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16. Abstract This project defined an approach to integrating data collected and traveler information displayed in a work zone with a regional transportation management center and/or other state websites. The project conducted a literature review to define the state of the practice in work zone Intelligent Transportation Systems (ITS; smart work zones) and worked with the Texas Department of Transportation traffic managers to identify their safety and mobility needs in a work zone and where ITS can play a role. The research conducted a market review to find current product offerings that provide solutions to address the identified work zone needs. It also developed two levels of architecture for integrating work zone ITS data from these products into a regional transportation management center. The project also explored new uses of work zone information and made recommendations for operating existing ITS systems in concert with Smart Work Zones.			
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USE OF INTELLIGENT TRANSPORTATION SYSTEMS IN RURAL WORK ZONES

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TABLE OF CONTENTS

	Page
List of Figures.....	ix
List of Tables	xi
Chapter 1. Introduction.....	1
Overview.....	1
Background.....	1
Objectives	2
Organization of the Report	2
Chapter 2. Literature Findings.....	3
Introduction.....	3
General Smart Work Zone Treatments	7
Specific Smart Work Zone Treatments	15
Guidelines for Use of ITS in Work Zones.....	28
Criteria for Justifying Smart Work Zones	46
Chapter 3. Work Zone ITS Needs Assessment	55
Introduction.....	55
Work Zone ITS Survey.....	55
Needs Assessment.....	61
Chapter 4. Technology Review	63
Introduction.....	63
ITS Components and Systems	63
Market Matrix.....	80
Chapter 5. Development of ITS Architecture	83
Introduction.....	83
Current Private Provider Offerings.....	85
ITS Implementation Categories	90
Chapter 6. Proof of Concept–Queue Warning.....	101
Introduction.....	101
Initial Plan Using Field Data Collection.....	101
Alternative Plan Using Simulation	102
Objective.....	102
Queue Warning Simulation	103
Benefits of Smart Work Zones	116
Comparison of Benefits and Costs.....	119
Summary and Conclusions	121

Chapter 7. Proof of Concept–Travel Time	123
Introduction.....	123
Overview.....	123
Algorithm.....	123
Simulation Test Bed.....	128
Evaluation.....	136
Simulation Conclusion.....	139
Chapter 8. Integrating an SWZ and Permanent ITS	141
Introduction.....	141
Innovative Uses of Work Zone ITS Data.....	141
Potential Application Areas.....	141
Operating an Existing ITS in Combination with a Work Zone ITS.....	144
Chapter 9. Summary and Conclusions	147
Introduction.....	147
Summary.....	147
Conclusions.....	151
References	153
Appendix A. Crash Cost Graphics	173
Appendix B. Crash Cost Reduction Tables for Nighttime Work Zones	181
Appendix C. Crash Cost Reduction Tables for Daytime Work Zones	191
Appendix D. ITS in Work Zone Survey	201

LIST OF FIGURES

	Page
Figure 1. Indiana Lane Merge.....	16
Figure 2. PennDOT Late Merge.	17
Figure 3. Layout of the Maryland DLM System.	18
Figure 4. Layout of the CALM System in Kansas (22).	20
Figure 5. Condition-Responsive Speed Advisory System and Its Effect on the Average Speed Profile of Vehicles Approaching the End of Queues (35).	23
Figure 6. ADAPTIR Advisory Speed Message.	25
Figure 7. Concept of Adaptive Queue Warning System with Smart Barrels (41).	25
Figure 8. Speed Detection Using Smart Barrels (41).	26
Figure 9. Speed Sensor Technologies Tested (41).	26
Figure 10. Driving Simulator Test of Post-Mounted Warning Lights (41).	27
Figure 11. Speed Harmonization in the Netherlands (31, 48).	28
Figure 12. Dynamic Work Zone Safety System Layout and Operation (49).	30
Figure 13. Mn/DOT Schematic for Travel Time Information (51).	33
Figure 14. Mn/DOT Schematic for Travel Delay Information (51).	35
Figure 15. Mn/DOT Schematic for Speed Advisory Information (51).	36
Figure 16. Mn/DOT Schematic for Congestion Advisory (51).	38
Figure 17. Mn/DOT Schematic for Stopped Traffic Advisory (51).	40
Figure 18. Mn/DOT Schematic for Dynamic Late Merge (51).	42
Figure 19. Mn/DOT Schematic for Dynamic Early Merge (under Development) (51).	44
Figure 20. Mn/DOT Schematic for Temporary Ramp Metering(under Development) (51).	45
Figure 21. Simulation Network Schematic (53).	49
Figure 22. Response to Question 1a of TxDOT District Survey.	56
Figure 23. Response to Question 1b of TxDOT District Survey.	57
Figure 24. Response to Question 1c of TxDOT District Survey.	58
Figure 25. Response to Question 2 of TxDOT District Survey.	59
Figure 26. Response to Question 2a of TxDOT District Survey.	59
Figure 27. Response to Question 3 of TxDOT District Survey.	60
Figure 28. Map Showing Route 68 Location (57).	64
Figure 29. Light and Camera Used for License Plate Recognition (57).	65
Figure 30. I-15 Project and Nearby Highway Network (59).	68
Figure 31. Automated Work Zone Information Systems (61).	71
Figure 32. Website Display for Real-Time Work Zone Information System (63).	73
Figure 33. Example Motorist Information Displays (63).	73
Figure 34. Hillsboro Area of I-35, I-35E, and I-35W (67).	78
Figure 35. Locations of Additional Sensors (67).	79
Figure 36. Plot Showing Volume Fluctuations on Mainline and Ramp (67).	80
Figure 37. Logical Architecture for the ASTI Smart Work Zone System.	87
Figure 38. Layout of an iCone Queue Warning System.	87
Figure 39. Logical Architecture for a Ver-Mac Smart Work Zone System without TMC Involvement.	89

Figure 40. Logical Architecture for a Ver-Mac Smart Work Zone System with Partial TMC Involvement.....	89
Figure 41. Logical Architecture for a Ver-Mac Smart Work Zone System with Full TMC Involvement.....	89
Figure 42. Layout of ADAPTIR System.....	90
Figure 43. Stand-Alone Schematic.....	94
Figure 44. Integrated Schematic.....	95
Figure 45. Stand-Alone Data Flow Schematic.....	98
Figure 46. Integrated Data Flow Schematic.....	99
Figure 47. Rear-End Collision Potential Upstream of Work Zone Lane Closures.....	104
Figure 48. Queue Warning System.....	105
Figure 49. Platoon Approximation.....	107
Figure 50. Prediction Error.....	109
Figure 51. Data Processing for MOE Calculation.....	112
Figure 52. Queue Length Results.....	114
Figure 53. Percentage of Temporary Lane Closures Performed at Night at Each Project (10).....	117
Figure 54. Increased Crash Costs with Active Work and Lane Closure Present (10).....	117
Figure 55. Cost Savings per 100 Hours due to Daytime SWZ.....	118
Figure 56. Cost Savings per 100 Hours due to Nighttime SWZ.....	118
Figure 57. Expected Reduction in Crash Costs Due to Smart Work Zone.....	120
Figure 58. Smart Work Zone System Diagram.....	123
Figure 59. Experienced versus Reported Probe-Based Travel Time.....	125
Figure 60. Simulation Overview.....	129
Figure 61. Screenshot of Simulation—Queue and Travel Time Reporting.....	131
Figure 62. Comparison of Travel Time Reporting Errors.....	132
Figure 63. Relationship between Queue Conditions and Unaccounted Delay.....	133
Figure 64. Example of Empirical Model for Unaccounted Delay.....	134
Figure 65. Simulation Screenshot with Proposed Algorithm Implemented.....	135
Figure 66. Comparison of Travel Time Information.....	136
Figure 67. Volume Profiles.....	137

LIST OF TABLES

	Page
Table 1. Roadway Operations and Maintenance Benefits Summary.	4
Table 2. Guidance for DMS Message Phases.	10
Table 3. Operational Logic and Transitional Speed Thresholds for the CALM System.	21
Table 4. Input Parameters for Analysis of Smart Work Zone Deployment (54).	47
Table 5. SWZ Benefit-Cost Breakeven Duration (55).	51
Table 6. B-C Ratios for 30- and 150-Day Project Durations (55).	52
Table 7. Project Selection Checklist.	53
Table 8. Summary of ITS Technology to Meet Work Zone Needs.	81
Table 9. Typical Road Construction and Maintenance Activities in Rural Areas.	84
Table 10. Potential ITS Solutions for Rural Work Zones. ^a	86
Table 11. Description of Control Levels.	92
Table 12. Speed Limit Thresholds and PCMS Displayed Messages.	97
Table 13. Message Selection Based on Speed Conditions.	105
Table 14. Hourly Volume Distribution (vph) during the Nighttime Lane Closure.	106
Table 15. Design Parameter Values.	108
Table 16. Example of Records in the DCPR File.	109
Table 17. Example of Records in the QLR File.	110
Table 18. Example of Records in the VR File.	110
Table 19. Percent of Vehicles Encountering Queue without Warning.	115
Table 20. Recommended System Design Parameters.	115
Table 21. Comparison of Literature Sources that Considered Benefits and Costs.	121
Table 22. District Information on Potential Sites.	102
Table 23. Evaluation Results.	138

CHAPTER 1. INTRODUCTION

OVERVIEW

This project explored the value of and defined an approach to integrating Intelligent Transportation Systems (ITS) into work zones in Texas. In some cases, these smart work zones (SWZs) send data to transportation management centers (TMCs). The project conducted a literature review to define the state of the practice in work zone ITS and conducted a survey of Texas Department of Transportation (TxDOT) traffic managers to identify their safety and mobility needs in work zones to determine where ITS can play a role. The project also conducted a market review to find current product offerings that provide solutions to address the identified work zone needs. The project also developed architecture for integrating work zone ITS data from these products into a transportation management center. Finally, the project explored new uses of work zone information and made recommendations for operating existing ITS systems in concert with the SWZs.

BACKGROUND

The use of ITS technology to monitor traffic conditions in work zones and provide real-time information to motorists has been an area of emphasis within the Federal Highway Administration (FHWA) and many state departments of transportation (DOTs) for several years. Most existing TMCs in urban areas will support work zone operations, collecting information on planned or current lane closures and disseminating that information out to drivers via traveler information websites, dynamic message signs, highway advisory radio, or even 511 telephone systems. Normal TMC functions (i.e., incident detection, monitoring, and response) are also performed in these work zones. In some locations, this information is tracked for performance monitoring purposes, although the format and content of such efforts varies from location to location.

Where traffic-monitoring infrastructure does not exist, such as in most rural areas, portable ITS technologies have become available to help monitor and mitigate the effects of the work zone on the motoring public. A variety of systems have been designed and tested, many of which are now available as commercial systems. Some systems are designed to be operated as a typical manned TMC from a contractor or state DOT field office, where an operator makes decisions on how to respond to the information received and what information to display to the traveling public. Other systems operate automatically, detecting certain traffic conditions (i.e., speeds, occupancies, volumes) and disseminating certain information (travel times, speeds, delays, queues) on portable changeable message signs or highway advisory radio. In a few instances, a vendor monitors the conditions of the field devices and provides that information to the public on a vendor-developed website. In both types of systems, the general approach taken is that the vendor builds the overall system from components based on requirements specified by the highway contractor or the state

DOT, monitors the system, and provides necessary maintenance support. However, there have been a few instances where state DOTs have purchased and operated their own systems.

OBJECTIVES

The objectives of this research were as follows:

- Determine the state of the practice in smart work zones across the U.S.
- Develop an architecture to integrate work zone ITS into existing TMCs.
- Use simulation to develop proof-of-concept testing of selected ITS treatments.
- Identify new and innovative uses of ITS as a result of SWZs.

ORGANIZATION OF THE REPORT

This research report consists of nine chapters organized as follows: Chapter 2 presents a detailed review of literature and case studies related to the use of ITS in work zones. In particular, the overall findings showed that work zone management systems have positive impacts on the ITS goal areas of safety, mobility, efficiency, productivity, and customer satisfaction.

Chapter 3 builds upon the Task 1 literature review by surveying sources within the department to determine the current usage of ITS components within the state, the expectation of their benefits, and the use of any warranting information as thresholds for the deployment of various technologies. Chapter 4 consists of a technology review that addresses the needs assessment from Task 2 to determine what systems currently meet some or all of the needs for work zone ITS systems.

Chapter 5 investigates the requisite architecture needed by TxDOT to capitalize on the technologies and techniques investigated earlier. There is an emphasis on integration into a TMC, although a TMC is not always involved. Chapter 6 reports on a methodology for determining when Smart Work Zones might be justified using a benefit-cost approach. It uses VISSIM software to develop a proof-of-concept for a queue warning system. It also includes a discussion on how this project was originally intended to cover field site investigations where TxDOT was planning to integrate ITS into a rural work zone and where this project could further utilize the ITS components for research purposes. However, sites were not available, so the project monitoring committee (PMC) agreed that simulation would be a viable alternative to achieve project objectives.

Chapter 7 uses VISSIM to develop a proof-of-concept for a travel time system using Bluetooth®. Chapter 8 investigates new and innovative uses of information/data coming from work zones. This chapter also develops recommendations for the use of work zone ITS with existing permanent non-work zone rural ITS. Chapter 9 includes a summary and conclusions based on the research findings.

CHAPTER 2. LITERATURE FINDINGS

INTRODUCTION

The American Recovery and Reinvestment Act of 2009 allocated \$26.7 billion to state transportation agencies for highway infrastructure investment projects. In a typical year, work zones affect about 25 percent of the National Highway System during the summer when the construction season reaches a peak. For example, in 2003, states were involved in 7200 work zones, which resulted in 480 million vehicle-hours of delay (1).

Obviously, congestion costs time and money. In moderate- to large-sized urban areas around the United States., there is a daily process, playing out in the form of traffic jams, increased travel time, increased fuel consumption, bottlenecks, and incidents. The latest Urban Mobility Report estimated a loss of nearly \$90 billion and nearly 3 billion gallons of gasoline (2). With these sobering and continually increasing statistics as the backdrop, ITS has become available as a solution to offset some of the growth of congestion. In the big picture, an ITS is the application of technology to reduce congestion, improve safety, improve mobility, and enhance productivity (3). Well-planned work zones that use ITS technologies to manage traffic and mitigate the impacts of lane closures, detours, and other factors are commonly referred to as SWZs. As Table 1 indicates, evaluations of work zone management systems have indicated positive impacts in five of the six ITS goal areas.

Benefits of Work Zone ITS Implementation

As the highway infrastructure continues to age and deteriorate, work zones are an increasingly common aspect of not only the daily commute but also a significant percentage of overall trips. The use of ITS has been shown in numerous applications to be a mitigating factor in work zones, reducing the overall congestion, increasing the mobility, and increasing the safety. Results of various ITS work zone implementations have been shown to positively impact work zones by reducing queues, reducing speeds, reducing crashes, and providing route guidance information to drivers (4).

Some of the documented successes from smart work zones include:

- Fifty to 85 percent of drivers surveyed changed their route based on work zone ITS messages.
- Reductions in queue lengths of about 60 percent are possible.
- Speed monitoring displays reduced speeds in the range of 4 to 6 mph.

Table 1. Roadway Operations and Maintenance Benefits Summary.

Category	Safety	Mobility	Efficiency	Productivity	Energy & Environment	Customer Satisfaction
Information Dissemination		+				
Asset Management	++					
Operations & Fleet Management	+					
Work Zone Management	++	++	+	+		+

Source: Reference (5).

++ Substantial positive impacts.

+ Positive impacts.

Blank: Not enough data.

Network simulation models estimate that smart work zones can reduce total delay in work zones by 41 to 75 percent. Evaluation of freeway reconstruction project data suggests that SWZ technologies can reduce traffic queues by 50 percent. In addition to improving operations, SWZs can improve safety. Speed monitoring displays have demonstrated vehicle speed reductions ranging from 4 to 6 mph and reductions in the number of speeding vehicles from 25 to 78 percent. SWZs also improve driver behavior. For example, dynamic lane merge systems help reduce driver confusion at merge points and reduce aggressive driving (5).

Costs of Work Zone ITS Implementation

A review of work zone deployments in 17 states indicated that costs vary significantly depending on the following factors:

- Purchasing vs. leasing system equipment.
- Temporary vs. permanent components (e.g., equipment used for work zone is used permanently).
- Size and function of the equipment.

Costs ranged from \$100,000 to \$2.5 million with most systems ranging from \$150,000 to \$500,000. Quantifying benefits is not as straightforward as quantifying costs. This document provides information on both quantitative and qualitative assessment of benefits.

Based on a survey of all 50 states conducted in 2006, most of the responding states were using the Internet, portable dynamic message signs (PDMSs), and highway advisory radios (HARs) for disseminating information to motorists in work zones. This same survey revealed that 38 states use ITS technologies such as lane control signs, PDMSs, and dynamic lane merge systems to notify motorists of changes in lane configurations approaching work zones. Twenty-nine states use ITS technologies either as stand-alone treatments or to supplement existing systems to support temporary traffic management in work zones (5).

Typical ITS Work Zone Applications

Even though the use of ITS in work zones has become more common, it is not a panacea. In most cases, there are simply too many vehicles on the roadways for the number of available lanes. ITS will not turn this condition around and erase the impact of the work zone, but it has been shown to have positive impacts in the areas of mobility, safety, and cost savings. ITS applications in work zones have included:

- Traffic monitoring and management.
- Traveler information.
- Incident management.
- Safety enhancement for both the road user and the worker.
- Capacity increases.
- Enforcement.
- Contract incentives/disincentives (performance-based contracting) tracking and evaluation.
- Work zone planning (6).

In terms of mobility, a primary application of ITS in work zones is to provide or enhance traveler information, which allows motorists to adjust their route or travel times. Mobility applications may also include work zone programs for incident management that can decrease delay. Mobility applications may also work to smooth traffic flow in work zones.

In terms of safety, numerous applications exist such as providing advance notice of work zone conditions, stopped or slowed traffic, and queues. Cost savings may be realized when work zone traffic management systems are automated and actually reduce the staff needed or time associated with management of the work zone (6).

The *Manual on Uniform Traffic Control Devices* (MUTCD) contains significant guidance on temporary traffic control. Elements of the manual address the constantly changing work zone conditions and the resulting vulnerability of roadway workers, as well as the unexpected situations faced by road users (7).

Over time and across the numerous agencies involved in work zones, a number of work zone ITS applications have evolved. A typical listing of work zone ITS applications might include the following:

- Dynamic message signs—portable or permanent.
- Highway advisory radios—portable (site specific) or permanent.
- Over-height detection systems.
- Intrusion detection systems.
- Portable signal systems.
- Speed detection and display.

- Speed violation and deterrent systems.
- Speed violation and enforcement.
- Variable speed limits.
- Automated flagger assistance.
- Flashing stop/slow paddles.
- Project information websites.
- Dynamic lane merge systems.
- Queue detection systems.
- Work zone integration into a TMC.

Certain ITS applications may be more applicable to individual components of the work zone, which the MUTCD classifies as an advance warning area, transition area, activity area, and termination area. In many cases, planning for work zones has evolved to using ITS components as a standard element or technique for managing work zone activities.

Also increasingly common is the use of several individual components, such as dynamic message signs (DMSs), speed detection, and public information websites, as part of a comprehensive methodology to address work zone safety and mobility. One impetus for that change was the FHWA Final Rule on Work Zone Safety and Mobility, which went into effect on October 12, 2007. The primary purpose of the rule is to enhance the overall safety of work zones. This can be done by systematically defining and addressing work zone impacts and developing strategies to mitigate these impacts across federal-aid highway projects.

Overall, the objectives of the rule are intended to facilitate the systematic consideration of the safety and mobility impacts of work zones, as well as the development of strategies and plans to reduce work zone impacts. Specifically, the rule intends to:

- Expand work zone planning and considerations beyond the physical project limits to address corridor, network, and regional issues. These issues may include planning for items such as alternate routes or modes of travel, special events, particular modes of travel (e.g., heavy trucks), and other strategies.
- Expand work zone management beyond the traditional focus of traffic safety and control to:
 - Address mobility in addition to safety.
 - Address current-day issues of operations, management, and public information.
- Promote innovative thinking in work zone planning, design, and management. The consideration of alternative or innovative strategies may provide additional solutions for a given work zone problem.

With respect to safety, ITS applications in the work zone seek to:

- Minimize the number and severity of crashes.
- Minimize the speed and speed differential of vehicles.

- Minimize the surprise element for both users and workers.
- Maximize safety of motorists and workers.
- Maximize driver alertness.
- Maximize the predictability of driving conditions (8).

With respect to mobility, ITS applications in the work zone seek to:

- Achieve efficient traffic flow.
- Minimize congestion.
- Minimize demand at the work zone approach.
- Maximize diversion to alternative routes.
- Maximize the capacity of the work zone (8).

The information in the remainder of this document begins with specific smart work zone treatments that states and local agencies might choose to develop in smart work zones. Following specific treatments are some case studies that demonstrate the use of these specific treatments by different states to achieve a safer and more operationally efficient work zone. The treatments and case studies lead into guidelines for future use of ITS in work zones. It is important to note that the existing guidelines are relatively limited, pointing to the need for this research project to amplify on the existing information to determine what will work best in Texas.

GENERAL SMART WORK ZONE TREATMENTS

Advanced Traveler Information Systems (ATIS)

The ATIS arena actually encompasses a number of the specific applications listed previously. Items such as highway advisory radio, dynamic message signs, and speed detection/advisory systems are all components of ATIS strategies. With respect to work zones, many of these systems have been implemented or tested on an experimental basis. While the literature contains a number of case study write-ups, the following sections do not reiterate that information but rather compile and highlight the best practices and available criteria/recommendations for implementation.

Overall, best practices suggest that the controlling guidelines for ATIS applications or strategies include maximizing accurate and up-to-date information for:

- Motorists.
- Trip planning.
- Transportation monitoring agencies.
- Incident management agencies (8).

General ATIS implementation guidance also stresses the fact that while accurate and reliable information is a must, the information dissemination options are also critical to achieving the

desired results. Typical guidance for ATIS information dissemination within the work zone includes specific and exact information pertaining to items such as:

- Delays.
- Causes of delays.
- Driving conditions.
- Location.
- Available detours.
- Alternate routes.
- Speed violations.
- Lane closures (8).

Portable Dynamic Message Sign

A portable DMS (also commonly referred to as a changeable message sign [CMS]) is a traffic control device capable of displaying letter- or symbol-based guidance to drivers. DMS equipment comes in many sizes and can be a vital part of many strategies for information dissemination. Portable dynamic message signs can be used in any number of work zone situations, such as:

- An expectation of a drop in vehicle speeds.
- An expectation of queuing.
- An expectation of delays.
- Changes in alignment or surface conditions.
- The presence of unfavorable environmental conditions.
- The need for advance notice required for ramp, lane, or roadway closures.
- The need to distribute incident management information.
- Changes in the road user patterns.

Within the work zone, DMS strategies can utilize stand-alone systems that simply rotate messages on a schedule with no external input, or as part of an integrated management strategy that may only activate the DMS under certain conditions, such as the presence of significant delays, speeding drivers, changing conditions, etc. Some literature refers to this strategy differential as being proactive or reactive. Specific guidance from the literature for implementing a portable DMS includes the following list.

- Establish the objectives for use of the portable DMS (what are you trying to accomplish?).
- Define the messages that will accomplish the objectives (determine wording, format, need for multiple phrases, etc.).
- Determine the distances required to allow drivers to read and comprehend the messages.
- Determine field DMS locations, taking into account the need for driver reaction time and the distances required to read and comprehend messages.

- Identify geometric or environmental conditions that would affect field locations.
- Identify criteria (change in conditions) in the work zone that will change messages or activate messages.
- In a multiple use environment, identify the priority of the message and do not override higher priority messages. One suggested priority listing (most to least) from the literature is:
 - Urgent messages.
 - Incident messages.
 - Planned roadway closures messages.
 - Toll rate messages.
 - Congestion messages.
 - Weather messages.
 - Special messages.
 - Action messages.
 - Safety messages (8, 9).

Because of the difference in display capabilities, decision makers must give careful consideration to the construction of the DMS message. Significant guidance exists in the literature as to the proper construction of DMS messages, and numerous studies have worked to build a lexicon of words and phrases that drivers clearly understand. An additional aspect of deploying DMS messages is the need to display a message in parts due to display limitations, known as phasing. Table 2 provides phasing guidance for various types of DMS equipment.

A growing consideration in many parts of the country is the potential need for bilingual messages or the use of dual DMSs at each location for areas with significant populations of persons for whom English is not the primary language.

Overall, the benefits of ATIS systems, such as PDMSs, have been difficult to quantify. Many of the existing case studies have wound up inferring benefits, as study periods have been too short to statistically prove significant to crash reductions. However, numerous other benefits such as reductions in traffic flow, delays, queues, and speeds have resulted. Some studies have reported diversion based on DMS messages as high as 10 percent. These benefits can accumulate significant cost savings over the life of a project. Because of the increased focus on providing tangible benefits, more installations are utilizing concepts of performance measurement to track items such as speed, volumes, queue lengths, crash frequency, and incident response and clearance times to substantiate the perceived benefits and justify the extra cost of deploying these systems. In addition, intangible benefits such as reduced driver frustration, calm traffic, orderly work zones, public perception of work zone operations, and similar effects can be appreciable even though not directly measurable.

Table 2. Guidance for DMS Message Phases.

One-Phase DMS	
Line 1	Describe problem
Line 2	Identify location or distance ahead
Line 3	Provide driver instruction
Two-Phase DMS	
Phase 1	Describe problem
Phase 2	Provide driver instruction
Three-Phase DMS	
Phase 1	Describe problem
Phase 2	Identify location or distance ahead
Phase 3	Provide driver instruction

Source: Adapted from (8).

Travel Time Systems

As described above, a portable DMS can be a stand-alone application supporting numerous types of information dissemination. One special type of ITS application gaining favor for work zone deployments is the use of a travel time system, which uses DMS in conjunction with sensors to determine and communicate the delay that motorists can expect through the work zone. While all of the guidelines in the previous section apply, users should consider a number of additional deployment factors for travel time systems.

The accuracy of the travel time information is critical. As with any type of information disseminated to the public, the data supporting the message should be accurate and timely. Travel time system data can come from many types of sensors, such as radar, or techniques, such as floating car. With sensor deployments, accuracy typically increases with increased numbers, but cost increases as well, both initial and operating. Due to the cyclic nature of work zones and the periodic activity in different areas, decision makers should give careful consideration to sensor deployment to ensure that data can be collected to support accurate information. Additionally, installers should give prior consideration to the deployment locations so as not to interfere with work zone activities or be blocked by work zone activities. Agencies generally reported poor public reception for information dissemination that relied only on historical information.

Frequency is another important factor for consideration in travel time systems. Frequency generally refers to the rate of providing updated information. If the information is changed infrequently, regular drivers (e.g., commuters) through the work zone will likely consider it as not very accurate or valuable.

The message content related to travel time systems can be a particularly troublesome issue. If a message is constructed that simply states a speed, travel time, or delay through the work zone, many drivers will not be able to appreciate the impact of that information to their individual trip without having the accompanying information about the length of the work zone. However, this leads to more complex messages that take longer to display and to be understood by drivers.

Some systems have tried to rectify this problem by relating travel time to a particular destination, assuming that most drivers familiar with the environment will be able to relate the data to their individual trip. This may be an imperfect assumption, and this practice may not work well in an urban environment with many destinations. In summary, however, display guidelines tend to suggest that some indication of distance or destination is most appropriate to allow a driver to relate the travel time information to his or her individual trip. Suggested destination information includes interstates, major state routes, major landmarks, and well-known venues along the route such as sports stadiums (9).

Designers should give special consideration to the potential message overload factor that could occur with several DMS installations within a work zone. Some agencies have reported using their travel time systems only within congested time periods through the work zone to mitigate some of the message overload concern, especially in a roadway environment that may be less forgiving than during normal, non-work-zone conditions.

Traveler Information Systems

Significant work zones often utilize another aspect of ATIS, which is a web-based traveler information system. In fact, the data that are developed from applications in the earlier discussions are often utilized to provide real-time updates to a website. The data are useful for both public and agency use.

Depending on the level of regional transportation development around the work zone, the website may be a stand-alone public information site conveying information such as speeds, average delays, travel times, and/or queues through the work zone. Demonstration projects of this type have shown considerable inferred benefits from making this level of information available to the public. While it is virtually impossible to accurately assess the trips that were not made through the work zone as a result of the information availability and the resultant congestion savings, anecdotal evidence, customer surveys, trip diaries, and other assessment means all show positive benefits to this type of information, which is essentially a rebroadcast of the on-site information to a larger audience.

If a transportation management center is present within the region, it can incorporate the data from the work zone into its existing real-time information displays to accomplish the same level of information dissemination. In the early stages of traveler information websites, most sites focused on reporting current conditions. However, continued advances have provided additional

capabilities, such as pre-trip planning for the best routes and predicted travel times. Work zone data may also be used in these applications to provide an accurate trip portrayal to the consumer. The combination of the growth in personal communications such as cell phones and the Internet has also enabled this reach to be extended into the vehicle and allow drivers to get information en route. Some websites even offer subscription-based text alerts to drivers on certain routes to inform them of up-to-the-minute changes in conditions such as an incident or increasing delays. At the impetus of the federal government, state agencies have also developed 511 systems, which provide a free public telephone number to call to obtain the latest traveler information. Although specific implementations and available information differ, 33 states now offer 511 systems, covering nearly 50 percent of the U.S. population (10).

Additionally, third-party vendors are now in the marketplace providing information and updates en route to subscribers. It is possible that work zone data can even be a revenue source for agencies in the future, albeit this is not likely to be a significant source of income.

One of the keys behind understanding traveler information services, whether pay or free, is determining exactly what drivers want. A number of studies have looked at what *specific* pieces of information a driver wants. One oft-cited reference states that drivers experienced in traveler information systems want the following:

- Camera views that show road conditions.
- Detailed incident information.
- Direct measures of speed on highway segments.
- Travel time between user-selected origin and destination pairs.
- Coverage of all major roadways, including arterials.
- En-route access (11).

Another study that is essentially a compilation of ATIS literature from the 1990s and early 2000s states that drivers want:

- In-car display of external traffic control signals.
- Information on traffic congestion.
- Indication of the presence of multiple compounding hazards in a driving situation.
- Information about road construction activities (12).

The types of systems discussed earlier can provide aspects of the desired information. While the costs associated with these systems may be significant, the benefits may also be of the same magnitude. Unfortunately, as has been previously stated, the benefits are harder to quantify, and many are intangible.

Aside from traveler information uses, agencies can also use work zone data. As an example, agencies can analyze work zone data on a periodic basis to assess the effectiveness of the work zone traffic control, assess any potential problems, keep track of desired performance metrics,

and, overall, provide a tool to assist in the effective management of the work zone. While there are many other aspects of ATIS applications, such as 511 and HAR, the previous sections have detailed the predominant on-scene and regional approaches to delivering work zone specific traveler information.

Speed Systems

One of the primary characteristics that work zone ITS applications seek to control or modify is speed. There are two main types of speed systems that can be used in work zone applications. These are speed feedback (speed monitoring) systems and variable speed limit systems.

Speed Monitoring. Speed monitoring systems generally work off the principle that displaying a driver's speed, in conjunction with the speed limit, will voluntarily cause compliance and slow the driver prior to entering the work zone. Results reported in the literature, however, do not support such a straightforward conclusion, as results vary significantly.

Literature results from one implementation show that a speed monitoring system had a measurable effect on the fastest portion of the driving population, those significantly exceeding the speed limit. However, the overall effect on the entire traffic stream was negligible. Another study showed a very measurable result in the number of vehicles speeding, the type of vehicle (car vs. truck), and the actual speeds. The variations in results appear to be typical in this type of application, as they are repeated across multiple studies and summaries of previous applications. This finding points to the fact that work zone characteristics and driver population factors are a main predictor of the potential results, as opposed to any particular validation of the type of technology or applications (13).

Guidance abstracted from the literature suggests that the type of work zone (rural vs. urban) may have some effect. Drivers in urban areas are potentially more likely to react to these types of deployments, particularly if worker activity can be seen from the speed message point. Placement of the device also appears to be a factor, but the reported information does not lead to specific conclusions. Positions ranged from 300 ft to 1250 ft in advance of the work zone.

Some implementations have utilized a twist on the speed monitoring by displaying the speed of the traffic ahead or downstream of the reporting location. The intent is to reduce the speed of vehicles prior to entering the congested portion of the work zone and prevent rear-end collisions. The systems can be set to activate based on configurable conditions downstream. Guidance abstracted from the literature suggests that the main factors to consider for implementation include the vehicle approach speeds, the speed monitoring sign locations, and the actual message on the sign or used in conjunction with a variable speed display.

Variable Speed Limit (VSL). Variable speed limits provide the ability to set the speed limit in the work zone based upon either the type of work being performed or the characteristics of the work zone. The primary stated advantage of the system is improved control of work zone traffic by regulation of the speed. Statistical evaluation of previous implementations supports the fact that speed differentials observed in VSL-equipped work zones are due to the VSL. Other benefits observed in the literature, some from overseas deployments, include a reduction in crashes and increased work zone throughput (14).

Field deployments of VSL do, however, pose some challenges, which can be discerned from the implementation guidance in the literature (13, 15).

- *Place VSL equipment at locations highly visible to drivers*—Changing construction activities or significant congestion can decrease the efficacy of the VSL at some locations.
- *Activate VSLs on a consistent basis*—Users can perceive the VSL to not be active if it does not change the vast majority of the time. Instead of a VSL, the equipment is viewed as a static speed limit displayed on a DMS type of display.
- *Consider that VSL systems offer no substantial benefit when significant congestion is present*—When demand exceeds capacity significantly, the speed reduction or harmonization benefits of VSL vanish due to the congestion.
- *Make VSL control algorithms reactive to congestion*—The sophistication of the VSL control logic should be investigated prior to implementation to assess its reaction to the formation of congestion, which limits VSL effectiveness.
- *Consider outflow when placing VSLs*—The final VSL location should typically be after the end of the work zone activity, to return drivers to their normal speed, reducing their overall trip time and potentially increasing the effectiveness of the system by limiting the speed reductions.
- *Consider the update frequency*—The update frequency of the speed can have an impact on the effectiveness or observable benefits of the system. Changing speeds too rapidly reduces the benefit of lowering speeds throughout the work zone area.
- *Consider that type of work zone contributes to effectiveness of VSL*—In some evaluations, the type of work zone has been found to contribute to the effectiveness. Long and simple work zones with short sections of actual work were found to have greater application and potential benefits from VSL.

SPECIFIC SMART WORK ZONE TREATMENTS

Introduction

This research conducted a review of relevant literature and recent research results on work zone traffic control. It paid particular attention to studies evaluating:

- The benefits of using ITS in work zones.
- Various merge control strategies in advance of work zone lane closures.
- Variable advisory and posted speeds.
- Dynamic queue warning systems.

Early Merge Control

Early merge strategies encourage drivers to merge into the open lane farther in advance of the lane closure. These strategies are of two basic types: static and dynamic.

Static Early Merge

Static forms of early merge provide advance notice at a fixed distance ahead of the lane closure. They place additional advance lane closed signs at approximately 1-mile intervals for several miles in advance of the lane closure. The additional signs reduce the probability of drivers encountering congestion without knowing which lane is closed. The early advance lane closure notice enables them to merge into the open lane before arriving at the end of the queue, which may reduce the potential for merge-related crashes. Also, it may reduce rear-end crash potential by alerting drivers to the possibility of congestion farther in advance of the lane closure. Simulation studies indicated that early merge control strategies significantly reduced the frequency of forced merges but increased travel times, especially at higher traffic volumes (16). Vehicles are more likely to be delayed over greater distances by slower vehicles ahead of them in the open lane. This may in turn increase the likelihood of drivers attempting to use the discontinuous lane to pass slower vehicles, which would increase the potential for lane-change accidents.

Dynamic Early Merge Strategies

Dynamic forms of the early merge strategy provide advance notice over a variable distance ahead of the lane closure based on real-time measurements of traffic conditions. One example is the Indiana lane merge system (17, 18) developed by the Indiana Department of Transportation. Figure 1 illustrates this concept. This system creates a dynamic no-passing zone to encourage drivers to merge into the open lane before reaching the end of a queue caused by congestion and to prohibit them from using the closed lane to pass vehicles in the queue and merge into the open lane ahead of them. The system uses vehicle detectors to determine the presence of a queue in the open lane. Static signs displaying the message DO NOT PASS WHEN FLASHING provide

the support for these detectors. The signs are located adjacent to the discontinuous lane at ¼- to ½-mile intervals. Stopped vehicles detected in the open lane next to the signs cause the system to transmit a signal to the next upstream sign to activate its flashing strobes. As vehicles resume movement, the system sends a signal to turn off the strobes. Therefore, the length of the no-passing zone is tailored to the actual queue length.

McCoy and Pesti (19) conducted field tests in Indiana and found that merging operations with the Indiana lane merge system occurred more uniformly over a much longer distance than they did with the conventional work zone traffic control. Spreading the merging operation over a longer distance made it easier for drivers to find sufficient gaps for lane-changing maneuvers. It resulted in fewer forced merges where vehicles in the open lane had to decelerate abruptly or stop to allow vehicles in the closed lane to merge into the open lane. However, a disadvantage of the dynamic early merge strategy is that long queues may result during peak hours with high traffic volumes. If the queues grow beyond the advance warning signs, many of the noted benefits are lost.

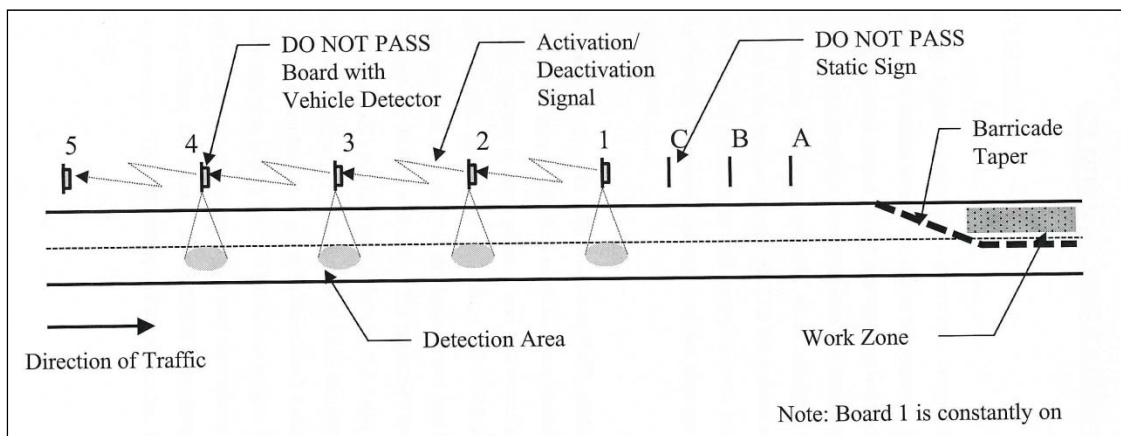


Figure 1. Indiana Lane Merge.

Late Merge Control

The late merge strategy is the opposite of the early merge in that it encourages drivers to stay in their lane until they reach the merge point at the lane closure taper instead of merging as soon as possible into the open lane. The Pennsylvania Department of Transportation (PennDOT) developed one version of the late merge control, with the main intent being to reduce road rage between early and late mergers. They accomplished this goal by letting drivers know that it is permissible for traffic to travel in both lanes to the merge point. Figure 2 shows a typical traffic control plan for the PennDOT late merge system.

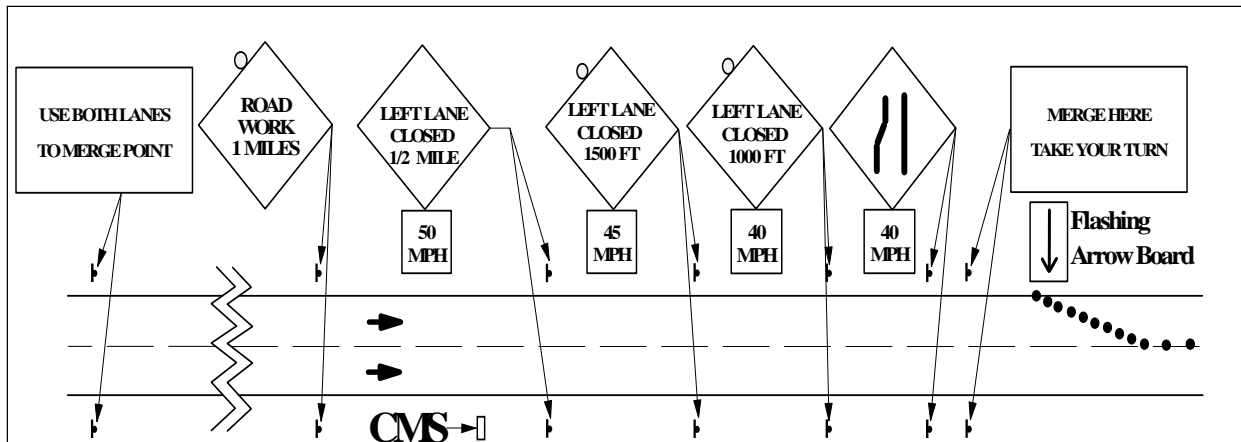


Figure 2. PennDOT Late Merge.

Conceptually, the late merge control addresses many of the problems that are associated with traffic operations in advance of lane closures at work zones on rural interstate highways. In particular, the queue length should be reduced by about 50 percent. Shorter queues would reduce the likelihood of the queues extending beyond the advance warning signs and surprising approaching drivers, which in turn would reduce the potential for rear-end accidents. In addition, this treatment should reduce driver anxiety of knowing which lane is closed because they can use either lane to reach the merge point. Also, this treatment should result in less driver stress among drivers in the open lane due to other motorists passing them in the closed lane because this maneuver is permissible. Drivers are able to select the lane with the shortest queue without being concerned about others blocking their path to the merge point.

Pesti et al. (20) evaluated the PennDOT late merge system at a work zone on I-79 in Pennsylvania. Results of the study indicated that the late merge control is more effective than the conventional early merge treatment under congested conditions. The late merge has higher capacity and results in fewer traffic conflicts. The higher capacity and larger queue storage area reduce the probability of congestion extending back beyond the advance warning signs, thus reducing the potential of rear-end collisions on the approach to the work zone. The higher capacity also reduces the duration of congestion, which in turn reduces the exposure to rear-end collisions. In addition, because of its higher capacity, the late merge reduces congestion delay, whereas the early merge increases travel times, especially under high traffic volumes. However, some motorists did not follow the directions given by the traffic control signs, thus reducing the effectiveness of the merging operation. Research is needed to minimize the potential for driver confusion at the merge point of the late merge treatment, especially under high-speed, low-volume conditions, which could adversely affect safety.

Dynamic Late Merge (DLM) Concept

Based on findings of previous merge control research (21), the late merge treatment seems to provide the most effective control during peak periods. However, because of some operational and safety issues regarding its operation under high-speed, low-volume conditions, the late merge may not be the most appropriate treatment during off-peak periods. Maintaining optimum merging operations at all times might require conversion from the early merge during periods of non-congested flow to the late merge during periods of congested flow. This recognition prompted the development of the dynamic late merge system by McCoy and Pesti (21). This merge control strategy is expected to provide the safest and most efficient merging operations at all times in advance of the lane closure by switching between the early merge-type conventional traffic control and the late merge control, based on real-time measurements of traffic conditions.

The traffic control plan for the dynamic late merge system consists of a series of sensors and dynamic messages signs. Detection of congestion in the open lane adjacent to the signs causes the signs to be activated to advise drivers to stay in their lane until they reach the merge point. A sign at the merge point advises drivers to alternately merge. When congestion clears, the signs deactivate or the message can change to advise drivers of the lane closure or display speed advisory messages. The signs could be variable message signs equipped with traffic detectors similar to the radar-equipped sign shown in Figure 3, which is based on the automated data acquisition and processing of traffic information in real-time (ADAPTIR™) system. Alternatively, the signs could also be static signs equipped with traffic detectors and flashing strobes.

