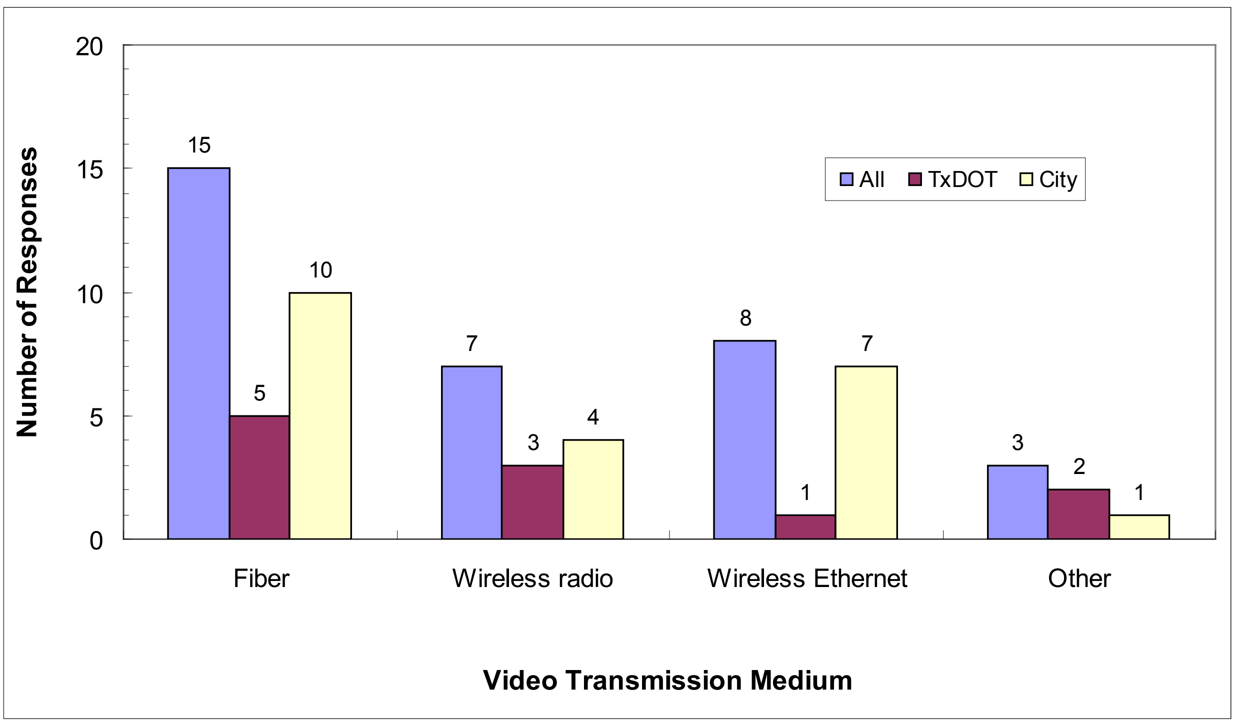

Figure 9. Video Transmission Mediums in Use.

Several interviewees explained that fiber lines were being installed in their city for various reasons besides communicating with traffic signal controllers. In various cases, fiber lines were being planned and installed to provide for the communications needs of other city departments or to provide broadband service to the public. In these cases, the city was able to use fiber lines for video transmission if the fiber line passed near signalized intersections that had camera equipment (either VIVDS cameras or pan-tilt-zoom cameras installed exclusively for surveillance needs).

The most commonly-cited problem with video transmission was the speed or reliability of the communications connection. One interviewee noted that video transmission requires a stable, consistent link, and that in his experience transmitting video through wireless radio, the footage tends to become spotty as frames are lost due to the connection speed. Other problems with video transmission include the initial implementation cost, particularly if the city's traffic department is made to bear the entire cost of installing the needed communications medium. The interviewees generally agreed that video transmission is very reliable if fiber is available, but only somewhat reliable if other communications mediums are used.

STATE OF THE PRACTICE AND CONCLUSIONS

The surveys and in-person interviews indicated the following:

- Many agencies prefer fiber optic cables as compared to any of the other communication mediums since fiber optic cables allow large sizes of data to be transferred at a faster rate.
- The challenges, however, are the cost of fiber and the non-existence of a dedicated communication system to monitor traffic. Agencies responsible for managing traffic signal systems often have to wait for fiber to be installed for other reasons, and then obtain permission to use the fiber network.

CHAPTER FIVE – PERSONNEL TRAINING AND INFORMATION TECHNOLOGY SUPPORT

This chapter discusses the qualifications and training requirements/types for traffic signal personnel.

LITERATURE REVIEW

The retention of properly trained staff to deploy, operate, and maintain systems is necessary for ensuring that traffic signal control systems do not deteriorate over time. Without the proper knowledge, agencies can find themselves in a quagmire of software, hardware, maintenance, and communications problems.