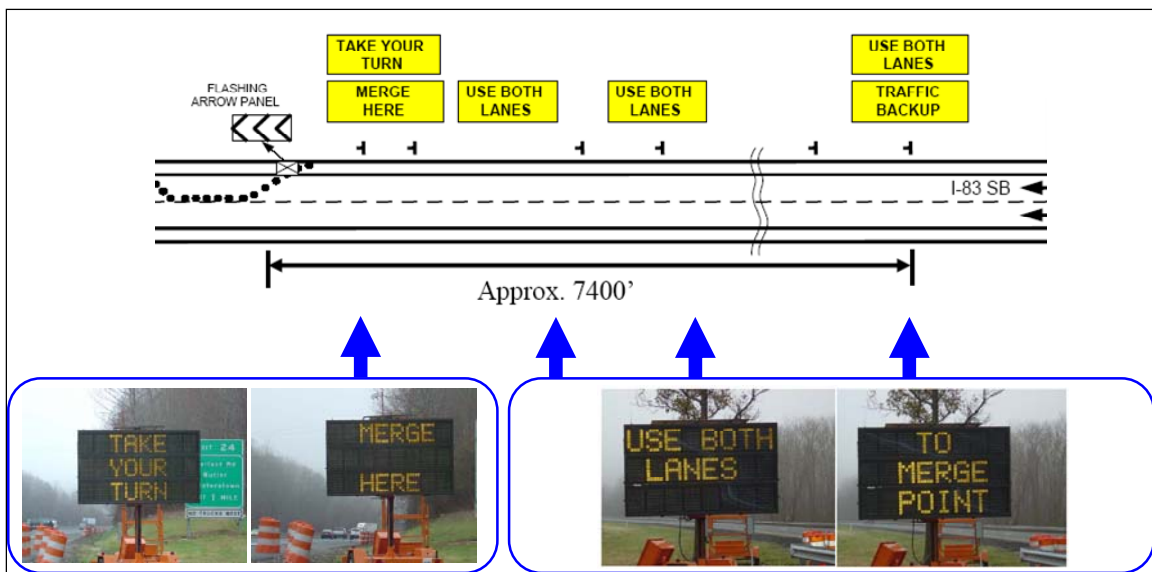


Figure 3. Layout of the Maryland DLM System.

Dynamic Late Merge Evaluations

Several states have evaluated the dynamic late merge (or simply dynamic merge) control in work zones. In 2003, the Maryland State Highway Administration, in cooperation with International Road Dynamics Inc., implemented and evaluated the dynamic late merge at a freeway work zone in Maryland (10). Figure 3 shows the layout of the field study site. The DLM system operated on one control threshold (occupancy) with the “All On—All Off” algorithm; that is, occupancies below 5 percent deactivated all portable changeable message signs (PCMSs), and any occupancy among the deployed sensors over 15 percent activated all PCMSs. However, the PCMS closest to the lane closure taper, which displayed the messages TAKE YOUR TURN and MERGE HERE, was always active (22).

The evaluation focused mainly on operational performance (e.g., work zone throughput, volume distribution, and resulting queue length), finding that a properly deployed DLM system can indeed outperform the conventional merge control with respect to the total work zone throughputs. However, it may result in excessive traffic conflicts if not properly integrated with existing static warning signs for work zone operations. Researchers recommended potential improvement of the DLM performance.

In 2003, the University of Kansas, the Kansas DOT, and the Scientex Corporation evaluated a DLM system called Construction Area Late Merge (CALM). They deployed the CALM system on a three-lane section of I-70 in Kansas City, Kansas, where road construction required closure of one of the three lanes. The CALM system utilized Remote Traffic Microwave Sensors (RTMSs) to monitor vehicle speeds, PCMSs to display messages to drivers under all traffic conditions, and wireless communication between RTMSs and PCMSs. Figure 4 illustrates the system layout. The CALM system was capable of operating in three modes—early merge, late merge, and incident mode—depending on the observed average speeds. The system activated the incident mode when traffic speeds were “exceptionally low” (22).

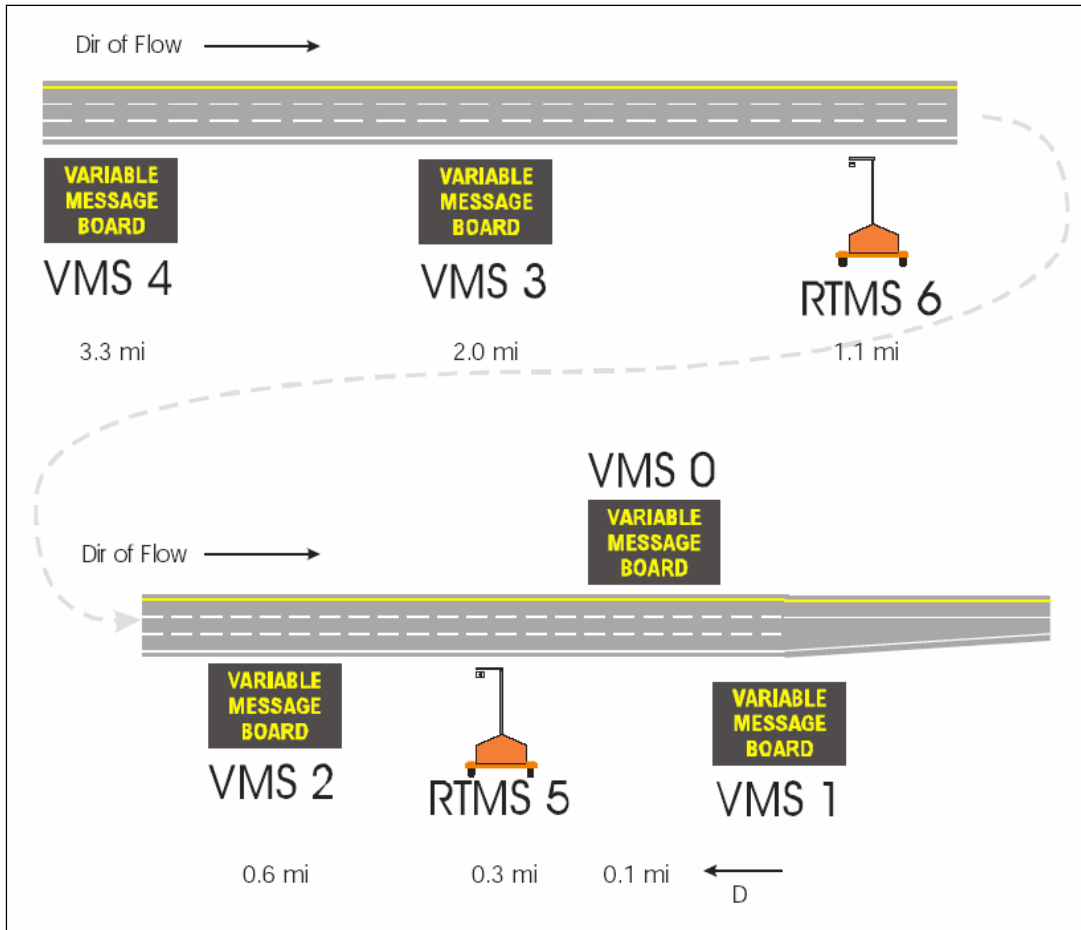


Figure 4. Layout of the CALM System in Kansas (22).

Table 3 shows the operational logic and transitional speed thresholds for switching between the three modes. Although results were inconclusive due to data sparseness (i.e., congestion rarely occurred), the researchers believed that the dynamic late merge systems have the potential to improve the freeway operations at construction lane closures. They also made recommendations to improve the system. They suggested avoiding locations near entrance and exit ramps for deploying message signs and sensors. They also recommended the use of densities in addition to speed thresholds for activating the different modes. They also suggested placing PCMSs on the shoulder closest to the lane being closed.

Table 3. Operational Logic and Transitional Speed Thresholds for the CALM System.

Operating Speed Categories

Speed Category Transition Points

Level	Speed Range (Lane 2)	Speed Range (3-lane average)
1	>35 mph	> 46 mph
2	15 to 40 mph	15 to 51 mph
3	0 to 20 mph	0 to 20 mph

From	To	At
Level 1	Level 2	46
Level 2	Level 1	51
Level 2	Level 3	15
Level 3	Level 2	20

Merge Assisting Strategy

In a study, Finley et al. (23) assessed the effectiveness of a sequential warning-light system for work-zone lane closures. The system consisted of a series of interconnected, synchronized flashing warning lights that produced the illusion of motion. The field results revealed that the prototype warning light system may encourage motorists to vacate a closed travel lane farther upstream from the work zone. The system was particularly effective for a relatively new closure at the urban freeway test site. However, the system did not significantly affect lane choice at the rural road test site where the lane closure had been in place for 6 months. The authors suggested that the warning light system could result in the greatest potential safety benefit when used in conjunction with short-duration or intermediate-term maintenance or construction projects.

Variable Speed and Queue Warning

A combination of slow/stopped traffic conditions and insufficient stopping distance can create situations with high risk of rear-end collisions. Major causes of slow/stopped traffic on the freeway are:

- Recurrent traffic congestion.
- Work zones.
- Incidents.
- Low visibility and adverse weather.
- Inadequate geometric design.

Numerous studies found that rear-end collisions are the most frequent type of crashes on freeway facilities, especially at work zones (24, 25). Several human factor studies concluded that drivers approaching the end of queues often have poor perception of the time and distance needed to safely decelerate or stop. A research project (26) conducted in Texas observed between one and 16 hard braking maneuvers (defined by significant drop in vehicle nose) per 1000 approaching vehicles at two work zone sites. A Canadian study (27) determined that drivers were usually aware of approaching slow-vehicle queues, but in cases of large speed differentials (over 25 mph), they often had poor perceptions of how quickly they could slow down before getting

too close or colliding with slower vehicles ahead. A Texas Transportation Institute (TTI) report by Wiles et al. (28) provided a comprehensive review of published research in this area.

A number of studies have estimated the benefits of providing advance warning of slow/stopped traffic on freeway facilities. For example, researchers at Daimler-Benz (29) estimated that about 60 percent of rear-end collisions could be prevented by providing an additional half-second warning time to passenger car drivers. They also estimated that an extra second of warning time would prevent about 90 percent of rear-end collisions. An evaluation of a queue warning system in Amsterdam found a 23 percent decrease in overall collision rates, a 35 percent reduction in serious collisions, and a 46 percent reduction in secondary collisions at the back of the queue. A German autobahn using queue protection and freeway lane control showed a 20 percent decrease in collision rate. A queue warning system in England paid for itself within a year based on the estimated savings associated with the reduction in collisions (30).

Findings of a 2006 Scan Tour in four European countries confirmed the safety and operational benefits of congestion warning systems. They reported that implementation of a congestion warning system combining temporary use of shoulder lanes and speed harmonization using variable speed limits resulted in a 15 to 25 percent decrease in primary accidents and a 40 to 50 percent decrease in secondary accidents in the Netherlands. The operational benefits of such systems typically included improved traffic stream stability and a 4 to 5 percent increase in vehicle throughput (31).

Providing effective advance warning to drivers approaching stopped or slow queues requires an understanding of queue dynamics. The appropriate number and spacing of detectors and warning message signs depend on a number of factors including queue characteristics (e.g., maximum queue length and shockwave speed) and roadway geometry. The queue characteristics can be measured in the field for certain limited traffic and roadway conditions and estimated using shockwave simulation models for any operating speed, traffic volume, and lane configuration. During peak hours when demand exceeds capacity, shockwaves may rapidly propagate upstream. An Iowa study (32) of a rural interstate work zone with lane closures determined shockwave speeds as high as 30 to 40 mph. Another study on the Metropolitan Expressway in Japan (33) determined an average shockwave speed of approximately 11 mph. A Canadian study (34) of a short section of the Gardiner Expressway found similar results.

Devices typically used for providing advanced warnings of slow/stopped traffic are:

- Static signs.
- Dynamic message signs.
- Lane control signals (LCSs).

- Incident response vehicles.
- In-vehicle devices.

The following segment focuses primarily on active warning systems for slow/stopped traffic conditions.

Active Speed Warning Signs (ASWSs)

Pesti (35) evaluated an ASWS system deployed at a construction zone on I-80 near Lincoln, Nebraska. The system consisted of three speed monitoring displays equipped with radar units. They were deployed at approximately ¼-mile intervals in advance of the work zone lane closure. The radar units measured the speed of downstream traffic, and the speed messages displayed were intended to warn drivers of stopped or slow-moving traffic ahead and thereby enable them to reduce their speeds and avoid rear-end crashes with these vehicles. Figure 5 shows the speed display and its effect on average speed.

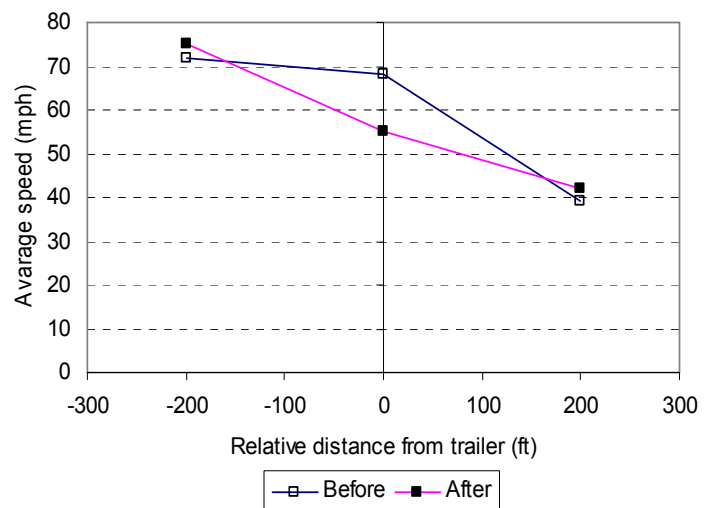


Figure 5. Condition-Responsive Speed Advisory System and Its Effect on the Average Speed Profile of Vehicles Approaching the End of Queues (35).

When a traffic slowdown was detected, the strobe lights began flashing. When there was no slowdown, the strobe lights remained off and the sign displayed either the speed of traffic downstream or the work zone speed limit, whichever was lower. The results of the analysis indicated that the speed messages were effective in reducing the speed of vehicles approaching queued traffic during time periods when congestion was building. Before the speed advisory was deployed, vehicles began decelerating later but more intensively than after its deployment. After deployment, vehicles began decelerating sooner and reduced their speed over a longer distance. The change in mean deceleration due to the speed advisory system was statistically significant at the 95 percent confidence level. In addition to the advisory speed messages, approach speed and

trailer location also significantly affected vehicle deceleration. Due to the limited time available for the field studies, the long-term effectiveness of the speed advisory system could not be determined.

Several other studies evaluated the effectiveness of ASWSs. Kathmann (36) found that the effectiveness of an ASWS depends on the layout of the system. Examination of speed profiles gathered from both inductive loop and empirical data indicated that the speed reductions were significant. The Colorado Department of Transportation (CDOT) identified a downgrade curve on I-70 in Glenwood Canyon as a truck-accident-prone location due to limited sight distance. CDOT installed a radar gun that activated a DMS reading YOU ARE SPEEDING AT XX MPH, 45 MPH CURVE AHEAD. The 85th percentile speed fell by 27 percent after the installation (37).

Kaub and Rawls (38) used simple in-pavement magnets to detect speed and activate roadside or in-vehicle warnings for motorists approaching isolated stop controls, sharp curves, hazardous intersections, work zones, etc. Another study (39) evaluated the effect of dynamic advisory speeds provided specifically for heavy vehicles. Truck drivers responded favorably to dynamic message signs with weight-specific advisory speeds on severe grades.

ADAPTIR

The Scientex Corporation developed another portable, condition-responsive work zone traffic control system, the ADAPTIR, through a cooperative agreement with the Federal Highway Administration and the Maryland State Highway Administration. Researchers at the University of Nebraska (40) evaluated an ADAPTIR system at a work zone on I-80 between Lincoln and Omaha. It utilized radar sensors mounted on three portable changeable message signs and an arrow panel at the merging taper to continuously measure speeds at four locations along the approach to a freeway work zone. Figure 6 shows a PCMS with the radar unit. When the average speed at the next downstream radar sensor was more than 10 mph slower than the average speed at a PCMS, the system displayed a speed advisory message indicating the downstream speed rounded down to the nearest 5 mph. Otherwise, the PCMS remained blank unless it was the PCMS closest to the merging taper; in that case, it displayed the RIGHT LANE CLOSED message.

The intent of messages was to advise drivers of the speed of slower traffic ahead and thereby encourage them to slow down. Researchers measured and compared speeds downstream of the PCMSs to the speeds displayed in the messages. Results indicated that the messages were only slightly effective in reducing speeds, but their effectiveness could have been improved if the distances between the PCMSs had been shorter. Interviews revealed that drivers understood the advisory speed messages, and drivers who recalled seeing them thought they were useful. However, other drivers questioned their usefulness and reliability because they had not seen any other reason to slow down.



Figure 6. ADAPTIR Advisory Speed Message.

Adaptive Queue Warning System

The University of Michigan developed and evaluated a Work Zone Safety System for adaptive queue warning (41). It is a distributed queue-warning system that automatically adapts to the current traffic-flow situation within and upstream of the work zone. Figure 7 illustrates the concept of the adaptive queue warning system. A core component of the system is the so-called “smart barrel” (iCone®). The smart barrel is a typical orange traffic-control barrel equipped with an inexpensive speed sensor, a simple, adjustable signaling system, and the necessary equipment for communication to a central controller. Figure 8 illustrates the speed detection system using smart barrels.

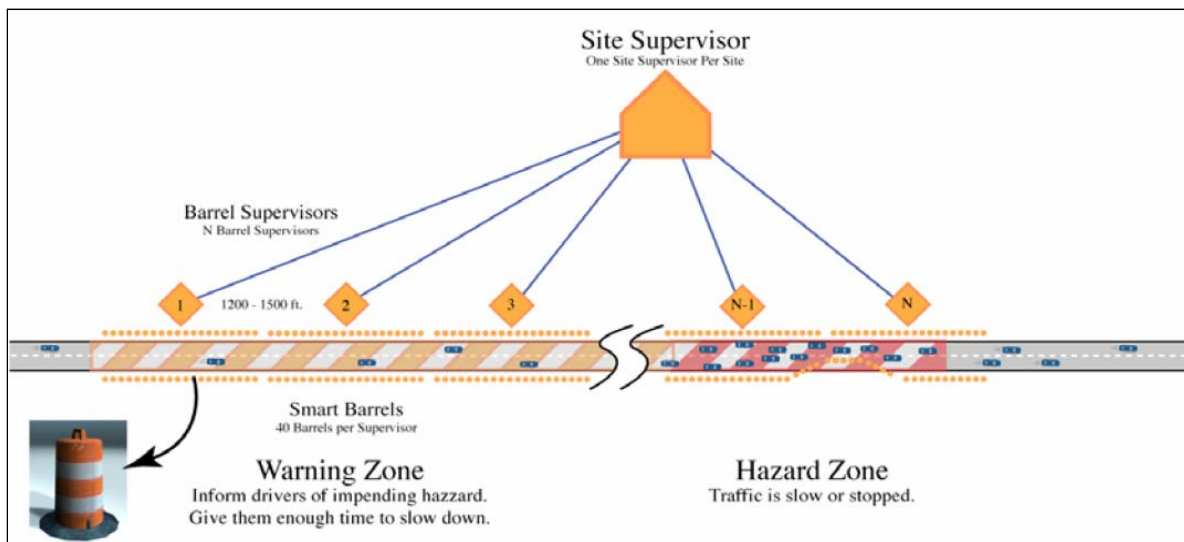


Figure 7. Concept of Adaptive Queue Warning System with Smart Barrels (41).

The Michigan study focused on finding two critical elements of the system: an inexpensive but sufficiently accurate speed sensor and a simple but effective signaling system. The study evaluated three prototype speed sensors in a limited field study. Figure 9 shows the three

sensors—active infrared, passive infrared, and magnetic sensor technologies. Findings indicated that the active infrared system was the most accurate but consumed the most power (41).

The Michigan study prototyped and tested a simple signaling scheme using a series of pole-mounted warning lights in a driving simulator, as illustrated in Figure 10. Driving simulator results indicated that drivers find adaptive systems more helpful than static road signs. Analysts observed systematic positive change in driving performance, which indicates enhanced safety. The technology shows promise in addressing problems of work zone rear-end crashes (41).

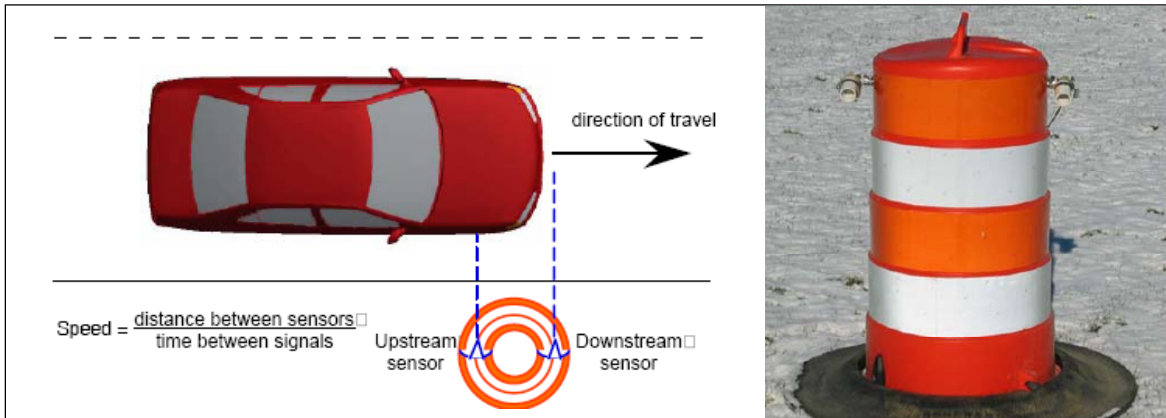


Figure 8. Speed Detection Using Smart Barrels (41).

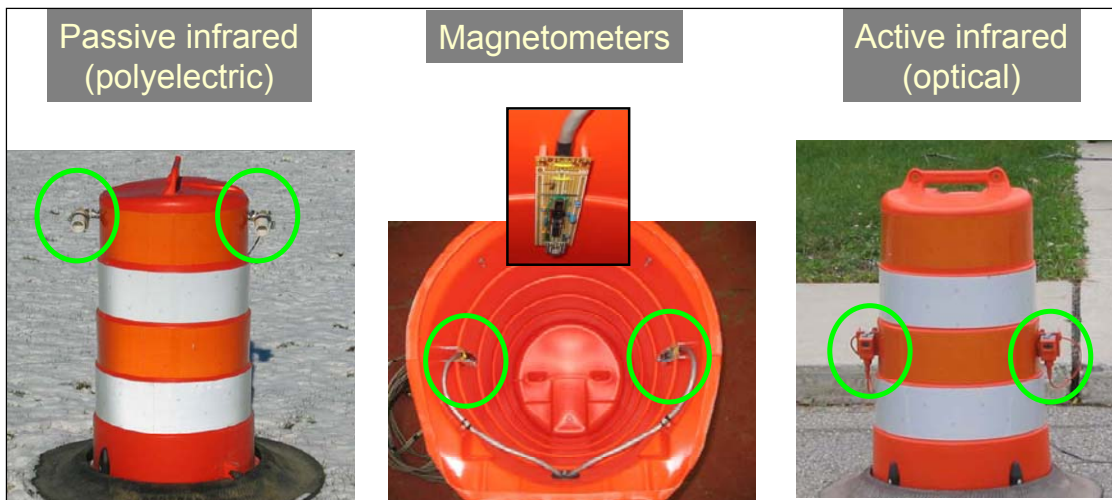


Figure 9. Speed Sensor Technologies Tested (41).

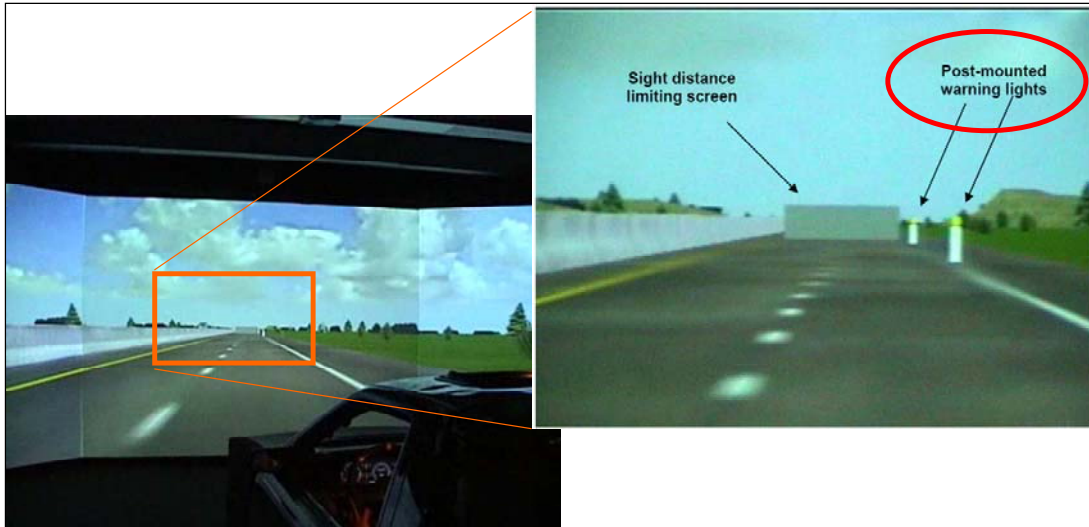


Figure 10. Driving Simulator Test of Post-Mounted Warning Lights (41).

Variable Speed Limits for Speed Harmonization

The goal of speed harmonization is to improve safety and mobility of traffic through freeway bottlenecks during congested periods. It uses VSLs or variable advisory speed messages to suppress stop-and-go conditions by reducing the speed differential between free-flowing and queued vehicles.

Hoogen and Smulders (42) evaluated the effectiveness of VSLs on motorways in the Netherlands, finding that VSL improved the uniformity of traffic flow (i.e., volume, speed, and occupancy variances between and within lanes decreased). Borrough (43) found that the enforcement of VSL in England resulted in a 28 percent reduction in the number of crashes within an 18-month period, during which time the number of lane changes decreased and motorists tended to keep proper following distances when a “faster lane” no longer existed. Hegyi et al. (44) developed a method for optimal coordination of VSL and ramp metering. They demonstrated the potential benefits of variable speed limits in minimizing total travel time and suppressing shockwaves.

Park and Yadlapati (45) evaluated a number of variable speed limit control logics at work zones using microscopic simulation (VISSIM). They used a minimum safety distance equation as a surrogate safety measure, finding that VSL can improve both mobility and safety at work zones. Zhicai et al. (46) tested VSL strategies for various traffic demands and for different roadway geometry, lane closure, and incident scenarios. Abdel-Aty et al. (47) investigated the safety benefit of selected VSL strategies at three locations using traffic data from I-4 in Central Florida. The authors found that reducing the speed limit upstream of the risk-prone location while increasing the downstream speed limits maximized the benefit of VSLs.

Speed harmonization techniques using VSLs are common in many European countries. Such systems may be deployed to promote safer driving during recurring congested periods, incidents, or under adverse weather conditions. Figure 11 shows a VSL system operated in the Netherlands (31, 48).

GUIDELINES FOR USE OF ITS IN WORK ZONES

Introduction

This portion of the literature review covers some guidelines for using ITSs in work zones. The treatments covered in this section include the following:

- Dynamic no-passing zone.
- Travel time information.
- Travel delay information.
- Stopped traffic advisory.
- Dynamic lane merge.



Figure 11. Speed Harmonization in the Netherlands (31, 48).

Criteria for Use of Dynamic Lane Merge

Klashinsky and Bushman (49) describe a dynamic work zone safety system developed by International Road Dynamics Inc. in partnership with the Indiana Department of Transportation to improve traffic operations and safety at lane closures. As traffic approaches the closure, some

drivers will attempt to stay in the dropped lane as long as possible in an attempt to get ahead of the developing queue. These motorists must then perform a risky merge maneuver in congested traffic with limited time and space available.

Drivers can be discouraged from attempting to enter the continuous lane at the lane drop point by creating a no-passing zone in advance of the lane closure. The intent of this action is to force drivers into the continuous lane upstream of the merge point, thus avoiding the problems associated with late merge. Since traffic volumes and congestion vary significantly throughout the day, this system needs to be dynamic, adjusting to the traffic demand. Thus, the point at which vehicles need to merge will change throughout the day. As congestion increases and the queue in the continuous lane lengthens, the opportunity for smooth lane changes moves farther back from the previous safe merge point (49).

The dynamic work zone safety system should, by design, react automatically to the changing queue length and traffic flow conditions and adjust the length of the no-passing zone. This dynamic no-passing zone uses a combination of static traffic signs and flashing beacons. The static signs (no beacons) are located nearest the lane drop to create a permanent no-passing zone. Other signs with beacons are located upstream, forming three to six (or more) control stations that are activated as traffic congestion increases. Portability is an essential part of these stations since the work zone could shift with time. Therefore, this technique requires that the equipment be mounted on trailers that are moveable as traffic and construction conditions warrant. The traffic sensors mounted on the trailers monitor vehicle presence and lane occupancy to determine when to activate the flashers. Detections at or above a predetermined threshold level trigger a signal being sent to the next upstream station via radio frequency communication. Figure 12 illustrates the layout and operation of this system (49).

In Figure 12, construction creates a lane restriction on a two-lane, one-direction roadway. The dynamic work zone safety system creates a dynamic no-passing zone just in advance of the lane restriction. The sign structure supports non-intrusive traffic sensors used to detect traffic queues. Sign #1 is always activated to warn of the lane restriction. Detection of vehicle congestion at Sign #1 causes activation of the second warning sign. Detection of congestion at Sign #2 causes the third warning sign to be activated, and so on. The no-passing zone is dynamic. Each no-passing sign is activated/deactivated in sequence as detectors sense changing conditions in vehicle congestion. Activated signs have flashing lights, whereas non-activated signs have lights turned off. Anyone attempting to pass the waiting traffic queue and then attempting a forced merge near the taper would be subject to a traffic citation since the no-passing-zone sign is an enforceable regulatory sign.

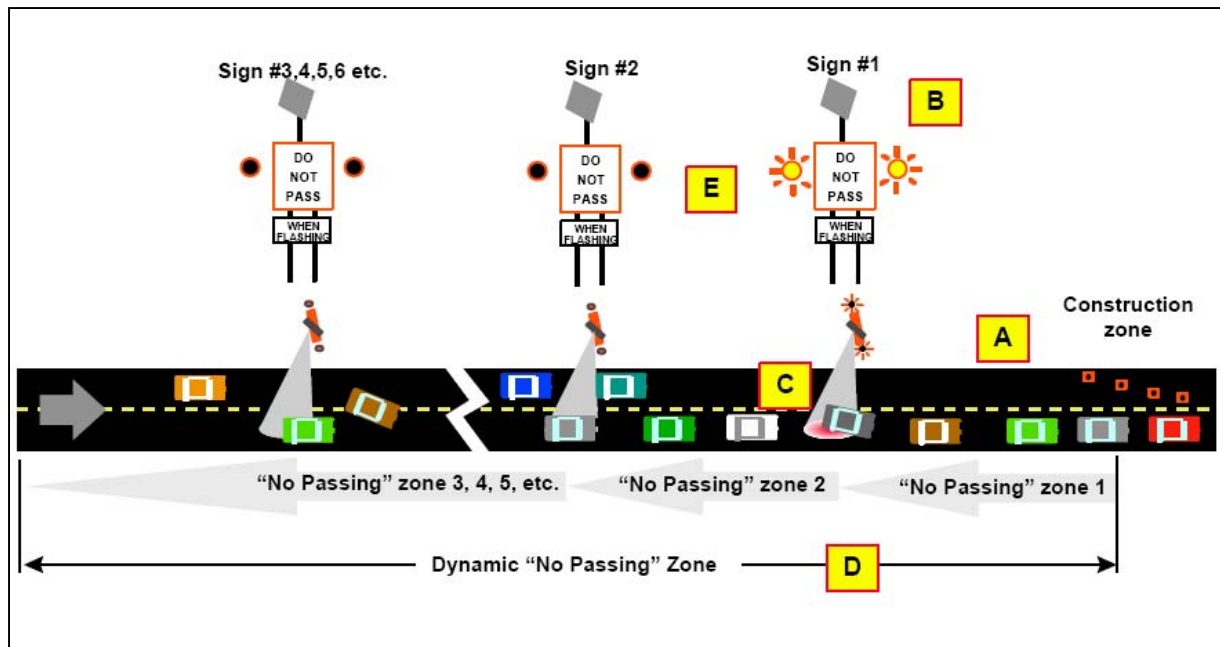


Figure 12. Dynamic Work Zone Safety System Layout and Operation (49).

The authors believe the work zone system is feasible if the following conditions are met:

- The work zone should be reasonably long (at least 0.8 km) for drivers to adjust to a desirable speed in the work zone.
- The freeway traffic flow should reach the capacity of the open lane, resulting in queue formation. Driver compliance improves when the volume is high.
- There should be no entry or exit ramps within 3 to 5 km along the approach zone or within the work zone (49).

Lachwani and Horowitz (50) conducted a study to determine the best practices for the temporary deployment of ATIS in highway work zones. In so doing, they compared and contrasted 16 different devices in 27 separate deployments throughout the United States. The authors emphasized system configuration, message content, media, information processing, and real-time data collection methods. They compared systems for their effectiveness in warning drivers, improving safety, calming traffic, reducing delay, and promoting smoother traffic flow. The study recommends an 11-step procedure for choosing the most appropriate ATIS configuration for any given work zone.

As part of the multi-step process, the authors promote some thresholds for decision making with respect to real-time ATIS in work zones. They recommend that real-time systems that predict delays and provide detour information should be used in the following situations:

- Locations where traffic volumes are consistently above 1500 vphpl (vehicles per hour per lane, for lanes remaining open).
- Locations where excessive queuing is predicted.

- Rural locations where recurring queue lengths are expected to exceed 15 minutes.
- Any rural or urban location with infrequent queues greater than 30 minutes and where en-route information is sparse but viable alternate routes exist (50).

The authors consider stand-alone systems separately from real-time systems and limit them to simple tasks such as displaying a single vehicle's speed. Stand-alone systems are less flexible and less expensive than real-time systems, but tests of these systems in or near work zones have demonstrated their effectiveness in calming traffic in a variety of traffic conditions. The authors recommend their use anytime speeding might be a problem and where static signing might be insufficient to control that speeding (50).

The Minnesota Department of Transportation (Mn/DOT) developed an intelligent work zone (IWZ) toolbox as a guideline for selecting an appropriate IWZ system to mitigate anticipated issues on scheduled projects (51). Mn/DOT intended descriptions contained in the toolbox to serve as brainstorming materials that should lead to practical solutions to unique problems. The IWZ systems in the toolbox are as follows:

- Travel time information.
- Speed advisory information.
- Congestion advisory.
- Stopped traffic advisory.
- Dynamic merge—late or early.
- Traffic responsive temporary signals (sheet under development).
- Temporary ramp metering (sheet under development).
- Excessive speed warning (includes dynamic speed display signs).
- Over dimension warning.
- Work space/haul road intrusion warning.
- Construction vehicle warnings—merging, crossing, and exiting.
- Hazardous condition warnings—road surface or visibility.
- Changeable work zone signage (includes work zone speed limits).
- Traffic surveillance camera (sheet under development).

In providing this list, Mn/DOT adds the following note to its decision makers: “The systems may be combined, modified, enhanced or simplified as necessary for a particular project. Please use these toolbox sheets to brainstorm IWZ possibilities, and consider what conditions may be needed to make the application viable.” In other words, the idea is that users should not use the toolbox as a “cookbook” and apply the concepts narrowly or only as they are presented in this document.

Mn/DOT categorizes these IWZ systems into one of the following categories:

- Traffic Responsive Systems—collect and respond to average traffic characteristics, such as speed and volume of a group of vehicles, and react to trends of increasing or decreasing values. These applications might include:
 - Travel time advisory system.
 - Speed advisory information.
 - Congestion advisory.
 - Stopped vehicle advisory.
 - Dynamic merge.
 - Traffic responsive temporary signals.
 - Temporary ramp metering.
- Vehicle Responsive Systems—collect and respond to individual vehicle characteristics such as speed, dimensions, and location. When the systems detect adverse conditions, motorists need immediate warnings for quick response. These applications might include:
 - Excessive speed warning.
 - Over dimension warning.
 - Work space/haul road intrusion warning.
 - Construction vehicle warning.
- Environmentally Responsive Systems—collect and respond to changing non-traffic conditions of weather, roadway, or working characteristics such as visibility conditions or roadways surface conditions and hazards. These applications might include:
 - Hazardous condition warnings (flooding, ice, fog, smoke, dust, etc.).
 - Changeable work zone signage (work zone speed limit signs).
 - Traffic surveillance cameras (51).

The following information covers some of the IWZ systems but only the Traffic Responsive Systems category. It shows the schematic provided in the Mn/DOT toolbox and includes warrants, benefits, options, and notes for each IWZ system in the toolbox.

Travel Time Information

Figure 13 shows the Mn/DOT schematic for travel time information. This schematic and following Mn/DOT schematics are not drawn to scale (51). The following list provides information for decision makers when considering the use of travel time information.

Warrants for Travel Time Information

- The work zone may cause 15 minutes or more of additional travel time.
- The work zone causing the delay should be within 10 miles of the DMS location.

Benefits for Travel Time Information

- The system should inform drivers of the estimated travel time between their current location and a specific destination beyond them (up to 10 miles maximum).
- The system will give drivers information that will allow them to decide whether to change routes and provide them opportunity to notify others of their estimated arrival time.

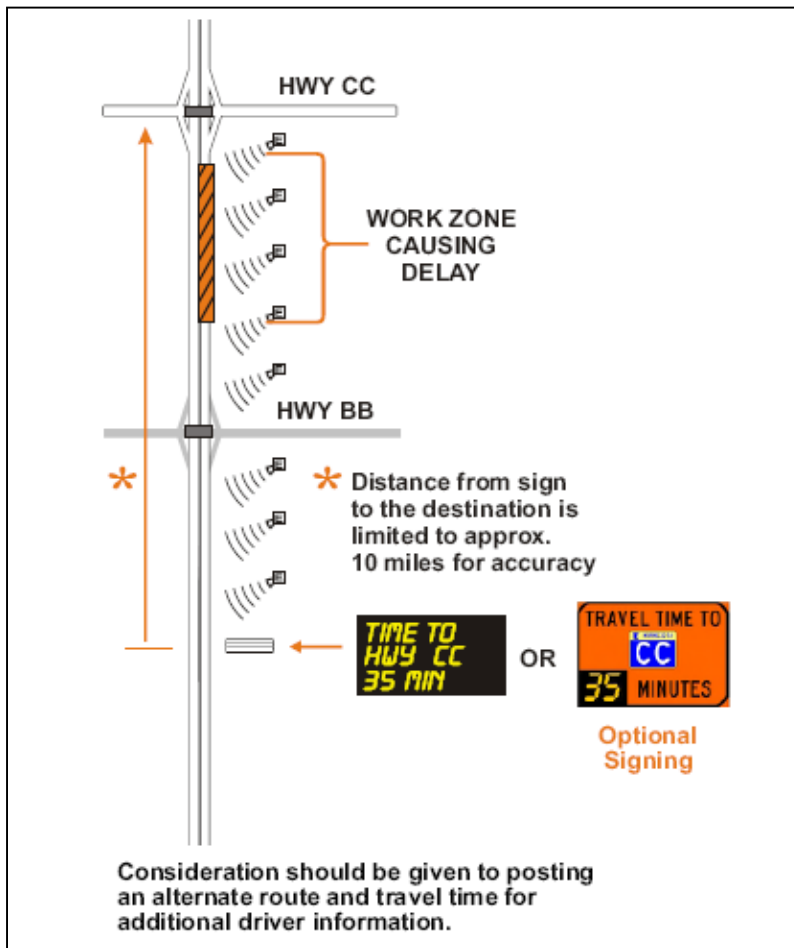


Figure 13. Mn/DOT Schematic for Travel Time Information (51).

Options for Travel Time Information

- The DMS may be replaced with static warning signs equipped with two DMS characters in dynamic mode. The characters would display the real-time travel time in the work zone downstream.
- Consideration should be given to posting an alternate route and travel time for additional driver information.
- The DMS may be supplemented with other informational devices such as a HAR.

Notes for Travel Time Information

- The figure does not show advance warning signs and other standard temporary traffic control devices.
- The Mn/DOT Office of Traffic, Safety, and Operations should review all IWZ guide signs and DMSs for design and message approval.
- Approved DMS messages should be listed in the Special Provisions, and approximate DMS locations should be shown on the plans. All DMS displays should be blank when messages are not warranted (51).

Travel Delay Information

Figure 14 shows the Mn/DOT schematic for travel delay information.

Warrants for Travel Delay Information

- The work zone may cause 15 minutes or more of additional travel time.
- The work zone causing the delay should be located more than 10 miles beyond the DMS location (preferably 25 to 50 miles or more, such that multiple alternate routes are available).

Benefits for Travel Delay Information

- The system should inform drivers of the estimated delay between their current location and an approximate location along the roadway downstream. The delay is calculated based on queue speeds vs. normal travel speeds.
- The system will give drivers information that will allow them to decide whether to change routes and provide them opportunity to notify others of their estimated arrival time (51).

Options for Travel Delay Information

- The DMS may be replaced with static warning signs equipped with two DMS characters in dynamic mode. The characters would display the real-time travel delay in the work zone downstream.
- Consideration should be given to posting an alternate route and travel time for additional driver information.
- The system may be converted to a travel time system within 10 miles of the destination location.
- The DMS may be supplemented with other informational devices such as a HAR.

Notes for Travel Delay Information

- The figure does not show advance warning signs and other standard temporary traffic control devices.

- The Mn/DOT Office of Traffic, Safety, and Operations should review all IWZ guide signs and DMSs for design and message approval.
- Approved DMS messages should be listed in the Special Provisions, and approximate DMS locations should be shown on the plans. All DMS displays should be blank when messages are not warranted.

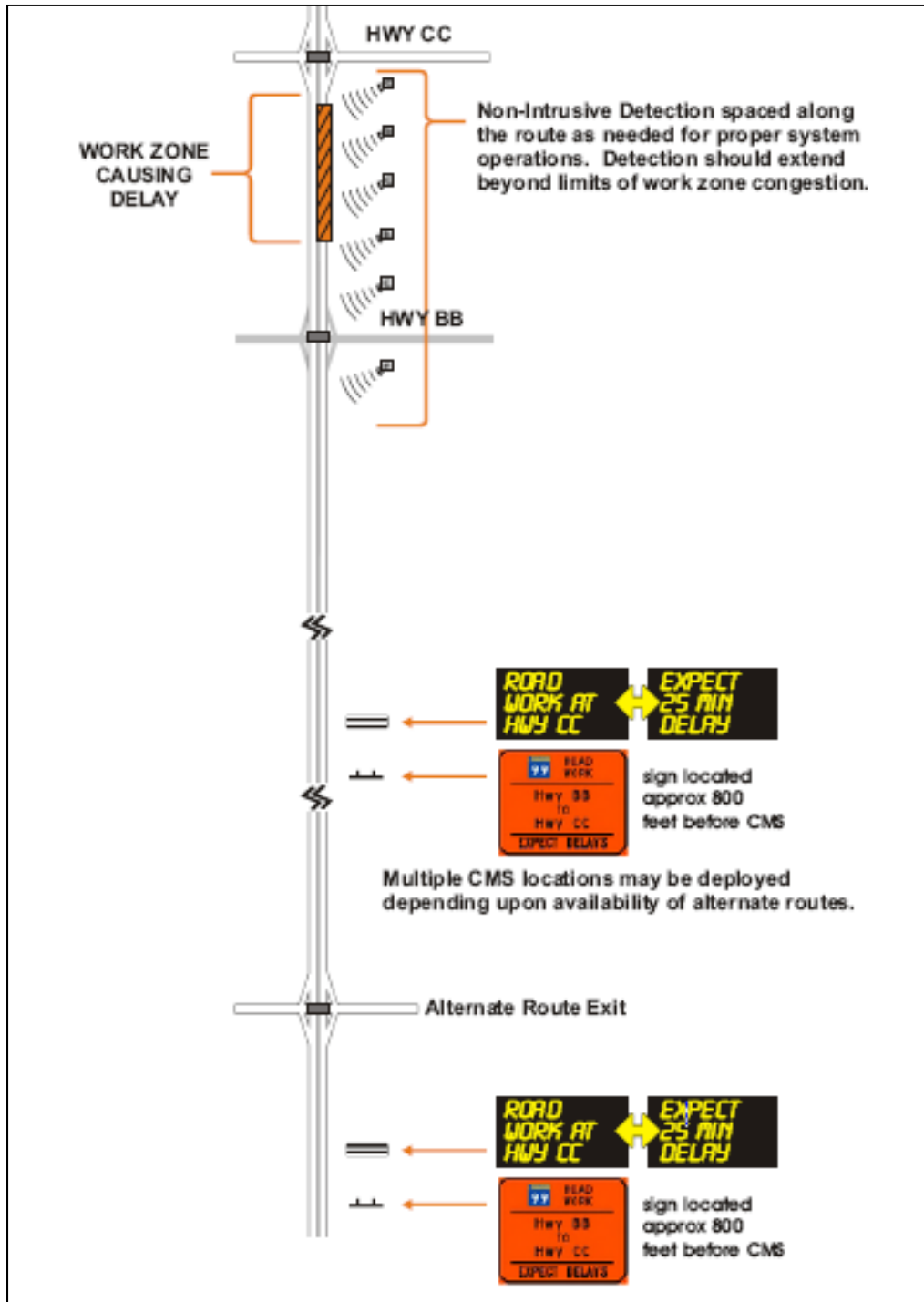


Figure 14. Mn/DOT Schematic for Travel Delay Information (51).

Speed Advisory Information

Figure 15 shows the Mn/DOT schematic for speed advisory information (51).

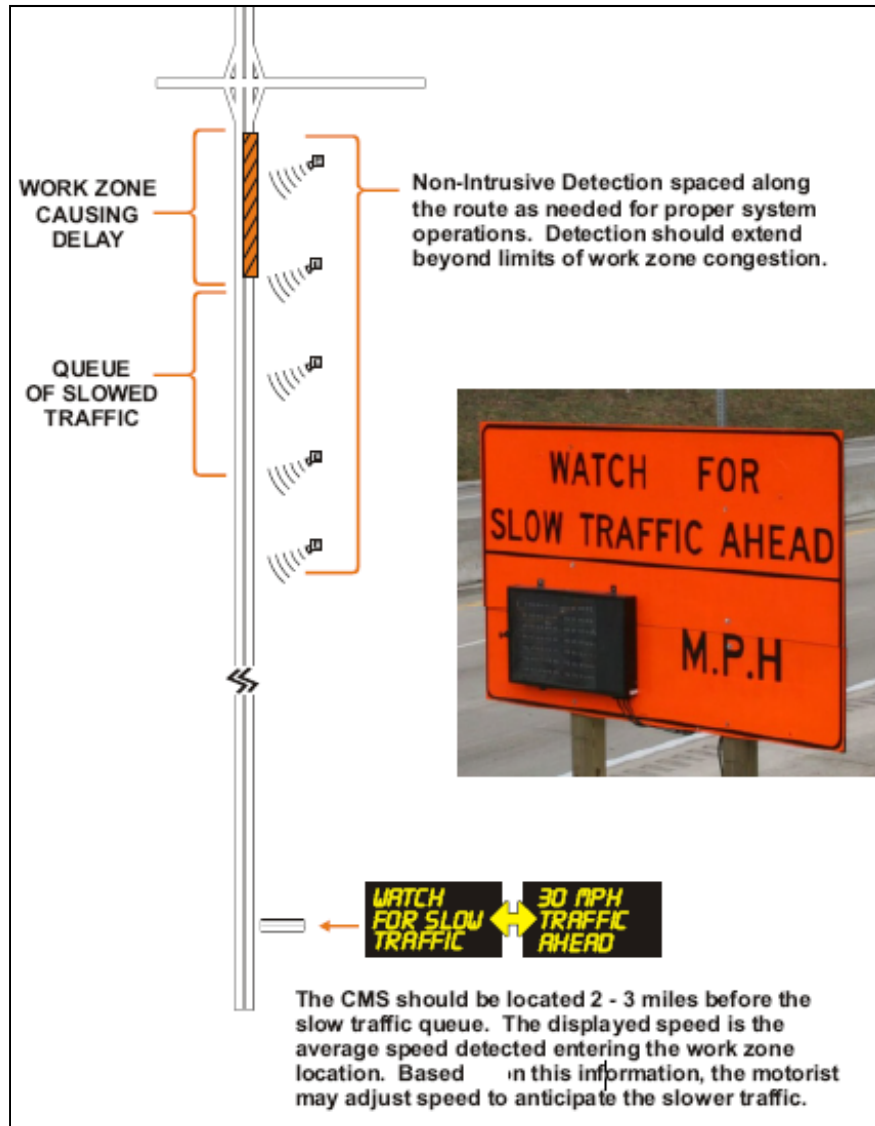


Figure 15. Mn/DOT Schematic for Speed Advisory Information (51).

Warrants for Speed Advisory Information

- The work zone will cause additional travel time.
- The work zone queue is expected to slow traffic at least 20 mph below the posted speed limit.

Benefits for Speed Advisory Information

- The system should advise motorists of an appropriate speed to allow them to travel through the work zone with minimal braking.
- The system will smooth the transition between faster- and slower-moving traffic.
- The system should provide an increase in capacity of the roadway through the work zone area.

Options for Speed Advisory Information

- The DMS can be replaced with static warning signs equipped with two DMS characters in dynamic mode. The characters would display the real-time average speed in the work zone downstream.

Notes for Speed Advisory Information

- The figure does not show advance warning signs and other standard temporary traffic control devices.
- The Mn/DOT Office of Traffic, Safety, and Operations should review all IWZ guide signs and DMSs for design and message approval.
- Approved DMS messages should be listed in the Special Provisions, and approximate DMS locations should be shown on the plans. All DMS displays should be blank when messages are not warranted (51).

Congestion Advisory Information

Figure 16 shows the Mn/DOT schematic for congestion advisory information.

Warrants for Congestion Advisory Information

- Queue lengths are estimated to vary greatly day by day and hour by hour such that a suitable location for the temporary traffic control (TTC) advance warning signs cannot be predicted.
- Queue lengths may encroach upstream beyond a motorist's reasonable expectations for stopped traffic, and there is probability that the geometrics may cause poor visibility of the end of the traffic queue, causing short reaction times and panic stopping.
- The queue is estimated to stop downstream of the last DMS in the system.

Benefits for Congestion Advisory Information

- The system should alert drivers of an upcoming traffic slow-down or stopped traffic, providing drivers time to determine possible route alternatives and to be prepared to stop safely.
- Traffic may divert to alternate routes.

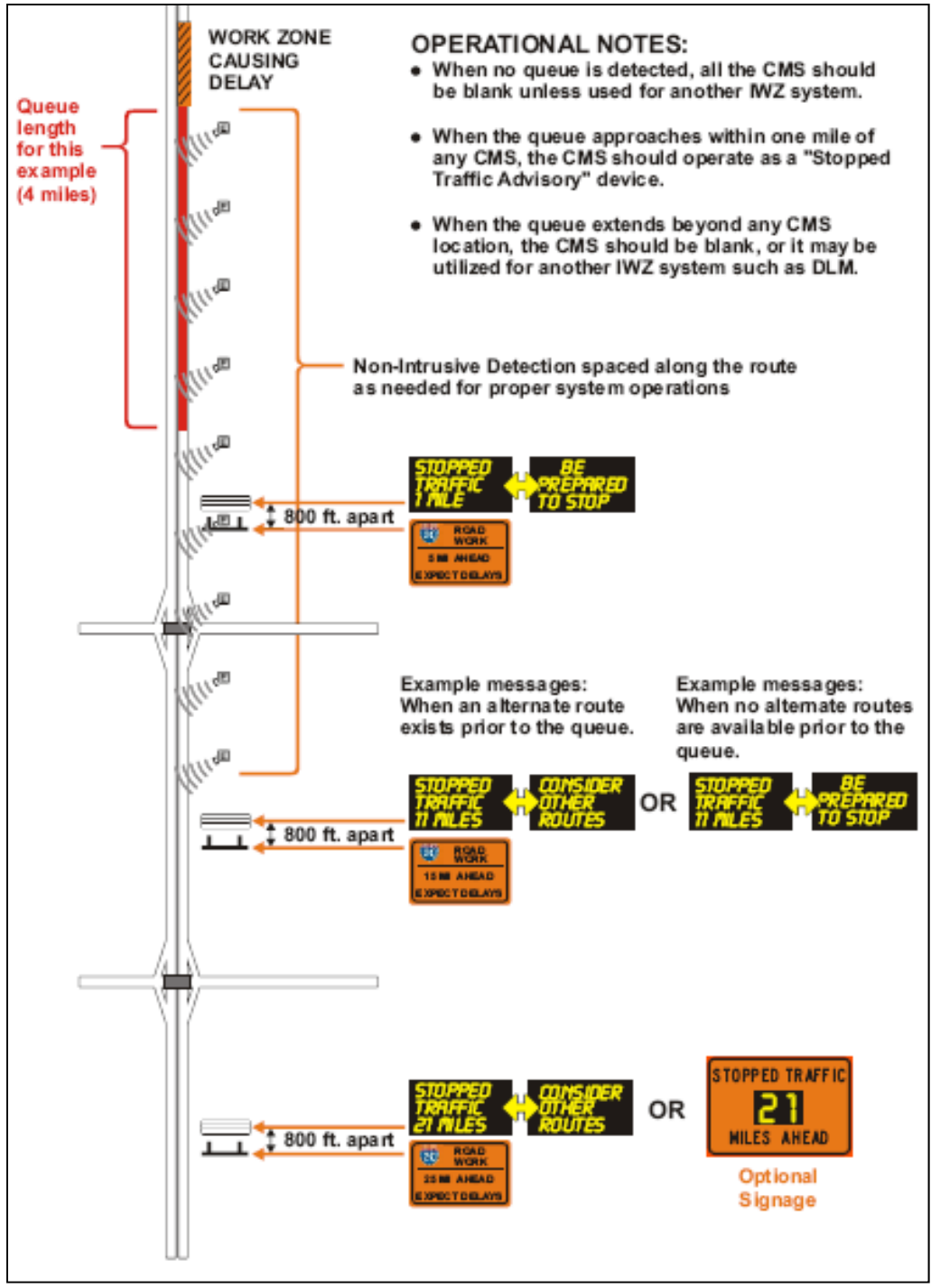


Figure 16. Mn/DOT Schematic for Congestion Advisory (5I).

Options for Congestion Advisory Information

- When queues are not expected to ever extend to the DMS location, the DMS may be replaced with a static warning sign equipped with two dynamic DMS characters for mileage. When no queues are detected, the mileage display would correspond with the accompanying guide sign for ROAD WORK XX MI AHEAD.

- When traffic queue lengths are reasonably predictable, warning motorists of stopped/slowed traffic may be accomplished with the use of typical TTC warning signs placed prior to the anticipated beginning of queue.
- The system may be combined with dynamic merge, stopped traffic warning, and travel time and/or delay systems.

Notes for Speed Advisory Information

- This figure does not show advance warning signs and other standard temporary traffic control devices.
- The Mn/DOT Office of Traffic, Safety, and Operations should review all IWZ guide signs and DMSs for design and message approval.
- Approved DMS messages should be listed in the Special Provisions, and approximate DMS locations should be shown on the plans. All DMS displays should be blank when messages are not warranted (51).

Stopped Traffic Advisory Information

Figure 17 shows the Mn/DOT schematic for stopped traffic advisory information.

Warrants for Stopped Traffic Advisory Information

- Queue lengths are estimated to vary greatly day by day and hour by hour such that a suitable location for the TTC advance warning signs cannot be predicted.
- Queue lengths may encroach upstream beyond a motorist's reasonable expectations for stopped traffic, and there is probability that the geometrics (terrain) may cause poor visibility of the end of the traffic queue, causing short reaction times and panic stopping.
- Queues initiated on crossroads are estimated to cause traffic conflicts and/or delays on the mainline road, such as backups beyond the length of ramps, thru- or around-turns in intersections, or other hazardous congestion situations.

Benefits for Stopped Traffic Advisory Information

- The system should alert drivers of an upcoming traffic slow-down or stopped traffic, providing drivers time to determine possible route alternatives and to be prepared to stop safely.
- It is anticipated that the system will reduce rear-end crashes.
- Traffic may divert to alternate routes.

Options for Stopped Traffic Advisory Information

- The DMS may be replaced with an appropriate warning sign equipped with dynamically automated flashing lights.

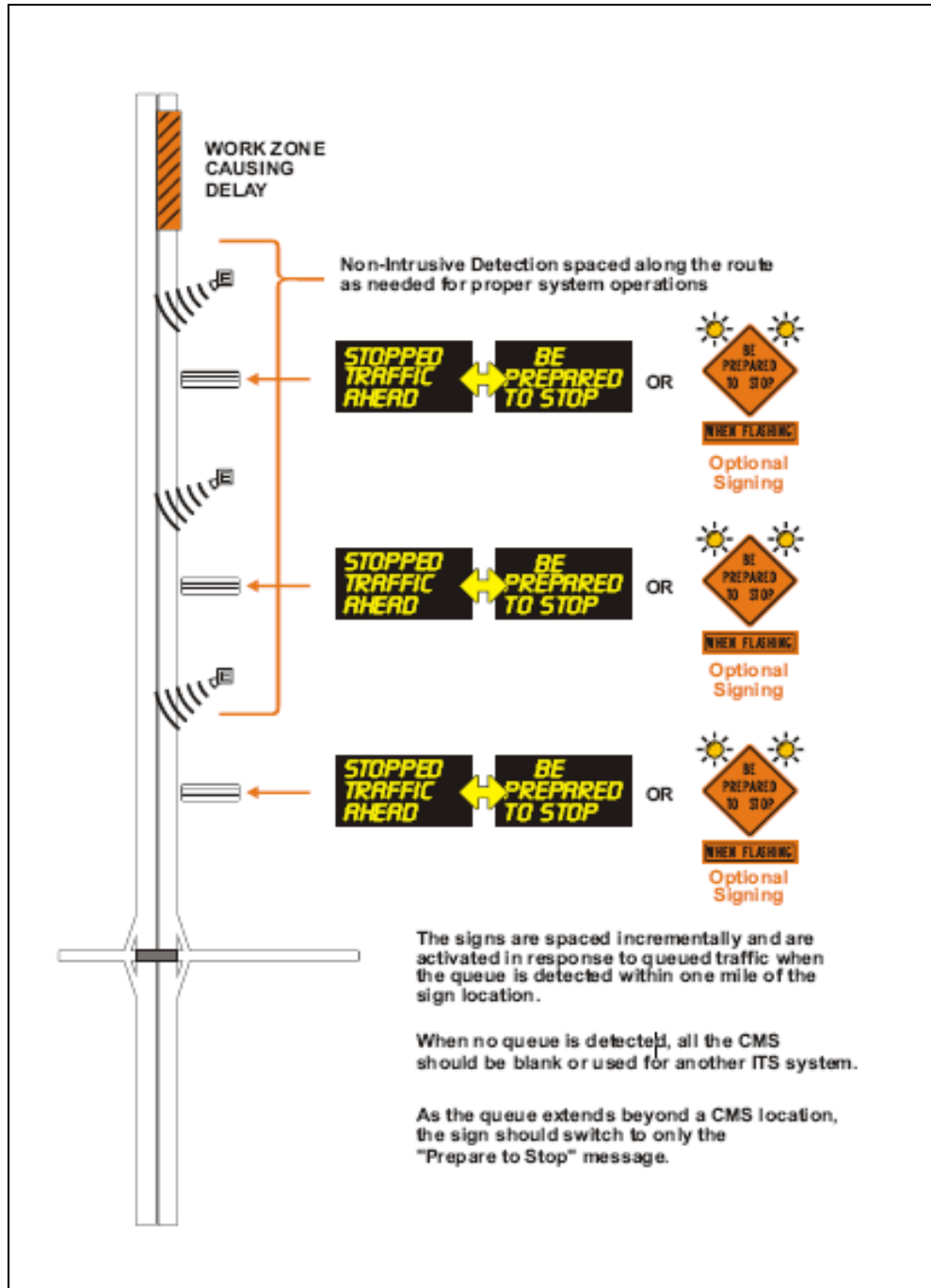


Figure 17. Mn/DOT Schematic for Stopped Traffic Advisory (51).

- The static signs are spaced incrementally and the individual flashers are activated in response to queued traffic when the queue is detected within 1 mile of the sign location.
- When traffic queue lengths are reasonably predictable, warning motorists of stopped/slowed traffic may be accomplished with the use of typical TTC warning signs placed prior to the anticipated beginning of queue.
- The system may be combined with dynamic merge and stopped traffic advisory systems.

Notes for Stopped Traffic Advisory Information

- The figure does not show advance warning signs and other standard temporary traffic control devices.
- The Mn/DOT Office of Traffic, Safety, and Operations should review all IWZ guide signs and DMSs for design and message approval.
- Approved DMS messages should be listed in the Special Provisions, and approximate DMS locations should be shown on the plans. All DMS displays should be blank when messages are not warranted (51).

Dynamic Late Merge

Figure 18 shows the Mn/DOT schematic for the dynamic late merge (51).

Warrants for Dynamic Late Merge

- Two lanes of traffic must merge into one lane and traffic must merge.
- Although queues may develop at low volumes, typically the volume must exceed 1500 vehicles per hour to sustain a queue that is caused by merging lanes.
- Estimated queue lengths may encroach beyond an upstream intersection or interchange operations.
- The speeds and lane occupancy volumes are anticipated to vary unpredictably, causing drivers to have trouble identifying the best lane usage practice, such as using both lanes versus moving into the continuous thru-lane.

Benefits for Dynamic Late Merge

- The system should alert drivers of an upcoming traffic slowdown or stopped traffic and inform them to use both lanes until the designated merge point.
- Mn/DOT anticipates that the system will reduce the length of the upstream queue by 40 percent, which may reduce conflicts at nearby intersections.
- By utilizing both traffic lanes, the differential speed between lanes is greatly reduced since both lanes travel at approximately the same speed.
- Motorists are given positive directions on lane usage and merging, which clears misunderstandings between drivers and reduces road rage.

Options for Dynamic Late Merge

- The dynamic system may be combined with congestion warning and travel time and/or delay systems.

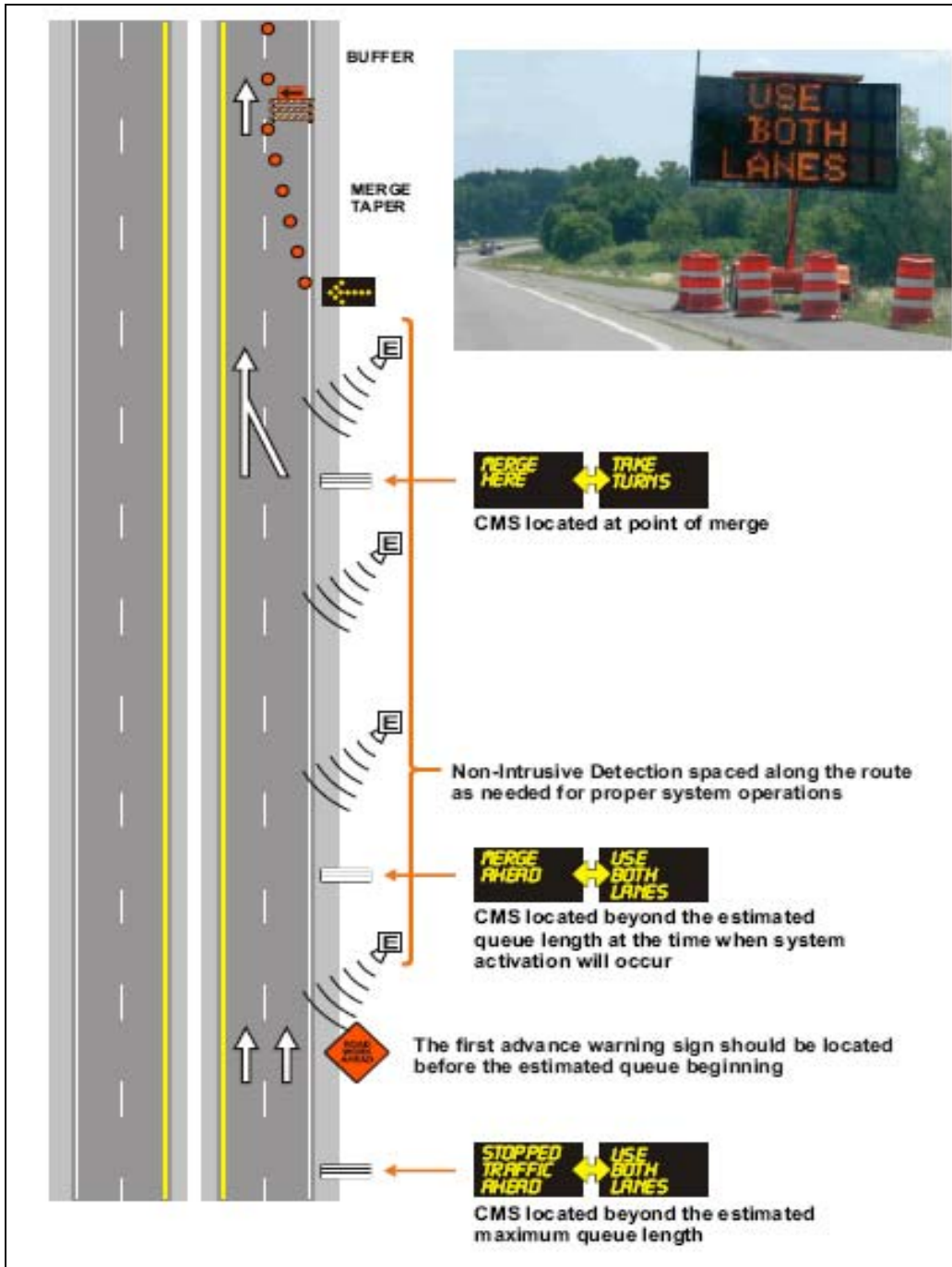


Figure 18. Mn/DOT Schematic for Dynamic Late Merge (5I).

- When the speeds and lane occupancy volumes are anticipated to increase predictably and hold at a high level, the motorist should have little trouble identifying when the traffic is congesting and begin to follow the posted merging procedure, such as using both lanes. The following two options may be used:
 - Directions may be provided on static guide signs posted beyond the anticipated queue length and repeated within the queue area.

- When the congestion time is highly predictable, the directions may be posted on DMSs, as shown in Figure 18, and activated by timers rather than traffic conditions.
- When traffic queue lengths are reasonably low and predictable, instructing motorists of proper lane usage may be accomplished with the use of typical TTC warning signs placed prior to the anticipated beginning of queue.
- The system may be combined with dynamic merge and stopped traffic advisory systems.

Notes for Dynamic Late Merge

- The figure does not show advance warning signs and other standard temporary traffic control devices.
- The Mn/DOT Office of Traffic, Safety, and Operations should review all IWZ guide signs and DMSs for design and message approval.
- Approved DMS messages should be listed in the Special Provisions, and approximate DMS locations should be shown on the plans. All DMS displays should be blank when messages are not warranted (51).

Dynamic Early Merge (Sheet under Development)

Figure 19 shows the current Mn/DOT schematic for the dynamic early merge.

Warrants for Dynamic Early Merge

This portion of the sheet is under development.

Benefits for Dynamic Early Merge

This portion of the sheet is under development.

Options for Dynamic Early Merge

This portion of the sheet is under development.

Notes for Dynamic Early Merge

- The figure does not show advance warning signs or other standard temporary traffic control devices.
- The Mn/DOT Office of Traffic, Safety, and Operations should review all IWZ guide signs and DMSs for design and message approval.
- Approved DMS messages should be listed in the Special Provisions, and approximate DMS locations should be shown on the plans. All DMS displays should be blank when messages are not warranted (51).

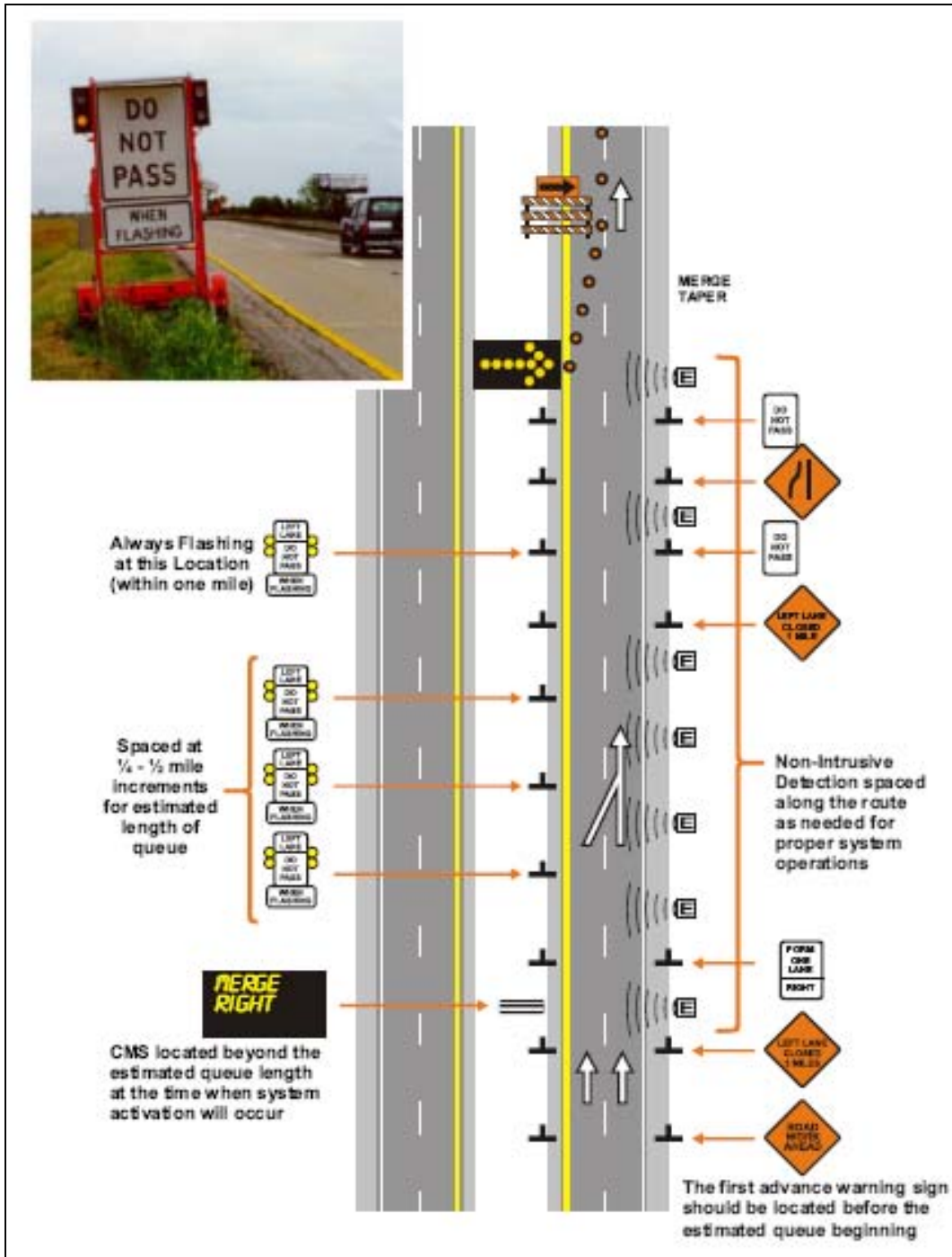


Figure 19. Mn/DOT Schematic for Dynamic Early Merge (under Development) (51).

Temporary Ramp Metering (Sheet under Development)

- Figure 20 shows the current Mn/DOT schematic for temporary ramp metering.

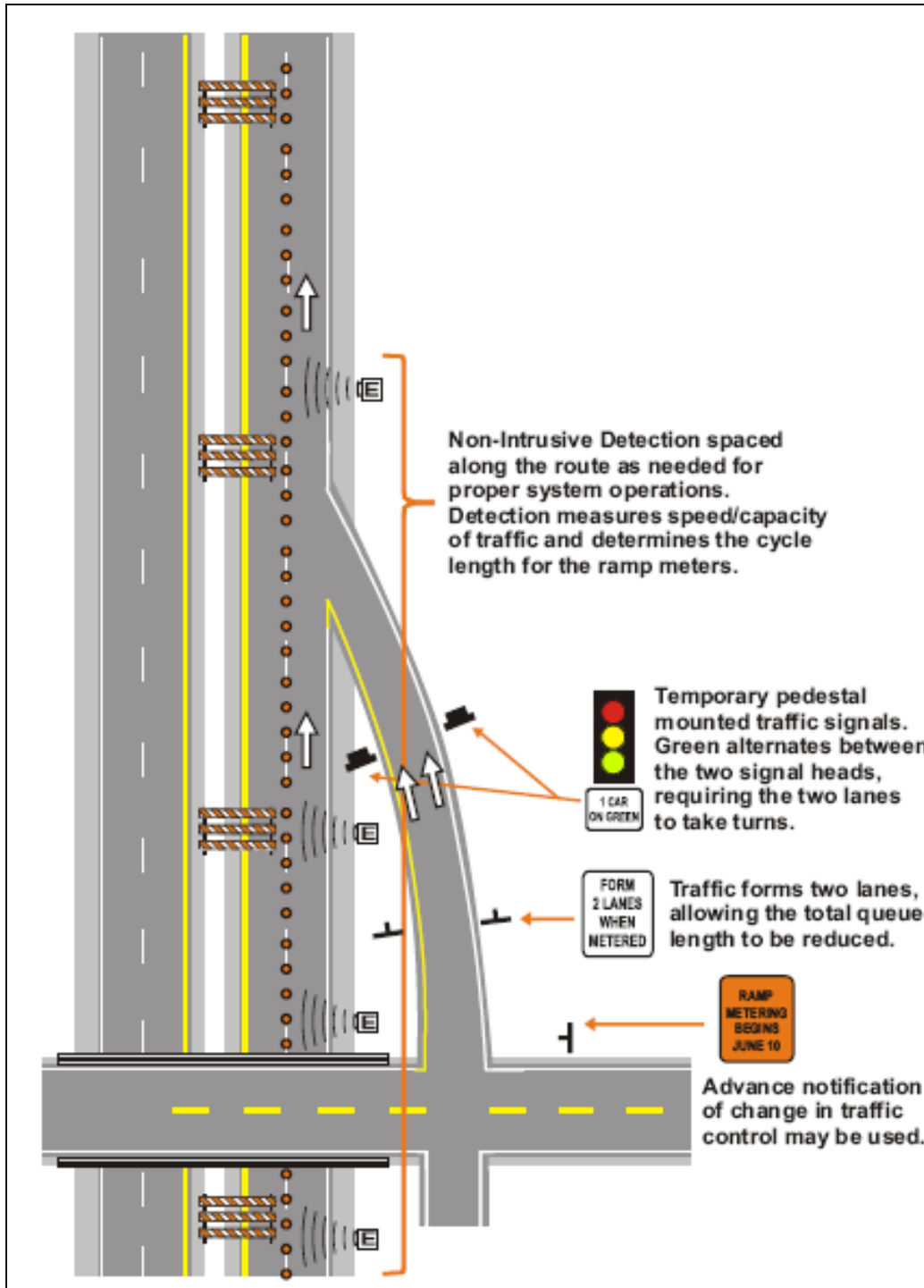


Figure 20. Mn/DOT Schematic for Temporary Ramp Metering (under Development) (51).

Warrants for Temporary Ramp Metering

- This portion of the sheet is under development.

Benefits for Temporary Ramp Metering

- This portion of the sheet is under development.

Options for Temporary Ramp Metering

- This portion of the sheet is under development.

Notes for Temporary Ramp Metering

- The figure does not show advance warning signs and other standard temporary traffic control devices.
- The Mn/DOT Office of Traffic, Safety, and Operations should review all IWZ guide signs and DMSs for design and message approval.
- Approved DMS messages should be listed in the Special Provisions, and approximate DMS locations should be shown on the plans. All DMS displays should be blank when messages are not warranted (51).

CRITERIA FOR JUSTIFYING SMART WORK ZONES

The transportation agencies that might consider the use of intelligent transportation systems in work zones will want to know when the potential benefits of installing a system justify the cost. One of the typical approaches to establishing the criteria for when to use ITSs in work zones is a benefit-cost (B-C) approach. The cost portion of the equation is relatively easy to establish, especially in situations where the public agency subcontracts the SWZ system and the costs accrue only during the time the system is operating. Benefits, at least for some components of SWZs, have not been well established, but Fontaine and Edara (52) addressed this subject, as did Bushman et al. (53). Bushman et al. used results from traffic modeling, previous research, and project-specific characteristics to examine quantitatively the economic benefits from deployment of a Smart Work Zone. The economic benefits derived from:

- Mobility benefits in the form of reduced delay, reduced vehicle operating cost, and reduced emissions.
- Safety benefits from reduced injury and fatal crashes.

The costs were direct agency costs for procurement, mobilization, and operation of an SWZ. The analysis resulted in a probabilistic distribution of expected benefit-cost ratio and expected net value. On the benefits side of the equation, this process considered mobility effects and safety effects. The subparts of mobility effects were user delay, vehicle operating cost, and emissions, although the authors did not attempt to quantify the value of emissions. The authors offered some methods to estimate the safety effects of SWZs such as use of historical values (typically 7 percent to 30 percent increase due to work zone activity) or models to predict work zone crashes (53).

Bushman et al. applied the methodology to a smart work zone on I-95 in North Carolina to demonstrate its usefulness. The result was a range of benefit-cost values, considering variations

in traffic conditions. This work zone had an alternate route that could be used for traffic diversion from the main route. Table 4 indicates the variables used by this method along with a description of the variable and the ranges included for this case study (53).

Table 4. Input Parameters for Analysis of Smart Work Zone Deployment (53).

a. Mobility Effects

Variable	Description	Minimum	Maximum
Delay reduction	Reduction in user delay (hr/mo)	1063	7460
Truck delay value	Cost of delay for trucks (\$/hr)	\$25	\$125
Car delay value	Cost of delay for cars (\$/hr)	\$10	\$25
Truck operating cost	Cost of fuel (\$/hr)	\$1.00	\$1.50
Truck emissions rate	Idling emissions of CO, NO _x , and VOC (g/truck idling hour)	VOC = 12.1 CO = 109.6 NO _x = 43.1	VOC = 14.0 CO = 189.7 NO _x = 26.7
Car operating cost	Cost of fuel (\$/hr)	\$0.50	\$1.00
Car emissions rate	Idling emissions of CO, NO _x , and VOC (g/car idling hour)	VOC = 16.7 CO = 234.5 NO _x = 4.9	VOC = 19.3 CO = 273 NO _x = 5.1
Emissions value	Value of emissions of CO, NO _x , VOC (US \$/1000 kg)	VOC = \$1802 CO = \$23 NO _x = \$2608	VOC = \$6700 CO = \$6360 NO _x = \$12,875

b. Safety Effects

Variable	Description	Minimum	Maximum
Exposure	Vehicle-miles traveled	439,000	1,091,000
Work zone fatal crash rate	Fatal crashes per 100 million veh-mi traveled	1.44	1.69
Work zone injury crash rate	Injury crashes per 100 MVMT	24.85	29.82
Safety improvement factor	% reduction in crashes	0%	10%
Non-fatal injury crash cost	Average value of injury crash (\$/injury crash)	\$19,000	\$46,000
Fatal crash cost	Average value of fatal crash (\$/injury crash)	\$1,300,000	\$3,700,000

c. Agency Costs

Variable	Description	Minimum	Maximum
Months	Duration of operating period (mo)	7	9
Mobilization	Cost of system mobilization (\$)	\$50,000	\$100,000
Operating cost	Monthly system cost (\$/mo)	\$10,000	\$15,000

Next, the process performed a sensitivity analysis followed by a risk analysis. The results of the sensitivity analysis showed the range of change in the benefit-cost ratio and a ranking of the uncertainty of input variables. The four most sensitive variables determined in this analysis were related to the delay caused to motorists: car delay reduction, time value for trucks, truck delay reduction, and time value for cars. The authors suggested that the models that might be useful in this process include VISSIM and QuickZone. Results indicated that the total estimated benefits of the SWZ deployment amounted to \$140,000 per month and the estimated costs were \$22,000

per month. With the risk profile developed in the case study, the predicted B-C ratio, with 68 percent confidence interval, is between 3.3 and 9.1, and at a 95 percent confidence interval, the predicted B-C is between 1.2 and 11.9.

The outcome of this case study indicated positive results within the range of expected conditions. As further research is completed in this area, there might evolve enough archived results to cover a wide variety of conditions so that future analyses will not always be necessary. The proposed framework appears to have merit in developing this archive (53).

The efforts of Fontaine and Edara (52) built on the findings of Bushman et al., looking primarily at trends in the impact of SWZ systems on traffic operations and safety. They somewhat narrowly defined a Smart Work Zones as an automated system that provides real-time information on work zone traffic conditions and only included those with minimum human intervention. They focused on two commonly used functions, *speed advisory messages* and *travel time or delay messages*. Speed advisory messages, typically provided by DMSs, alert motorists to slower speeds in the work zone to advise them to slow down. Travel time or delay messages provide information to motorists to encourage the use of alternate routes (where they exist) or simply to inform motorists. Cases where SWZs were not able to improve operations or other aspects of the work zone usually coincided with uncongested conditions or locations without a viable alternate route. Fontaine and Edara focused on instances where improvements were expected and omitted other specialized SWZ systems such as variable speed limits and demand-responsive late-merge systems (52).

This research effort identified and reviewed 15 successful tests in eight states that had all deployed SWZ systems that provided either a congestion warning, a travel time warning, or a speed advisory message. The researchers used the following categories for these evaluations:

- Driver response—the evaluations conducted surveys that asked drivers to self-report how they reacted to an SWZ.
- Effect on operations—these tests attempted to measure how the SWZ impacted traffic operations (e.g., by measuring diversion from the main route to alternate routes).
- Effect on safety—these tests analyzed the impact of the SWZ on crash statistics or surrogate safety measures such as speed (52).

The conditions varied among deployments investigated, but results collectively indicated some common trends in SWZ impacts. The potential diversion impacts of SWZs were best documented. Safety and speed impacts showed more variation, which is thought to result from a lack of high-quality data in some of the studies. There were at least two SWZ deployments contributing to each of the following impacts:

- Two studies of driver attitudes showed that drivers who drove a corridor frequently were more likely to change their route in response to travel time or delay information than drivers who were infrequent users.

- Travel time or delay information resulted in diversion rates ranging from 4 to 20 percent of mainline traffic. There was minimal diversion due to speed advisory information. Specific route information usually caused greater diversion compared to less-specific information.
- Speed advisory systems were effective in reducing speeds, but the reduction was greater in congested conditions. It was unclear whether this reduction was a direct result of the congestion or improved credibility of the speed advisory systems during congested flow.
- The impact of SWZs on safety is inconclusive, primarily due to limited data. Studies that addressed crash frequency or rate have shown conflicting results, although the increased crashes could have resulted from other work zone features (52).

Fontaine and Edara (52) reflected on the findings of the Bushman et al. (53) study and concluded that, in many ways, it represents a best-case scenario where benefits could accrue over a long period of time and there is an attractive alternate route. These findings did not address projects of shorter duration or situations in which drivers would be diverted to congested roadways. This finding led Fontaine and Edara to model a hypothetical work zone to test the effects of diversion rate, traffic volume, and alternate route speed on benefits and costs. Figure 21 is a schematic of the roadway they used in this research. It included a two-lane directional freeway segment with a single (right) lane closure. The plan diverted traffic about 5 miles in advance of the lane closure and merged traffic back onto the mainline about 1 mile downstream of the closure. Speeds on the mainline had a mean value of 65 mph and standard deviation of 5 mph.

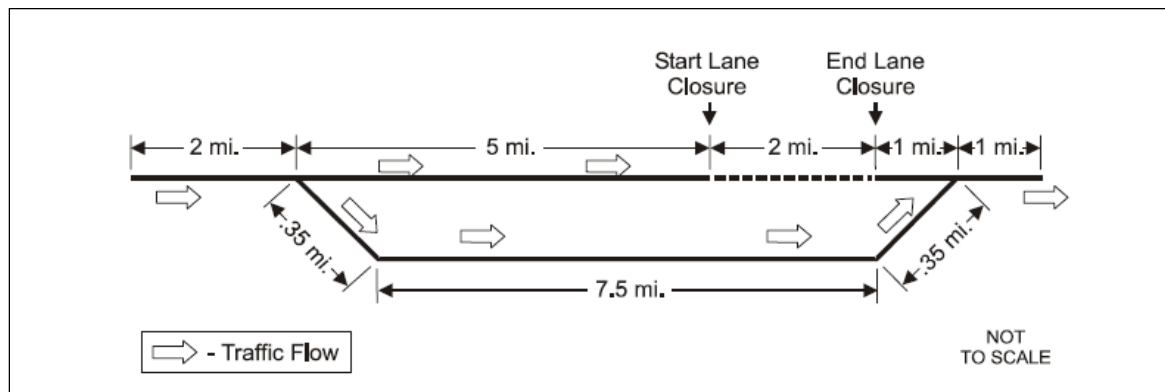


Figure 21. Simulation Network Schematic (53).

The researchers used three factors to determine their effect on system performance—diversion rate, traffic volume, and alternate route speed—as described below:

- Diversion rate—They tested three diversion scenarios: (a) no diversion, (b) 5 percent diversion, and (c) 15 percent diversion. These levels came from observed diversion percentages in prior tests of SWZs.
- Traffic volumes—Researchers examined traffic distributions on major freeways in northern Virginia to determine an average distribution of annual average daily traffic (AADT) by hour throughout the day. They applied these traffic values to determine the

performance of an SWZ over the course of a day but only used time periods when the demand exceeded capacity when deriving B-C estimates. All cases assumed 5 percent large trucks.

- Alternate route speed—This analysis investigated two alternate route speeds: a mean speed of 25 mph and a mean speed of 35 mph. The assumption was that using a homogeneous route with a single desired speed would facilitate extension of results to other situations where mean speeds were similar, regardless of the actual traffic control (52).

Measures of Effectiveness

The simulation runs captured the total system travel time in the network, which was the sum of travel times of all vehicles in the network (both vehicles that stayed on the mainline and those that diverted). The potential benefits of the SWZ system resulted from calculating the system-wide travel time savings produced by the SWZ system. Comparing periods when there was a standing queue in the no-diversion case to other scenarios when there was diversion formed the basis of comparison.

The next step involved using these travel time savings and assessing the potential B-C ratio of deploying an SWZ under various scenarios. The analysis used a value of time equal to \$15.14 per hour and initial capital costs for SWZ systems ranging from \$150,000 to \$300,000 (based on those recently deployed in North Carolina). The goal was to determine combinations of project durations, traffic conditions, and system costs to develop guidelines for situations where SWZ systems provide a $B-C > 1.0$ (52).

Fontaine (54) developed general guidance for the use of SWZs. These guidelines fall into four categories:

- Presence of congestion—Congestion must be present for at least some part of a day. If not, static signing or normal DMSs may be sufficient to provide information when congestion consistently occurs at the same time of day and most of the traffic stream is commuters.
- Duration of the work zone—SWZs should only be considered for long-term (e.g., several months) construction or maintenance projects.
- Speed-advisory messages—These messages appear to be effective only under congested conditions where traffic density exceeds 40 vehicles per mile. Placement of DMSs should be in areas where vehicles may be transitioning between congested and uncongested flow.
- Delay, travel time, and alternative route advisories—When an SWZ provides specific information about an alternate route, the operating agency must be confident that the alternate route will significantly improve travel time around the work zone.

The author concludes by stating that more objective research is needed to fully assess the abilities of these systems. Since field testing has not shown conclusive benefits at all sites, states need to carefully document the results of future deployments (54).

In Fontaine and Edara (52), simulation results provided the basis for determining the number of days that an SWZ would need to operate before accrued delay savings would justify the initial cost of the system. Table 5 summarizes the results of the analysis for the different combinations of traffic variables and potential system costs.

Table 5. SWZ Benefit-Cost Breakeven Duration (54).

Peak Hr Volume (vph)	Diversion (%)	Alternate Rte Speed (mph)	Daily Travel Time Savings (veh-hr)	Days in Operation until B-C > 1.0			
				\$150k	\$200k	\$250k	\$300k
1500	5	25	164.4	61	81	101	121
	5	35	272.1	37	49	61	73
	15	25	None	None	None	None	None
	15	35	196.1	51	68	85	102
1600	5	25	738.0	14	18	23	27
	5	35	836.2	12	16	20	24
	15	25	786.6	13	17	21	26
	15	35	1206.3	9	11	14	17
1700	5	25	1502.4	7	9	11	14
	5	35	1661.9	6	8	10	12
	15	25	2467.8	5	6	7	9
	15	35	3054.4	4	5	6	7
1800	5	25	2262.5	5	6	8	9
	5	35	2517.9	4	5	7	8
	15	25	4362.6	3	4	4	5
	15	35	5221.4	2	3	4	4

Note. An alternative way of evaluating potential B-C ratios for SWZs is to examine the ultimate B-C achieved for a fixed project duration and cost assumptions. This comparison used a 30-day timeframe and longer-term 150-day duration SWZ along with costs of \$150,000 and \$300,000.

Table 6 shows that SWZs cannot be justified based on operational improvements for projects of short duration where the peak volume is just over the capacity of the work zone. B-C ratios increase significantly as the level of congestion increases (54).