A synthesis of best practices reveals the tremendous need to hire knowledgeable employees and to keep them current in the ever-advancing technologies that influence the design, deployment, and operation of traffic signal systems (*3*). It has been found that appropriate use of signal timing tools and the quality of the entire signal timing process depend, in large measure, on the capabilities of the personnel responsible and the adequacy of staffing (*23*).

It is advised that at a minimum, signal timing and operations should be supervised by personnel with Professional Engineer (PE) and Professional Traffic Operations Engineer (PTOE) qualifications (*24*). Since engineers have a myriad of responsibilities to juggle apart from signal timing, it is almost unlikely that an agency that is understaffed will be able to operate signals optimally. Without proper staffing and training, it will be difficult for agencies to exploit the additional capabilities gained through a successful systems update.

Training practices should include the following (*24*):

- A plan to ensure that the required number of qualified personnel will be available when required. The plan should prepare for retirements and other personnel losses.
- Support for training programs to achieve personnel proficiency requirements including the education required for continued PE and PTOE certification.
- Support for training provided by suppliers and others relating to specific equipment or software currently in use or planned.

Agency staff are advised to attend technical professional conferences, meetings, and seminars through which professional networks can be established and new information is readily available. A list of recommended qualifications for traffic signal technicians is described in Table 5. Specific technician positions and/or titles differ from agency to agency but this table attempts to provide titles that are common to most agencies.

Table 5. Recommended Qualifications for Maintenance Personnel (*24*).

Requirement	Technician 1	Technician 2	Maintenance Supervisor
General Task	• Replacement and repair of controllers, signals, wiring and other field equipment. Works under direction.	• Skills include programming of traffic controllers, troubleshooting controllers, and ancillary equipment. Requires minimal direction. Provides direction and training to Technician 1 level.	• Full supervisory responsibility. Supervises Technician 1 and Technician 2 levels. Greater technical knowledge than Technician 2 is required. Administrative duties include ordering spare parts and supplies, contract administration, budgets, and provision for training.
Education and Experience	• High school (minimum). • Knowledge of electrical standards, codes, practices, and repair techniques. • Certification to IMSA Traffic Signal Level I within one year of employment.	• Minimum of 2 years of experience as Technician 1. • Certification to IMSA Traffic Signal Level II.	• Combination of training, education, and experience for a total minimum of 5 years. • Certification to IMSA Traffic Signal Level II. • Additional training beyond IMSA Traffic Signal Level II.
Physical Requirements	• Must be able to work for long periods in inclement weather. • May be required to lift heavy objects, work from bucket trucks.	• Same as Technician 1.	

ONLINE SURVEYS AND IN-PERSON INTERVIEWS

Signal Technician Training

Other State Departments of Transportation Surveys

The interviewees were asked what type of training their technicians/engineers received within the past five years for them to be effective. This question was open-ended and responses were received from eight agencies. Table 6 shows the responses received from the agencies.

Table 6. Training for Traffic Signal Technicians/Engineers.

Count	Response
3	2070 controller training
2	On-the-job or in-house training
1	Software manufacturer/vendor training
1	SYNCHRO software training
1	Software training
1	332 Cabinet training
1	Webinar (teleconferencing)
1	Technology transfer classes

Texas Surveys

The interviewees were asked what types of training they provide for their traffic signal technicians, and what additional types of training they would like to obtain or provide. The questions were asked in open-ended format. The following paragraphs contain discussion about responses that were received from multiple interviewees.

Table 7 lists the responses for current types of training. The two most common responses include IMSA courses or certification (15 responses) and on-the-job or in-house training (16 responses). The latter response took various forms. For many agencies, on-the-job training involved simply pairing experienced technicians with junior-level technicians so the latter could learn from the experience of the former. Other agencies took the time to provide training cabinets or controllers at the signal shop that could be used to simulate common problems and give technicians opportunities to learn troubleshooting techniques.

Various agencies receive training and support from vendors, particularly those who sell communications, controller, or detection equipment. Twenty-four interviewees acknowledged receiving vendor training for one or more products. Additionally, five interviewees stated that they have provided opportunities for their technicians to attend TEEX training courses.

Table 7. Current Training for Traffic Signal Technicians.

Count	Response
16	On-the-job or in-house training
15	IMSA course or certification
10	Vendor training/support (general)
6	Vendor training/support for detection equipment
5	TEEX courses
5	Vendor training/support for communications equipment
4	TxDOT courses (including electrical courses)
3	Vendor training/support for controller hardware or software
2	Safety training

The interviewees' desires for future training opportunities are listed in Table 8. One of the most common requests was a resumption of the TEEX cabinet troubleshooting course. Ten interviewees expressed a need for cabinet troubleshooting training. There were also 11 responses stating a need for training on communications equipment, particularly equipment using fiber or wireless Ethernet technology. As was shown in Table 8, fiber and wireless Ethernet are the two most commonly-used technologies to transmit video footage from signalized intersections to the TMC.