Table 6. B-C Ratios for 30- and 150-Day Project Durations (54).

Peak Hr Volume (vph)	Diversion (%)	Alternate Rte Speed (mph)	\$150,000 Initial Cost		\$300,000 Initial Cost	
			30-Day B-C	150-Day B-C	30-Day B-C	150-Day B-C
1500	5	25	0.5	2.5	0.2	1.2
	5	35	0.8	4.1	0.4	2.1
	15	25	None	None	None	None
	15	35	0.6	3.0	0.3	1.5
1600	5	25	2.2	11.2	1.1	5.6
	5	35	2.5	12.7	1.3	6.3
	15	25	2.4	11.9	1.2	6.0
	15	35	3.7	18.3	1.8	9.1
1700	5	25	4.5	22.7	2.3	11.4
	5	35	5.0	25.2	2.5	12.6
	15	25	7.5	37.4	3.7	18.7
	15	35	9.2	46.2	4.6	23.1
1800	5	25	6.9	34.3	3.4	17.1
	5	35	7.6	38.1	3.8	19.1
	15	25	13.2	66.0	6.6	33.0
	15	35	15.8	79.1	7.9	39.5

An Alternative Method for Justifying Smart Work Zones

Another approach besides benefit-cost is to consider the factors that influence the decision on use of ITS in work zones and to assign values to them according to their relative importance. This is a subjective methodology, but it appears to have merit in cases where costs and benefits are not well understood. The research team found out about one such method through an SWZ vendor. The FHWA was apparently considering this methodology in 2011 (55). The checklist that was an integral part of this methodology included the following factors:

- Duration of the work zone.
- Impact exposure.
- Queuing and delay.
- Temporal aspects of the work zone.
- Specific issues expected.

Table 7 lists the subparts of these items and the number of points suggested for assignment. The result of the project selection checklist is a comparison of the total sum of the points assigned to the following list:

- ≥ 30 points—ITS is likely to provide significant benefits relative to cost.
- Total between 10 and 30—ITS may provide some benefits and should be considered.
- Total < 10 —ITS may not provide enough benefit as a treatment to justify the cost.

Table 7. Project Selection Checklist.

<p>Factor 1: Duration</p> <ul style="list-style-type: none"> • Long-term stationary work with duration greater than one construction season (10 pts). • Long-term stationary work with 4 to 10 months duration (6 pts). • Long-term stationary work with less than 4 months duration (3 pts).
<p>Factor 2: Impact Exposure</p> <ul style="list-style-type: none"> • Project is expected to significantly impact traffic, businesses, other destinations (10 pts). • Project is expected to moderately impact traffic, businesses, other destinations (6 pts). • Project is expected to minimally impact traffic, businesses, other destinations (3 pts).
<p>Factor 3: Queuing and Delay</p> <ul style="list-style-type: none"> • Expected queue length 2 miles or greater for more than 2 hr per day (8–10 pts). • Expected queue length 1 mi but < 2 mi for > 1 hr but < 2 hr per day (6–8 pts). • Expected queue length 1 mi or less, or unknown, but pre-construction recurring congestion exists for up to 1 hr per day (4 pts).
<p>Factor 4: Temporal Aspects of Traffic Impacts</p> <ul style="list-style-type: none"> • Unreasonable traffic impacts expected for more than just peak hours (10 pts). • Unreasonable traffic impacts expected during most of a.m. and p.m. peak hours in either direction (6 pts). • Unreasonable traffic impacts expected during most of a peak hour in either direction (3 pts). • Unpredictable highly variable traffic volumes (1 pt).
<p>Factor 5: Specific Issues Expected (1 to 3 pts each)</p> <ul style="list-style-type: none"> • Traffic speed variability. • Back of queue and other sight-distance issues. • High speeds/chronic speeding. • Work zone congestion. • Availability of alternate routes. • Merging conflicts and hazards at work zone tapers. • Work zone hazards/complex traffic control layout. • Frequently changing operating conditions for traffic. • Variable work activities (that may benefit from variable speed limits). • Oversize vehicles (% heavy vehicles > 10%). • Construction vehicle entry/exit speed differential relative to traffic. • Data collection for work zone performance measures. • Unusual or unpredictable weather patterns such as snow, ice, and fog.

Source: Reference (55).

Issues Related to Transportation Management Centers

Information related to work zones with interactions with either permanent or interim TMCs was limited. Lou (56) describes a setup known as the Interim Transportation Management System (ITMS) designed for an 8-year, 45-mile, I-95 restoration project in Palm Beach County, Florida. The reasons a work zone ITS application differs from a traditional ITS application include:

- The temporary nature of work zones, which makes permanent device placement difficult.
- The deployment during road construction activities.
- The lifespan of the system (during construction).
- The need for fast-track deployment.

The subject ITMS defined a smart work zone that included closed circuit television (CCTV), dynamic message signs, a radar detector, and wireless communications. It deployed a total of 30 of these systems, with an additional 38 portable DMSs as a supplementary communication mechanism. The deployment methodology for the smart zones was to allow a group of the devices (typically three), to communicate wirelessly via spread spectrum technology. Each hub was then connected back to the regional TMC via a leased T-1 line. The locations of the Smart Zones and hubs were in part driven by the line-of-sight requirements and the reduction in bandwidth as transmission distances increased. Typically, the distance between a Smart Zone and the corresponding hub was less than 2 miles. The deployment methodology for the portable DMSs utilized cellular digital packet data services from a wireless provider.

The CCTV installations in the Smart Zones encoded the video using Motion JPEG (Joint Photographic Experts Group), at a rate of 15 frames per second and a resolution of 352×240 pixels. The resultant stream consumed an average bandwidth of 384 kilobits per second (kbps). The serial data produced by/destined for the DMS and radar detector were sent through a terminal server, which converts serial data to Internet Protocol (IP) packets and vice versa.

Due to the duration of this particular project, the central TMC was constructed in leased facilities near the work zone, which significantly reduced the cost of leased telecommunication lines. The author provides significant discussion on the network construction within the TMC, including segmentation via routers and virtual local area networks, security, and power backup.

While this particular application was for a long-term (8 years) work zone, several of the conclusions reached during the project are viable for shorter-term projects, including:

- Highly integrated portable devices are effective for work zones.
- Network topologies including wireless links, hubs or collection points, and higher bandwidth transmission links are a feasible design for providing communications.
- IP-based video compression is an effective technique to significantly reduce bandwidth requirements for video transmission.

Security and power backup considerations are necessary for many deployments, to preserve the integrity of the data and direction to the public.

CHAPTER 3. WORK ZONE ITS NEEDS ASSESSMENT

INTRODUCTION

This chapter reports results of the Task 2 work zone ITS needs assessment. The objective of Task 2 was to compile a needs assessment based primarily on a survey of TxDOT personnel, supplemented with findings from the Task 1 literature review. The goal of the survey was to determine:

- What ITS components TxDOT districts are currently using in work zones.
- The benefits being experienced.
- If there are any warrants or criteria that districts have developed for the application of ITS to work zones.

Appendix D contains the survey. Researchers condensed the information gathered by the survey into a needs assessment that helped to identify the intended functions of the work zone system. Example functions that researchers hoped to discover included:

- Informing motorists of current work zone travel conditions.
- Alerting motorists to stopped vehicles or queuing vehicles.
- Providing information for motorists to make an alternate route choice.
- Providing travel time/delay information through the work zone.

WORK ZONE ITS SURVEY

A discussion of the survey questions and the results gathered from TxDOT respondents follows. Question 1 of the survey focused on determining what types of ITS components are currently used within work zones. The survey had a set of possible answers and checkboxes, including an optional box that allowed respondents to answer with any items not presented in the checklist.

Part (a) of Question 1 pertained to real-time information for motorists, with choices including:

- Speed advisory messages:
 - Speed display trailers.
 - Variable message signs (VMSs).
- Travel time information:
 - Specific travel time.
 - General travel time (e.g., expected delays).
- Delay warnings:
 - Smart system to predict delay of x minutes.
 - Categorized as moderate delays, long delays, etc.

- Dynamic queue warnings for slowing or stopped vehicles.
- Incident detection.
- Internet website to disseminate work zone information to the public.

Figure 22 shows the tally of responses from the 10 districts that answered the survey. Virtually all of the districts (9 out of 10 responding) use speed advisory messages. The response listing for speed advisory messages includes both of the categories offered in the survey (i.e., speed display trailers and VMSs). Researchers received a total of seven responses indicating the use of a speed display trailer and nine indicating the use of a VMS. Each of the seven districts that use speed display trailers also uses VMSs.

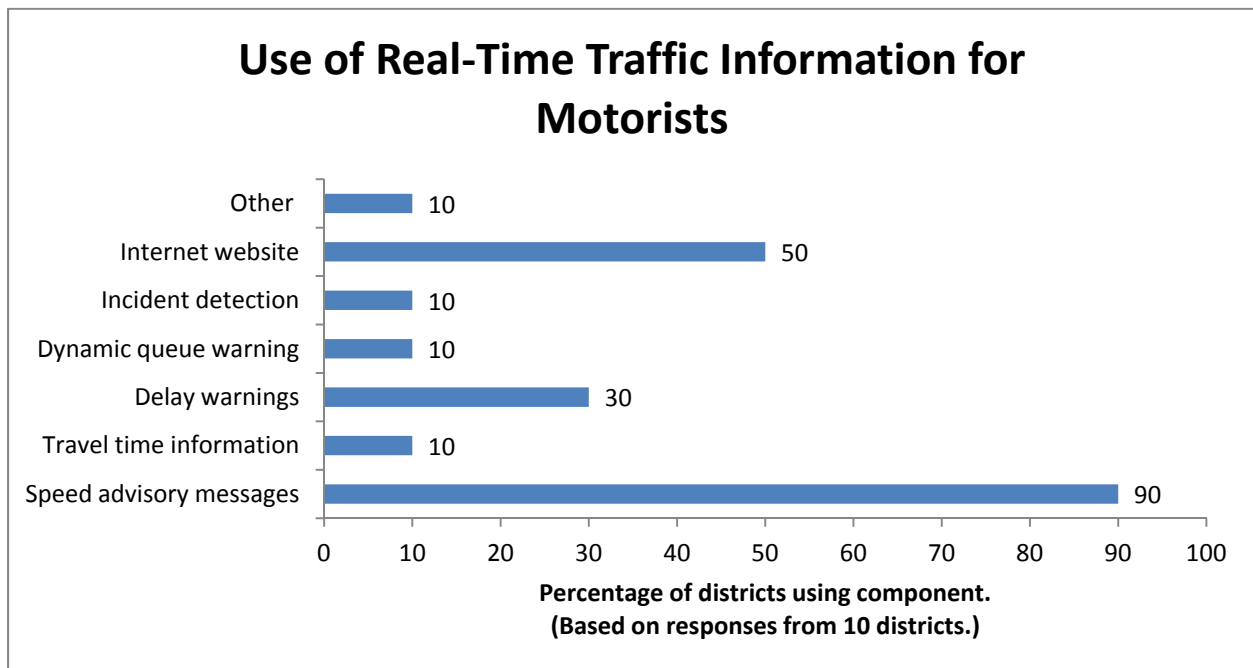


Figure 22. Response to Question 1a of TxDOT District Survey.

Figure 22 shows that one of the responding districts indicated the usage of another ITS component for real-time traffic information dissemination—the use of Twitter, the social networking and micro-blogging site. It accepts input messages up to 140 characters in length and allows people to follow or receive these messages on an as-desired basis. The use of social networking within transportation is steadily increasing and may represent a fundamental shift in information transfer in the future.

Part (b) of Question 1 pertained to the use of merge-control systems with choices including:

- Early merge.
- Late merge.
- Dynamic merge.

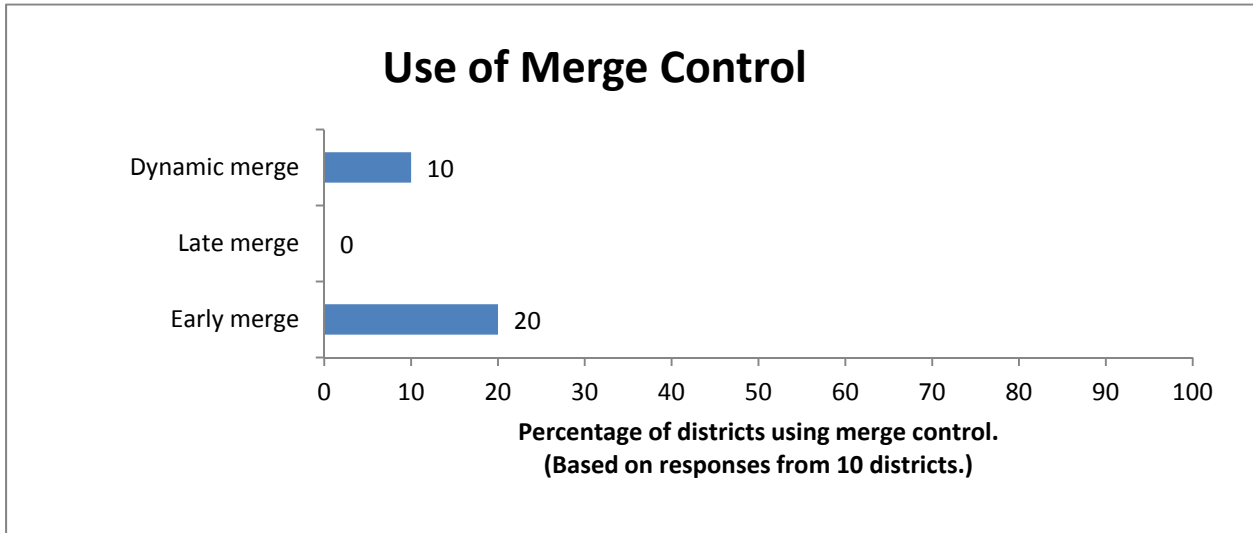


Figure 23 illustrates that among the responding districts, the use of a merge control strategy is not significant. The two districts indicating the use of early merge are different from the district indicating the use of a dynamic merge, which may indicate the chosen strategy is more by preference as opposed to being dictated by the type of work zone situation.

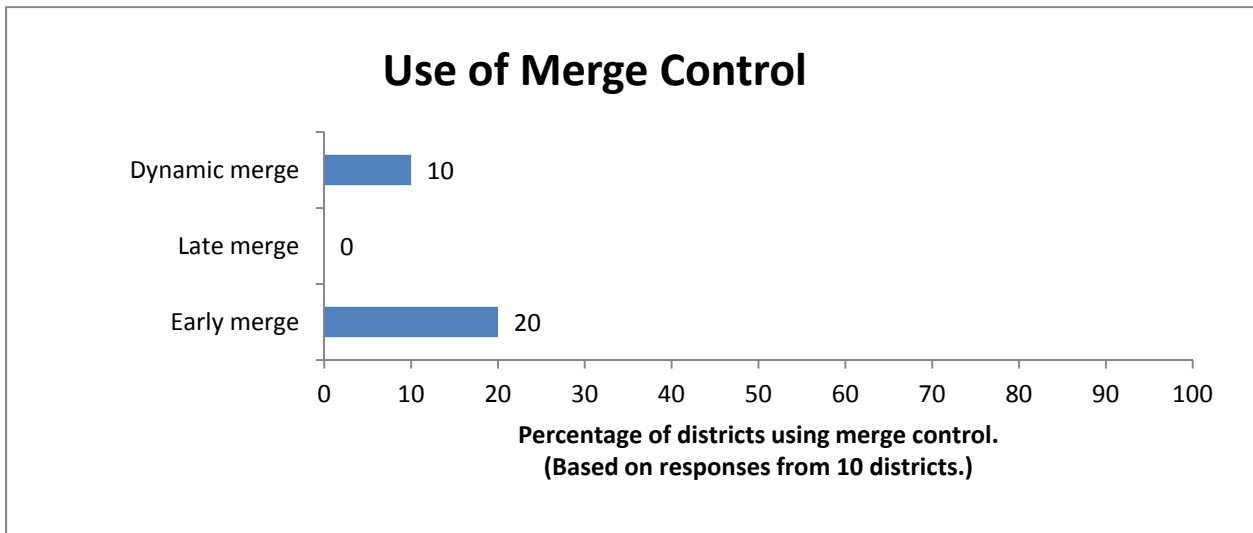


Figure 23. Response to Question 1b of TxDOT District Survey.

Part (c) of Question 1 pertained to the use of alternate route information with choices including:

- Never.
- When travel time $> T$ minutes.
- When average speed $< V$ mph.

In both of the last two bullets, T and V were boxes that the respondents selected to indicate their criteria (e.g., 10 minutes or 30 mph).

Figure 24 indicates that over half of the responding districts do not employ alternate route information. One response indicated the use of a delay warrant exceeding 30 minutes to provide alternate routes. No responses indicated what criteria they used as a basis for average speed. The 30 percent of districts responding with an “Other” indicated the use of an alternate route for a total road closure.

Question 2 of the survey asked respondents if they felt that the typical work zone would benefit from ITS technologies. This was essentially a reality check on the premise of the project efforts by determining whether work zone decision makers would support the use of ITS technologies within work zones. The results, shown in Figure 25, indicated that the majority of the respondents (7 out of 10) would expect benefits from ITS deployments in work zones.

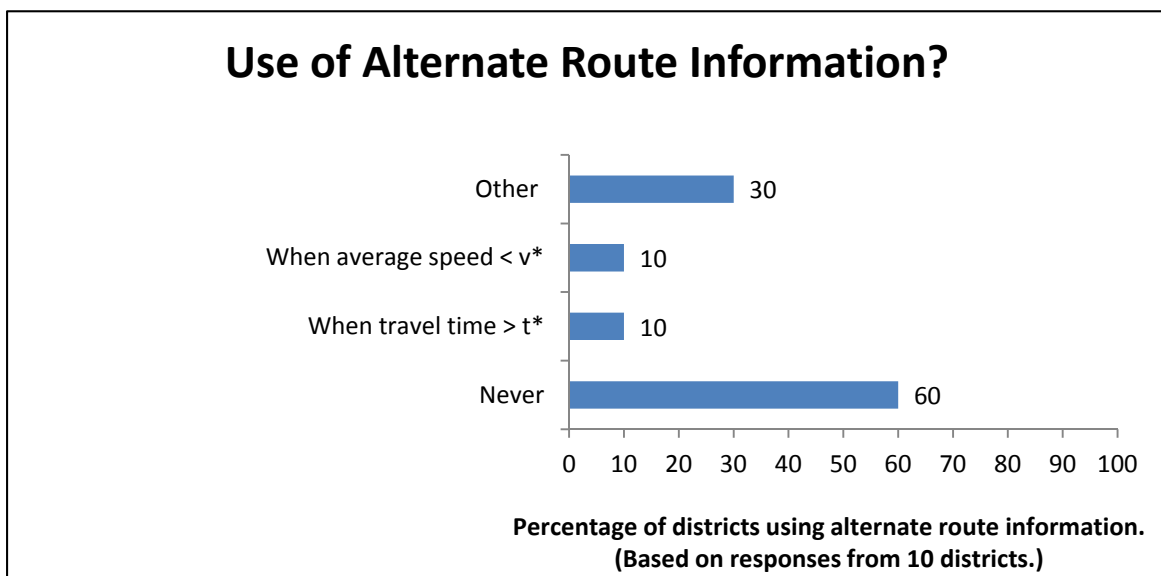


Figure 24. Response to Question 1c of TxDOT District Survey.

The second part of question 2 asked survey respondents to specify what they felt those benefits would be. The initial choices were:

- Reduced congestion.
- Shorter travel times and delays.
- Improved traffic safety (less crashes).

They also had a choice of Other where they could specify additional benefits.

Figure 26 shows the tally of responses to the breakdown of benefits. Half of the responding districts expect improvements in safety and reduction in congestion, while 4 of the 10 respondents expect shorter travel times and delays. Two responses were received under the category of Other. One response indicated the use of alternate routes, while the second response indicated improved communication with drivers.

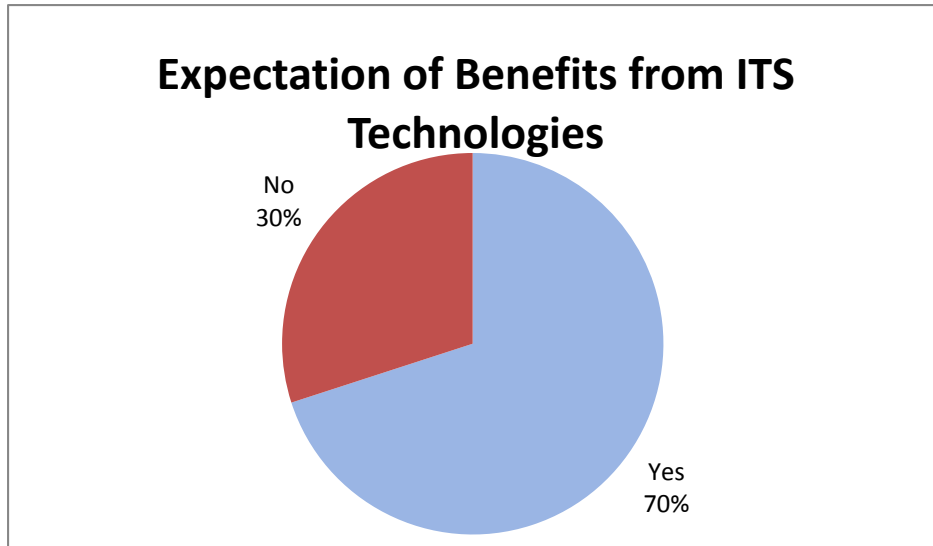


Figure 25. Response to Question 2 of TxDOT District Survey.

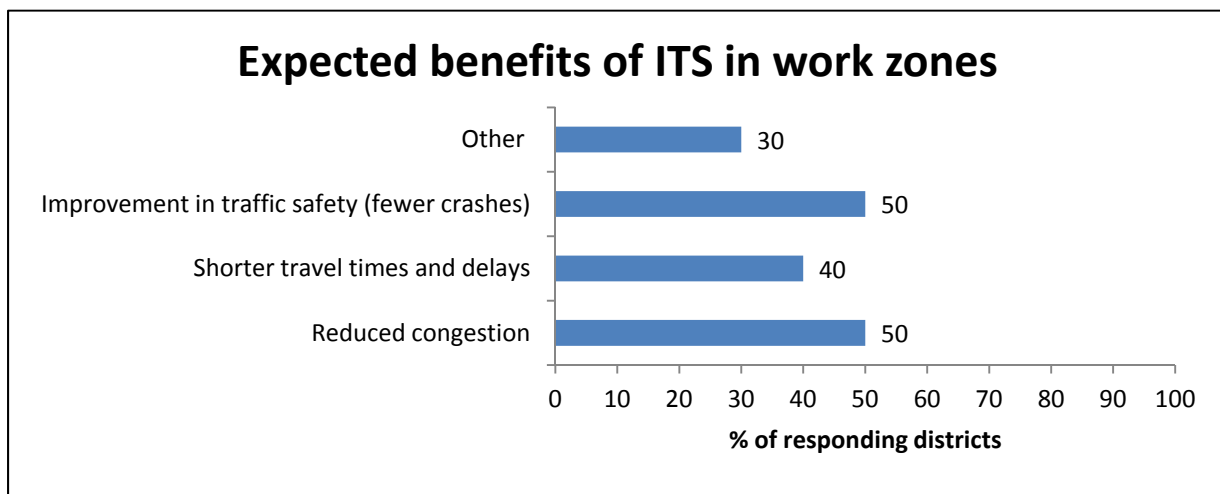


Figure 26. Response to Question 2a of TxDOT District Survey.

Question 3 of the survey asked respondents to specify the warrants, or criteria, under which various ITS applications would be warranted. The applications detailed in the question included:

- Provision of real-time motorist information.
- Use of queue detection and warning system.
- Provision of alternate route information.

For each application, respondents could indicate a warrant (criteria) of:

- Daily traffic volume (AADT) greater than X number of vehicles.
- Length of work zone greater than Y number of miles.
- Other (criteria specified by respondent).

Figure 27 shows the compilation of responses from the question. Half of the respondents indicated that AADT or volume criteria would be a warranting criterion for real-time motorist information or queue detection systems. The values provided for the volume threshold ranged from 20,000 to 75,000 vehicles per day for real-time information and 20,000 to 100,000 for queue warning. Both sets of responses showed a wide spread, and there was no significant clustering of responses around any particular value or range. While the responses for alternate route information indicated a lower percentage of districts that would implement this option (3 out of 10), the volume range was the same, ranging from 20,000 to 100,000 vehicles per day.

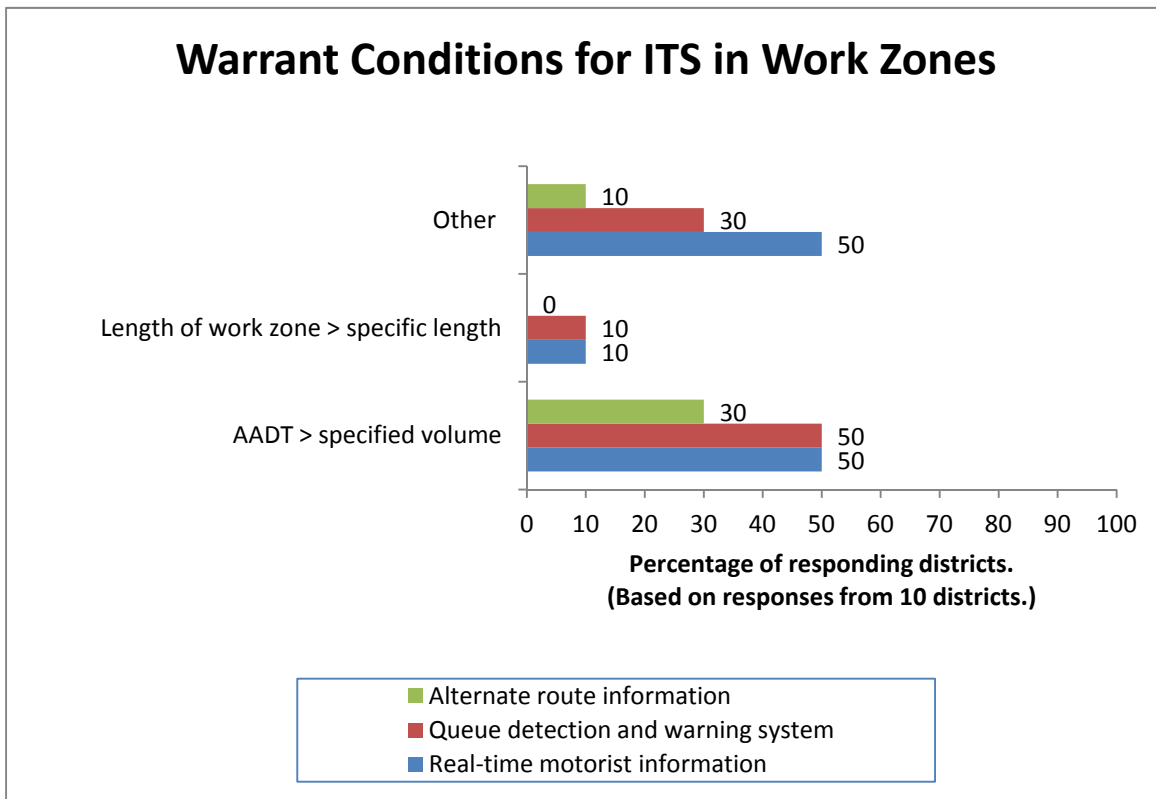


Figure 27. Response to Question 3 of TxDOT District Survey.

Very few respondents indicated that the length of the work zone would be a warranting criterion for any ITS application. Only one respondent (10 percent) indicated length as a criterion for either queue detection or real-time motorist information. In both cases, the suggested criterion was a work zone longer than 5 miles.

A number of other warrants or criteria were suggested as implementation triggers for various ITS applications in the work zone. Of particular note, and received from a number of respondents, were conditions that would reduce the number of lanes and/or violate driver expectancy. Other triggers included:

- High-speed approaches.
- The expectation of a complete stop situation.
- The average speed on the approach to the work zone.
- The use of flaggers.

In general, these criteria were most prevalent for implementing real-time motorist information.

The final question on the survey asked respondents if they had work zones that they felt would be suitable for a trial implementation of a particular work zone application. The research team received a number of responses to this question and analyzed the suggestions for potential sites in conjunction with the project leadership from TxDOT. Unfortunately, none of the sites offered by districts were suitable for implementation of ITS within the time frame available. The finding led the research team to propose and the PMC to approve the use of simulation instead of field data collection.

NEEDS ASSESSMENT

The survey responses from the department clearly indicate not only support for ITS applications within work zones but also an expectation of direct benefits. Some applications, such as Internet websites and speed advisory messages, appear to be almost standard practice based on the 10 responses. It is therefore unnecessary for the project to focus on those areas since there would be little additional knowledge or information gained to promote their use.

The benefits, however, of focusing on the implementation of applications that are currently second-tier could be substantial. Given the information in the Chapter 2 literature and case study reviews, the benefits of applications such as queue warning, incident management, and merge control are real, measurable, and substantial. What is currently lacking, however, is a clear and consistent criteria-based methodology for assessing the benefits of their implementation. It is here that the project can make the largest advances in the state of the practice by the department. Chapter 6 presents guidance for application of ITS treatments.

As both the survey and the literature show, an ITS application such as the use of an alternate route appears to be more of a special case situation, predicated first by the availability of the route, and second, by the ability of the route to be safe, simple, and capable of handling the additional traffic volume.

CHAPTER 4. TECHNOLOGY REVIEW

INTRODUCTION

The needs assessment covered in Chapter 3 and the literature and survey findings from Chapter 2 served as the basis for a market technology review. The needs assessment provided information on some of the functions and capabilities that managers need to increase safety and efficiency in work zones. The market review evaluated what is currently being offered in the marketplace, including:

- The systems and vendor capabilities.
- The technology employed.
- Potential for integration into a regional TMC.

The task produced a market snapshot matrix that can be used to match traffic management needs with solutions. This chapter adds to the earlier information by investigating how the technologies were applied in some case studies in different states. The task examined the following areas:

- Approaches/solutions promoted by smart zone vendors.
- Technology being applied to deliver their solution.
- Data elements being measured or calculated.
- Integration potential for the solutions, including a look at data management and communication needs.

The review paid particular attention to complete, turn-key solutions offered by vendors. These solutions require the vendor to deploy and operate the equipment and provide data from the work zone equipment to the operating agency. It is these data that will be considered in Task 6 and targeted for integration either into a TMC or used more locally.

ITS COMPONENTS AND SYSTEMS

This chapter provides case studies from literature sources that used components or systems reported in Chapter 2. It then uses all information to develop solutions for TxDOT.

Case Studies

This section provides information on 10 SWZ case studies in eight states and one other jurisdiction: Arizona, Arkansas, California, District of Columbia, Georgia, Illinois, New Mexico, North Carolina, and Texas. The types of work zones vary from major interchange reconstruction to widening of two-lane roadways, and include both rural and urban settings. They used a variety of different ITS components and treatments.

Arizona DOT State Route 68

The Arizona Department of Transportation (ADOT) used ITS to support work zone operations during the reconstruction of SR 68 in northern Arizona (see Figure 28). SR 68 is a critical highway in northern Arizona serving nearby cities of Laughlin, Nevada, and Bullhead City, Arizona. Traffic is generally steady throughout the day from early morning to late evening. This project involved widening about 13.5 miles of an existing two-lane roadway into a four-lane divided highway (57).

One of the more unique features of this project involved a \$400,000 bonus fund to encourage the design-build contractor to maintain a target travel time through the construction zone. In addition, if these bonus funds were depleted during the course of the project, the contractor would be charged additional fees incurred for continuing to exceed the 27-minute target travel time. The project used an automated license plate recognition (ALPR) system to determine actual travel times through the work zone. Other technologies considered for measuring travel time included cell phone tracking, vehicle probes, and radar systems. ADOT allowed the contractor to choose the technology.

Figure 29 shows the camera and light source used to read license plates. The project required two systems at each end—one set for each direction of traffic flow. The trigger for the camera system was an inductive loop in each lane. Sending ALPR data utilized point-to-point microwave communication technology that was already available at the project site. Its line-of-sight requirement dictated having repeaters. The primary maintenance issue with these cameras was high winds causing them to move and not be oriented correctly. Detection of the problem usually surfaced when ADOT personnel noticed data errors.



Figure 28. Map Showing Route 68 Location (57).



Figure 29. Light and Camera Used for License Plate Recognition (57).

Results indicated that the system functioned as intended, reading about 60 percent of license plates and matching about 11 percent of the ones photographed. ADOT considered this level of performance to be adequate. One problem near the beginning of the project was a power surge that caused damage to the 12-volt power supply, resulting in it being off-line for about 30 days. Finding that the area was prone to power surges prompted installation of surge protection equipment. For the most part, the contractor was able to maintain the required speeds through the work zone. The contractor was charged almost \$15,000 against the \$400,000 travel time bonus incentive, so the contractor earned 96 percent of the bonus fund (57).

Arkansas Interstate Rehabilitation

The Arkansas State Highway and Transportation Department (AHTD) began a massive interstate rehabilitation program (IRP) to rebuild 380 miles (60 percent) of Arkansas' total interstate mileage. This program was scheduled to run from 2000 to 2005. AHTD chose to use an automated work zone information system (AWIS) at five IRP projects to improve work zone safety, increase merging and speed limit compliance, and increase driver awareness. The main objectives for choosing this system were to:

- Reduce rear-end and other crashes.
- Improve work site safety.
- Provide motorists with real-time information about lane closures.
- Improve incident response.
- Improve congestion management (58).

AHTD investigated two AWIS types: Scientex Corporation's ADAPTIR and ASTI Transportation Systems' computerized highway information processing system (CHIPS). Both systems consisted of traffic sensors and changeable message signs equipped to communicate with a central computer via radio to provide traveler information. Each system had to send notification to project personnel, media outlets, and emergency services.

Each of the sites had both common and unique features. The site in Lonoke County (central Arkansas) was rural, requiring queue detection equipment that would reduce rear-end collisions. A second site in North Little Rock was urban, requiring equipment that would provide information to motorists to manage congestion and improve incident response. The evaluation conducted by AHTD focused on problems encountered, accuracy, and effectiveness (58).

The Lonoke County system (ADAPTIR) consisted of:

- A central system controller.
- Two HARs, five traffic sensors.
- Five CMSs.
- Two supplemental speed stations.

At a cost of \$322,500, the system was supposed to display downstream traffic speed information followed by delay information with 40 preset scenarios. The original plan was to display REDUCE SPEED TO XX MPH messages followed by YY MINUTE DELAY messages if speed differentials between monitoring stations reached 10 mph. Below this differential, the message would only pertain to delay. The system had a 600-second cycle time. Delays of 20 minutes or longer prompted the system to send messages to pagers worn by contractors and selected AHTD engineering staff (58).

Problems occurred with the RTMS detectors, with the delay algorithms, with the cycle length, and with some of the communications functions. RTMS detectors were replaced by Doppler radar units (brand not specified). AHTD dropped the delay calculation due to inaccuracies and replaced the message to motorists with two that simply said EXPECT DELAYS or EXPECT LONG DELAYS. The result was fewer complaints from motorists after the change. Due to the dynamic nature of the work zone environment, the 600-second cycle time was too long for optimum accuracy, so AHTD reduced it (value not specified). Finally, the communications issues had to do with the central system controller not being able to contact the HARs in some cases. Delays of up to 23 minutes occurred. Pagers did not function well in this rural area, so AHTD discontinued their use.

Evaluations of both system accuracy and effectiveness were disappointing. As noted earlier, delay estimates were off, prompting a number of complaints even though discrepancies were as low as 5 minutes. The system overestimated delay by as much as 12 minutes and 35 seconds and underestimated delay by as much as over 2 hours. Effectiveness in terms of fatal crash reductions compared the Lonoke site with two control sites without the AWIS. The Lonoke County site showed a reduction in fatal crashes, but its rear-end crash rate results were mixed—better than one site and worse than the other. Incident response time did not appear to change.

Problems at the North Little Rock site (using the CHIP system) were primarily with communications issues. Cell phone communication with the HARs experienced cell carrier drops

in service when motorists used their cell phones during a queue. The contractor found that switching to landline service improved the situation. The contractor remedied a pager issue by switching carriers. The master computer for the system exhibited problems with locking up, so the contractor added a second computer to do things like handle sending emails and updating web pages. System accuracy at the NLR site was based on comparisons of messages displayed to motorists and actual conditions. Comparing results from 77 travel time runs, 90 percent of the messages matched actual conditions. For effectiveness of the system, there was a direct correlation between traffic volumes counted on a parallel route and messages displayed on the CMS (58).

For example, westbound traffic on the parallel route increased by a factor of 2 for all vehicles and a factor of 9 for trucks when the CMS displayed messages such as SLOW TRAFFIC AHEAD—BE PREPARED TO STOP and FIVE MILE BACKUP AHEAD—BE PREPARED TO STOP. Comments from the AHTD site engineer were favorable.

The conclusions section of this article indicated that with each successive installation of AWIS, there were improvements in the effectiveness, reliability, and practicality of the systems, resulting in greater confidence with AHTD personnel and the motoring public. The Lonoke County system was the first, whereas the NLR system was the fourth. There were three final conclusions:

- Email communications were effective for this application.
- Traffic sensors need to be placed throughout the length of the project.
- Reporting queue lengths instead of delay times resulted in fewer motorist complaints and improved satisfaction among road users (58).

I-15 near Devore, California

In 2004, The California Department of Transportation (Caltrans) rebuilt a heavily traveled 2.8-mile segment of badly damaged concrete lanes by applying an innovative, fast-track reconstruction program on I-15 in the city of Devore in southern California. Caltrans rebuilt the pavement in two single-roadbed continuous closures (also called extended closures) totaling 210 hours, using counterflow traffic (opposite direction to the main traffic flow) and 24-hour-per-day construction operations. Using the more traditional nighttime-only closures would have required 10 months' time instead of the actual rebuilding time of 19 days, with each extended closure for one roadbed lasting 9.5 days. Figure 30 shows the location of the reconstruction project (59).

Caltrans used other innovations on this I-15 Rapid Rehabilitation (Rapid Rehab) project to expedite the process as follows:

- Automated work zone information systems to update travelers with real-time work zone travel information.

- Web-based information systems for disseminating project updates and surveying public reactions.
- An outreach program to gain public support.
- Incentive/disincentive provisions to encourage the contractor to complete the closures on time (59).



Source: Google Maps.

Figure 30. I-15 Project and Nearby Highway Network (59).

Project engineers used analysis software, including traffic simulation models, to develop an optimal and economical scenario for rehabilitation closures, a construction schedule, and a traffic management plan. They selected the most economical closure scenario based on the analysis software’s estimates from the perspective of closures, schedule, traffic delay, and total cost.

The Devore corridor of I-15 experiences consistently high weekday commuter peaks, including heavy truck traffic, and an even higher volume of 120,000 vehicles per day average daily traffic on weekends. The project scope called for replacing severely deteriorated concrete slabs and base pavement with a new cross-section of 11.4-inch doweled slabs using rapid-strength concrete and a 5.9-inch asphalt concrete base on top of the remaining aggregate base or native material.

Innovation and Technology. This project combined conventional construction materials and operations with state-of-the-practice technologies to expedite construction and minimize traffic impacts. Additional project features that contributed to traffic control included the following:

- A project command center facilitated coordination between construction, traffic, design, and public affairs and with other agencies. The command center used closed circuit television to enable remote monitoring of traffic and construction.

- The Construction Zone Enhanced Enforcement Program provided \$300,000 to improve traffic control and enforcement in the work zone.
- Caltrans shared information and received constructive feedback from the local community.
- Caltrans provided incentives to promote ridesharing, adding 14 buses to existing lines.
- The Freeway Service Patrol tow-truck service removed 1243 disabled vehicles from the work zones at a cost of about \$100,000 (59).

The Devore Project was the first implementation in California of an automated information system in work zones for this type of project. Caltrans planned for a 24-hr command center as part of the pre-construction planning. It had several monitors displaying real-time data that were available to the public, so motorists had access to real-time information on travel and detour routes. The travel information was provided to roadway users on permanent and temporary changeable message signs strategically placed at key decision points. The project website also provided information in the form of a traffic roadmap, which was part of an interactive public outreach campaign.

Public Outreach. Convincing motorists to use alternate routes or adjust their commuting modes to avoid traffic disruption during construction was critical to the project's success. Prior to construction, large employers and affected businesses were informed through project fliers, public meetings, and intensive media outreach. Project planners hoped for a 20 percent reduction in peak-hour traffic demand, but they acknowledged the lack of detour routes close to the work zone and the uniqueness of the I-15 Devore corridor (59).

Caltrans implemented a project information telephone hotline, a media campaign, and a project information website. Caltrans printed and disseminated a comprehensive project brochure and distributed construction flyers. Email contact included a construction advisory electronic bulletin and a fast-fax system for project alerts. All these efforts focused on informing the public about the project and providing area travelers with the information required either to divert to alternate routes around the work zones or to time their trips to coincide with construction schedules.

Use of the Internet. Project planners initiated the project website 3 months before construction started in October 2004 to provide up-to-date, comprehensive project information. Upon visiting the website, users would see "I-15 Devore Rapid Rehab Project," which appeared as the first headline on the Caltrans District 8 homepage. It linked this site with those of neighboring local agencies and the surrounding three Caltrans district offices in southern California. Caltrans kept the website updated with the latest information on detour routes, traffic control plans, real-time travel information, construction progress, press releases, and used fast-faxes for project updates (59).

Caltrans met its two critical traffic management goals—reducing overall traffic volume through the work zones by 20 percent and reducing the maximum peak-hour delay by 50 percent. Early predictions placed delays for the extended closures at 90 minutes, but in reality, the maximum peak delay was 45 minutes on weekdays.

Traffic diversions significantly reduced demand through the work zones. Eastbound I-10 served as the northbound I-15 detour, resulting in a 10-percent daily traffic volume increase, reaching as high as 36 percent during morning peak hours. Southbound I-215 served as the southbound I-15 detour, resulting in a 15 percent daily volume increase.

Seventy percent of the respondents to the post-construction survey expressed support for Rapid Rehab projects, indicating that the California public is willing to bear increased traffic delays for a short period in exchange for compressed construction schedules.

Through a combination of diversions and travel mode changes, Caltrans met the preconstruction goal of 20 percent reduction in traffic. Only 24 percent of drivers responding to surveys did not change travel plans based on Caltrans information compared to 61 percent of respondents in the before-construction period. Forty percent of respondents reported that they adjusted their departure times based on Caltrans outreach efforts, and 32 percent changed their route to utilize detours around the construction. The comprehensive public outreach program was responsible for the changes in public attitudes (59).

Caltrans also employed an AWIS for this I-15 project at Devore, as Figure 31 illustrates. A preliminary traffic analysis using the Highway Capacity Manual Demand-Capacity (D-C) Model (60) indicated that a 20 percent reduction in traffic would result in 45-minute delays compared to 95 minutes with a 10 percent reduction. Caltrans implemented the AWIS to help achieve this level of reduction. Caltrans posted probe vehicle measurements of travel time on the project website and on CMSs (61).

The AWIS consisted of three major components:

- Traffic monitoring devices (RTMSs).
- The portable CMS.
- The server station, which estimated travel time.

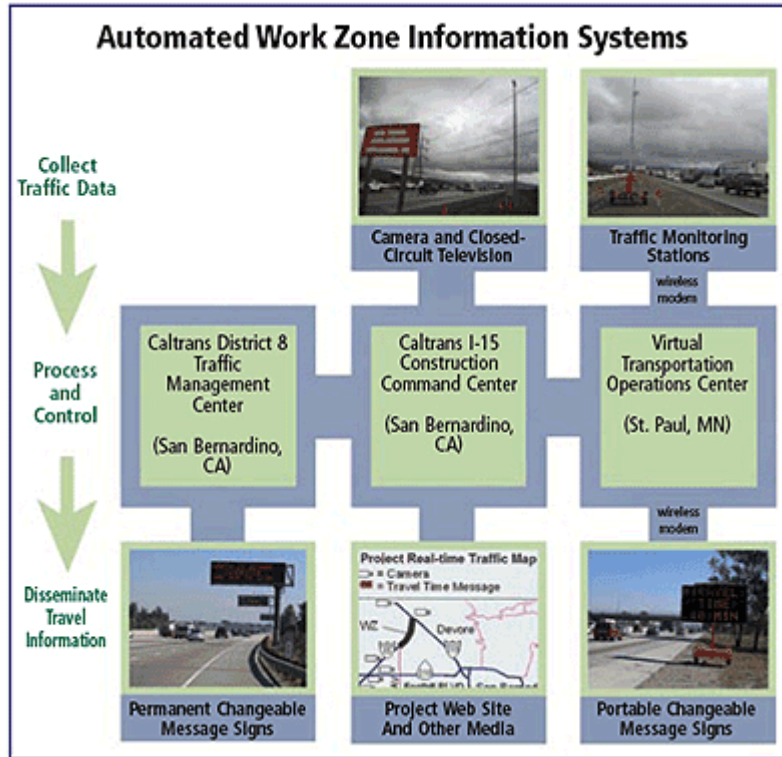


Figure 31. Automated Work Zone Information Systems (61).