Table 8. Desired Future Training for Traffic Signal Technicians.

Count	Response
11	Communications equipment (including wireless Ethernet and fiber)
10	Cabinet training/troubleshooting course (TEEX or other)
5	IMSA Level 2 certification
3	Satisfied with current training
2	Asset/inventory management system
2	Detection equipment
2	ITS training
2	New signal controller types (e.g., Intelight)
2	Traffic-related conferences (e.g., annual traffic signal conference)

Some suggestions were also made to provide IMSA Level 2 certification (4 responses) or training on inventory management systems, detection equipment, or new signal controller types (2 responses each). Three interviewees stated that they were satisfied with the current training opportunities that are provided for signal technicians.

Information Technology Support

Other State Departments of Transportation Surveys

The interviewees were asked to indicate what level of cooperation they received from the Information Technology (IT) department and to describe it. A follow-up open-ended question was asked about what different aspects of interaction the traffic department had with the information technology department.

Only one rated the level of cooperation from the IT department to be high. Four rated it to be medium and three to be low. The main reasons for rating medium were because the IT was understaffed or needed to approve equipment. The main reasons for rating low were mainly because IT was being difficult at times and they had their own priorities. Figure 10 illustrates the level of cooperation the traffic departments receive from the IT department.

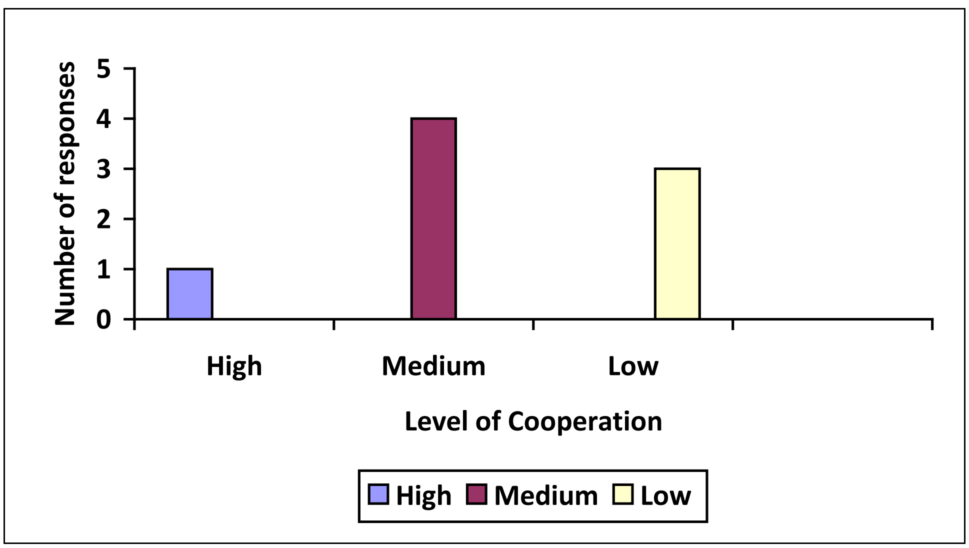

Figure 10. IT Level of Cooperation.

The interviewees were also asked if their IT department was skilled enough to handle issues; if yes, what type of skills they had, and if no, what type of skills they required. Six interviewees stated that their IT departments were skilled enough to assist with issues. The answers varied on the level of skill the IT department possessed. One mentioned that it depends on the personnel since some have extensive schooling/experience, and others have on-the-job training. Another said that the main skill was networking and computer setup and maintenance.

Only four answered the last question that dealt with the areas on which they required the IT department's support. The responses were network availability and dependability, procurement, installation, troubleshooting, network rules, firewall setup, and acquisition.

Texas Surveys

The interviewees were also asked about the type of support they receive from their IT department, and what type of support they would like to receive. The questions were asked in open-ended format. The following paragraphs contain discussion about responses that were received from multiple interviewees.

Seven interviewees indicated that their IT department assists with software support (installing, updating, or troubleshooting computer programs), and 20 interviewees stated that their IT department provides support with maintaining communications hardware (e.g., modems) or servers. Four interviewees stated that the IT department should assign higher priority to the needs of traffic personnel, by decreasing response times for requested assistance or even increasing staffing if needed. Three interviewees also stated that IT personnel need to develop an improved understanding of the objectives and goals of the traffic department. Three interviewees explained that they do not want any support from the IT department and would prefer to handle all of their IT needs with their own personnel.

Several interviewees expressed specific desires for help with implementing enhanced communications capabilities. Three interviewees indicated that they would like assistance from the IT department in developing and installing a communications network that could be used for signal control as well as other agency needs. Three interviewees also stated that they would like the IT department to install and implement video transmission capabilities.

STATE OF THE PRACTICE AND CONCLUSIONS

The surveys and in-person interviews indicated the following:

- IMSA certification and on-the-job training are the most commonly-provided types of training for signal technicians in Texas.
- There is an unmet need for Texas signal technicians to obtain cabinet troubleshooting training (e.g., the former TEEX course) and training with fiber or wireless Ethernet communications equipment.
- Most agencies are equipped with IT personnel who possess adequate skills to handle traffic signal control related issues.
- Most agencies do not receive the expected/prompt response from their IT departments when they call on them to handle issues.
- Some agencies would like to have a separate IT department/personnel dedicated to traffic signal control issues.

CHAPTER SIX – SIGNAL CONTROL PERFORMANCE MONITORING

This chapter covers the methods traffic departments use in monitoring signal control performance.

LITERATURE REVIEW

Performance monitoring measures are used to quantify the degree to which a signal system provides efficient traffic service (*25*).

All of the techniques used to obtain values for the measures are subject to errors that result from the measurement technique, or from the processes used to compute the measure from the data that is collected. The presence of these errors should be considered when the measures are used for management purposes such as resource allocation. Consistent measurement and computation techniques used over a period of time develop values useful for estimating the relative performance improvement provided by signal timing (*23*).

The measures traditionally used to quantify system efficiency can vary, depending on whether the system is operating in under-saturated or over-saturated conditions. Different measures may be used to evaluate traffic operation during peak and off-peak periods (*25*).

Table 9 lists typical performance measures. Most of the measures are available as output from a variety of signal timing software products (e.g., HCS, PASSER II, Synchro, TRANSYT-7F, SimTraffic, and CORSIM).

Table 9. Performance Measures for Evaluating Signal Systems (*25*).

Traffic Volume Condition	Traffic Period	Useful Performance Measures
Unsaturated	Peak	Average travel speed for movement served by coordinated phases. Average stop rate for movement served by coordinated phases. Queue storage by movement (based on maximum-back-of-queue)
	Off-peak	Total delay for all vehicles served by the system.
Over-saturated	Peak and off-peak	Number of street segments with spillback. Duration of over-saturation. Total travel time for all vehicles served by the system.

Chapter 18 of the *2010 Highway Capacity Manual* (HCM) identifies three performance measures for signalized intersections. The measures are:

- Level of Service (LOS).
- Delay.
- Queue Storage Ratio.

LOS depends on control delay and whether the volume-to capacity ratio is greater than 1.0. Control delay includes delay associated with vehicles slowing in advance of an intersection, the time spent stopped at an intersection approach, the time spent as vehicles move up in the queue, and the time needed for vehicles to accelerate back to their desired speed (*23*). Table 10 shows the LOS thresholds for signalized intersections.

Table 10. LOS Criteria for Signalized Intersection.

Control Delay (s/veh)	Level of Service by Volume to Capacity Ratio ≤ 1.0	> 1.0
≤ 10	A	F
> 10–20	B	F
> 20–35	C	F
> 35–55	D	F
> 55–80	E	F
> 80	F	F

Source: 2010 Highway Capacity Manual

Chapter 31 of the HCM describes a procedure for estimating the back-of-queue size, which is defined as "the position of the vehicle stopped farthest from the stop line during the cycle as a consequence of the display of a red signal indication." The procedure accounts for the signal timing, the vehicle arrival pattern, and the presence of vehicles that might not have cleared the intersection during the preceding cycle. Queue storage ratio is defined as "the proportion of the available queue storage distance that is occupied at the point in the cycle when the back-of-queue position is reached." A queue storage ratio of greater than 1.0 indicates that an entire roadway link is filling with queued vehicles and spillback may occur. The measures in Table 11 are commonly used to evaluate the benefits associated with the implementation of revised signal timing plans.

Table 11. Commonly Used Evaluation Measures.

Measure	Type of Benefit
Delay	Traveler Utility
Travel Time and Travel Time Reliability	Traveler Utility
Stops	Traveler Utility
Crashes	Safety
Fuel Consumption	Out-of-pocket cost
Emissions	Environment

Source: NCHRP Synthesis 409

Some of these measures are included in the HCM methodology. Others are computed using traffic simulation tools. The measures in Table 11 can be used to estimate road-user costs and benefits as a supplement to the HCM evaluation methodology.

ONLINE SURVEYS AND IN-PERSON INTERVIEWS

Texas Surveys

The interviewees were asked about their signal control performance monitoring. The questions were asked in open-ended format. The following paragraphs contain discussion about responses that were received from multiple interviewees.