There were three monitoring stations northbound and two for southbound traffic, located at about 1-mile intervals upstream of the construction zone. The equipment list also included three CMSs for northbound traffic and one for southbound. The contractor positioned the CMSs upstream of the junction with I-15 to provide advance notice to motorists who might want to detour around the work zone. Travel times measured by the field system compared well with those determined using probe vehicles. For example, the average measured travel time using seven samples for I-15 southbound during the morning peak was 34.7 minutes (standard deviation of 4.5 minutes), while the average estimated travel time was 36.4 minutes (standard deviation of 6.9 minutes). For the northbound direction, the average measured travel time was 51.3 minutes (standard deviation of 20.4 minutes), and the estimated travel time was 45.0 minutes (standard deviation of 17.8 minutes). The measured reduction in traffic was 19 percent southbound and 16 percent northbound during weekday closures. These values were close to the goals initially set, resulting in an estimated traffic delay reduction from 95 minutes to about 50 minutes. The resulting estimated road-user cost savings were about \$3.8 million (61).

In 2006, the District of Columbia Department of Transportation (DDOT) installed ITS components on a 7-mile stretch of Highway 295 (Kenilworth Avenue) in northeast Washington, DC, with additional components on adjacent routes. Kenilworth Avenue is a six-lane barrier-separated freeway serving as a link between other major corridors within the District of Columbia. Traffic volume on this segment exceeds 100,000 vehicles per day. DDOT installed

the system to mitigate congestion and provide real-time information to motorists in the field and via an Internet site. The primary goals for installing the system were to monitor conditions in real time and improve mobility and safety through the work zone. DDOT anticipated that lane closures would produce abnormally long queues and create the potential for crashes outside the work zone. The system provided real-time delay and speed information based on predetermined delay and speed thresholds and could recommend alternate routes via dynamic message signs if needed during congested conditions (62).

The primary objectives of this system were to:

- Reduce work-zone-related congestion.
- Provide real-time delay and speed information to motorists.
- Provide information to commuters for trip planning and to DOT personnel for condition and system monitoring via the website.
- Build public confidence in real-time traveler information.

Findings. The analysis of queues before and after implementation was inconclusive. There was a large difference between the estimated and observed queue lengths on nearly all of the data collection days (based mostly on recurring congestion and not due to the work zone). Traffic diversion was a different story—volume levels changed significantly when the system posted delay information and recommended that motorists divert to alternate routes. On one occasion, the system observed traffic volume reductions of 90 percent. Overall, the data indicated a range of 3 to 90 percent lower mainline traffic volumes, with an average 52 percent reduction. The data available did not facilitate determining what portion of the mainline volume was due to diversion versus demand reduction versus congestion (62).

I-20 Reconstruction in Augusta, Georgia

This project consisted of widening 6.25 miles for additional lanes along I-20, adding collector-distributor lanes along eastbound and westbound I-520 and eastbound I-20, and reconstructing the I-20/I-520 interchange. This interchange improvement included adding two flyover ramps and a grade-separated interchange at a nearby intersection. The contract award was in April 2007, and the project had an expected duration of 3 years. Means to mitigate impacts on traffic movement included off-peak and night operations as well as a real-time work zone information system to keep motorists informed of traffic conditions. This information was available on roadside message boards and on an Internet website. The real-time traffic system consisted of 20 PCMSs, 20 portable traffic sensors (details not specified), and a project website. Figure 32 and Figure 33 indicate the information that was available to motorists on the website and on the CMSs along the roadway. PCMSs provided speed, delay, length of traffic queue, and lane closure advisories to motorists, whereas the website depicted the entire project area, indicating current traffic conditions using color coding. The available information did not discuss the effectiveness of these tools or the costs (63).

Reconstruction of I-55 Lake Springfield Bridge in Illinois

This case study applies to the use of ITS for Illinois Department of Transportation (IDOT) work zone operations for a major bridge and highway reconstruction project on I-55 south of Springfield. The ITS application, called the Real-Time Traffic Control System (RTTCS), covered the northbound and southbound approaches to the work zone, extending for about 40 miles along I-55. Detours along bypass routes were apparently not an option for this construction since none were mentioned in the available information (64).

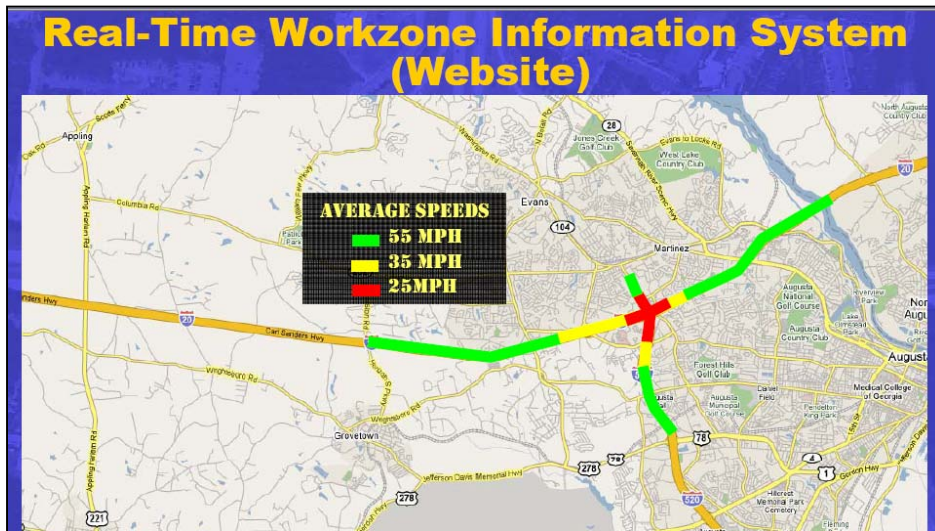


Figure 32. Website Display for Real-Time Work Zone Information System (63).

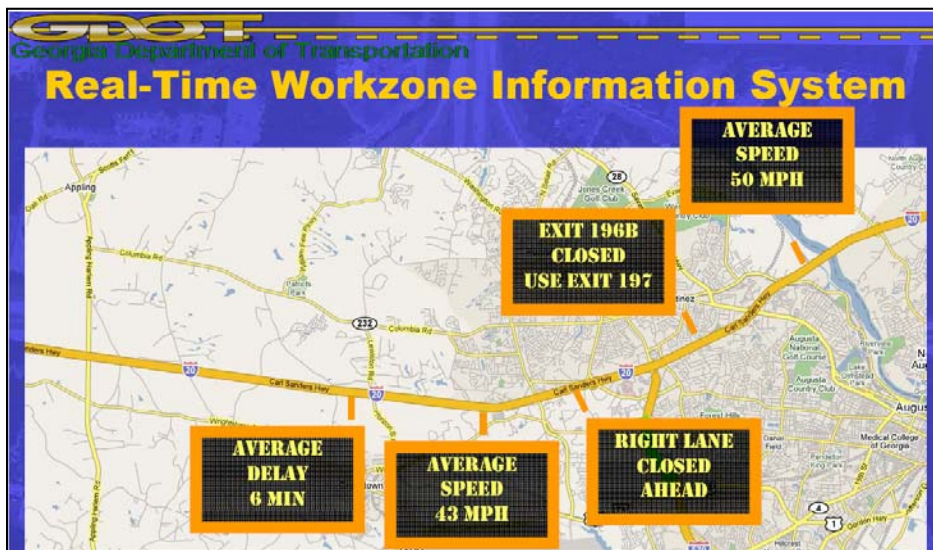


Figure 33. Example Motorist Information Displays (63).

The RTTCS functionality included:

- Acquiring and processing traffic data (e.g., speeds) in all weather conditions and selecting messages for DMSs without human intervention.
- Displaying independent advisory messages on each DMS based on conditions near specific DMSs.
- Operating continuously for the duration of the project.
- Allowing IDOT staff to manually override motorist information messages for a user-specified time.
- Providing current traffic condition information via the Internet using colors to depict traffic conditions.
- Archiving camera imagery.
- Displaying sensor data and imagery at a central location (64).

The prime contractor leased the system from a firm specializing in work zone systems, claiming significant cost savings. This option also placed responsibility for maintenance of the RTTCS components on the vendor. IDOT's contract required the vendor to dispatch sufficient resources within 2 hr of notification of a problem to correct deficiencies and to complete the remedy within 12 hr. The components of the RTTCS included the following:

- Seventeen remotely controlled portable DMSs.
- Eight portable traffic sensors (details not specified).
- Four portable CCTV cameras.

The roadside systems operated from batteries and used solar panels to recharge the batteries. The RTTCS is a good candidate for rural applications where utilities are not available or where frequent changes in roadway alignment occur. All components were electronically linked to a central base station using wireless communications (64).

IDOT found that the system worked well with little downtime and indicated that it would use RTTCS again. However, IDOT did not perform an official evaluation of the results. IDOT attributed the lack of severe congestion through the work zone to the absence of major incidents and a reduction in enforcement ticket-writing, which typically causes traffic delays.

IDOT reported no significant traffic backups while the RTTCS was in place, despite the relatively high traffic demand of about 41,000 vehicles per day. Of the two crashes known to occur during the construction activity, one resulted from driver fatigue and the other involved driving while impaired. RTTCS DMSs displayed the number of citations issued in the work zone, which might have played a role in the downward trend in the citations issued following the displayed information (64).

IDOT did not receive significant positive or negative public reaction to the RTTCS. The project website received 2400 hits during the course of the project, which is higher than the number typically received by IDOT construction project websites.

In conclusion, IDOT staff reported a high level of satisfaction with RTTCS. Any downtime was typically attributed to recalibration of the system following movement of the sensors. The system enhanced IDOT incident detection in the work zone, though that was not the main goal or function of the system (64).

Interchange Reconstruction in Albuquerque, New Mexico

The New Mexico State Highway and Transportation Department (NMSHTD) rebuilt the “Big I” interchange (intersection of I-40 and I-25) in Albuquerque to improve safety and capacity. The 2-year project, involving 111 lane-miles of freeway, began in June 2000. It involved 45 new bridges and 10 rehabilitated bridges. NMSHTD used an ITS in the form of a mobile traffic monitoring and management system to increase throughput along the extensive construction area. The reasons NMSHTD cited for using ITS were:

- Changes in traffic patterns, alternate routes, and nighttime closures required that motorists have high-quality real-time information on route availability.
- The high volume of traffic moving through the Big I required reductions of about 20 percent to keep traffic moving. Incidents would create additional congestion and would require rapid response to minimize delays. These factors necessitated accurate information provided quickly to motorists to manage traffic through the area (65).

The primary goals of the ITS were:

- To enhance traveler safety.
- To minimize capacity restrictions due to incidents by quicker response to incidents.
- To provide traffic management capabilities and traveler information on traffic routing, detours, and significant incidents (65).

The ITS equipment included a series of cameras and sensors to monitor traffic conditions and detect incidents, along with electronic signs, a HAR, a website, and other media to transmit traveler information. (No additional details were available on the sensors, their placement and use, or how data flowed from sensors to the TMC.) To expedite incident clearance, NMSHTD used its motorist assistance program, which was in existence prior to the Big I project. The Highway Emergency Lender Program (HELP) consisted of two vehicles patrolling the Albuquerque metropolitan area. FHWA provided \$250,000 for purchasing two additional HELP trucks (65).

The NMSHTD chose to purchase ITS components so that the remaining components would continue to function after construction and become a permanent system. The total cost of the ITS components was \$1.5 million. System components included:

- Eight cameras.
- Eight modular (expandable) dynamic message signs.
- Four arrow dynamic signs.
- Four all-light emitting diode (LED) portable DMS trailers.
- Four portable traffic management systems (which integrate cameras and DMS on one fully portable unit).
- Four HAR units.

The system was portable and used wireless communications. The listed components linked electronically to a temporary Big I TMC. NMSHTD employees staffed the TMC and monitored camera displays from 5:00 a.m. to 8:00 p.m. Monday through Friday to detect incidents (65).

Three major benefit areas NMSHTD identified were mobility, safety, and cost savings. Pertaining to mobility was incident response and clearance time, which dropped from 45 minutes (historically) to 25 minutes with the use of the ITS in the work zone. There was also a reduction in travel demand of 15 percent as a result of outreach efforts. There was a 7 percent increase in crashes over the first year of the project, but this increase was smaller than NMSHTD expected due to the complexity of the work zone. Cameras provided views of driver behavior in the work zone and resulted in changes in traffic control if problems were observed. Under the cost savings category, TMC operators could activate pre-programmed message scenarios with a few keystrokes without leaving the TMC. System information allowed emergency responders to assess incident severity and send the appropriate equipment with less delay.

Public acceptance of the system (including ITS components) was favorable. More than 60 percent of responses to a survey by NMSHTD indicated that motorists were pleased with the accuracy and timeliness of the information provided (65).

North Carolina Smart Zone

The initial I-95 Smart Zone deployment on I-95 near Fayetteville involved:

- Six speed sensors.
- Eight CMSs (two used on alternate routes).
- Six cameras (with pan-tilt-zoom).
- One command center.
- One laptop computer.
- A project website (66).

The cameras were not essential for system operation but were intended for North Carolina DOT (NCDOT) observation purposes only. Specific hardware used along the roadway included solar-powered CMSs with RTMS and speed sensors. Apparently, NCDOT used the RTMS detectors to

get vehicle counts and used a separate sensor (e.g., Doppler radar) for speed. The successful bidder on the Smart Zone was Scientex Corporation at a total bid price of \$235,000.

Results indicated that the Smart Zone reduced traffic queues, on average, to 2 miles or less, whereas before deployment, queues exceeded 5 miles. There were no recorded rear-end crashes and no fatalities. The delay information was accurate, although the available information did not give details. There was some utilization of alternate routes, but again, there were no specifics given on percentages or counts. There was significant positive response from the news media and from motorists (66).

Problems with the equipment included equipment malfunction due to lightning strikes and communication problems with cameras. The latter problem resulted in resorting to satellite communications. In the future, NCDOT plans to use an on-site technician to troubleshoot problems as they occur. There is also a need to have the system notify appropriate personnel if a malfunction occurs. This notification might be via pager, email, or cell phone. There are also contractual changes such as reduction of pay for system downtime.

Application guidelines from the NCDOT following completion of one project and planning for two others suggest that:

- Smart Zones work well on rural interstate routes with AADTs up to 55,000 vehicles per day (vpd) with available alternate routes. Interstate rehabilitation projects are ideal for this concept primarily due to their high frequency of lane closure.
- Smart Zones might have application on roadways with higher AADTs (55,000 to 65,000 vpd) rather than restricting lane closures to night only.
- Smart Zones might have limited application on high-volume roadways (above 65,000 vpd) with a few reasonable alternate routes. If recurring congestion is a problem, the technology might provide real-time delay information in lieu of congestion mitigation (66).

I-35 in Hillsboro, Texas

In October 2006, TxDOT implemented an ITS system in a work zone near Hillsboro, Texas. The purpose of this system was to monitor traffic conditions and improve mobility and safety along I-35W, I-35E, and along I-35 to the south of the split. Figure 34 shows the Hillsboro area and indicates the work zone. I-35 splits north of Waco into I-35E to Dallas and I-35W to Ft. Worth. All three roadways are freeways with four lanes, two in each direction, and are otherwise similar. The work zone project was 10 miles in length, began construction in July 2006, and was scheduled for completion in mid-2008. The system provided real-time delay information to motorists based on predetermined speed and occupancy thresholds and recommended alternate routes via DMSs. Three wireless closed circuit cameras provided imagery for monitoring traffic by TxDOT (67).

The work involved reconstructing the main interchange and rehabilitating the pavement and structures along the route. Lane closures were involved, reducing the capacity of the roadway. TxDOT expected long queues and delays, especially along southbound I-35W upstream of the split. Much of the traffic was commuter traffic.

ITS Components. The system consisted of the following components:

- Six solar-powered portable microwave detection trailers (sidefire orientation).
- Six solar-powered PCMSs.
- Three portable video trailers (with cameras).
- A system server, web host, and associated software and equipment.
- A website for use by the general public and TxDOT (67).

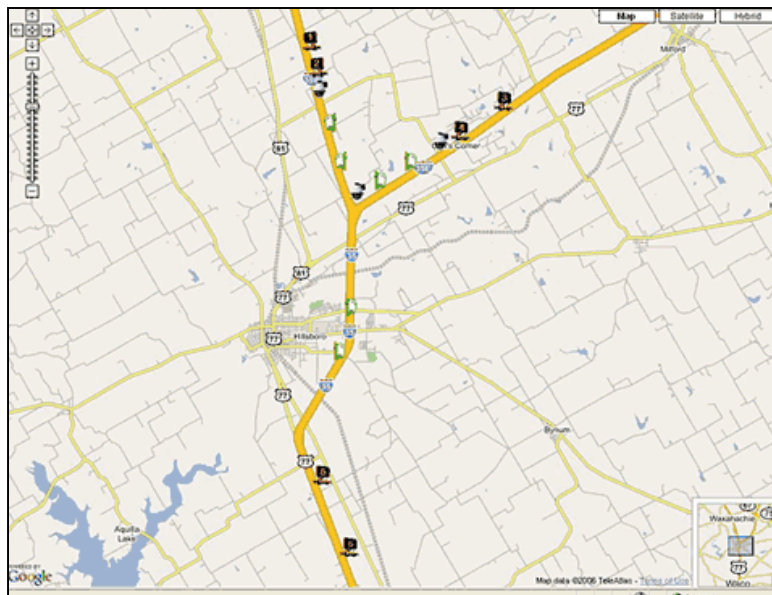


Figure 34. Hillsboro Area of I-35, I-35E, and I-35W (67).

Two sensors monitored traffic on each approach to the work zone and sent messages to two PCMSs based on predetermined speed and occupancy thresholds. TxDOT had the ability to:

- Dynamically adjust queue thresholds.
- Preempt messages.
- Alert appropriate personnel if problems occurred.

Objectives of the ITS system included:

- Provide delay information and route guidance to motorists.
- Reduce demand and congestion by diverting traffic as needed.
- Provide trip planning information to commuters and system management information to TxDOT.

Objectives of the evaluation included:

- Determine traveler response to the work zone information.
- Determine the effect of traveler response on traffic conditions.
- Determine whether the system detected congestion in real time and posted appropriate messages (67).

Measures and Metrics. The study team used diversion rates at freeway exit ramps as the primary measure of effectiveness (MOE) to evaluate system effectiveness. Team members used three additional queue trailers with sidefire radar at three key diversion locations where access to alternate routes was available. Sensors upstream of the work zone and system detectors downstream of the PCMSs provided the necessary input for determining mainline and ramp volume, speed, and occupancy at each location. Travel time runs, which were originally planned, were scrapped due to excessive cost and difficulty in properly capturing conditions during impact periods. Figure 35 shows locations of the additional sensors.

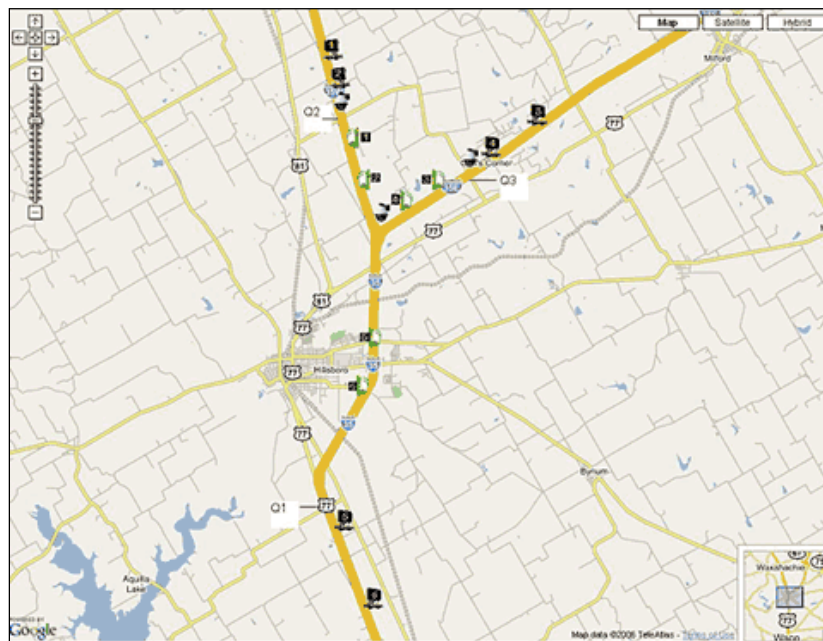


Figure 35. Locations of Additional Sensors (67).

The evaluation's success hinged upon the accuracy and completeness of the following key factors:

- Traffic volumes and average speed and occupancy measurements.
- Message logs showing the times and dates that messages were activated.
- Time-specific information recorded by inspectors on construction activities and delay observations.

Findings. During times of heavy congestion, motorists were more likely to follow diversion guidance posted on message boards. The system demonstrated that it could detect congestion and display appropriate messages, although the minimum diversion message post time was likely too short in some cases. Specifically, it posted travel times for free-flow conditions, SLOW TRAFFIC AHEAD and similar messages when speeds dropped, and diversion messages when occupancy met the desired threshold. When the system posted messages recommending motorists use the signed alternate routes, reasonably large percentages of traffic diverted. During major incidents, for example, the system diverted an average of 10 percent of mainline traffic to alternate routes. The highest diversion was about 28 percent (67).

Figure 36 indicates volumes on each lane and ramp, indicating that there was a higher diversion rate (ramp volume increase) during a period that coincided with an incident on the mainline recorded in the inspector log. Results from 20 observation periods revealed that from 1 to 28 percent reductions in mainline traffic volume occurred during congested periods (average 10 percent), reducing the demand for restricted mainline capacity.

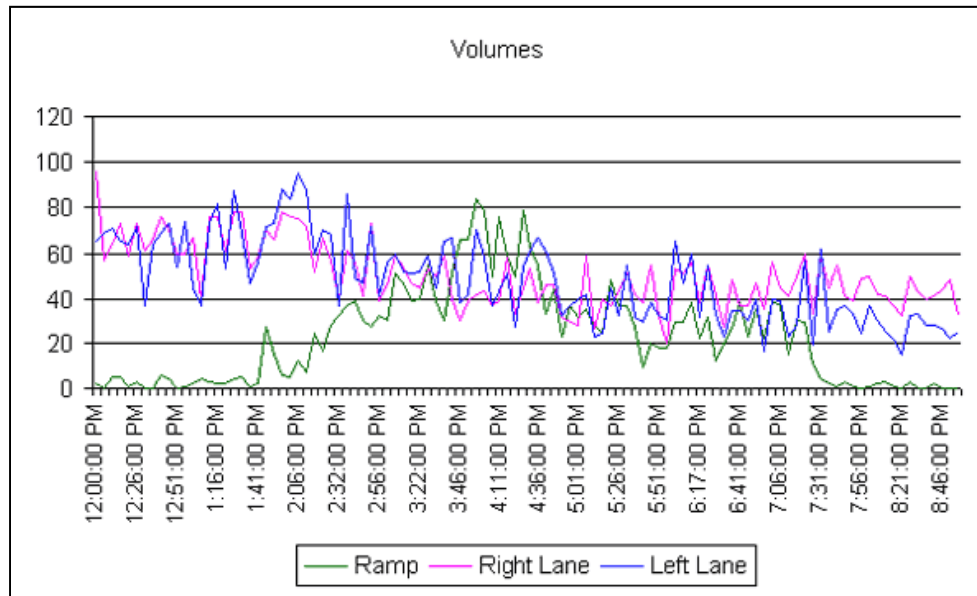


Figure 36. Plot Showing Volume Fluctuations on Mainline and Ramp (67).

MARKET MATRIX

Chapter 3 survey results indicated that:

- TxDOT traffic management engineers believe ITS can make a positive difference in work zone safety and operations.
- Some specific ITS treatments are available and have been successfully used elsewhere but have not experienced much use in Texas.

These underutilized treatments are merge control, queue warning, and incident response. However, to make these ITS treatments of greatest benefit to TxDOT, the market matrix needs to provide some of the criteria for applying them. Table 8 summarizes the concepts, their objectives, and the ITS equipment typically used for deployment. The Comments section includes criteria for application of each concept where they were available.

Table 8. Summary of ITS Technology to Meet Work Zone Needs.

Concept	Objective	ITS Equipment	Comments
Dynamic Early Merge	Provide advance notice over variable distance warning motorists of slowing vehicles ahead.	Sidefire radar, flashing lights activated by speeds below X mph	Radar can be mounted on DO NOT PASS WHEN FLASHING signs. Result: more uniform merging at low demand levels.
Dynamic Late Merge	Encourage drivers to remain in the closed lane.	Sidefire radar, DMS, PDMS activated by speeds	Used for congested flow. Dynamic: switch back and forth based on demand.
Queue Warning	Encourage drivers to reduce speeds at a safe rate.	Trailer-mounted active speed warning system	Criteria from MD: <5% occ—deactivate DMS; >15% occ on any detector—activate DMS.
Incident Response	Allow for accurate detection of incidents and efficient response to clear the roadway safely.	Speeds and/or occupancy monitoring, surveillance cameras at key positions	Drivers with cell phones are often a good source of incident verification.

CHAPTER 5. DEVELOPMENT OF ITS ARCHITECTURE

INTRODUCTION

The goal of Task 4 was to establish a working solution whereby a regional TMC can access data in real time or near real time from a work zone within the TMC's sphere of influence and fuse the content with the TMC's permanent ITS.

The technology review from Chapters 3 and 4 provided a broad overview of the products and technologies available for smart work zones and their operation. Given this information, the research team created a roadmap on how to utilize these systems in a more fully integrated way. The initial goal was to establish a working solution whereby a regional TMC could access data in real time or near real time from a work zone within the TMC's sphere of influence and fuse the content with the TMC's permanent ITS. However, TxDOT practice will not always involve interaction with a TMC, though in such cases an ITS might still make sense, so researchers established a two-level scheme, with one of them having potential interaction with a TMC.

The architecture should describe how a third-party ITS system might operate and provide the needed local functions at the work zone and a data feed to at least one identified regional traffic management center. The local work zone functions may include operations where data collected within the work zone trigger actions defined by the traffic management plan. One example could be displaying messages on changeable message signs based on measured traffic statistics. The message might involve general delay information and/or it might direct motorists to an alternate route. In these cases, the messages are based solely on information gathered by a smart work zone system and are not generated by a TMC.

The feed to the associated TMC (if available and used) would potentially include traffic monitoring data such as speed, volume, and environmental sensor system (ESS) data such as rain, flooding, or wind speed/direction. The architecture covers issues such as:

- Needs and criteria that require integration with a TMC.
- Responsibilities of the smart work zone vendor.
- Requirements for TMC integration (defined in TxDOT engineering software documents).
- Conceptual operation of the integrated system.

The architecture proposed for this effort follows the guidelines and concepts of the TxDOT statewide core architecture.

Table 9 lists the typical road construction and maintenance activities (emphasis on rural areas) that are appropriate for this project. This list comes directly from the *Texas Manual on Uniform Traffic Control Devices* (TMUTCD) (68), forming a subset of the larger list in the manual.

Table 9. Typical Road Construction and Maintenance Activities in Rural Areas.

Description of Work (Scenarios or Use Cases)	TMUTCD TA-Number	Duration ^a L: Long I: Intermediate S: Short-term	Schedule 24-hr, D: Daytime N: Nighttime	WZ Boundary S: Stationary M: Mobile	Potential Impacts D: Delays Q: Queues RE: Rear-End Collision SC: Sideswipe Collision FC: Frontal Collision
Work within the Traveled Way of Two-Lane Highways					
Lane Closure on 2-Lane Road—Traffic Signals	12	L	24	S	D, Q, RE
Work within the Traveled Way of Multilane Undivided Highways					
Interior Lane Closure on Multilane Street	30	L, I, S	24, D, N	S	D, Q, RE, SC
Lane Closure on Street with Uneven Dir. Volumes	31	L, I	24	S	D, Q, RE, SC
Half Road Closure on Multilane, Hi-Speed Hwy	32	L	24	S	D, Q, RE, SC
Work within the Traveled Way of Multilane Divided Highways					
Lane Closure on Divided Highway	33	L	24	S	D, Q, RE, SC
Lane Closure with Temporary Traffic Barrier	34	I, S	24, D, N	S	D, Q, RE, SC
Mobile Operation on Multilane Road	35	S	D, N	M	D, Q, RE, SC
Work within the Traveled Way of Expressways and Freeways					
Lane Shift on Freeway	36	L	24	S	SC
Double Lane Closure on Freeway	37	L, I, S	24, D, N	S	D, Q, RE, SC
Median Crossover on Freeway	39	L	24	S	D, Q, RE, SC
Median Crossover for Entrance Ramp	40	L	24	S	D, Q, RE, SC
Median Crossover for Exit Ramp	41	L	24	S	D, Q, RE
Work in Vicinity of Exit Ramp	42	L, I, S	24, D, N	S	D, Q, RE, SC
Partial Exit Ramp Closure	43	I, S	24, D, N	S	D, Q, RE
Work in Vicinity of Entrance Ramp	44	L, I, S	24, D, N	S	D, Q, RE, SC
Temporary Reversible Lane—Movable Barriers	45	L	24	S	D, Q, RE, SC
Work in the Vicinity of Highway-Rail Grade Crossings					
Work in Vicinity of Highway-Rail Grade Crossing	46	I, S	D, N	S	D, Q, RE, FC

^aDuration definitions by MUTCD (68)—The five categories of work duration and their time at a location:

- A. Long-term stationary is work that occupies a location more than 3 days.
- B. Intermediate-term stationary is work that occupies a location more than one daylight period up to 3 days, or nighttime work lasting more than 1 hour.
- C. Short-term stationary is daytime work that occupies a location for more than 1 hour within a single daylight period.
- D. Short duration is work that occupies a location up to 1 hour.
- E. Mobile is work that moves intermittently or continuously.

The research team chose each “Description of Work” in the first column based upon how amenable the type of work might be to use of an ITS as a feasible solution to improving traffic operations and/or safety in construction and maintenance work zones. The second column references the specific TMUTCD typical application (TA) number from the manual. The remainder of the table required decisions of the research team pertaining to duration, schedule, stationary vs. mobile, and potential impacts of each scenario.

Table 10 lists potential ITS solutions for the activities in rural work zones listed in Table 9. One of the solutions, variable speed limit, is likely to be only a variable speed advisory in Texas.

CURRENT PRIVATE PROVIDER OFFERINGS

The research team contacted the following private work zone providers to determine their capabilities in implementing an ITS Smart Work Zone architecture with or without a TMC:

- ASTI.
- iCone.
- Ver-mac.
- Scientex.

ASTI

The ASTI Smart Work Zone system is a real-time traveler information system for work zone applications. The system is comprised of several portable trailer-mounted components such as sensors for queue detection, video cameras, and DMSs. Other system components available from ASTI include the CHIPS software and a project website. The website has two layers, offering both a public page and the administration page, allowing DOT personnel to maintain control of the system. The individual components are also equipped with GPS transponders that offer a constant tracking for all units in the field. The latitudes and longitudes provide an immediate overview of all units by placing them on a mapping system displaying their exact location at all times. All of the devices run on a solar-powered battery management system.

The system can collect speed, volume, and occupancy data, process them with the CHIP software, select appropriate messages (e.g., travel time, queue warning, detour), and display them on PDMSs. ASTI can also integrate TMCs into its system. In this case, raw data collected by field detectors are transferred as an extensible markup language (XML) data stream through an automated file transfer protocol (FTP) server to the TMC. Then, the TMC can control the PDMSs and web-based traveler information through the ASTI web server. The flowchart in Figure 37 indicates how the TMC as an optional component fits into the logical architecture of the ASTI Smart Work Zone system.

Table 10. Potential ITS Solutions for Rural Work Zones.^a

<p>Dynamic Congestion Advisory Purpose:</p> <ul style="list-style-type: none">• Alert drivers of congestion downstream.• May be combined with queue warning and/or variable speed advisory (VSA).• May encourage diversion to alternate routes. <p>Dynamic Merge (at work zones with lane closures) Purpose:</p> <ul style="list-style-type: none">• Reduce queue lengths, speed differentials between lanes, and merge-related erratic maneuvers during congested periods.• Maintain safe and smooth merge operations and effective vehicle throughput during both non-congested and congested periods. <p>Dynamic Queue Warning Systems Purpose:</p> <ul style="list-style-type: none">• Warn motorists of stopped or slow traffic ahead.• Reduce the risk of rear-end collisions.• May be combined with VSA. <p>Excessive Speed Warning Purpose:</p> <ul style="list-style-type: none">• Encourage speed limit compliance (primarily under free-flow conditions). <p>Haul Road Warning Purpose:</p> <ul style="list-style-type: none">• Alert drivers of slow construction vehicles entering, exiting, or crossing the roadway. <p>Optimized Restriction/Closure Purpose:</p> <ul style="list-style-type: none">• Monitor traffic conditions and close only when conditions warrant (as in Europe). <p>Travel Time/Delay Information Purpose:</p> <ul style="list-style-type: none">• Provide motorists with estimated travel times or delays.• Reduce driver frustration.• May also encourage diversion if alternate route is available. <p>Variable Speed Limit/Variable Speed Advisory Purpose:</p> <ul style="list-style-type: none">• Reduce speed differentials between consecutive vehicles within the traffic stream.• Delay traffic break-down.• Prevent or mitigate the occurrence of stop-and-go conditions.• Reduce the risk of rear-end crashes. <p>Work Space Intrusion Warning Purpose:</p> <ul style="list-style-type: none">• Alert drivers if they inadvertently follow a construction truck into the work area.• Alert workers when a vehicle accidentally enters into the work area.

^aOther ITS approaches (e.g., traffic-responsive temporary signals, temporary ramp metering) that are more applicable to urban areas are not listed.

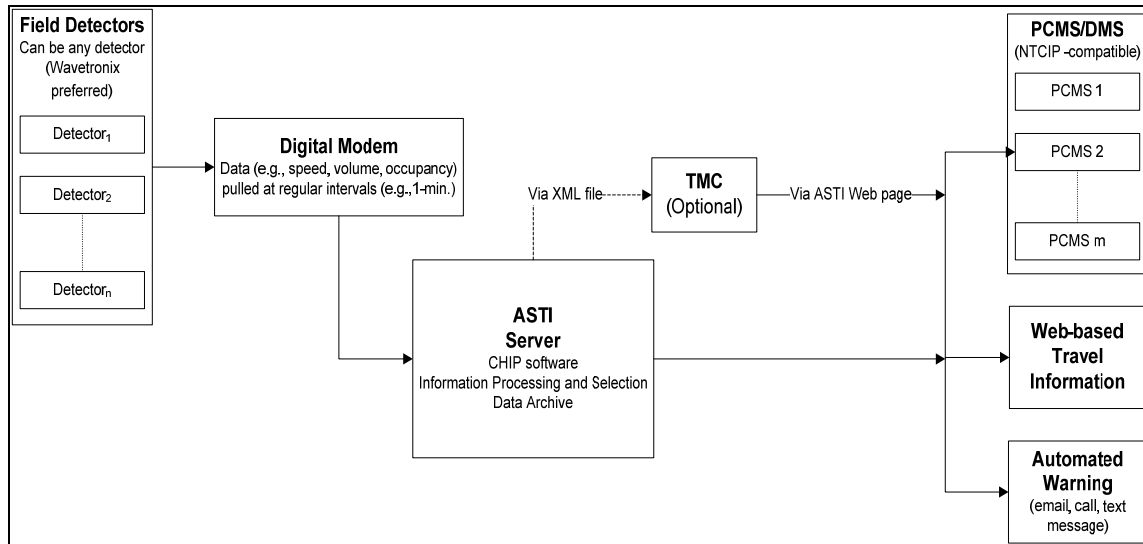


Figure 37. Logical Architecture for the ASTI Smart Work Zone System.

iCone

The iCone system uses smart cones to measure vehicle speeds and transmits the speed and location information to a national database. It can provide real-time information on traffic conditions (e.g., travel time through the work zone, speeds at selected locations, and approximate location of the end of the queue) upstream of a work zone lane closure. The iCone system can communicate with any National Transportation Communications for ITS Protocol- (NTCIP-) compliant PDMS and has a dual communication feature; the system attempts to communicate over its cell modem first, and if that is not successful, it uses a satellite modem.

A typical application of the iCone queue warning system consists of a series of iCones deployed along the roadside where formation of vehicle queues is expected. Figure 38 illustrates a queue warning system deployed at a work zone.

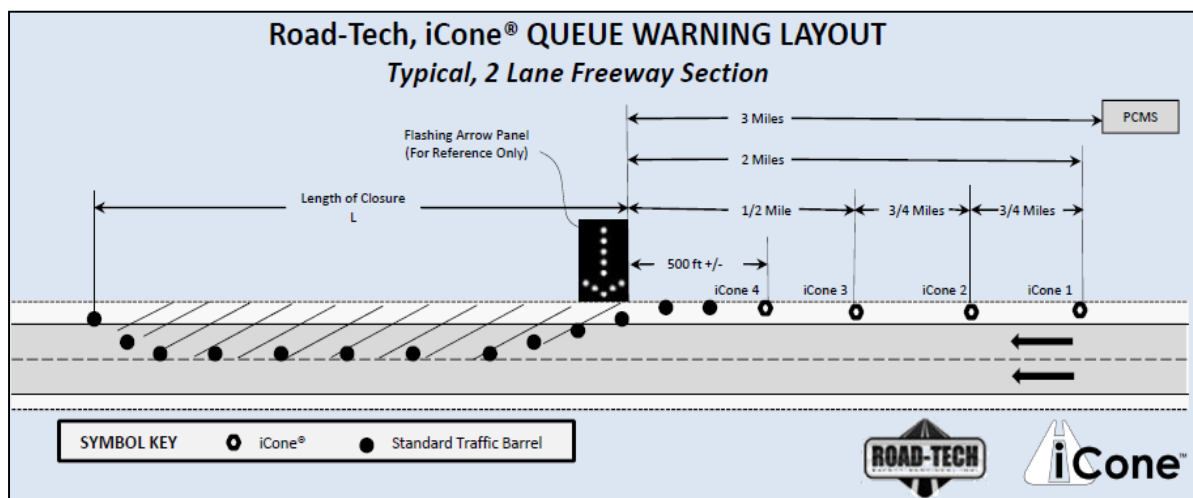


Figure 38. Layout of an iCone Queue Warning System.

Different work zones may require different system specifications. The specification should include sensor spacing and coverage, speed averaging interval (e.g., 2 min), and speed thresholds for message selection rules. Average speeds might vary significantly across lanes, so it is important to specify which side of the road the iCone will be located on. Certain events can also trigger an automated message to be sent to the iCone center or to a construction crew supervisor. For example, the system can send out special warning messages if the speed at the most upstream work zone traffic control sign drops below some threshold (e.g., 45 mph). A speed reduction at this location would mean that the queue has grown beyond the point where the first advance warning sign is located, and vehicles approaching the end of queue will not get any warning about the queue and the work zone.

Although the iCone system can be integrated with TMC operations, the typical setup does not include communication with a TMC. If a TMC is included, the iCone field system sends data initially to the iCone server, and the server gives out a URL and password so the TMC can access the server and get the data in the form of XML streams. Although the TMC receives the data, iCone still sends the messages to the message boards.

Ver-mac

Ver-mac offers a traffic-responsive smart work zone system that continuously monitors traffic conditions upstream and within work zones and provides real-time information to motorists using automated dynamic messages displayed on PDMSs and on a traveler information website on the Internet. The system can provide travel time and delay messages, route management information, and slow and stopped traffic warnings, and it can also be used as a dynamic lane merge system.

Ver-mac can integrate TMCs at different levels into its smart work zone system. The schematics that follow are three ways that Ver-mac can provide a logical architecture for smart work zones, but in actuality, company offerings represent a continuum of options. These options include:

- Install all the on-site equipment (e.g., detectors [RTMS, Bluetooth®, etc.], PCMSs, and on-site personal computers [PCs]) to monitor, report, and control PCMSs, with no TMC involvement (see Figure 39).
- Install all the on-site equipment to monitor, report, and control PDMSs, with partial TMC involvement (reports to TMC [e.g., for web page], but TMC does not control; see Figure 40).
- Install all the on-site equipment to monitor, report, and control PCMSs, with full TMC involvement (TMC receives report and can intervene at whatever level desired or needed; see Figure 41).
- Install all the on-site equipment and provide a virtual TMC (could be on site).

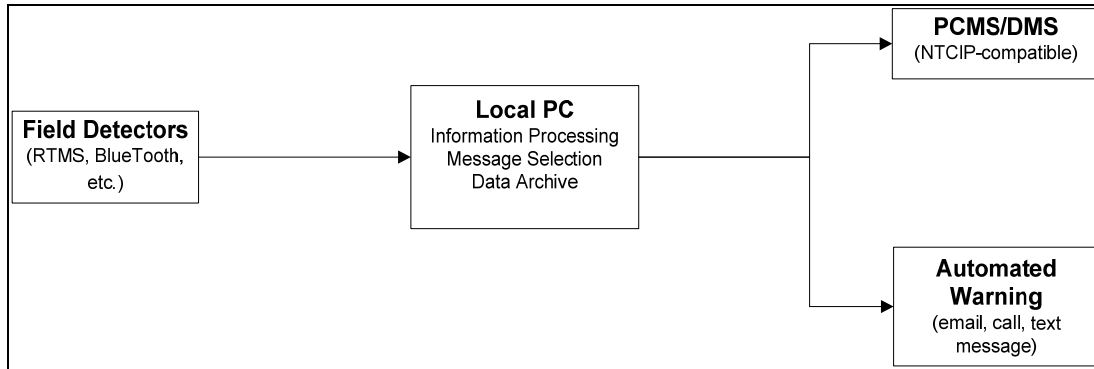


Figure 39. Logical Architecture for a Ver-Mac Smart Work Zone System without TMC Involvement.

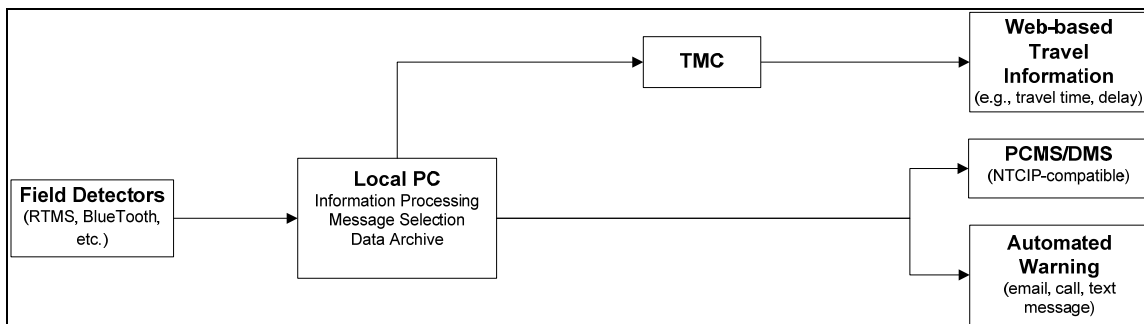


Figure 40. Logical Architecture for a Ver-Mac Smart Work Zone System with Partial TMC Involvement.

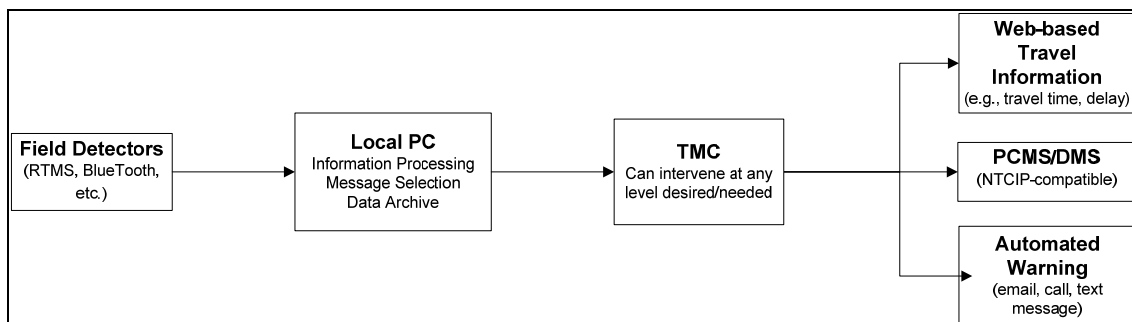


Figure 41. Logical Architecture for a Ver-Mac Smart Work Zone System with Full TMC Involvement.