Table 12 lists the interviewees' methods for monitoring signal control performance. The most common method was citizen feedback (17 responses). The interviewees generally explained that if few citizen complaints are received, the signals are generally operating reasonably (though not necessarily optimally). Some agencies also conduct anecdotal observations of vehicle speeds, stops, and queue lengths in the field or through the video footage that is transmitted back to the TMC; travel time runs; or observations during periodic equipment maintenance checks. Three interviewees stated that they conduct level of service analysis or simulations to assess the performance of their signal timing.

Table 12. Signal Control Performance Monitoring Methods.

Count	Response
17	Citizen feedback
11	Anecdotal field or video observation
6	Travel time runs
3	Level of service analysis or simulations
3	Periodic equipment maintenance checks

Four interviewees stated that they conduct utility/benefit to cost analyses of their traffic signal systems. These analyses do not influence their choice of traffic signal system (i.e., choice between the options that were listed in Table 2). Rather, the utility/benefit to cost analysis results are used to identify beneficial tweaks to signal timing plans or needed geometric improvements like roadway widening or addition of turn lanes.

STATE OF THE PRACTICE AND CONCLUSIONS

The surveys and in-person interviews indicated the following:

- Most agencies depend on public complaints to assess efficiency of traffic signal control systems.
- Utility/benefit to cost analyses of traffic signal systems are conducted by some agencies to identify the need for improvement in traffic signal systems or roadway geometrics.
- Few agencies utilize level of service analyses/simulations.

CHAPTER SEVEN – INTERAGENCY SIGNAL COORDINATION

This chapter discusses the technical, institutional, and resource needs of agencies to coordinate signal timing plans across boundaries.

LITERATURE REVIEW

Coordination of traffic signals across agencies is a common requirement to optimize signal timing. Timbrook et al. describe a series of case studies of signal coordination across boundaries (*26*). The study showed that coordination across agency boundaries was possible, even if the equipment and traffic system communications used by the agencies differ. The most important factor conveyed by the report is cooperation and communication among agencies.

In three of the in-depth case studies, regional government agencies such as Metropolitan Planning Organizations (MPOs) have been instrumental in achieving seamless coordination across agencies. Individual agencies are advised to adopt less than optimal cycles or offsets to achieve the common goal of seamless transition across boundaries. At the same time, each of the agencies wants to be able to respond to its inhabitants. As such, open communication between agencies is desirable and in some cases, memoranda of understanding will be needed to formalize arrangements. Decisions can sometimes be taken ad-hoc when the situation calls for it.

Sharing of Information

With the increased use of variable message signs and CCTVs on surface streets, it is desirable to share the use of these devices among agencies. This is sometimes facilitated by co-location of traffic management centers or by agencies that coordinate information among operating agencies (such as TRANSCOM in the New York City metropolitan area or by the I-95 Corridor Coalition). The increasing of the National Transportation Communications for ITS Protocol (NTCIP) standards facilitates the mobility of this type of information (*23*).

Gaps in Guidance or Tools

Traffic signal practitioners underemphasize some issues related to traffic signal timing either because these issues are not well understood or because there are no commonly accepted techniques.

Controller Option Interactions

Most controllers on the market have the features defined as minimum by the NEMA TS2 standard (*27*). Many controllers have additional capabilities. Most of the earlier controllers commonly in use also contain some of these features. Although guidance is available for many of the parameters taken separately, because of the complexity of their interactions, it is difficult to predict their operation under certain traffic conditions. Although tools exist to simulate or test these interactions, many agencies do not have the resources to use these methodologies for a significant number of intersections (*23*).

Selection of the Number of Timing Plans and Their Deployment Periods

Commonly employed practice basically depends on judgments by analyst, and no evidence is offered to indicate that the approach leads to the best selection of plans and their deployment periods.

CASE STUDY – CITY OF HOUSTON, TEXAS (*28*)

The City of Houston is within the jurisdiction of the TranStar TMC, where all participating agencies are housed in a central facility. TranStar is consortium founded in 1994 with the City of Houston, Harris County, the Metropolitan Transit Authority of Harris County (Metro), and the Texas Department of Transportation (TxDOT). Each agency maintains control over their jurisdictional system, but the agencies readily share information, technical expertise, jointly fund projects, barter activities based on the individual capabilities of each agency, and cooperate in a wide ranging program of regional activities including incident management and emergency management.

The City of Houston is currently developing a traffic signal control system in conjunction with the county. This system will allow signal coordination to extend into currently-unincorporated areas.

CASE STUDY – LOS ANGELES, CALIFORNIA (*28*)

Traffic management in Los Angeles grew and developed with a series of projects. Several example projects are described in the following paragraphs.

Smart Corridor

The Santa Monica Freeway Smart Corridor Demonstration project is an operational test of various Intelligent Transportation Systems (ITS) technologies and traffic management strategies. The Smart Corridor project boundaries consist of a 14-mile segment of the Santa Monica Freeway (I-10) from the Santa Ana Freeway (I-5) to the San Diego Freeway (I-405) and five parallel major arterials streets: Adams, Washington, Venice, Pico, and Olympic Boulevards.

The agencies involved in this joint regional corridor project include: Caltrans District 7, Los Angeles County Metropolitan Authority (MTA), City of Los Angeles Department of Transportation (L.A. DOT), California Highway Patrol (CHP), and the Cities of Santa Monica, Beverly Hills, and Culver City. The operational test began in 1996 and was considered a national example of successful implementation of inter-jurisdictional traffic management. The expert system, however, was deactivated in the late 1990s as Caltrans felt that a different organizational model would be scalable to cities in the entire county.

Bus Priority

L.A. DOT collaborated with the MTA to implement ad Advanced Priority System project for buses along two major transit corridors. Under this system, signal timings can be adjusted as buses approach an intersection in order to help buses catch up to schedule when needed. Four types of signal priority action can be taken, including an early green signal and extending the green when a bus is approaching. The system also provides information on bus locations and travel times for MTA managers. This demonstration project has been implemented on Ventura Boulevard and Wilshire/Whittier Boulevards. The Ventura Corridor connects the Metro Red Line subway station at Universal City with the Warner Center, a major commercial and business center in the Western San Fernando Valley. The Wilshire/Whittier Corridor connects east Los Angeles with the central business district. Together, the two corridors include 200 signalized intersections on over 38 miles of arterial road.

County-Wide Signal Synchronization Program

The project, led by the MTA with the active support of the county, involves synchronizing traffic signals across jurisdictional boundaries. The MTA divided Los Angeles into eight areas and formed a forum or working group for each area. The working group in the southeast part of the county is planning major traffic signal improvements in five corridors in the area. The synchronization program will involve direct information sharing on a distributed network among the County, MTA, Caltrans, and nine municipalities in the southern part of LA County.

ONLINE AND IN-PERSON INTERVIEWS

Texas Survey

The interviewees were asked about coordinating signal timing along roadways that pass through multiple jurisdictions. The questions were asked in open-ended format. The following paragraphs contain discussion about responses that were received from multiple interviewees. Table 13 lists the interviewees' suggestions for improving signal coordination across jurisdictional boundaries.

Table 13. Suggestions for Coordinating Signals across Jurisdictional Boundaries.

Count	Response
16	Communication between agency officials
5	Uniformity in communications or controller equipment
4	Clock synchronization technology or hard interconnect to common master
3	Provision of assistance or oversight from a regional authority (e.g., MPO)

The interviewees were in general agreement that communication between agency officials is key to achieving effective signal coordination between neighboring jurisdictions. This communication involves maintaining good working relationships among traffic engineers, conducting formal meetings to discuss the needs of the agencies involved, and informing each other of upcoming changes that affect signal timing (e.g., the adjustment of a posted speed limit, the addition or removal of a protected left-turn phase, or the adoption of a completely new timing plan). Two interviewees suggested reviving the annual state traffic signal conference, as it provided opportunities for traffic engineers to correspond about signal timing issues, and it also provided good training opportunities for signal technicians. One interviewee indicated that the Texas Institute of Transportation Engineers (TexITE) could be used as an avenue to discuss issues pertaining to interagency coordination.

Several interviewees acknowledged that timing signals across jurisdictional boundaries is an art of compromise, as the best overall timing plan is likely different from the plan that would minimize delay for any individual agency involved with the coordination. Hence, it is important to understand the goals and needs of other agencies. For example, at diamond interchanges, a signal timing plan that accommodates excellent progression on the arterial street may cause queues on the frontage roads to spill back onto the freeway mainline.

Five interviewees stated that it is easier to coordinate signals across jurisdictional boundaries if the agencies involved use the same types of communications and/or controller equipment. Four interviewees acknowledged that it is necessary to keep signal controllers synchronized in time or to connect all controllers to a common master. In one case, two city agencies that share boundaries enable each other to share Synchro data files and as such are able to adjust timing plans to suit each party when needed.

Three interviewees suggested that assistance or oversight from a regional authority could facilitate signal coordination across jurisdictional boundaries. Metropolitan planning organizations (MPOs) could serve this role. The assistance could involve collecting and tabulating turning movement counts at signalized intersections and sharing these data with all cities in the region. One interviewee opined that the involvement of a regional authority would be essential if traffic adjusted, responsive, or adaptive control is desired along an arterial street that passes through multiple jurisdictions.