Scientex Corporation

The ADAPTIR system developed by Scientex Corporation is a portable, automated condition-responsive traffic control and management system. It uses wireless communications technology and integrates roadside speed sensors, PDMSs, and an on-site PC. Optionally, it can also integrate with HARs, portable CCTV cameras, and TMCs. The system has several

applications, such as smart work zone, speed control, queue detection/warning, dynamic merge control, and special-event traffic management. In work zone applications, the system collects speed data at multiple locations upstream of the lane closure, analyzes the data using software running on an on-site PC, and provides time-stamped advisory messages displayed on PDMSs. Figure 42 is a typical layout of the ADAPTIR system when used for speed control in advance of a work zone.

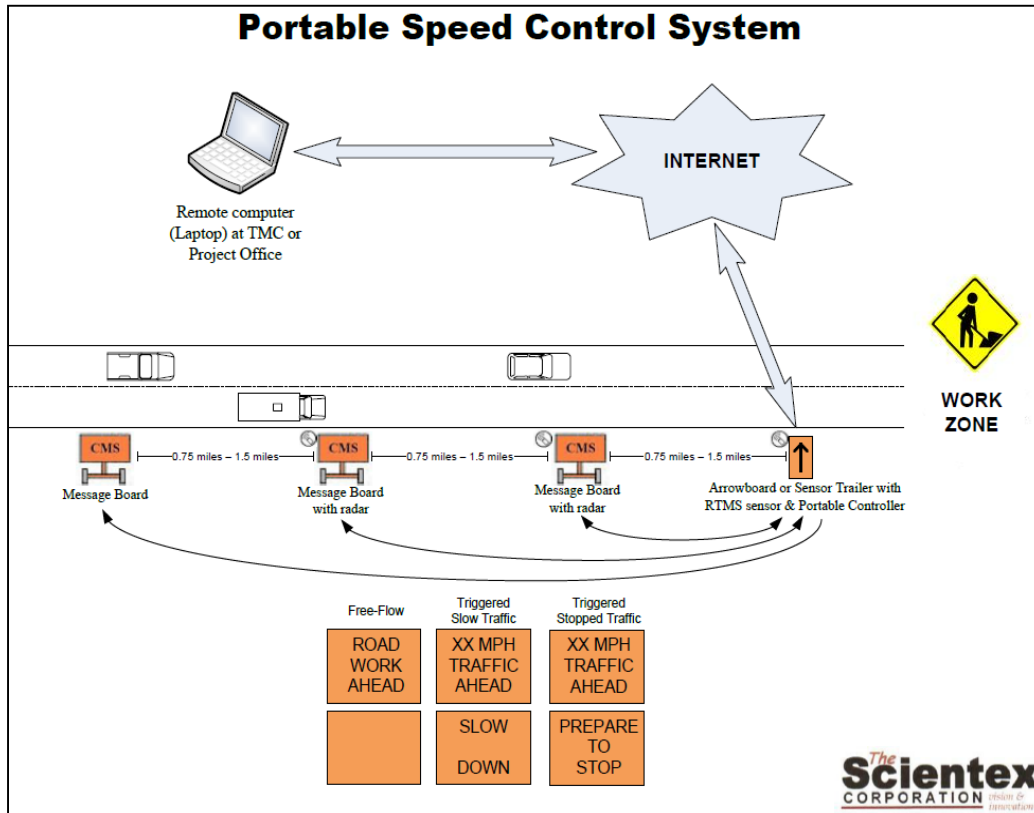


Figure 42. Layout of ADAPTIR System.

ITS IMPLEMENTATION CATEGORIES

For simplicity and for coverage of different needs of work zones, the research team developed two implementation categories as described below. In the first level, called stand alone, there would be no TMC involved, but a local TxDOT Area Office would likely monitor data/information coming from the site and provide on-site manpower as needed in a responsive mode. The second level, called integrated, would involve integration into a TMC using some of TxDOT’s LoneStar sub-systems. In summary, the two levels are as follows.

Stand-alone architecture would involve:

- Vendor collecting Smart Work Zone data like speed and volume.
- Vendor controlling PDMSs deployed at the Smart Work Zone segment.

- Vendor providing alarms (based on speed thresholds and queue length thresholds) to Public Information Officer via text messages, email, or some other electronic format.
- Vendor providing data to a Public Information Officer through a web interface.

Integrated architecture would involve:

- Vendor collecting Smart Work Zone data like speed and volume.
- Vendor controlling PDMSs deployed at the Smart Work Zone segment.
- Vendor sharing speed (and possibly volume) data with TxDOT's LoneStar TSS subsystem.
- Vendor providing alarms (based on speed thresholds) via TSS subsystem.

At the stand-alone level, there would be no TMC involvement, but a local TxDOT Area Office would likely monitor data/information coming from the work zone site and provide on-site manpower as needed. A commercial provider would likely provide the on-site traffic control, although TxDOT might provide its own equipment in some cases. Alarms coming from the site indicating an emergency or incident could cause the local Area Office to initiate a response to send TxDOT personnel to the site or could result in a notification being sent to the Public Information Officer, or both.

The stand-alone level could also involve dissemination via the Highway Condition Reporting System website. TxDOT districts are required to enter highway and weather conditions into the Highway Condition Report every workday morning and update the information as needed. The level of traffic disruption requiring input from TxDOT includes highway conditions that close travel in one direction for more than 4 hours or create hazardous travel. This hazardous travel could include work zone sites where incidents or other problems have occurred. Interested parties can access the information by calling TxDOT or via TxDOT's web page. Control of messages to motorists at the stand-alone level could utilize PDMSs or the Internet and would be the responsibility of the on-site provider of traffic control. Conditions where this stand-alone level might be appropriate include low- to mid-volume roadways with minimal traffic interference for relatively short periods of time.

Integrated architecture would involve full integration into a TMC using TxDOT's LoneStar system. Communication between the site and the TMC for integrated control would involve C2C and LoneStar protocols. Rural (or urban) areas with four or more thru-lanes, average daily traffic (ADT) of 50,000 vehicles per day, and lengths of 5 miles or more would likely be candidates for integrated or high-level control. Also, the existence of non-work-zone ITS components operated by a local TMC and in near proximity to a work zone would be likely candidates for integrated control. Table 11 summarizes some aspects of the two levels and ranges of values that might be expected.

Table 11. Description of Control Levels.

Description	Control Type	
	Stand-Alone	Integrated
No. of thru-lanes	2 or 4	≥ 4
TMC involvement	No	Yes
Monitoring by TxDOT	Yes	Yes
TxDOT vs. private control	Either	TxDOT
Requires LoneStar and C2C	No	Yes
Traffic volume (AADT)	< 50,000 vpd	≥ 50,000 vpd
Length (miles)	< 5 miles	≥ 5 miles
Time duration	< 6 months	≥ 6 months
Includes other TxDOT ITS components	Not likely	Likely
Urban/Rural	Either	Either
Field equipment (TxDOT or private)	Either	Either
Surveillance cameras	Likely none	At critical points

Potential ITS User Needs

The following list of ITS user needs begins the process of establishing the ITS architecture.

At the stand-alone level, TxDOT must be able to:

- Monitor the work zone site.
 - Speeds from detectors.
 - Messages sent to PDMSs.
 - End of queue.
- Receive alerts or alarms indicating problems.
 - Text message or other correspondence.
 - Speed reductions below thresholds.

At the integrated level, TxDOT must be able to:

- Maintain full control.
 - Integrate with normal TMC operation.
 - Integrate using LoneStar protocols and C2C functionality.
- Monitor and control the work zone site.
 - Speeds and counts from detectors.
 - Notification of equipment malfunctions (optional).
 - Messages sent to PDMSs.
 - Alternate route (if available).
 - Real-time weather information at key locations.

Figure 43 and Figure 44 illustrate these two categories schematically. Figure 43 provides an illustration of the data flow and interaction between the various components and entities in a stand-alone smart work zone deployment. Along a segment of freeway upstream of the lane

closure, the vendor deploys a set of detectors that are at least 1 mile apart. The worst-case scenario of the estimated length of queue due to the lane closure determines the length of the freeway segment upstream of the lane closure that needs to be monitored. The estimated worst-case queue length also determines the number and placement of the PDMSs that should be deployed by the vendor to provide the public with information based on measured traffic statistics upstream of the lane closure. For example, if the maximum estimated queue length is 5 miles, the vendor needs to deploy five detectors at 1 mile apart upstream of the lane closure to monitor the traffic. One PDMS needs to be placed at least 1 mile upstream of the maximum queue length (i.e., at 6 miles). A second PDMS could be placed in the middle of the segment being monitored (i.e., at 2 or 3 miles) upstream of the lane closure. The detectors monitor the segment upstream of the lane closure and provide speed and volume data every 5 minutes to a remote vendor server that is monitoring the site via either a cellular or satellite communications link.

The Lane Closure Monitoring System (LCMS), residing on the vendor's server, receives the speed and volume data. Using other data elements stored locally on the server, like location of the lane closure, number of detectors deployed at the site, and the distance between consecutive detectors, the LCMS determines if a queue has formed upstream of the lane closure and, if so, the length of the queue. Based on the calculated queue length upstream of the lane closure and the location of the PDMSs, the LCMS selects the message to be displayed on each sign, updates a web interface with the latest information, and generates alarms to be sent to the TxDOT area engineer based on the thresholds for speeds and queue length that have been configured into the system. The vendor can also deploy cameras upstream and downstream of the lane closure to provide a visual verification of the traffic conditions at the lane closure site if required by TxDOT. The cameras can be used to provide snapshots of traffic conditions that can be displayed on the web interface provided by the vendor for the lane closure site.

Similarly, Figure 44 provides an illustration of the data flow and interaction between the components and entities in an integrated smart work zone deployment. As in stand-alone deployment, the vendor monitors and maintains control of the deployed equipment and infrastructure in the vicinity of the lane closure area. However, some of the data collected locally by the vendor can be shared with a TxDOT TMC if desired by TxDOT. The vendor is required to implement the TxDOT ATIS LoneStar subsystem protocols to share data collected locally at the lane closure site with a TxDOT TMC. Also, the vendor must use TxDOT C2C interfaces if he or she is required to communicate with TxDOT infrastructure like TxDOT DMSs deployed at the boundaries of the lane closure segment.

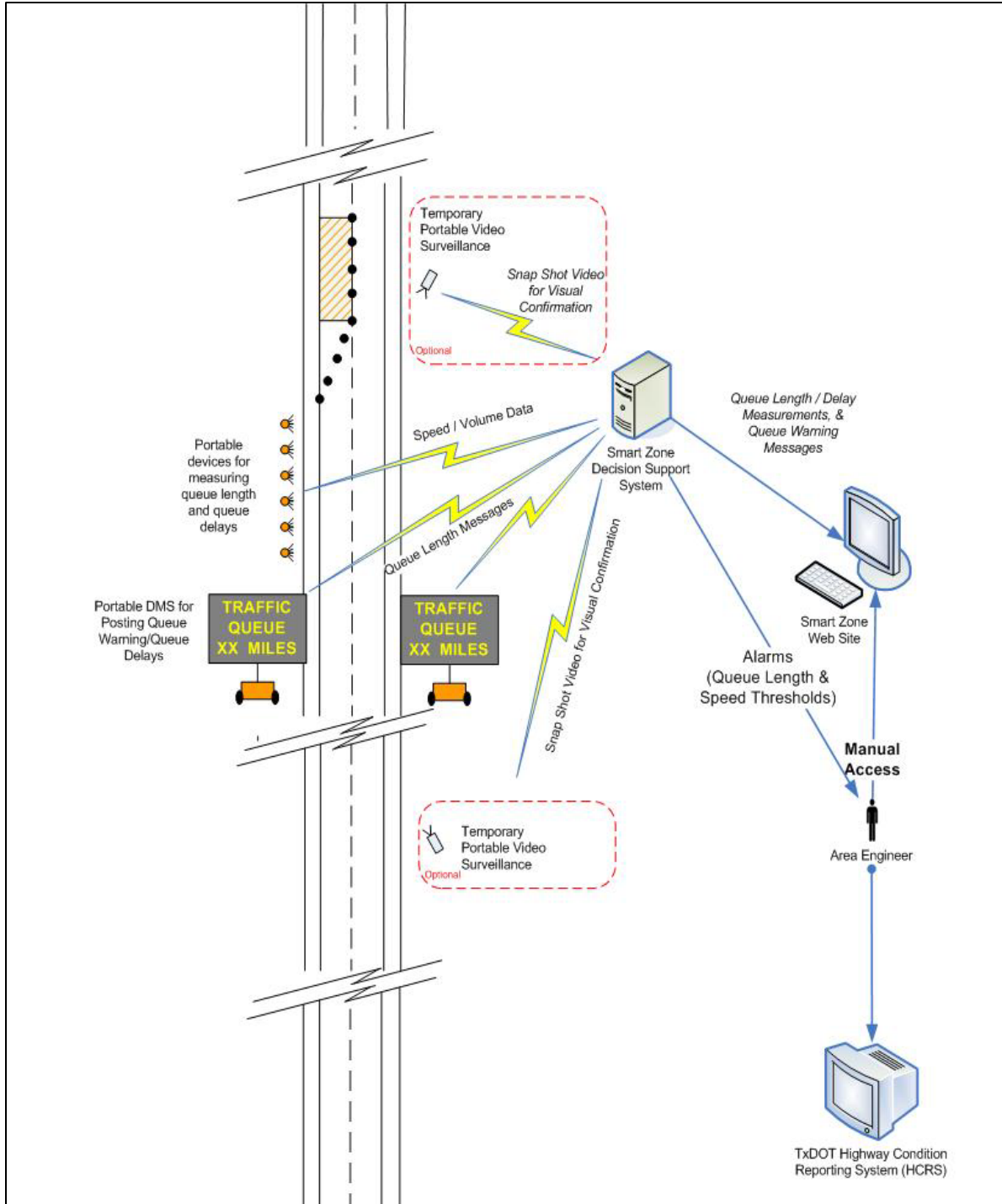


Figure 43. Stand-Alone Schematic.

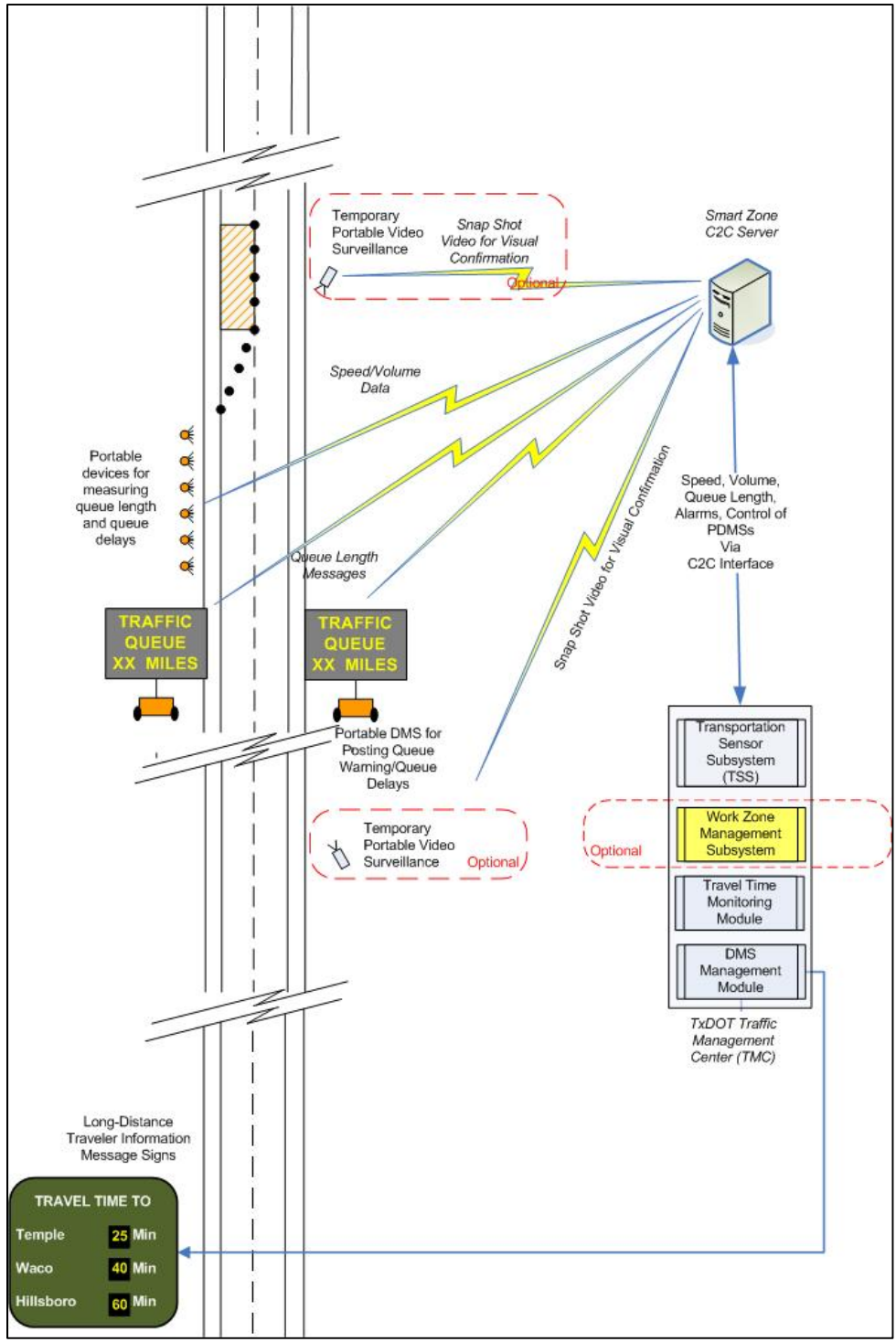


Figure 44. Integrated Schematic.

Some of the data elements that are collected locally at the monitored lane closure segment and can be shared with a TxDOT TMC include:

- Speeds.
- Volumes.
- Environmental data like rain, wind, flooding, and visibility.
- Alarms.

For example, to share the speed and volume data collected at different locations in the lane closure segment, the vendor must implement the TxDOT LoneStar interface defined by TxDOT's document entitled *Transportation Sensor Subsystem Protocol Document TSS-Protocol-1.0.6*, dated February 22, 2008 (69). On the other hand, to share any environmental data collected by the vendor with TxDOT's LoneStar, the vendor must implement the interface defined by TxDOT's document entitled *Environmental Sensor Station Protocol Document ESS-Protocol-1.0.0*, dated February 25, 2008 (69). For the vendor to be able to display any messages on TxDOT DMSs, the vendor needs to use the TxDOT C2C interfaces defined by the TxDOT document *Center-to-Center Communications Command/Control Interface Control Document C2C-CICD-4.3.0*, dated July 7, 2008 (69).

Developing the Architecture

Since most of the scenarios (Use Cases) in Table 9 involve lane closures, one of the selected scenarios used to serve as the model in this document for building the ITS architecture is queue warning. The other scenario that had merit for use of simulation and which has become popular for work zones and non-work zones alike is use of Bluetooth for speed and travel time measurements. Other treatments (e.g., work in vicinity of highway-rail grade crossing) might use some of the same components but would be unique in other ways.

The research team used the VISSIM simulation program to model the effects of different monitoring spacing along a segment of freeway upstream of a lane closure.

Table 12 indicates the messages to be posted on changeable message signs for a posted speed of 65 mph. The PDMS locations begin at 1 mile upstream of the lane closure and occur at each 1-mile point beyond that until simulation indicates that the end of queue is protected by at least one PCMS. The simulation used updates of vehicle speeds in 5-minute intervals, so the average speeds over the last 5 minutes is the value that causes the changeable message signs to change or remain the same. According to this scenario, average speeds above 35 mph constitute a "normal" condition and cause the following message frames to be displayed: ROAD WORK 3 MILES AHEAD and USE CAUTION. For 5-minute average speeds between 25 mph and 35 mph, the following message frames are displayed: CAUTION ROAD WORK AHEAD and SLOW X MILES AHEAD. For 5-minute average speeds below 25 mph, the message frames are CAUTION ROAD WORK AHEAD and STOPPED X MILES AHEAD.

Data Flow Schematics for Smart Zones

Figure 45 and Figure 46 illustrate the information flow for each of the two treatment categories.

Table 12. Speed Limit Thresholds and PCMS Displayed Messages.

Condition	5-Minute Speed	Message Frame 1	Message Frame 2
NORMAL	> 35 mph	ROAD WORK 3 MILES AHEAD	USE CAUTION
SLOW	25–35 mph	CAUTION ROAD WORK AHEAD	SLOW X MILES AHEAD
STOPPED	< 25 mph	CAUTION ROAD WORK AHEAD	STOPPED X MILES AHEAD

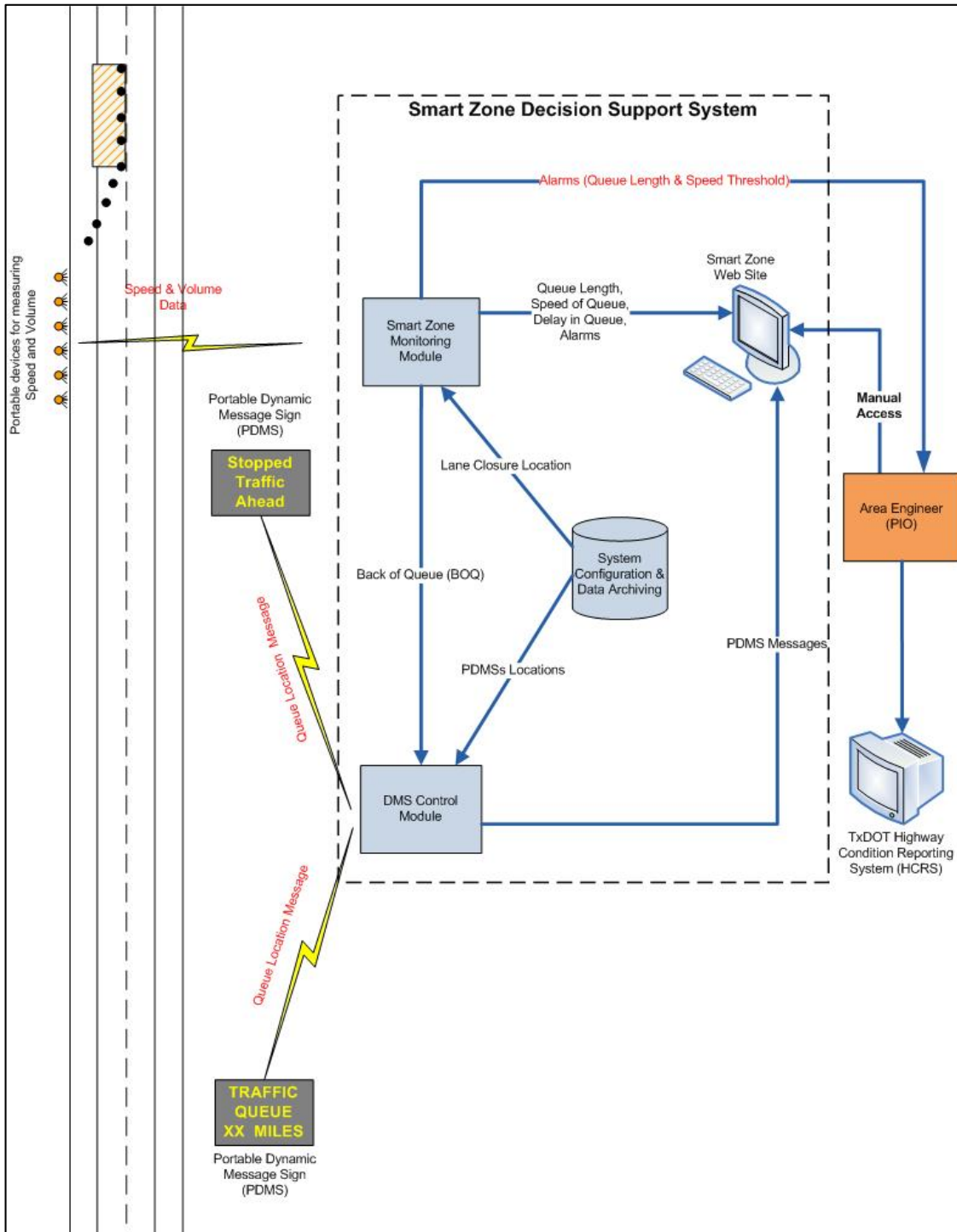


Figure 45. Stand-Along Data Flow Schematic.

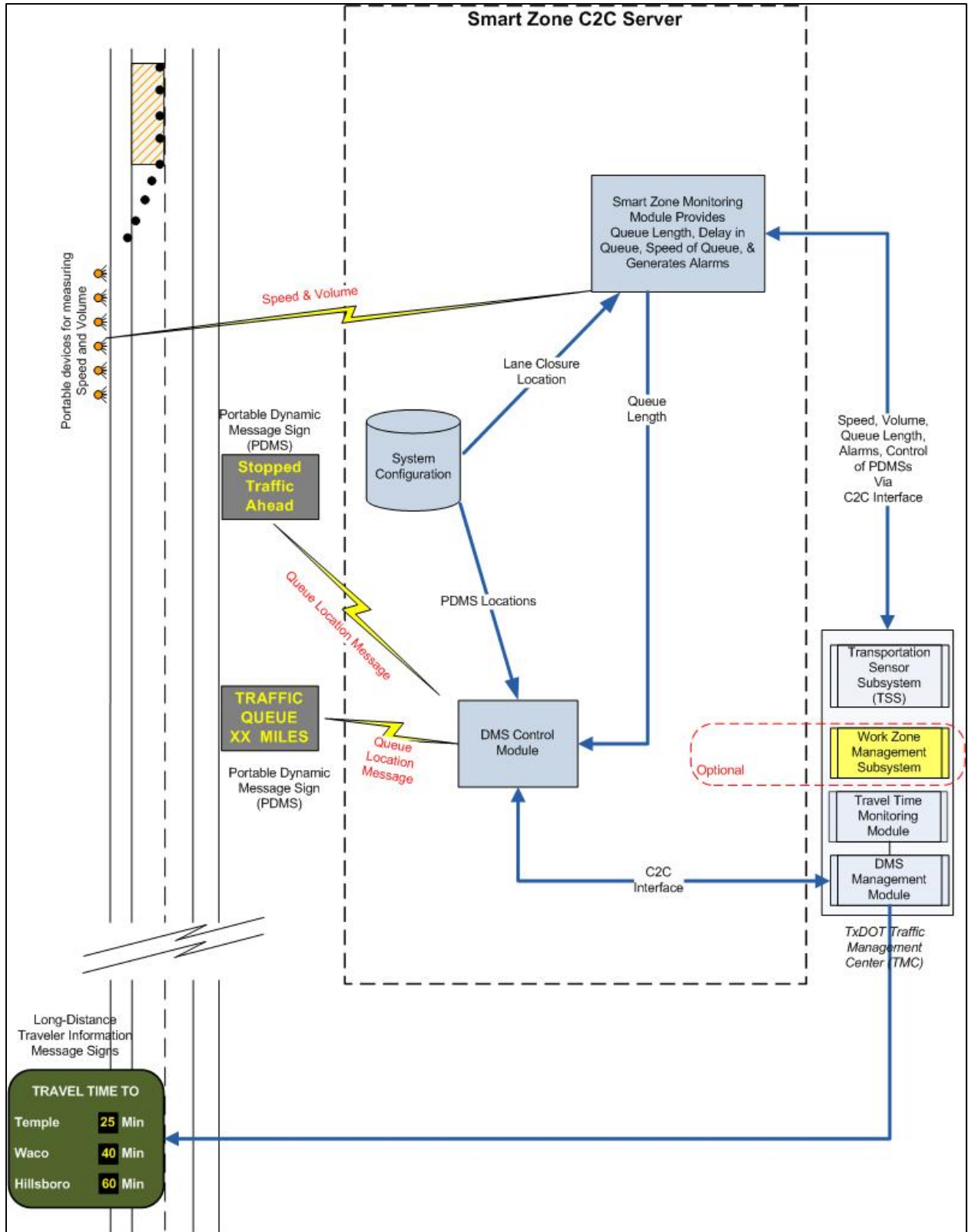


Figure 46. Integrated Data Flow Schematic.

CHAPTER 6. PROOF OF CONCEPT–QUEUE WARNING

INTRODUCTION

The research team developed draft guidelines and recommendations that could assist TxDOT in determining when to integrate ITS systems into its work zone traffic control requirements. Of the available scenarios covered earlier in this report, researchers chose queue warning with the presence of a lane closure for this proof of concept. Examples of the type of information that is included in these guidelines are as follows:

- Criteria for determining when to use ITS systems as part of an overall transportation management plan for construction activities.
- Recommendations for assisting TxDOT in determining the placement of these ITS systems inside a work zone to achieve specific traffic management objectives.

INITIAL PLAN USING FIELD DATA COLLECTION

Researchers and the PMC searched for as many as three candidate locations within Texas that were using a smart work zone system that had potential for some level of integration into a transportation management center. The smart zone system should have some ITS data items or elements that could be shared with the TMC. The research team intended to work with a local district, contractor, and smart zone product vendor to deploy a proof-of-concept system within at least one, but no more than three, selected work zone sites in the state of Texas for purposes of demonstrating the benefits and documenting lessons learned from integrating these systems into an existing TMC. Researchers searched for such a site during the first year of the project but were unable to find one that was suitable and that would come on line at the proper time.

One of the potential solutions to achieving a useful field setup was the use of iCone devices at a local work zone site near TTI headquarters. The iCone is an orange and white barrel that looks identical to the ones used along any construction or maintenance work zone, but its barrel structure houses other components. These components typically consist of:

- One or more vehicle detectors.
- A power source (e.g., a 12V battery).
- A GPS.
- Both a cell modem and a satellite modem for data transmission.

In some cases, these iCone devices communicate with an on-site PC, while in other cases, they communicate with a TMC. The purpose of the detection units is usually to provide vehicle speed data for processing by a PC located on site or in a TMC. Speed reductions might trigger changes in changeable message signs, also on site, and typically positioned upstream of a bottleneck such as a lane closure.

Given the ongoing and planned activities along the I-35 corridor and TTI involvement in other aspects of its reconstruction, the research team considered it as a possible candidate. However, the timing of I-35 reconstruction activities would not have worked well for this research project. Researchers contacted iCone representatives anyway to lay the groundwork and to discuss loaned units to be used at a yet-to-be-determined location.

Potential Sites Based on District Input

In early tasks during the first year of the research, the research team monitored upcoming work zone activities for a period of several months to identify a site where ITS equipment might be installed. The original intent in the TTI work plan was to use an existing ITS deployment in a work zone for this task. There was no money budgeted to buy equipment, so this scenario would be required unless vendors were willing to loan equipment. The survey sent out as part of Task 2 included a question asking districts to identify an upcoming project that might serve as a test case for this research. District personnel identified sites in the Waco, El Paso, and Bryan Districts for deployment of such equipment, but the districts did not commit to providing resources for installing ITS components; they were only considering installing these components. Table 13 summarizes these sites.

Table 13. District Information on Potential Sites.

Roadway	No. of Lanes	Work Zone Type	Duration
Loop 375 (ELP)	2	Construct main lanes	24 months
U.S. 290 (BRY)	4	Construct freeway	24 months
I-35 (WAC)	6	Add new lanes	Varies (7 contracts)

ALTERNATIVE PLAN USING SIMULATION

After unsuccessfully searching for a suitable site, the research team suggested to the PMC that the project change course and use simulation to address Tasks 6 and 7. The remaining tasks would not change in principle, so no modification was needed. The project director and members of the PMC agreed that this change would represent an appropriate approach since it looked unlikely that an ITS project would develop in time. This change in direction would produce meaningful results as well and could cover a broader range of inputs compared to field-testing at one or two sites. The change in direction still required some data acquisition to feed a calibrated simulation model. One option for acquiring these data would require researchers working with vendors to request their aggregation levels and show how data flows back and forth.

OBJECTIVE

The research team decided that a benefit-cost approach was best for determining when to use ITS in work zones. The objective of this benefit-cost analysis is to determine when the benefits represented by selected MOEs reach or exceed the costs of installing SWZs. The primary MOE

in this analysis is crash reduction. There are costs associated with crashes, so reductions in crashes accumulate on the benefits side of the equation. Including delay cost is often appropriate as another MOE, but the rural focus of this research causes crash reduction costs to be of greater significance than delay costs. Omitting delay savings will represent a conservative estimate of the actual benefits of SWZs. Where diversion routes are available, the user might also want to verify the accuracy of SWZs in determining when diversion is needed, and the amount of diversion that results.

Determining the cost of SWZs begins with investigating the characteristics of queue formation upstream of the work zone. In work zones where demand exceeds capacity, a queue forms. This area is especially important because of the conflicts that emerge due to speed change and vehicles changing lanes to merge from a lane being closed to an open lane. The critical factors are the maximum length of queue (in miles) and the duration of the queue by time of day. If the end of queue is not protected by warnings to motorists, rear-end crashes are highly likely. The duration of the queue is important in determining the need (and therefore the justification) for an SWZ. The following methodology begins by using simulation to determine the probable length of queue to determine the design of the SWZ.

QUEUE WARNING SIMULATION

The proof of concept testing in this project used simulation instead of the originally planned field data collection using ITS. This testing involved two scenarios:

- A queue warning simulation using spot speed sensor data.
- A travel time simulation using point-to-point Bluetooth data.

The remainder of this chapter focuses on queue warning simulation. Chapter 7 fully describes the methodology and results of Bluetooth simulation. Both simulations rely on VISSIM.

Vehicle queues and delays are common when traffic demand exceeds roadway capacity. They frequently occur upstream of work zone lane closures where roadway capacity is significantly reduced by lane drops and/or lower posted speeds. At such locations, high speed differentials at the upstream end of the queue may lead to increased risk of rear-end collisions. A particular safety concern is when vehicle queues grow beyond the advance warning signs, as Figure 47 illustrates. In such cases, the unexpected sudden encounter with congestion increases the risk of collision with other vehicles as they approach the end of the queue. An effective queue warning system that constantly monitors queue length and provides real-time warning messages for the drivers may significantly reduce the potential of rear-end collisions.

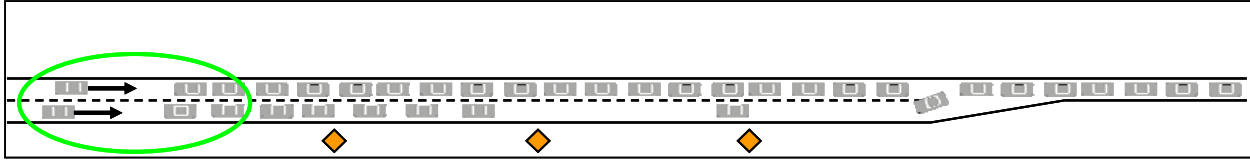


Figure 47. Rear-End Collision Potential Upstream of Work Zone Lane Closures.

Objectives of Queue Warning Simulation

The objectives of the queue warning investigation were to:

- Assess the expected performance and reliability of a proposed queue warning system to be deployed at future work zone lane closures.
- Evaluate the sensitivity of the system's performance on some key design parameters such as detector spacing, speed thresholds, and speed aggregation intervals.
- Determine the most appropriate settings for these parameters.

To achieve these objectives, researchers investigated different combinations of design parameters and traffic scenarios in a controlled environment; these studies could not be done in the field but were possible using microscopic traffic simulations.

Configuration of the Proposed Queue Warning System

System Components

The queue warning system considered in this study had the following components, as Figure 48 shows:

- Speed sensors to measure spot speeds in multiple points on the approach to the work zone upstream of the lane closure.
- A PCMS to provide the drivers with real-time queue warning (e.g., slow/stopped traffic) messages.
- A central processing unit (CPU) to select appropriate real-time warning messages based on sensor data.
- Communication between the sensors, CPU, and PCMS.

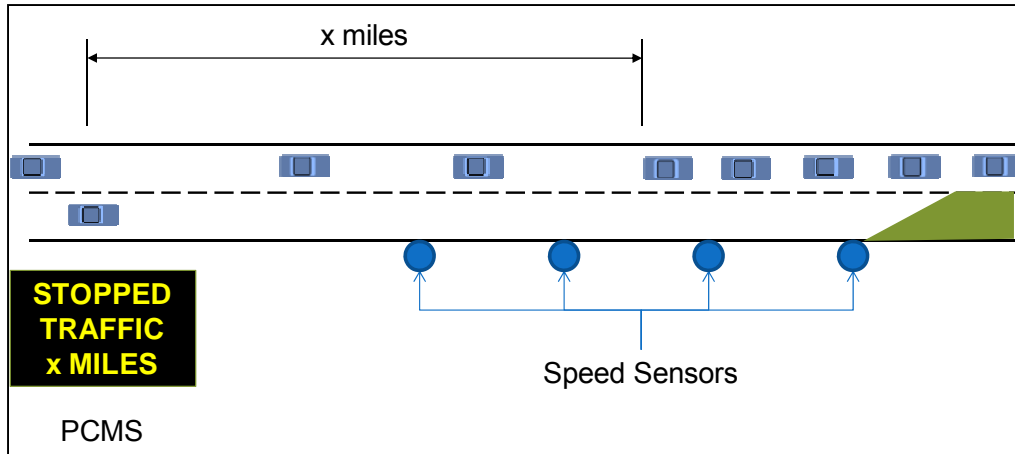


Figure 48. Queue Warning System.

Message Selection Logic

The system selects messages based on real-time traffic conditions determined from vehicle speeds averaged over a pre-defined time interval (e.g., 1, 2, or 5 minutes). Table 14 summarizes the speed thresholds for selecting specific messages.

Table 14. Message Selection Based on Speed Conditions.

Message	v : lowest time-mean speed considering all sensor locations		
	$v_1 < v$	$v_2 < v < v_1$	$v < v_2$
	LANE CLOSED AHEAD	TRAFFIC SLOWS X MILES	STOPPED TRAFFIC X MILES

Although the same threshold is defined for both activating and deactivating a warning message, the system allows the use of overlapping speed ranges (i.e., different speed thresholds for turning a message on and off). Using the thresholds, the following rules apply to selection of warning messages:

- Detection of non-congested conditions at all sensor locations (i.e., $v > v_1$) causes the message LANE CLOSED AHEAD to be displayed on the PCMS.
- The lowest average speed among all sensors in the range $v_2 < v < v_1$ causes the message TRAFFIC SLOWS X MILES to be displayed.
- The average speed at any sensor location below v_2 causes the message STOPPED TRAFFIC X MILES to be displayed.

The distance X in the warning messages is calculated as:

$$X = x_{PCMS} - \underbrace{\left[x_{DET}(i) + \frac{1}{2} \Delta x_{DET} \right]}_{\text{Estimated location of back of queue}} \quad (1)$$

where:

- X_{PCMS} : distance of PCMS from lane closure (miles).
- $X_{DET}(i)$: distance of speed sensor i that activates the message from lane closure (miles).
- ΔX_{DET} : detector spacing (miles).

Simulation Study

Study Area

To evaluate the expected performance of the proposed queue warning system, the research team selected a freeway work zone with nighttime lane closure from 7 p.m. to 8 a.m. The work zone was located at the southern boundary of an approximately 10-mile segment in the southbound direction of I-35 between Hillsboro and West, Texas. This freeway segment had two lanes to serve the southbound traffic, and the work required closing the left lane of the two lane section.

Approach

Researchers modeled the operation of the queue warning system over the entire period of a nighttime lane closure using the microscopic traffic simulation software VISSIM. The simulation replicated the speed sensors of the queue warning system by placing virtual detectors every half mile upstream of the work zone entrance point up to Hillsboro. Each virtual detector could be activated or deactivated during a simulation, making it possible to study the impact of different detector spacing scenarios.

The simulation used an ADT of 69,000 vpd and truck percentage of 37 percent as typical traffic demand and vehicle composition on a weekday along the studied section. The analysis used traffic counts from similar rural interstates to estimate the capacity of the work zone and the hourly distribution of traffic over the nighttime lane closure period of 7 p.m. to 8 a.m. Table 15 shows the distribution of hourly traffic volumes. The estimated capacity was 1285 vphpl.

Table 15. Hourly Volume Distribution (vph) during the Nighttime Lane Closure.

Hour	19-20	20-21	21-22	22-23	23-24	0-1	1-2	2-3	3-4	4-5	5-6	6-7	7-8
Volume (vph)	1690	1449	1241	1034	828	620	517	448	448	517	758	1104	1414

Within the study area, there were three entry ramps located at approximately 2, 3, and 5 miles upstream of the work zone lane closure. The analysis assumed an hourly volume of 180 vph for each of the ramps and assumed both random and platooned vehicle arrivals for freeway traffic. Figure 49 illustrates the two scenarios that were used. The first scenario used a peak that was 20 percent higher than the hourly volume and that arrived within the first 15 minutes of each hour. In the second scenario, this peak was 50 percent of the hourly volume but lasted only 2 minutes.

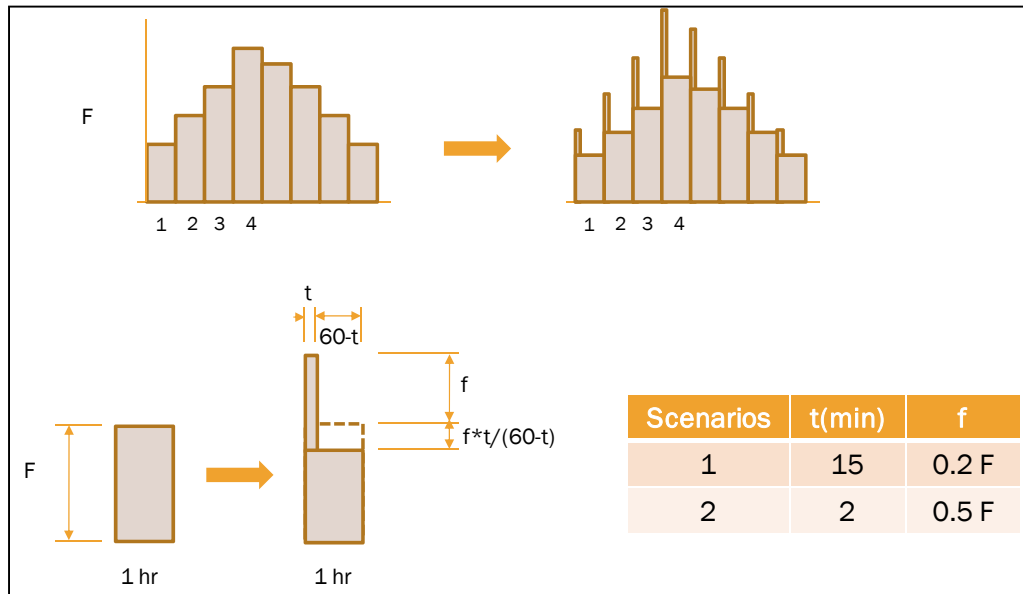


Figure 49. Platoon Approximation.

Design Parameters

One of the objectives of the simulation studies was to conduct a sensitivity analysis and make recommendations on the following design parameters of the queue warning system:

- Speed thresholds—for queue detection and warning message selection.
- Aggregation interval—for averaging vehicle speeds at each sensor location.
- Update interval—for updating messages based on the PCMS.
- Detector spacing—for distance between speed sensors deployed upstream of the lane closure.
- PCMS location—for distance from lane closure.

Table 16 provides the values and ranges considered for each design parameter. Various combinations of the design parameter values led to an evaluation of a total of 144 scenarios.

Table 16. Design Parameter Values.

Speed thresholds for stopped traffic warning (mph)			Speed aggregation interval (minute)			
25	30	35	1	5		
Speed thresholds for slow traffic warning (mph)			PCMS message update interval (minute)			
45	50	55	1	5		
Detector spacing (mile)			PCMS distance upstream of lane closure (mile)			
½		1	3	4	5	6

Measures of Effectiveness

The research team evaluated the following MOEs to judge the performance and reliability of the queue warning system:

- Queue prediction error, meaning the difference between the predicted queue length when a vehicle passed the PCMS and the actual queue length when it joined the queue.
- Percent of vehicles that did not see any warning on the PCMS but encountered a queue upstream of the work zone.
- Percent of vehicles that saw a PCMS warning message of STOPPED TRAFFIC X MILES without encountering a queue.

Figure 50 illustrates the queue prediction error ΔQ and its two components (ΔQ_1 and ΔQ_2). The spatial error component ΔQ_1 is the queue estimation error at the time when the vehicle passes the PCMS, and it is a function of detector spacing and speed aggregation interval. The temporal error component ΔQ_2 is due to shockwave propagation during the time period when the vehicle travels from the PCMS to the back of the queue.