CASE STUDY – TRAFFIC SIGNAL COORDINATION ACROSS JURISDICTIONAL BOUNDARIES

This case study was carved out of in-depth interviews conducted with two Texas transportation agencies. In a large urbanized area in Texas, a city and the TxDOT district were able to achieve effective signal coordination along an arterial street that crossed two jurisdictional boundaries. A drawing of the arterial is provided in Figure 11. As shown, the city-controlled a segment of the arterial is located between two TxDOT-controlled segments. The city-controlled segment is located within a large city, and the two TxDOT-controlled segments are located within separate cities that have than populations smaller than 50,000 people.

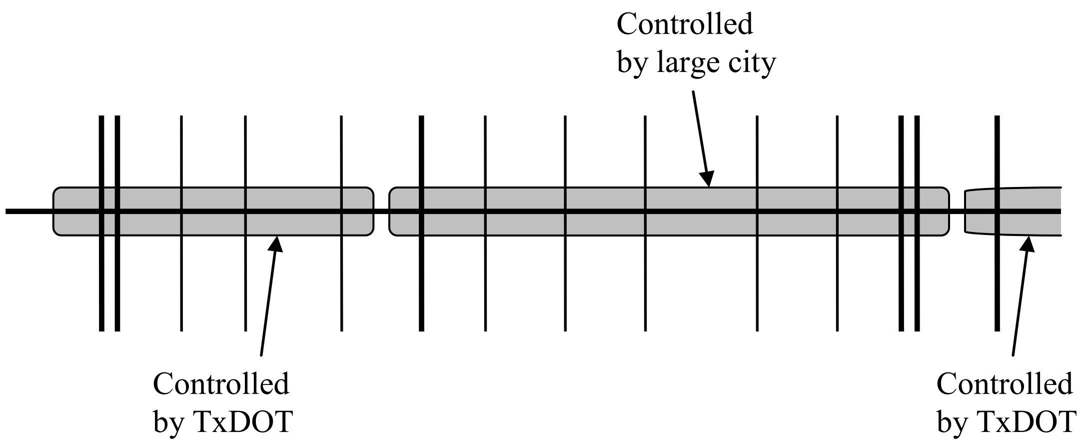

Figure 11. Schematic of Arterial Street Signal Coordination.

The large city developed time-based coordination plans for its portion of the arterial street. The city also provided documentation of the timing plans to the TxDOT district. Then, TxDOT and the city installed GPS clocks in their controller cabinets nearest to the agency boundaries. The clocks allow the signal controllers to remain synchronized. The TxDOT district then developed time-based coordination plans for their portions of the arterial street that would work well with the city's plans. As a result, the entire arterial street functions as a seamless coordinated route.

The city and the TxDOT district both agree that maintaining the signal coordination along this arterial will require communication between the two agencies' traffic engineers. Any time either agency wants to make a change in the timing or a related roadway characteristic (e.g., the posted speed limit), the other agency must be informed and must be given time to make necessary adjustments. The effect of the proposed changes on the signal coordination effectiveness would need to be considered along with other benefits and costs.

In this case study, the city and the TxDOT district successfully synchronized the signals using time-based coordination. One of the city's traffic engineers explained that time-based coordination can be achieved across jurisdictional boundaries as long as the agencies remain in communication with each other and maintain hardware that allows the controllers owned by the two agencies to remain synchronized in time. However, if a more sophisticated coordination strategy is desired (e.g., traffic-adjusted, traffic-responsive, or traffic-adaptive control), it would likely be necessary for a single agency to control all of the signals to be included in the coordination. This controlling agency could be a regional authority like an MPO.

STATE OF THE PRACTICE AND CONCLUSIONS

The surveys and in-person interviews indicated the following:

- Most agencies were of the opinion that communication between agencies would help bridge the cross-boundary coordination issues they encounter.
- Some agencies were of the view that the involvement of a regional authority such as the MPO would facilitate signal coordination efforts.
- Many agencies have done some signal coordination across jurisdictional boundaries, but the number of sites at which they do this is small. In Texas, the two most common situations for coordination across jurisdictional boundaries are (1) diamond interchanges, and (2) major arterials that pass through several jurisdictions, if the signal spacing lends itself to effective coordination.

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APPENDIX I-OTHER STATE DEPARTMENTS OF TRANSPORTATION QUESTIONS

1. What type of controller do you currently have in use?

- NTCIP Compliant Controller
- Local Protocol
- Other

2. Have you noticed any issues with the controller?

- Yes
- No
- If Yes, briefly explain:

3. Which type of maintenance do you use?

- In-House
- Outsourcing

What is the main factors that influence your selection type?

- Cost consideration
- Availability of in-house maintenance technicians
- Unavailability of in-house maintenance technicians
- Other:

4. Type of training your Technicians/Engineers received within the past 5 years for them to be effective?

5. What type of communication system do you use for rural areas?

- wireless radio
- wireless Ethernet
- dial-up
- fiber

What type of communication system do you use for urban areas?