Determine MOEs from Model Output

To obtain the stated MOEs, the research team processed VISSIM outputs using Visual C# and EXCEL. VISSIM generates several comma-delimited files, including Data Collection Point Record (DCPR), Queue Length Record (QLR), and Vehicle Record (VR). The DCPR file consists of records regarding each detector (data collection point) placed on the freeway. Each record includes the 1-minute volume counts and average speed at one of the detector locations. This information was used to estimate the back-of-queue and to determine the appropriate warning message to be shown on the PCMS. Table 17 shows an example of the DCPR file.

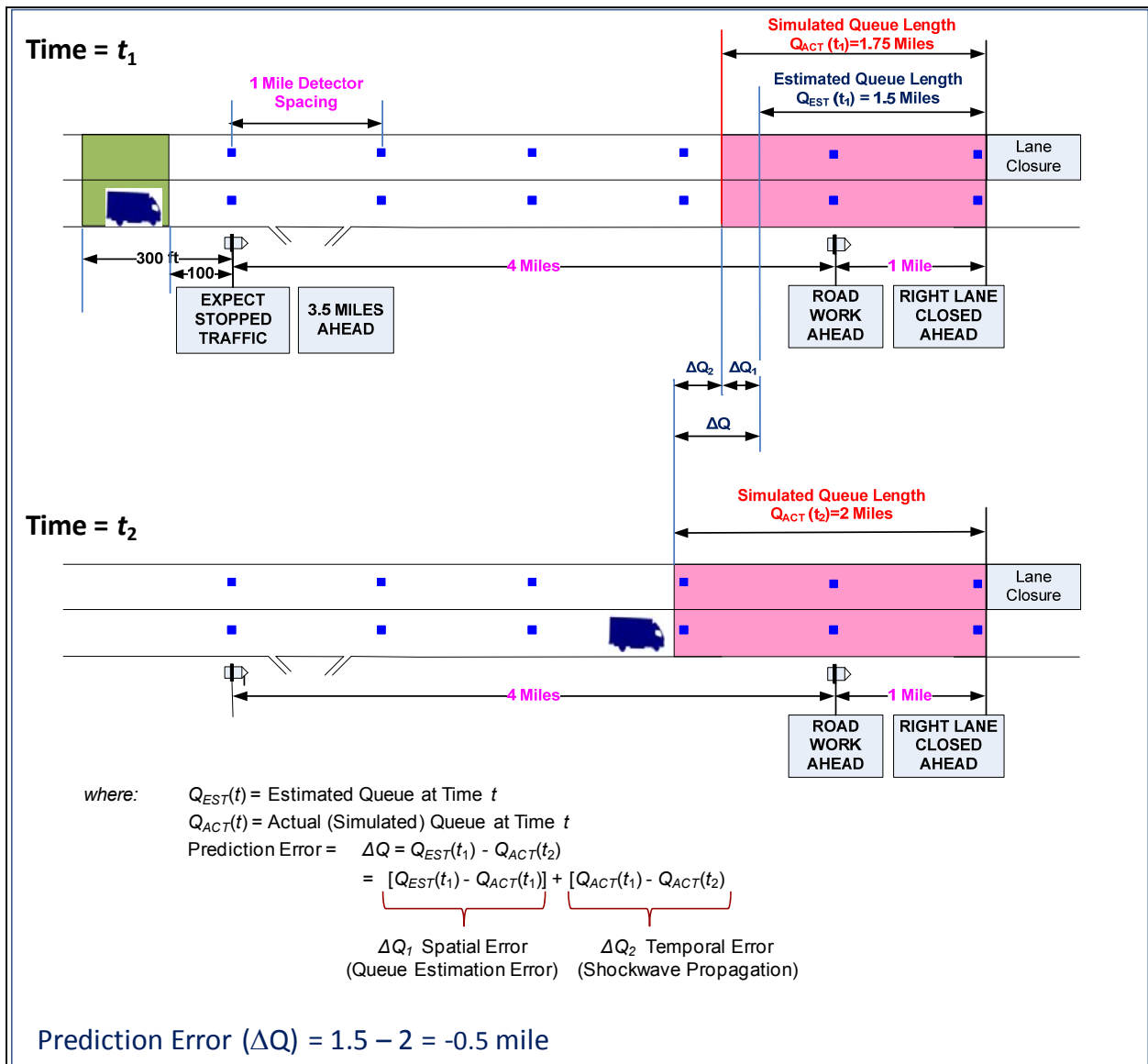


Figure 50. Prediction Error.

Table 17. Example of Records in the DCPR File.

Data Collection Point	Start Time	End Time	Number of Vehicles	Average Speed (mph)
1	300	360	7	69.7
2	300	360	6	70.4
1	360	420	5	69.9
2	360	420	9	70.5

The QLR file consists of records that the simulation logs every second. Each record consists of the following fields:

- Time slice in seconds.
- Average queue length in feet during the second.
- Maximum queue length in feet during the second.

Table 18 provides an example of records in the QLR file.

Table 18. Example of Records in the QLR File.

Time Slice (Sec)	Avg. Queue Length (ft)	Max. Queue Length (ft)
6640	6838	6838
6641	6837	6837
6642	6835	6835

The VR file consists of records indicating the location and speed of each vehicle during the simulation logged at 1-second intervals. Each record in the VR file consists of the following fields:

- Time slice in seconds.
- Vehicle number.
- Simulation link number.
- Distance from the beginning of the link.
- Vehicle speed.
- Lane number.

Table 19 provides an example of fields in the VR file.

Table 19. Example of Records in the VR File.

Time Slice (sec)	Vehicle Number	Simulation Link	Vehicle Location (ft)	Vehicle Speed (mph)	Lane Number
9.0	1	1	31.0	69.16	1
10.0	1	1	132.4	69.16	1
11.0	1	1	233.8	69.16	1

TTI researchers developed a tool to post-process these simulation files to estimate the back-of-queues and generate MOEs. The section below describes the post-processing procedures.

Back-of-Queue Estimation. The back-of-queue location was estimated using Equation (1). The speed sensor that activates a queue warning message is the most upstream detector station where the average speed falls below one of the speed thresholds specified in Table 16. Using the DCPR file, the back-of-queue location is estimated as follows:

Step 1. Sort the detector stations according to their distance to the work zone lane closure in decreasing order and store them in Detector List.

Step 2. When a PCMS message is updated at time T , calculate the average speed for each detector station as:

$$v_{ave} = v_{T-a,T} = \frac{\sum_{t=T-a}^T n_t v_t}{\sum_{t=T-a}^T n_t} \quad (2)$$

where:

$v_{T-a,T}$: average speed (mph) over time interval $[T-a, T]$.

v_t : average speed (mph) over time interval $[t-1, t]$ as reported in DCPR file.

n_t : total number vehicles detected over time interval $[t-1, t]$ as reported in DCPR file.

a : speed aggregation interval (min).

Step 3. From the sorted Detector List, find the first detector in which the corresponding v_{ave} falls below the speed threshold and calculate the distance to the back-of-queue using Equation (1).

MOE Calculation. The flowchart in Figure 51 summarizes the steps of calculating the MOEs. First, the configuration parameters and model output (queue length and vehicle record files) are read and aggregated queue values are calculated (Steps 1 through 4). Then, vehicle records are processed to determine:

- If a vehicle encountered a queue upstream of the lane closure.
- If it received a warning when it was within sight distance from the PCMS.

In addition, the following variables are recorded to calculate the required MOEs:

- Vehicle number.
- Timestamp.
- Message warning flag—TRUE, if the driver saw a queue warning message; otherwise, FALSE.
- Location of the queue at the time when the vehicle was within sight distance of the PCMS.
- Queuing flag—TRUE, if a vehicle encountered a queue; otherwise, FALSE.
- Location of vehicle where it joined a queue.
- Vehicle speed.

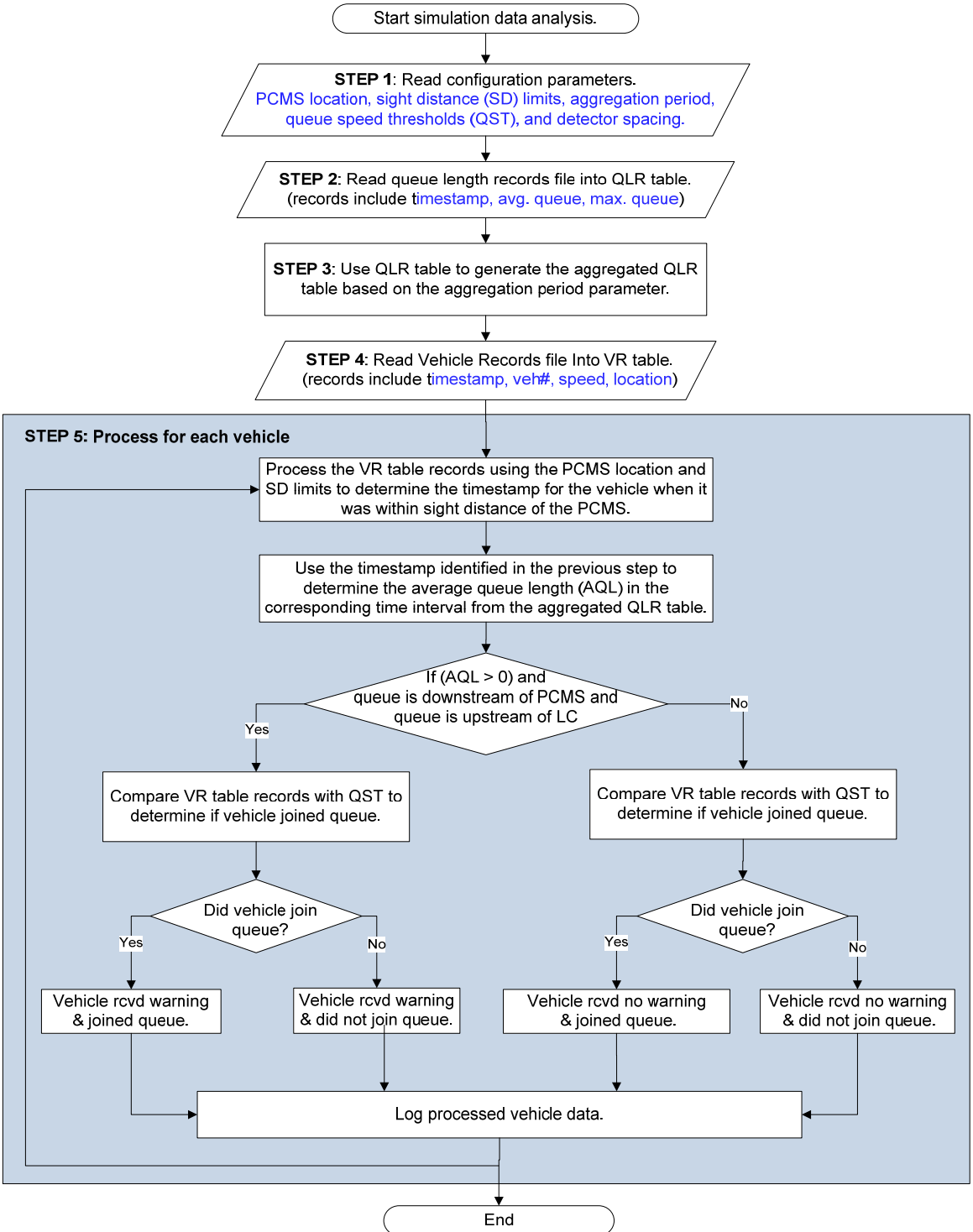


Figure 51. Data Processing for MOE Calculation.

Results

Figure 52 shows a plot of the queue length over the entire period of the simulated nighttime work zone lane closure. The unit of measurement of the queue is feet and is a measurement from the lane closure upstream. For this specific work zone, the maximum queue length was about 2.4 miles, and most of the queuing occurred between 7 p.m. and midnight.

The simulation analysis also looked at different speed aggregation and update intervals. Simulation results indicated that the queue warning system performed equally well using 25 mph, 30 mph, and 35 mph speed thresholds for queue detection, so analysts settled on a singular speed threshold of 35 mph. The effectiveness of the queue warning system was more sensitive to other design parameters such as detector spacing, speed aggregation, and PCMS update intervals. As expected, results indicated that half-mile detector spacings resulted in more accurate end-of-queue predictions than 1-mile detector spacings. The other obvious difference was that the combination of 5-minute speed aggregation and 1-minute PCMS update intervals was more stable and resulted in less oscillating warning messages than the other two scenarios (5-minute speed aggregation and 5-minute PCMS update, and 1-minute speed aggregation and 1-minute PCMS update).

Other performance measures determined from the simulation results were related to the reliability of warning messages provided to motorists during periods of traffic slowdowns and/or vehicle queues. They included the following:

- Queue prediction error distribution.
- Percent of vehicles encountering queues without warning.
- Percent of vehicles receiving a queue warning message without encountering a queue.

As speed drops and congestion begins to develop, the first message that drivers approaching the work zone will see is TRAFFIC SLOWS X MILES. When speeds further drop, drivers will see the queue warning message STOPPED TRAFFIC X MILES. The objective is to provide all drivers with either of the two messages when traffic slows or a queue forms in advance of the lane closure. However, at the time when speed drops and/or a queue begins forming at the lane closure, there are always some vehicles “trapped” between the lane closure and the PCMS located several miles upstream. These vehicles may encounter a slow or stopped queue without getting a warning. The number of such vehicles trapped without warning depends on the distance of the PCMS upstream of the lane closure.

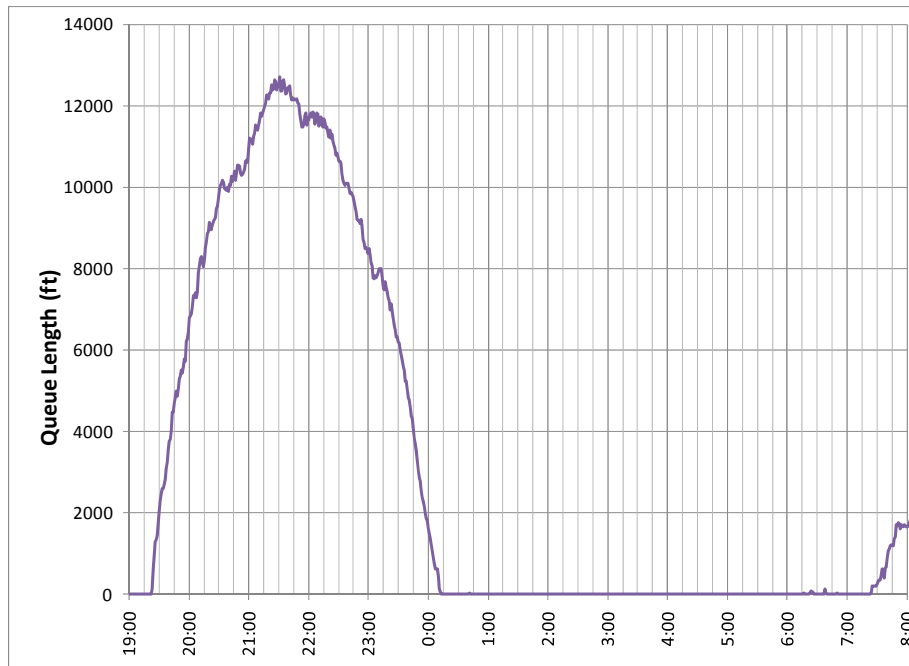


Figure 52. Queue Length Results.

In addition, there are some other vehicles upstream of the PCMS that may encounter a queue without getting a warning. This result is because of some delay in the warning messages after traffic begins to slow or a vehicle queue begins to form at the lane closure. This delay depends primarily on the warning message update interval. Longer message update intervals would likely cause even more vehicles to encounter a queue without warning.

The analysis determined the percent of vehicles that encountered a queue without warning for the combinations of three stopped traffic/slow traffic speed thresholds, four PCMS locations, and three speed aggregation and PCMS update intervals. Table 20 shows the percentages. The speed threshold scenarios included a fixed 35-mph threshold for stopped traffic and a variable (45, 50, or 55 mph) threshold for slow traffic detection.

As expected, the percent of vehicles without warning was generally higher for larger PCMS distances and longer PCMS update and speed aggregation intervals. In terms of speed thresholds, the percent of vehicles without warning was the lowest in the case of the 35/55 mph combination. Based on these findings, the recommended speed threshold for slow traffic detection is 55 mph. The difference between the three speed aggregation/PCMS update interval scenarios is relatively small. Cost considerations point to using the 5-minute interval for both speed aggregation and PCMS update.

Table 20. Percent of Vehicles Encountering Queue without Warning.

	Distance of PCMS Location Upstream of Lane Closure (miles)											
	3-Mile			4-Mile			5-Mile			6-Mile		
Speed Threshold Combinations for Warning Message Selection												
“Stopped Traffic” Threshold (mph)	35			35			35			35		
“Slow Traffic” Threshold (mph)	45	50	55	45	50	55	45	50	55	45	50	55
1-min PCMS update interval 1-min speed aggregation interval	2.0%	2.0%	1.6%	2.5%	2.5%	1.5%	2.9%	2.9%	2.2%	3.7%	3.7%	3.2%
5-min PCMS update interval 5-min speed aggregation interval	3.6%	3.6%	3.6%	4.0%	4.0%	4.0%	4.5%	4.5%	4.5%	5.5%	5.5%	5.5%
1-min PCMS update interval 5-min speed aggregation interval (Rolling Average)	2.6%	2.6%	2.0%	2.9%	2.9%	2.5%	3.5%	3.5%	2.9%	4.3%	4.3%	3.7%

Recommended Queue Warning Design Parameters

Based on findings of the simulation study, the authors recommend the queue warning system design parameters summarized in Table 21.

Table 21. Recommended System Design Parameters.

Design Parameter	Recommended Value
Speed threshold for STOPPED TRAFFIC	35 mph
Speed threshold for SLOW TRAFFIC	55 mph
Detector spacing	½ mile
Speed aggregation interval	5 minutes
PCMS message update interval	1 or 5 minutes
PCMS distance upstream of lane closure	1–2 miles upstream of the longest expected queue

Once the operational characteristics of the upstream work zone queue are understood through simulation, the number and spacing of detector stations can be established. The research team received cost information from one of the SWZ vendors for use on the I-35 project and used those costs in this analysis. The basic cost for rental of a queue warning system from this vendor is \$5,500 per month. For short-term work zones, renting the system could be practical. However, if the project lasts for a long enough period of time, purchasing the system should be the better option. This analysis only considers the purchase option.

The cost of a system with four speed sensor stations, two PCMSs, and ancillary equipment to complete the system is \$71,000. Of course, the number of sensor stations (and PCMSs) is a

function of the maximum queue length as stated earlier, which was determined by simulation. For the I-35 project, simulation results indicated a typical maximum queue length of 12,000 ft (2.3 miles; see Figure 52). The simulation also required the following inputs: spacing of the detector stations and the interval over which the SWZ averaged speeds. For evaluation purposes, research staff used ½-mile detector spacing, resulting in four detector stations. Actually, ¾ or even 1-mile spacings would also work but would leave less room for error.

BENEFITS OF SMART WORK ZONES

Introduction of a work zone generally increases the number of crashes and crash costs. National Cooperative Highway Research Program (NCHRP) 627 (70) is a good source of information for crash cost increases in work zones. Its crash costs are based on freeway crashes as follows (71):

- Injury crash (fatality or injury)—\$206,015.
- Property damage only crash—\$ 7,800.

Determining costs of crashes begins with determining whether to use daytime or nighttime work zones. The work zones used in NCHRP 627 that had low average annual daily traffic (AADT) used daytime work zone values, but nighttime work zones are more prominent at high AADTs, as Figure 53 indicates. Below about 40,000 vpd, practically none of the work zones involves night work, whereas at 100,000 vpd and above, almost all are performed at night. Between 40,000 and about 80,000 vpd, the range varies widely. Agencies will need to choose which option is best for their situation.

Figure 54 (taken from NCHRP 627) indicates the increase in crash costs for a specific condition—active work ongoing and a lane closure present. It indicates the discrepancy in costs of daytime versus nighttime work, indicating costs per 100 work hours per mile of roadway. This document builds on this scenario of a single lane closure along a rural section of I-35.

Crash Cost Reduction Due to Smart Work Zones

Since the reduction in crashes due to the SWZ is unknown, the user must estimate a value that is appropriate based on AADT, length of the work zone (miles), duration of the work zone (months), presence of entry/exit ramps, and other local factors. Based on earlier research and researcher experience, this range could fall between 0 and 25 percent for rural applications.

Figure 55 and Figure 56 show the resulting cost savings per mile of what might be termed the “zone of influence.” This zone of influence is the length of roadway within which the work zone activities plus the queue formed by the work zone influence the probability of crashes. Based on literature sources and researcher experience, the possible reduction in crashes estimated due to a SWZ evaluated in this analysis ranged from 5 to 25 percent. A reduction in crashes by some percent is expected to result in a commensurate reduction in crash costs for either daytime or

nighttime work zones. Again, these reductions in crash costs are per 100 hours of work zone activity per mile of roadway being impacted by the work zone.

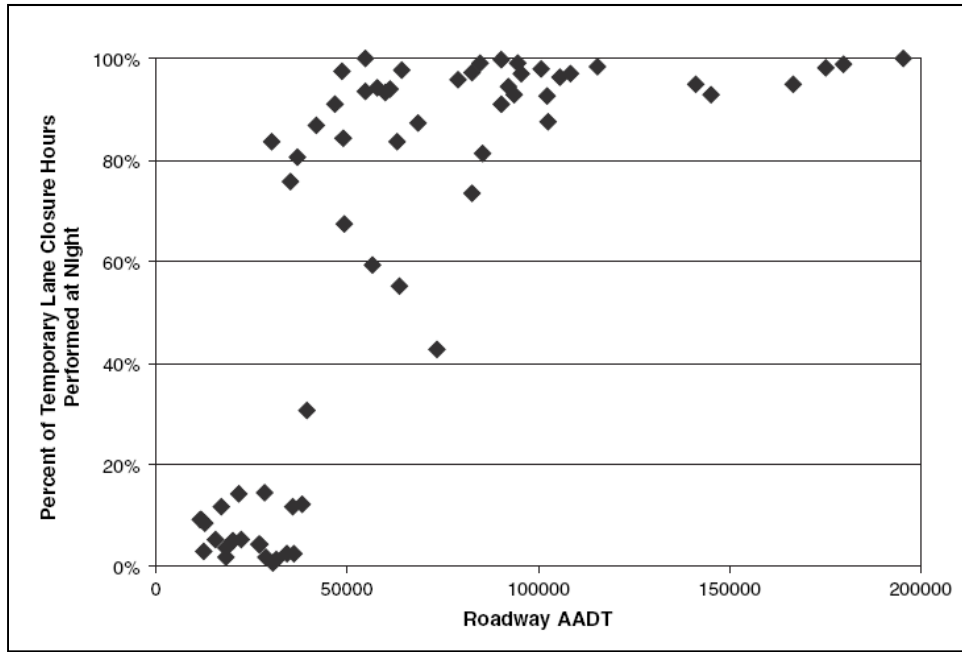


Figure 53. Percentage of Temporary Lane Closures Performed at Night at Each Project (10).

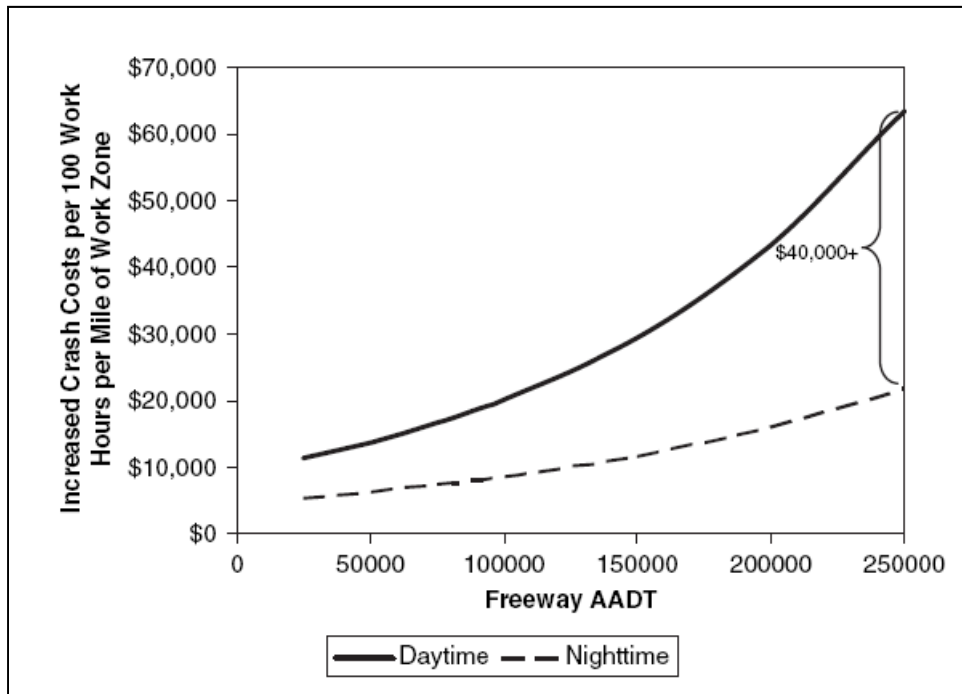


Figure 54. Increased Crash Costs with Active Work and Lane Closure Present (10).

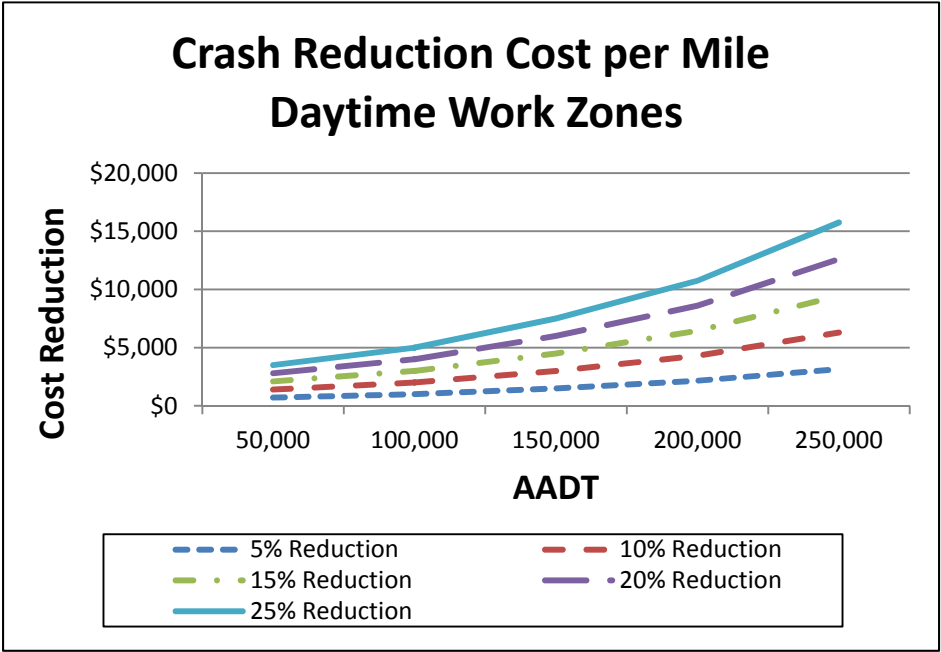


Figure 55. Cost Savings per 100 Hours due to Daytime SWZ.

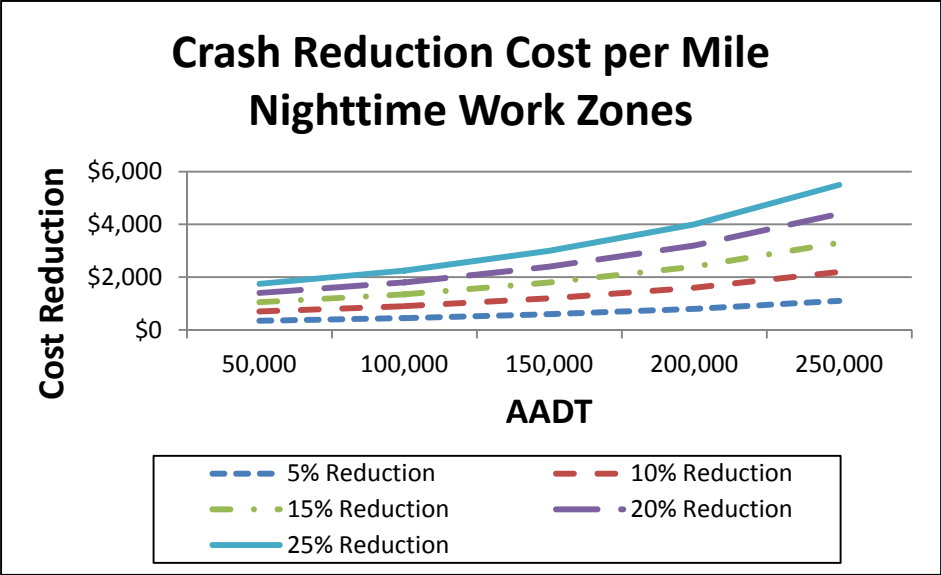


Figure 56. Cost Savings per 100 Hours due to Nighttime SWZ.

For purposes of this analysis, researchers assumed that the crash cost reduction benefits due to the SWZ only accrued during the time that a queue existed. Queue formation depends on traffic volume, the nature of the construction work, the length of the work zone, traffic mix (trucks vs. cars), speed limit (or actual speeds), and perhaps other factors. In other words, queue

characteristics vary by site. With that understood, simulation is a valuable tool in predetermining both the maximum queue length and the period of time within the work day (e.g., during lane closures) within which TxDOT can expect queue formation. Besides the maximum queue length, Figure 52 also indicates the period of time during which a queue was expected for the I-35 project. It shows that the queue began to form just after 7:00 p.m. and did not dissipate until just after midnight.

Another consideration where a viable alternate route exists is the amount of diversion that can be accomplished using a Smart Work Zone. In theory, the diversion would reduce the queue length by the amount of the traffic diversion and would improve travel time for those motorists. However, this result would not likely be as significant in rural areas compared to urban areas, so researchers did not include the potential effects of diversion.

COMPARISON OF BENEFITS AND COSTS

An operating agency might decide to make the B-C threshold greater than 1.0 due to the methodology. However, this analysis used a B-C of 1.0. The methodology sought to find the break-even point where the crash savings at least recouped the cost of the SWZ. To reiterate, savings due to delay reductions could also be incorporated but are not included in this analysis. Crash savings accrue over time and distance, so longer time intervals and longer influence zones result in greater benefits (holding other factors constant). On the cost side, the analysis considered the initial cost plus any maintenance cost as being practically fixed at \$71,000. For this document, the maintenance was considered negligible (e.g., recharging the onboard battery, etc.), so the objective was to determine conditions where benefits exceeded this cost.

Since NCHRP 627 (70) cost units are work zone costs per 100 work zone hours per mile of roadway, this analysis included both time and distance factors as variables. The methodology developed by the research team (using simulation) determined the proportion of a typical active work zone period that queues would be expected to form (20, 40, 60, 80, and 100 percent). The benefits of an SWZ would only accrue during that period. The research team developed a set of both tabular and graphical summaries to assist TxDOT in using these findings.

Figure 57 is an example of the results of this process on a per-mile of influence zone basis for an estimated crash reduction due to the SWZ of 10 percent and for daytime work zones. Nighttime work zones require a different set of tables or figures. Researchers also developed tables for 5 percent, 15 percent, 20 percent, and 25 percent reductions for both daytime and nighttime conditions. The user would need to multiply the values in tables and figures by the influence zone length of a particular work zone to arrive at the total cost savings due to the SWZ.

Using the values in Figure 57, one can determine whether a specific work zone would be a good candidate for an SWZ based on benefits and costs. Following are the specific details:

- Length of the influence zone of 3 miles.
- Assumed reduction in crashes due to SWZ of 10 percent.
- Daytime work zone lane closure.
- Average annual daily traffic of 100,000 vpd.
- Duration of the work zone (including lane closure) at 12 months.
- Percent of typical day requiring lane closure at 50 percent (5-hr queue divided by assumed 10-hr work day).

Figure 57 indicates an SWZ crash savings of \$50,000 per mile (of influence zone). For this example, the total savings for a 3-mile influence zone length where a queue forms 50 percent of the time would be $3.0 \text{ mi} \times \$50,000/\text{mi} \times 0.50 = \$75,000$. Using the SWZ cost of \$71,000, this result indicates a B-C of 1.1. If TxDOT's B-C threshold is 1.0, this work zone is a good candidate for a smart work zone based on benefits and costs.

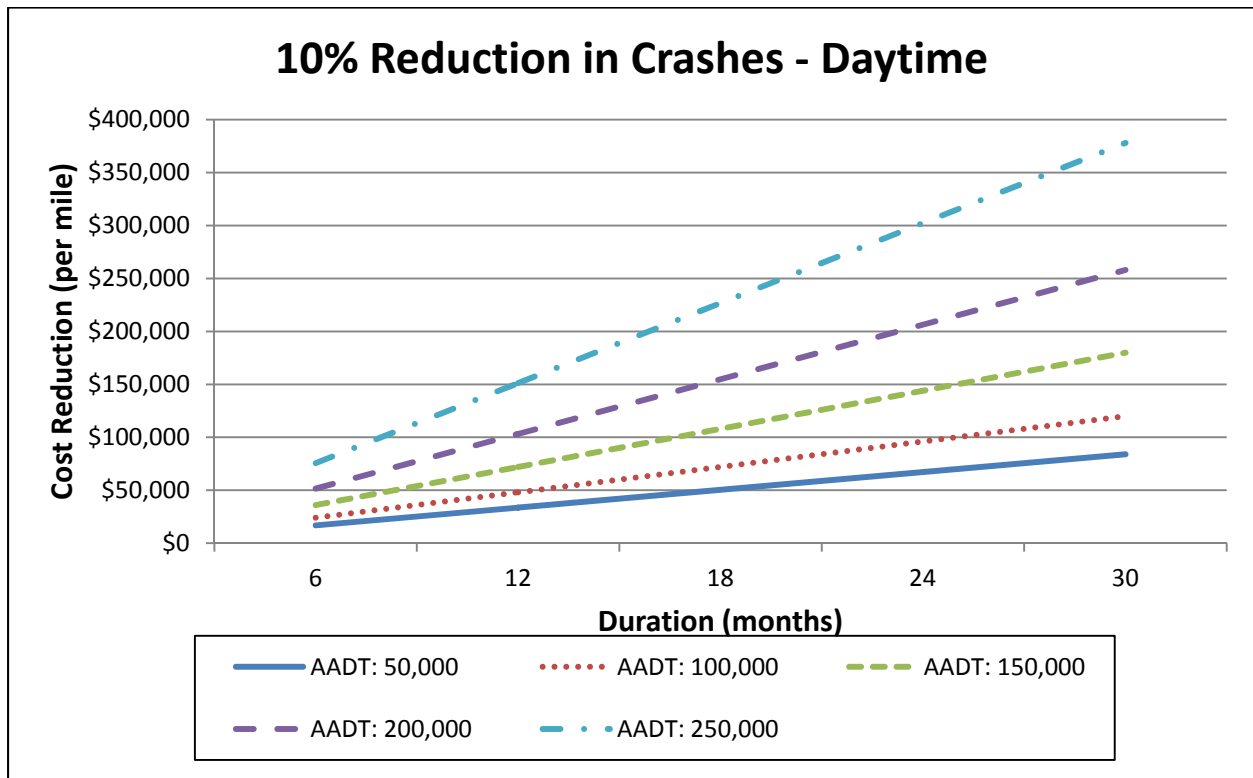


Figure 57. Expected Reduction in Crash Costs Due to Smart Work Zone.

SUMMARY AND CONCLUSIONS

Information from the literature sources attempted to either establish general criteria for installing SWZs or determine some of the benefits and costs based on isolated cases. None of these represents a wide range of real-world situations. The criteria included in these references include:

- Traffic volume (or density) above some value (usually capacity of remaining lanes).
- Excessive or recurring queuing (even if relatively short).
- Length or duration of work zone above some value.
- Absence of entry or exit ramps.

Projects that considered benefits and/or costs usually found positive results even though not always providing a B-C (see Table 22). Even though these sources are helpful, they do not provide a method for determining when an SWZ should be used. This document, however, fulfills this need.

Table 22. Comparison of Literature Sources that Considered Benefits and Costs.

Project	Benefits	Costs	B-C
I-95 (53)	\$140,000/mo	\$22,000/mo	Not provided
Fontaine and Edara (52)	Used travel time savings	\$150k to \$300k	B-C > 1.0 after x days (x varies from 2 to over 100)
I-95 (66)	Reduced queues from 5 mi to 2 mi or less	\$235,000	Not provided

Research findings based on the methodology described in this document indicate that without relatively high traffic demand, long work zones, long queues, and projects lasting longer than 1 year, conditions are not likely to meet the desired B-C criterion exceeding 1.0. For rural areas, the conditions would not be likely except on high-volume interstate highways—possibly on segments near urban areas. The lack of sufficient data to more accurately determine the expected crash reduction rates caused by SWZs is currently a limitation to the use of this methodology. Research is needed to investigate the difference in crashes before and after the installation of SWZs under a variety of conditions. Available information suggests that SWZs almost always reduce crashes and/or their severity, but the relationship is not well understood.

CHAPTER 7. PROOF OF CONCEPT–TRAVEL TIME

INTRODUCTION

This chapter describes a proposed algorithm for estimating travel time (or travel delay) in real time where a smart work zone is deployed. The research team evaluated and calibrated the algorithm using a simulation test bed for the southbound direction of I-35 from Hillsboro, Texas, to Waco, Texas (27.7 miles). Researchers used the VISSIM simulation package to simulate speed sensors and Bluetooth technology characteristics for the purpose of the algorithm evaluation. The evaluation results indicated that the proposed algorithm, once calibrated with historical data, can provide significant improvement in real-time travel time estimation when the volume to capacity (v/c) ratio is greater than 1 (involves queue formation).

OVERVIEW

The travel monitoring service utilizes Bluetooth technology where a Bluetooth reader is installed on the roadside to collect unique media access control (MAC) addresses and timestamps at regular intervals from in-vehicle Bluetooth devices as they pass by each reader. The segment travel time can be estimated by computing the time differences between the timestamps of the same MAC address detected at each pair of Bluetooth readers for the direction and link of interest.

ALGORITHM

Figure 58 describes the SWZ system configuration. The speed sensors are deployed upstream of lane closure to monitor the speed conditions and determine if a queue exists. Bluetooth readers are located upstream and downstream of the work zone beyond the queue in either direction.

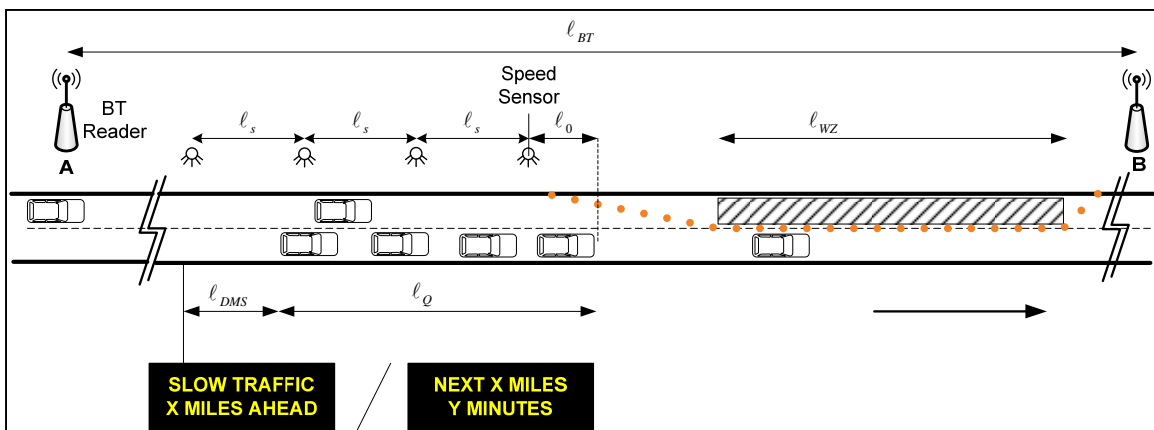


Figure 58. Smart Work Zone System Diagram.

Travel Time Estimation Algorithm

In the simplest case, the segment travel time between two Bluetooth readers can be disseminated to travelers based upon the matching of MAC addresses of those that arrived at the destination B within the previous time interval, which can be expressed as:

$$tt_{t+\Delta t}^{A,B} = \frac{1}{n} \sum_{m=1}^n (T_{m,t,t+\Delta t}^B - T_{m,t<t+\Delta t}^A) \quad (3)$$

where:

$tt_{t+\Delta t}^{A,B}$ = average travel time from A to B calculated at time $t + \Delta t$.

$T_{m,t,t+\Delta t}^B$ = the time stamp of traveler m who arrived at the destination B between time t and $t + \Delta t$.

$T_{m,t<t+\Delta t}^A$ = the time stamp of traveler m who departed the origin A before time $t + \Delta t$.

n = the number of matched sample size.

The provision of real-time travel time information based on the most recent Bluetooth data generally works well for a relatively short segment (5 miles or less) under stable traffic conditions. For a longer segment and changing traffic condition (e.g., transitioning between peak and off-peak periods), the travel time reports based on the Bluetooth data will suffer from a time lag problem, which in combination with changing traffic conditions could produce substantial differences between the reported travel time and the actual travel time experienced by the travelers.

Figure 59 illustrates the issues commonly encountered with probe-based travel time reporting such as Bluetooth and automated vehicle identification (AVI) systems.

To minimize the errors in Bluetooth-based travel time reporting particularly when the lane closure is causing queue conditions, the SWZ can utilize the speed information from the queue monitoring system in conjunction with the work zone characteristics to calculate the real-time delay. The system can then use this real-time delay to compute the appropriate travel time. Later, this section provides the recommendations as to when the real-time delay algorithm is appropriate and how it can be used in conjunction with the Bluetooth travel time monitoring system.

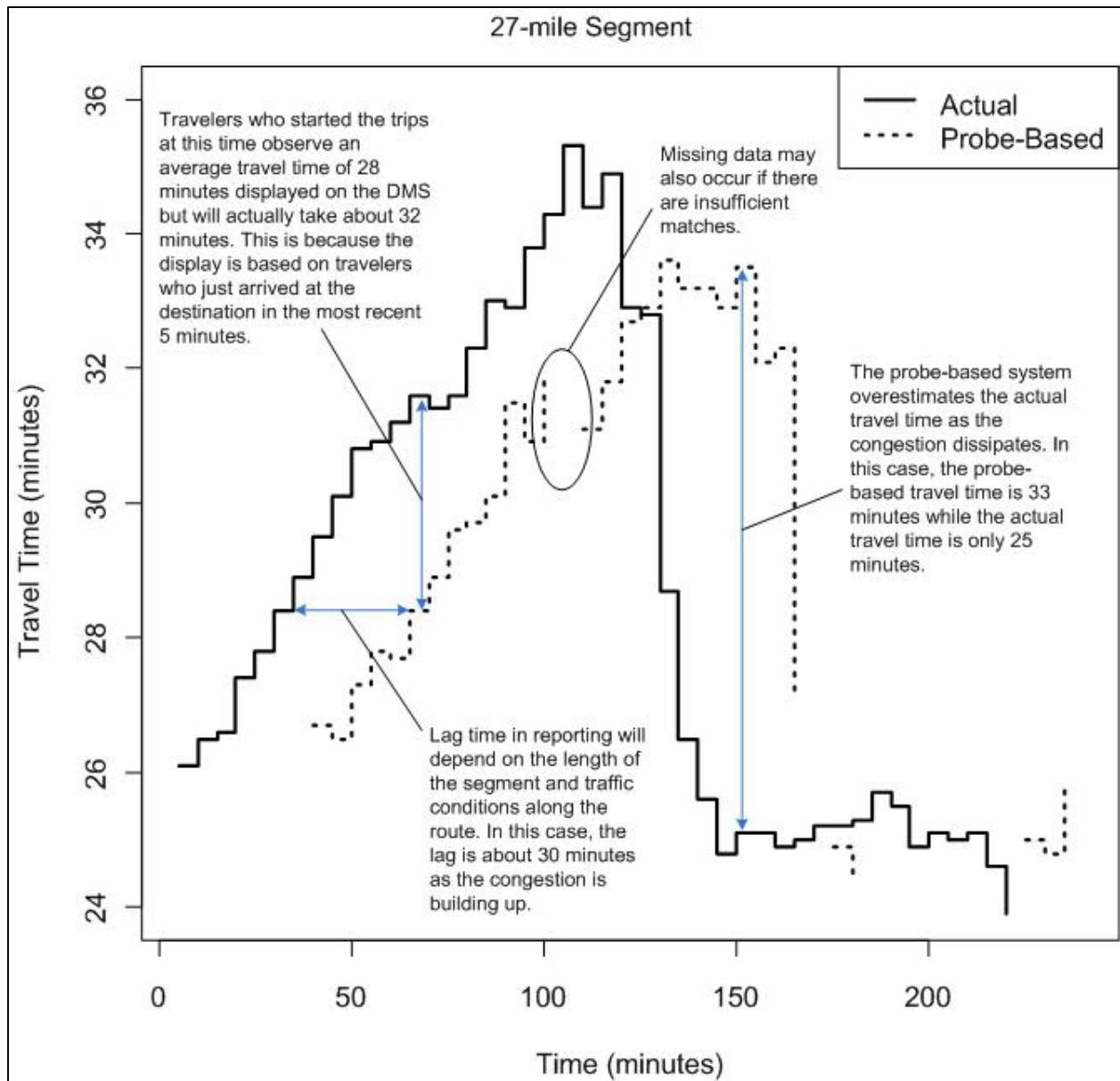


Figure 59. Experienced versus Reported Probe-Based Travel Time.