- wireless radio
- wireless Ethernet
- dial-up
- fiber

What are the network challenges faced in the communication system for both rural and urban areas (if any)?

6. What type of centralized system software do you currently have in use for

- Rural areas:
- Urban areas:

Please state the capabilities and challenges faced with the type of centralized system software:

7. What type of system are you currently using?

- Proprietary system
- NTCIP compliant system

Have you encountered a security breach, for example a potential hacking?

- Yes
- No

8. How are the licensing agreements set up to provide the most benefits to cost?

Are there any limitations to your licensing? (Example: The amount of intersections that can be set up with the software or how many computers can be included in a closed-loop system)

9. Has your signal system been replaced to produce a better outcome?

- Yes
- No

If yes, please name the old system and the new system:

According to your knowledge and experience, when would be the best time to replace older systems? Please explain:

How do you manage budgeting and financial challenges?

10. Have you done any trade-offs by using different manufacturers?
    - Yes
    - No

11. Is your system made up of different types of mixed equipment?
    - Yes
    - No

What are the main concerns or problems that you observe (if any):

12. What is the level of cooperation from the IT department?
    - High
    - Medium
    - Low

    Please describe it

    What are the different aspects of your interaction with the IT department?

13. Do you have separate networks installed for the field and business?
    - Yes
    - No

    What are the rules and regulations set up for the networks?

14. Is your IT department skilled enough to assist with issues?
    - Yes
    - No

    If yes, what level of skill do they have?

    If no, what level of skills do they require?

    What are the areas in which you require their support?

APPENDIX II-TEXAS SYSTEMS SURVEY QUESTIONS

1. How many signalized intersections do you have in your jurisdiction?

2. What traffic controller type(s) do you utilize for traffic signal control? Choose all answers that apply.

- Diamond controller
- NTCIP-compliant controller
- TS1
- TS2
- Local protocol
- Other (please explain)

3. What is the reason for the choice of traffic signal controller and what have been your experiences with it?

4. What type(s) of traffic signal operations do you currently use? Choose all answers that apply. See Table 2 for more details.

- Isolated signal operation
- Time-based coordination
- Traffic adjusted control
- Traffic responsive control
- Traffic adaptive control

5. What type(s) of vehicle detection applications do you use? Choose all answers that apply.

- Inductive loops
- Video-imaging vehicle detection
- Other (please explain)

6. Please discuss your reasons for the choice or under what situations you use particular applications.

7. What type of communications technologies do you use to connect your signalized intersections to your TMC? Choose all answers that apply.

- None (can only access in field)
- Dial-up modem
- DSL
- Cable modem
- Fiber
- GPRS
- Wireless radio
- Wireless Ethernet
- Other (please explain)

8. What percentage of your signalized intersections is equipped to transmit video to your TMC?

9. What type of communications technologies do you use to transmit video to your TMC? Choose all answers that apply.

- Dial-up modem
- DSL
- Cable modem
- Fiber
- GPRS
- Wireless radio
- Wireless Ethernet
- Other (please explain)

10. What challenges have you encountered with the transmission of video to your TMC, and how have you addressed these challenges?

11. What kind of support do you receive from your IT department?

12. What additional support would you like to receive from your IT department?

13. What kind of training do you provide for your traffic signal operations technicians?

14. What kind of training would you like to provide or obtain for your traffic signal operations technicians in the next five years?

15. How do you measure traffic signal control performance?

16. Do you perform a utility/benefit to cost analysis of your traffic signal control system(s)?

17. Does this influence your choice of traffic signal control system?

18. How best can coordination with signal systems for other agencies be achieved?

19. Please discuss suggestions for such cooperation.

APPENDIX III-ONLINE SURVEY INVITATION

Dear ________,

I am a graduate research assistant working for the Texas A&M University in Kingsville, Texas. We are currently conducting a research project on ***Traffic Control Signal Systems*** for the Texas Department of Transportation and would like to know if you would like to fill out a questionnaire regarding the research project. If yes, the online survey can be found on the following website: http://www.surveygizmo.com/s3/703855/Synthesis-Study-of-Texas-Signal-Control-Systems.

I appreciate your time and look forward to receiving your feedback. If however, you are not able to fill out this questionnaire, please forward this email to a designated person.

Thank you,

APPENDIX IV-IN-PERSON INTERVIEW INVITATION

Dear _________,

I am currently a graduate research assistant working for the Texas A&M University in Kingsville, Texas. We are currently conducting a research project on ***Traffic Control Signal Systems*** for the Texas Department of Transportation and would like to know if we could schedule an appointment to discuss survey questions related to the above project. If yes, kindly let us know when you will be available for the interview.

I appreciate your time and look forward to receiving your feedback.

Thank you,