The definition of delay is the difference between the actual travel time and the free-flow travel time. The analyst can determine the free-flow travel time based on the speed limit, the observed operating speed during off-peak conditions, or a combination of both. The total delay experienced by the drivers traveling through the work zone can be expressed as:

$$d_{total} = d_Q + d_{wz} + d_U \quad (4)$$

where:

d_{total} = the total delay per vehicle.

d_Q = the delay from queuing at the upstream of lane closure.

d_{wz} = the delay from traveling through the work zone at reduced speed.

d_U = the unaccounted delay component, which includes the process of slowing down to join the queue, merging at the upstream of lane closure, and site-specific traffic interruptions such as ramp traffic activities upstream of lane closure as well as within the work zone.

The first two delay components can be modeled using real-time speed data and work zone characteristics. However, the unaccounted delay component accounts for a number of factors that are somewhat difficult to quantify analytically. Therefore, the Bluetooth-based travel time data can be post-processed to determine the total delay for a specific site and a site-specific empirical equation can be calibrated to capture the unaccounted delay. More details are available on this process later in this section.

Let us define v_f as a free-flow speed for the segment. For equal sensor spacing, the delay-in-queue at time t , $d_{Q,t}$, can be estimated using speed sensor data as:

$$d_{Q,t} = \sum_{\forall i: v_{i,t} < v_f} 60\ell_i \left(\frac{1}{v_{i,t}} - \frac{1}{v_f} \right) \quad (5)$$

where:

$d_{Q,t}$ = delay-in-queue at time t (minutes/vehicle).

ℓ_i = the distance of influence of speed sensor i (miles).

$v_{i,t}$ = speed data from sensor i at time t (mph).

The delay from traveling through the work zone is attributed to the reduction in travel speed, which is assumed to depend on the queue condition upstream of the closure. Researchers assumed that if the queue condition exists upstream, the speed in the work zone will be the capacity flow, which is $v_f/2$; otherwise, the speed within the work zone is assumed to equal the work zone speed limit. Therefore, the delay within the work zone can be expressed as:

$$d_{wz,t} = \begin{cases} 60\ell_{wz} \left(\frac{1}{v_f/2} - \frac{1}{v_f} \right); & \text{if queue exists at time } t \\ 60\ell_{wz} \left(\frac{1}{v_{wz}} - \frac{1}{v_f} \right); & \text{if no queue exists at time } t \end{cases} \quad (6)$$

To estimate d_U , one would need to have historical data from the same site or sites with similar geometric and lane closure characteristics. The research team utilized the VISSIM simulation test bed with SWZ configuration deployed to test and evaluate the proposed procedure. The test bed was modeled after the I-35 corridor in the southbound direction from Hillsboro, Texas, to Waco, Texas. This analysis simulated the two-to-one 2-mile lane closure in the middle of the 27.7-mile segment. The next section discusses the simulation model in detail.

Bluetooth travel time monitoring was used to collect the travel time during the lane closure. The actual experienced travel time between time t and $t + \Delta t$ was calculated from the Bluetooth system by aggregating and averaging the travel times of those travelers who started the trip (passed the origin A) between time t and $t + \Delta t$. This is different from the aggregation technique used in real-time DMS display, which is based on those who completed the trip within time t and $t + \Delta t$ (see Equation (3)).

Using the experienced travel time from the Bluetooth monitoring system, the unaccounted delay can be computed as:

$$d_{total,t} = tt_{exp,t} - tt_f \quad (7)$$

where:

$tt_{exp,t}$ = experienced travel time of the travelers who departed the origin at time t .

tt_f = free-flow travel time.

$$d_{U,t} = d_{total,t} - d_{Q,t} - d_{wz,t} \quad (8)$$

Simulation scenarios were set up to collectively capture different volume patterns and ramp traffic interruptions for two-to-one lane closure. Details on simulation evaluation are discussed later in this document. Simulation evaluation results indicated that when the queue condition exists, i.e., when the v/c ratio is greater than 1, the d_Q can be calibrated to predict the d_U using the non-linear relationship of the form shown in Equation.

$$d_U = \alpha \left(1 + d_Q^\beta \right) \quad (9)$$

where:

α = calibrated parameter.

β = calibrated parameter.

d_Q = estimated delay-in-queue from the queue monitoring (min/vehicle).

Simulation evaluation indicates that for a two-to-one lane closure, the average values of α and β are approximately 0.4 and 1.5 when $v/c > 1$. When $v/c < 1$, the value of d_U is typically small and may be negligible.

Once d_U is estimated, the travel time can be estimated as:

$$tt_i = tt_f + d_{Q,i} + d_{WZ,i} + d_{U,i} \quad (10)$$

In summary, the proposed algorithm can provide estimated travel time based on three delay components. The d_Q and d_{WZ} can be estimated directly from the values observed from the queue monitoring system. The d_U can be empirically calibrated using historical travel time and speed data from the SWZ. The suggested parameters above from the simulation evaluation can be used when the local data are not yet available.

SIMULATION TEST BED

The research team utilized a VISSIM simulation model to conduct a proof-of-concept testing for the proposed algorithm. In addition, the simulation was also used to evaluate models for estimating the unaccounted delay. The research team coded the I-35 southbound segment from Hillsboro, Texas, to Waco, Texas. The total segment length was approximately 29 miles. A two-to-one lane closure was located at approximately 9 miles from the beginning of the simulated segment. The length of the closure was 2 miles.

Figure 60 displays an overview of the simulated segment. The queue monitoring service was simulated using a series of data collection points (DCPs) located at half-mile spacings covering a distance of 5 miles upstream of the closure. Only speed data were collected from these DCPs to replicate typical speed sensors used in the work zone applications. The Bluetooth travel time monitoring was modeled using the VISSIM C2X application programming interface (API). The Bluetooth reader was represented using a C2X roadside unit (RSU) with the effective range of 100 meters (Bluetooth Class 1 device). The reader was configured to ping the signal from the Bluetooth devices within the effective range at every second.

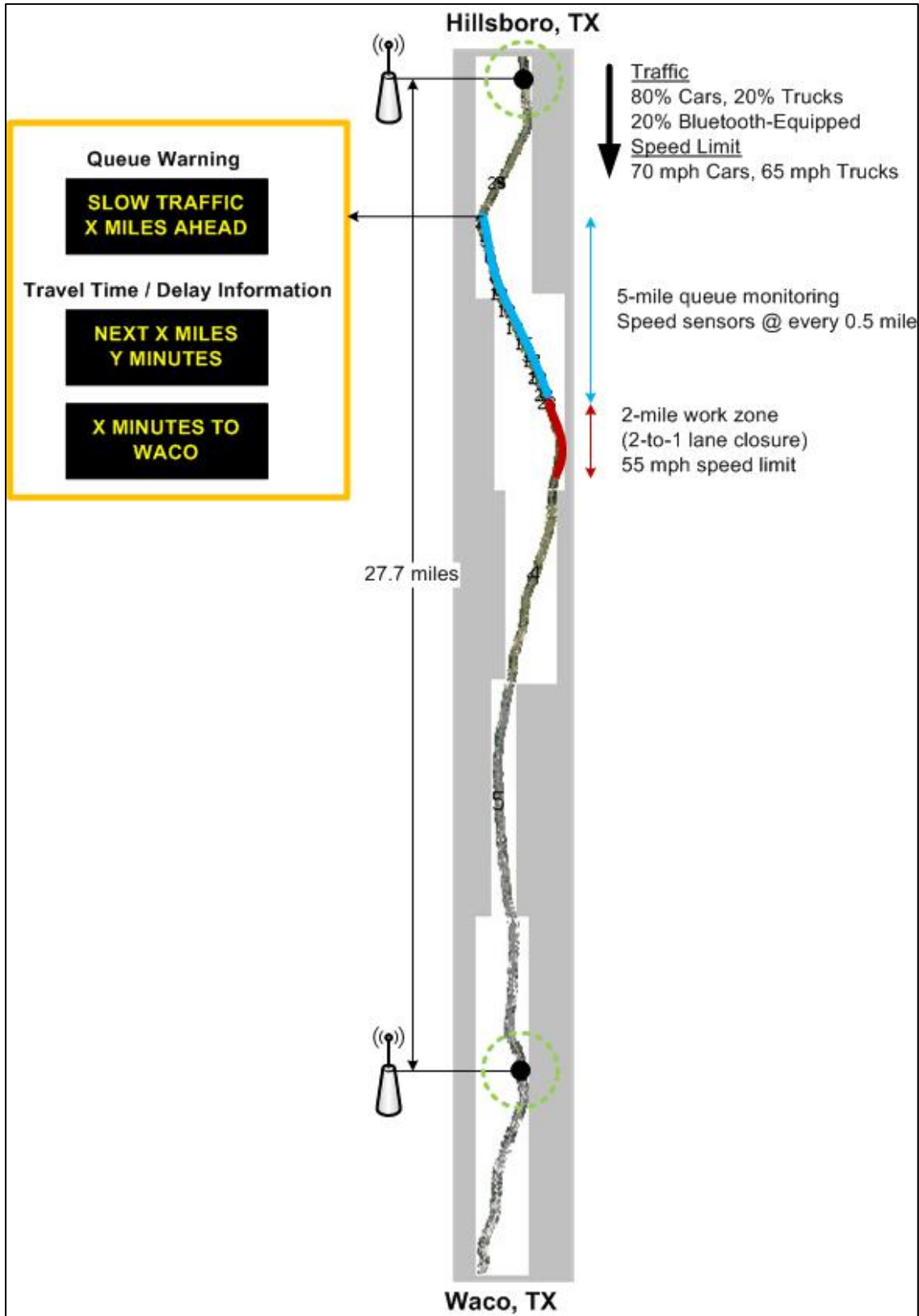


Figure 60. Simulation Overview.

The saturation flow rate is not a direct input in VISSIM, but the parameters in VISSIM's car-following models can be fine-tuned to achieve the desired saturation flow rate (I). According to the Highway Capacity Manual (2), the capacity of the two-to-one lane closure was observed to be in the range of 1550 to 1750 vphpl depending on the duration of the closure, the proportion of heavy vehicles, and whether the crossover was needed. In this study, the work zone capacity was calibrated to 1650 vph by adjusting the safety headway parameter (CC1) in the Wiedemann 99 car-following model used in the simulation.

The parameters used for the queue monitoring were determined in a separate concurrent study. In that study, the researchers examined various combinations of speed thresholds and aggregation intervals that would provide reliable real-time queue length estimates. Based on that study, the 35 mph speed threshold and 5-minute aggregation interval were used to configure the queue monitoring system in this simulation. The vehicle composition was specified as 80 percent passenger cars and 20 percent trucks. Twenty percent of all vehicles were assumed to be Bluetooth equipped for evaluating the algorithm.

SWZ Simulation

Figure 61 shows the simulated messages of DMSs based on the queue and travel time monitoring systems deployed in the SWZ. The messages were updated at 5-minute intervals.

The queue monitoring component monitored the speeds upstream of the closure and estimated the queue length in real time. Since the DMS was assumed to be located at 5 miles upstream of the closure, the display showed LEFT LANE CLOSED 5 MILES AHEAD when there was no queue. When the system detected the queue, the DMS displayed the warning message to the drivers upstream of the queue condition. The warning message included an approximate distance at which approaching motorists could expect to encounter the slow or stopped traffic. As indicated in this figure, the system-estimated queue length was 0.43 miles; therefore, the message displayed on the DMS was STOPPED TRAFFIC 4.5 MILES AHEAD.

The travel time component was based on Bluetooth MAC address matches at the destination reader in the past interval (i.e., 5 minutes in this case). When the number of matches did not meet the minimum requirement specified (three matches) in the simulation, the system did not calculate the travel time.

Performance Measures

The measure of travel time accuracy came from the difference between the travel time displayed on the DMS and the actual travel time to traverse the segment. The discussions earlier surrounding Figure 59 described this type of error. Calculating the aggregate measure of travel time reporting errors for the entire simulation period used the following formula:

$$RMSE = \sqrt{\frac{\sum_{i=1}^n (tt_{BT,i} - tt_{exp,i})^2}{n}} \quad (11)$$

where:

RMSE = root mean square of error (minutes).

$tt_{BT,i}$ = average travel time reported based on Bluetooth monitoring system at i^{th} interval (minutes).

$tt_{exp,i}$ = average experienced travel time at i^{th} interval based on post-processing of simulation data.

n = number of valid intervals for comparison (note that intervals with invalid travel time reports are omitted from the calculation).

Large RMSE values indicated that the travelers' actual travel times significantly differed from what they had seen on the DMS, which was estimated using Bluetooth matches.

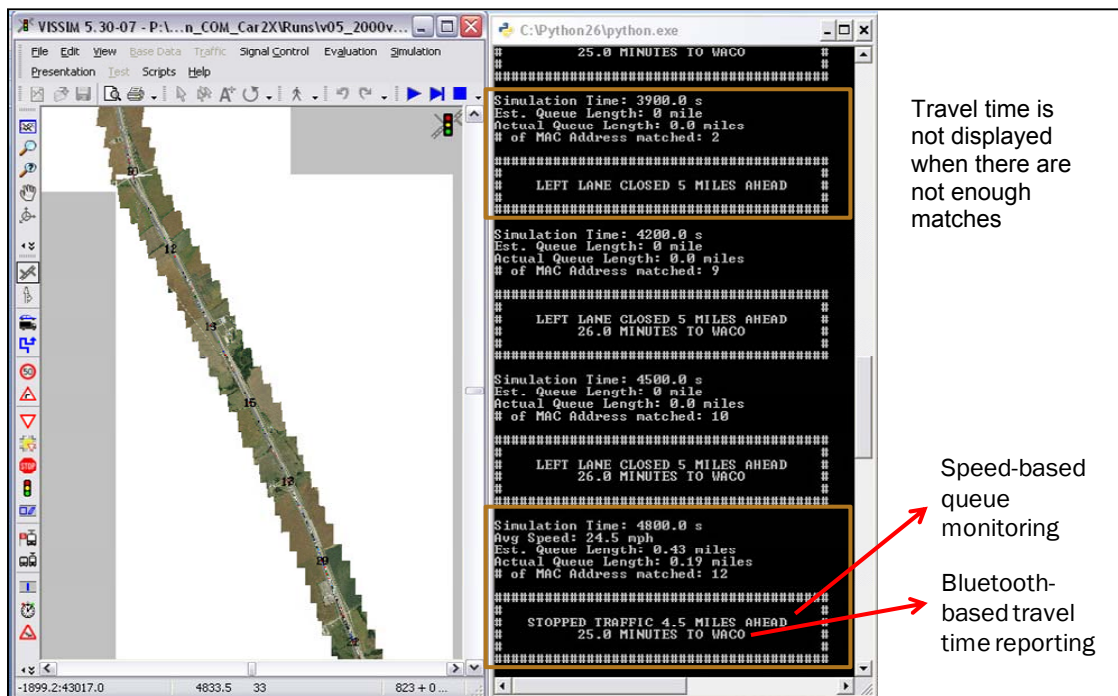


Figure 61. Screenshot of Simulation—Queue and Travel Time Reporting.

Factors Influencing Travel Time Reporting Errors

Several factors can influence the magnitude of errors in Bluetooth-based travel time reporting. The errors associated with Bluetooth-based travel time reports depends on the following factors:

- Longer Bluetooth segment can cause delay in travel time reports and thus increasing the potential errors in travel time reports.
- Severe congestion can cause significant delay for probe vehicles to reach the destination and thus increasing the error magnitude.
- The error magnitude tends to be larger if the congested location is relatively close to the beginning of the Bluetooth segment.

Figure 62 illustrates the effect of congestion on the errors from the Bluetooth system versus actual travel time. The left figure demonstrates the case of minor congestion with the v/c ratio of less than 1 and travel time in the range of 25 to 27 minutes. The largest error observed was 2 minutes, which is insignificant for a 27-mile segment. The right figure demonstrates the effect of heavy congestion where the v/c ratio is greater than 1 for an extended period of time. The Bluetooth travel time (dashed line) shifted horizontally to the right compared to the actual travel time due to congestion before vehicles entered the downstream Bluetooth detection zone. This time, the observed errors increased significantly and exceeded 10 minutes in some intervals.

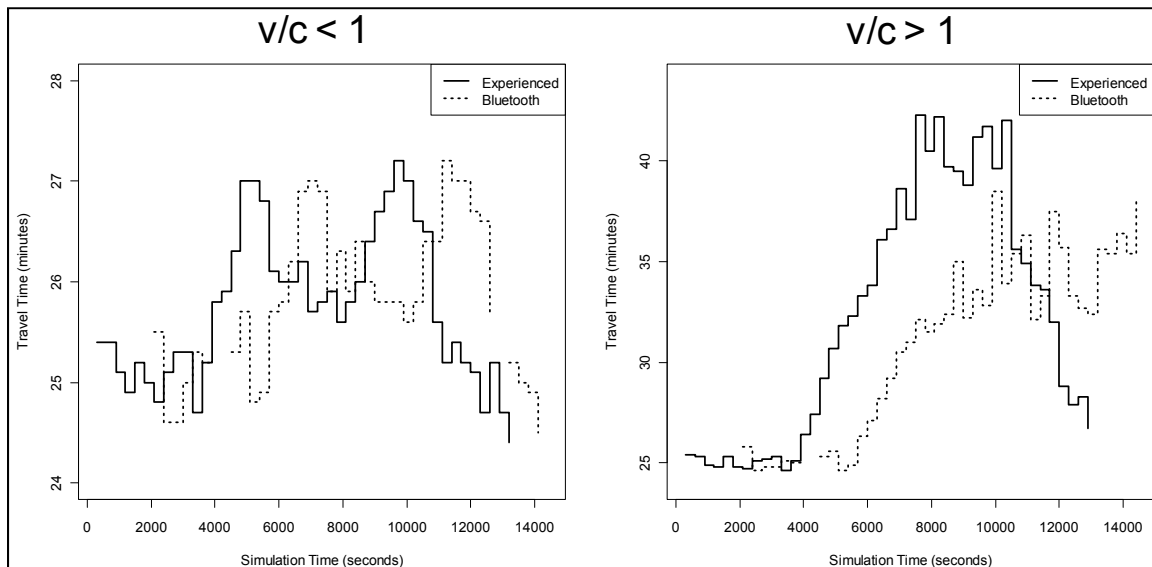


Figure 62. Comparison of Travel Time Reporting Errors.

Proposed Delay Estimation Algorithm

The previous section discussed the errors in travel time reporting from the Bluetooth-based algorithm. The next section describes a proposed algorithm for addressing such errors by utilizing the real-time data from the queue monitoring system to estimate the delay. The proposed algorithm requires an empirically calibrated model for a specific type of lane closure

and site-specific conditions to accurately predict the amount of unaccounted delay. This unaccounted delay component is negligible and can be omitted if predictions do not indicate queue formation at the SWZ.

To illustrate, Figure 63 shows observed relationships between unaccounted delay and system-observed queue conditions. These two figures are derived from a simulation of a two-to-one lane closure with a $v/c > 1$ for an extended period. The right figure shows the relationship between unaccounted delay and system-estimated queue length based on the algorithm described in Chapter 6. The unaccounted delay increases nonlinearly with the queue length. The left figure exhibits a more pronounced nonlinear trend when the system-estimated queue length is replaced by the delay-in-queue calculated using Equation (5). These plots indicated that the real-time queue conditions observed from the queue monitoring system could explain the unaccounted delay. Researchers tested several functional forms to capture this relationship. The use of real-time delay-in-queue in the nonlinear model of the functional form shown in Equation (9) provided the most appropriate fit in this study.

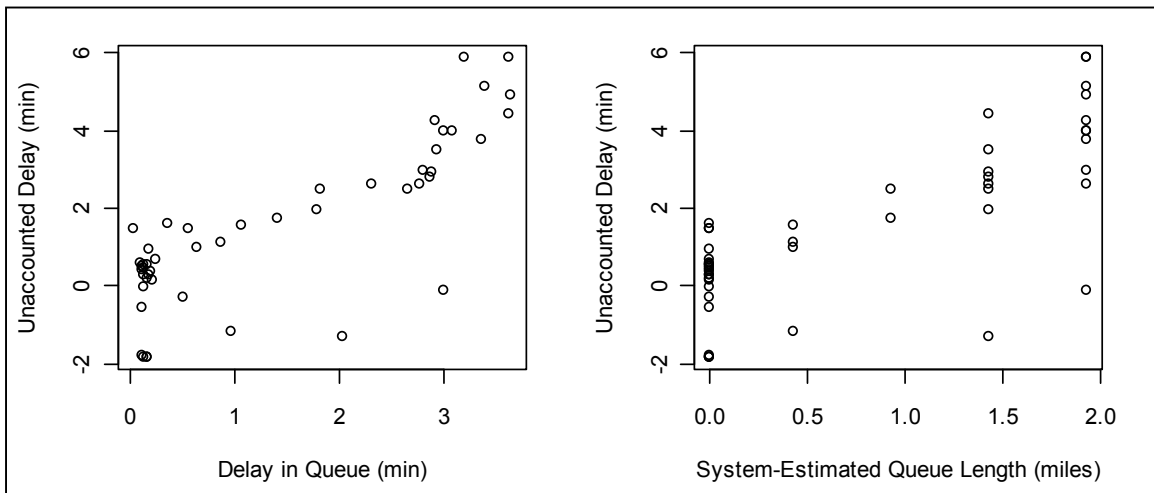


Figure 63. Relationship between Queue Conditions and Unaccounted Delay.

The unaccounted delay model calibration required a temporally synchronized data log of experienced travel time from Bluetooth monitoring and speed data at each queue monitoring sensor. Such data logs are best obtained from the lane closure of interest at the beginning of the SWZ deployment (for a long-term work zone). For short-term work zones, alternative sources include simulation models (recalibration may be necessary) and other SWZ locations with similar closure characteristics.

Once the data log is assembled, one can empirically calibrate the unaccounted delay component using the relationship between unaccounted delay and delay-in-queue components. An off-line evaluation of Bluetooth data can generate the unaccounted delay. Determining the unaccounted delay at each time interval requires deriving the experienced travel time from post-processing of

Bluetooth data. Then, the unaccounted delay is equal to the actual travel time subtracted from free-flow travel time, delay-in-queue, and work zone delay for each corresponding time interval.

Figure 64 shows an example of an empirically calibrated model from the simulated dataset. Researchers calibrated the model using the nonlinear regression “nls” function in R statistical software with the Gauss-Newton fitting algorithm. Once the unaccounted delay model is calibrated, one can estimate the travel time by adding the unaccounted delay to the free-flow travel time and other delay components, as shown in Equation (10).

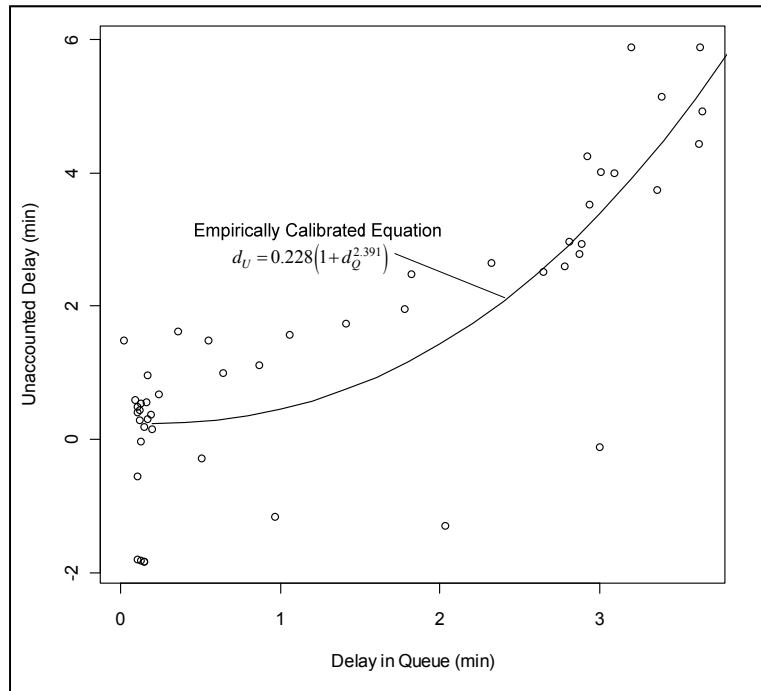


Figure 64. Example of Empirical Model for Unaccounted Delay.

The next step was to implement the proposed algorithm in the simulation test bed. Figure 65 shows a screenshot of a simulation run where the third row of the simulated DMS display shows the travel time estimate from the proposed algorithm. The first two rows in the simulated DMS are the same as discussed earlier in Figure 61. The message from the proposed algorithm was NEXT X MILES Y MINUTES. The distance was 7 miles in this case—measured from the DMS location to the end of the work zone. Calculating the travel time used the proposed algorithm and calculated the delay components in real time and adding them to the free-flow travel time, which was about 7 minutes in this case.

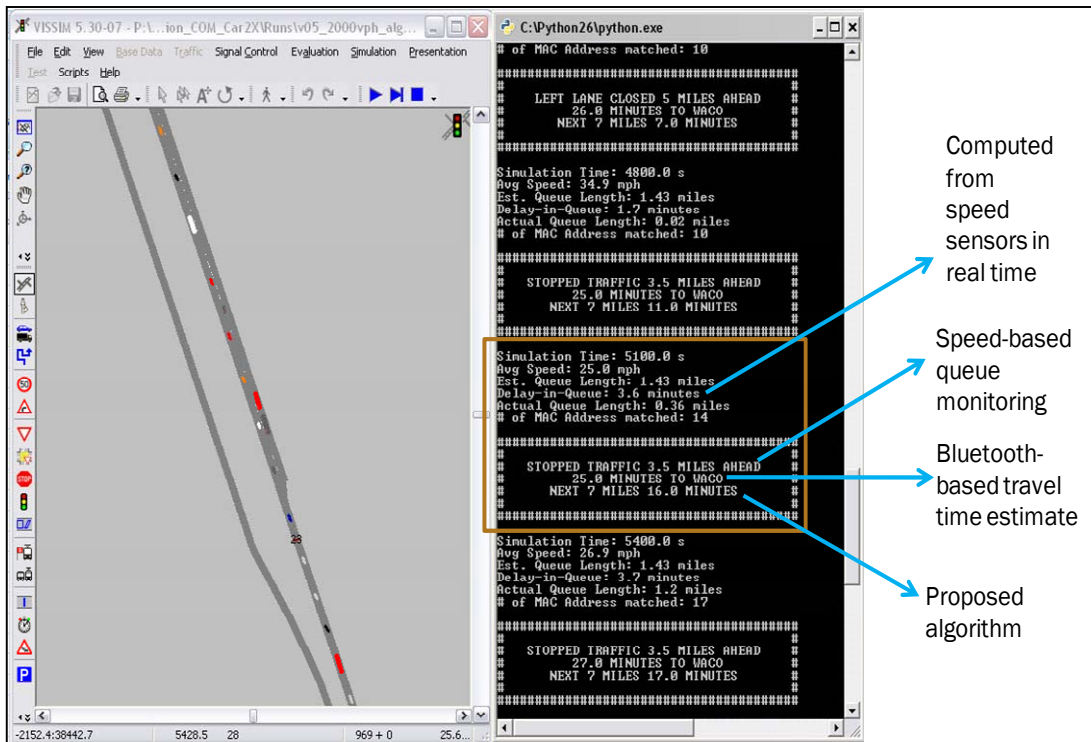


Figure 65. Simulation Screenshot with Proposed Algorithm Implemented.

Figure 66 shows the comparison of travel time information provided versus actual travel time. In the left figure, standard Bluetooth-based travel time exhibits a shifting pattern with respect to the experienced travel time due to congestion delay. The right figure shows a significant improvement in travel time estimate using the proposed algorithm. The algorithm performs better in capturing delay during queue formation compared to queue dissipation. There is still a lagging pattern observed during the queue dissipation. The errors observed at the peak are attributed to a combination of the stochastic nature of the queue and other influencing factors unaccounted for in the proposed model.

In the next section, the research team conducted a number of simulation scenarios to provide a preliminary evaluation of the performance of the proposed algorithm and to determine the conditions that warrant algorithm implementation.

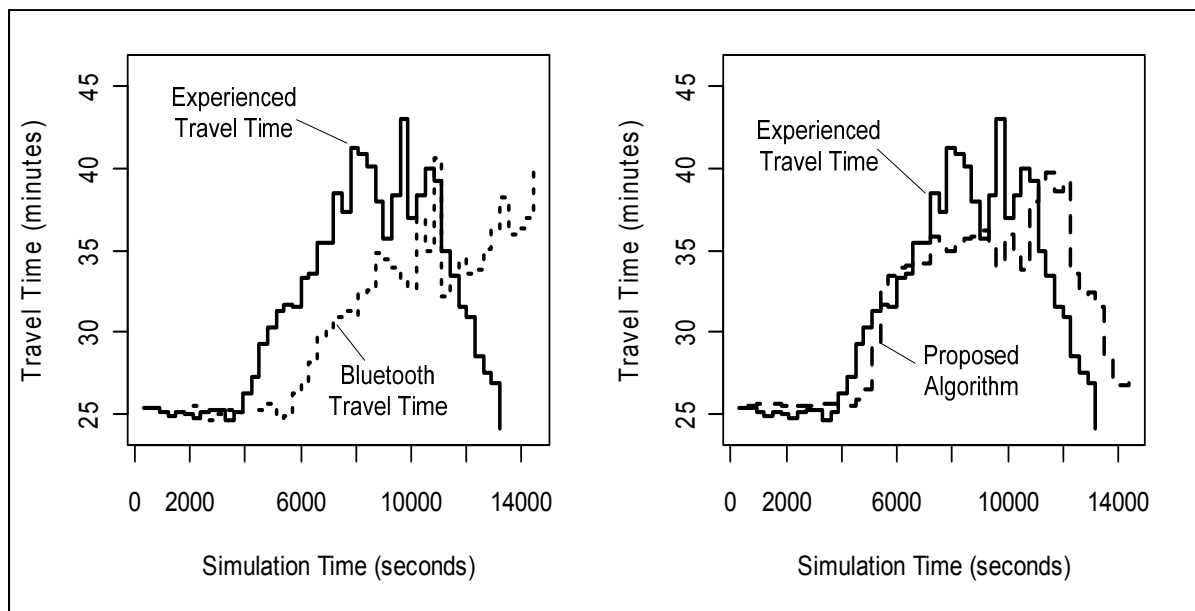


Figure 66. Comparison of Travel Time Information.

EVALUATION

This section describes the simulation evaluation runs used to evaluate the performance of the proposed algorithm. Quantifying the travel time errors used comparisons of RMSE measures for Bluetooth-based and proposed algorithm travel time estimates.

Scenarios

Researchers developed a set of simulation run scenarios to evaluate the performance of the proposed algorithm. The simulation period was 4 hours for all the runs. The evaluation scenarios considered the following three factors:

- Peak volume: 1600, 1800, and 2000 vph.
- Volume profile: single peak and dual peak.
- Ramp interruption: without and with ramp traffic activities upstream of the closure.

The evaluation used peak volume levels in conjunction with the volume profiles shown in Figure 67. In the single peak pattern, the simulation began with the low-level volume (800 vph) for 1 hour, then increased to the peak volume level for 2 hours (depended on the scenario; 1600 vph shown in Figure 67), and finally decreased back to 800 vph in the final hour. For the dual peak pattern, the first and the final hours were the same as the single peak pattern. In contrast to the single peak pattern, the volume reached the peak level twice but lasted for 40 minutes each in the middle 2-hour period.

The ramp traffic interruptions allowed 5 percent of the peak volume level to enter into and exit from the freeway using one on-ramp and one off-ramp at 2.7 miles and 0.8 miles upstream of the

closure, respectively. The analysis maintained the same volume level for performance comparison across all the comparative cases by balancing the incoming and outgoing ramp traffic volume.

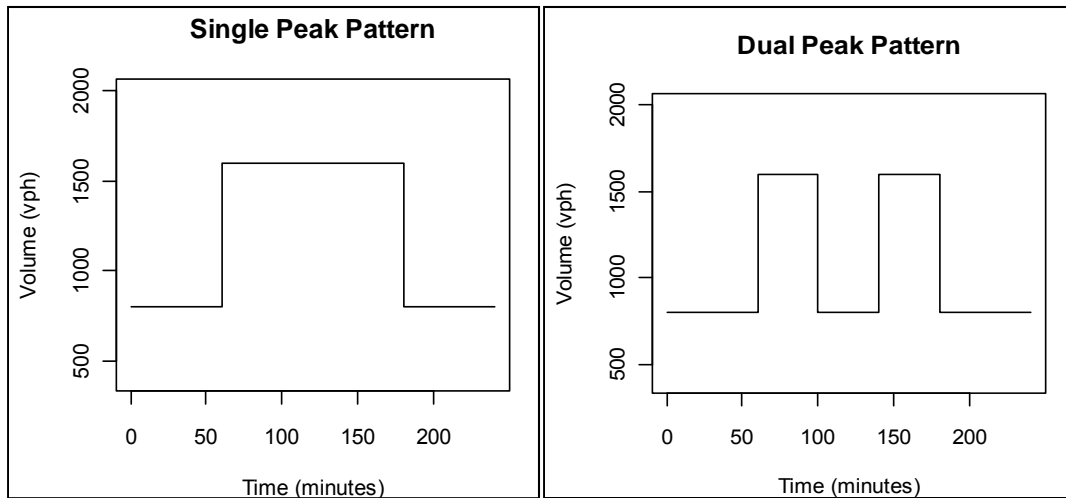


Figure 67. Volume Profiles.

Simulation Runs

A full factorial combination of the factors produced a total of $3 \times 2 \times 2 = 12$ evaluation scenarios. For each simulation run, analysts logged the queue conditions and the travel times for post-processing and empirical model calibration. The data logged for evaluating the queue monitoring system included:

- Actual queue length as measured by the VISSIM queue counter feature.
- Estimated queue length as determined by the SWZ using the algorithm described in Chapter 6.
- Speed data in 5-minute intervals at each speed sensor for calibrating the unaccounted delay model.

The data logged for evaluating travel time monitoring included:

- Bluetooth-based travel time as computed using Bluetooth matching in the simulation.
- Actual travel time based on the VISSIM travel time segment feature. The locations of the beginning and end of the travel time segment were the same locations as the RSUs in the network. The RSU served as a Bluetooth reader in the simulation.

Calibration of an empirical model for each scenario required using data from both queue and travel time components to compute the unaccounted delay as part of the proposed algorithm. The travel time estimates from the proposed algorithm were also logged for performance evaluation.

Results

Table 23 summarizes the evaluation results from the 12 simulation runs. The third column from the left has the peak v/c, calculated by dividing the peak volume by the work zone capacity (1650 vph). The peak v/c is a measure of the degree of congestion experienced in each scenario.

From the model calibration process, researchers observed that the unaccounted delay was negligible in cases where there was no unsteady queue condition ($v/c < 1$). This implies that the unaccounted delay component can be omitted in such cases.

Calculating the accuracy of travel time information used the RMSE. In Table 23, the third column from the right indicates the RMSE of the Bluetooth versus actual travel time. The second column from the right shows the RMSE of the proposed algorithm versus the actual travel time. The proposed algorithm generally outperforms the Bluetooth travel time in the range of 6 percent to 54 percent. The last column indicates the percent improvement in RMSE when comparing the proposed algorithm versus the Bluetooth-based estimate. The RMSE improvement tends to increase with the v/c ratio, which implies that the algorithm is likely to achieve greater benefits if deployed at lane closure locations with a high degree of congestion.

Table 23. Evaluation Results.

ID	SCENARIO INPUTS				RMSE		
	Peak Volume (vph)	Peak v/c	Ramp Interruption	Volume Profile	BT RMSE (min)	Proposed Algorithm (min)	Percent Change (%)
1	1600	0.97	Yes	Dual Peak	1.27	0.73	43
2	1800	1.09	Yes	Dual Peak	2.45	1.32	46
3	2000	1.21	Yes	Dual Peak	5.1	2.37	54
4	1600	0.97	Yes	Single Peak	1.08	0.74	31
5	1800	1.09	Yes	Single Peak	3.33	1.60	52
6	2000	1.21	Yes	Single Peak	5.66	3.72	34
7	1600	0.97	No	Dual Peak	1.09	0.77	29
8	1800	1.09	No	Dual Peak	2.47	1.42	43
9	2000	1.21	No	Dual Peak	4.96	2.27	54
10	1600	0.97	No	Single Peak	0.82	0.77	6
11	1800	1.09	No	Single Peak	3.24	1.61	50
12	2000	1.21	No	Single Peak	5.87	4.25	28

SIMULATION CONCLUSION

The research team examined the concept of an SWZ where the queue monitoring and travel time monitoring services are deployed. Under the queue monitoring, the SWZ utilizes speed-based information to keep track of the queue status and inform drivers upstream of the approximate back-of-queue location via portable DMSs. In the travel time monitoring, the Bluetooth technology provides a segment travel time estimate during the lane closure.

As with any probe-based travel time reporting system, including Bluetooth, there is an issue with the time lag in reporting, as the travel delay incurred within the segment may delay probe vehicles from reaching the destination. This problem leads to differences in travel time estimates that the drivers see on the DMS versus what they actually experience. The problem worsens when the Bluetooth segment is long and the congestion location is relatively closer to the beginning of the segment.

To address the problem of probe-based travel time reporting in an SWZ, the research team proposed an algorithm to improve the travel time estimate using real-time information from the queue monitoring system. The algorithm is based on three delay components—delay in queue, delay in work zone, and unaccounted delay. The speed data collected in real time are required to compute the delay in queue and the delay in work zone. Calibration of the empirical relationship is necessary to estimate the unaccounted delay. Travel time estimates are based upon these three delay components.

The research team developed a simulation test bed to demonstrate such an approach, using a 29-mile southbound segment of I-35 from Hillsboro, Texas, to Waco, Texas. The simulated features included both queue monitoring and travel time information services. The queue monitoring system used speed sensors deployed at half-mile spacings upstream of the closure. The Bluetooth feature used the C2X API feature in VISSIM. The proposed algorithm used models calibrated from the simulation data.

The evaluation results from simulation evaluation runs revealed that the proposed algorithm significantly improved the travel time (delay) estimate when queue conditions existed ($v/c > 1$). When compared with the typical Bluetooth-based travel time reports, the proposed algorithm reduced the RMSE from 6 percent to 54 percent. The proposed algorithm performed better when the congestion was building rather than when dissipating. The horizontal lag in travel time reports observed in the probe-based system still existed in the proposed algorithm, but to a lesser degree. It is possible to further address this shortcoming by incorporating the short-term traffic prediction capability into the system. The short-term traffic prediction will require historical volume data that are not currently available in the SWZ architecture considered in this study.

CHAPTER 8. INTEGRATING AN SWZ AND PERMANENT ITS

INTRODUCTION

This chapter includes results from two project tasks:

- Examining innovative uses of work zone ITS data.
- Operating a permanent ITS in combination with a work zone ITS.

INNOVATIVE USES OF WORK ZONE ITS DATA

A primary function of most transportation management centers in Texas is to disseminate travel information. However, with some work zone traffic management devices, TMCs could have different and unique types of data and information that they have not had before. For example, some work zone traffic management devices are designed to explicitly measure queue lengths and/or delays. In this task, the research team examined how TxDOT traffic managers with access to this type of work zone information could perform new and innovative traffic management activities. This task provides TxDOT with suggestions on how integrating construction-related traffic information might expand TxDOT traffic management capabilities.

POTENTIAL APPLICATION AREAS

First, the research team reviewed the road construction and maintenance activities that are typical in rural areas, along with the potential ITS solutions for these activities. Table 9 lists the typical road construction and maintenance activities (emphasis on rural areas) that are appropriate for this project. This list comes directly from the TMUTCD (68), forming a subset of the larger list in the manual.

The research team chose each Description of Work in the first column based upon how amenable each work activity might be to use of ITS as a feasible solution to improving traffic operations and/or safety within and upstream of construction and maintenance work zones. The second column references the specific TMUTCD TA number from the manual. The remainder of the table required decisions of the research team pertaining to duration, schedule, stationary vs. mobile, and potential impacts of each scenario.

The potential ITS solutions for rural work zones as identified in Chapter 2 are as follows:

- Dynamic congestion advisory.
- Dynamic merge (at work zones with lane closures).
- Dynamic queue warning system.
- Excessive speed warning.
- Haul road warning.

- Optimized restriction/closure.
- Travel time/delay information.
- Variable speed advisory.
- Work space intrusion warning.

Of this list, the ITS solutions that are most appropriate for consideration in this chapter are:

- Dynamic congestion advisory.
- Dynamic merge (at work zones with lane closures).
- Dynamic queue warning system.
- Travel time/delay information.

The first three solutions use speed as the primary input for determining decision strategies, so the list of four solutions involves measuring speeds and/or providing decision information based on these measured speeds. The dynamic congestion advisory and the travel time/delay solutions are more conducive to corridor applications than to short segment treatment, whereas dynamic merge and dynamic queue warning solutions are more conducive to shorter segments in the vicinity of work zones. In either corridor or segment scenarios, involvement of a TMC could be appropriate, but the same criteria proposed in Chapter 5 related to the ITS architecture would apply. The integrated architecture would apply where a TMC is involved, and the stand-alone architecture would apply where a TMC is not involved. Information in Chapter 4 provides general guidance to assist decision-makers in choosing between the two alternatives.

Information from Various ITS Solutions

Depending on the construction and maintenance activity, the location of the work zone, roadway type, traffic volume, and other factors, TxDOT might select any of the ITS technologies for deployment at a rural work zone. Each ITS solution has its own set of information and performance metrics that it can provide. In general, the information provided by any of the work zone ITS technologies is based on the following data and performance metrics:

- Average vehicle speed.
- Travel time.
- Delay.
- Queue length.
- Vehicle throughput.

Potential Use of Information

In rural work zone ITS applications, the use of these performance metrics is often limited to a localized area directly affected by the work zone. Their primary purpose is to improve traffic safety and mobility within and immediately upstream of the work zone. However, as noted above, some solutions apply to corridors and shorter segments alike.

There could be cases where TxDOT could more effectively manage traffic by providing advanced traveler information to motorists before they enter the corridor affected by the smart work zone—perhaps an hour or more upstream of the site. This improved traffic management could result from integrating SWZ information into the traffic management operation of the nearest major cities. For example, a rural smart work zone system with significant capacity reduction along the I-45 corridor between Houston and Dallas could provide useful delay information for TMC operators in Houston TranStar and in DalTrans. If the delay reported by the SWZ system is significant, the TMC operators might decide to use some of their DMSs to disseminate appropriate construction-related delay messages to motorists traveling in either direction on I-45. They might also use the information from the rural smart work zone system to provide web-based travel time and delay estimates for different segments along the I-45 corridor.

TxDOT has already installed Bluetooth readers along the I-45 corridor between Houston and Dallas and is monitoring vehicular speeds in almost real time. Even if these readers are providing accurate and timely speed information to the TMCs, there could be gaps in the data unless appropriate steps are taken to correct for gaps in the traffic stream (see discussion on Bluetooth travel time systems in Chapter 8). The addition of a smart work zone would add potentially critical information such as queue length and speeds in the immediate area in case the Bluetooth readers were not located at optimum positions to capture this information.

In this example, with involvement of TMCs, TxDOT would likely utilize the integrated architecture as covered elsewhere in this report. The intent of the second type of architecture, called stand-alone, is for lower-demand situations and no involvement of a TMC.

Queue length and average speed might also be used in TMC-operated, web-based real-time traffic information systems. However, other information that could be provided by rural work zone ITS solutions, such as work zone intrusion alerts, is not as well suited for integration into a large-scale TMC-based traffic management strategy, primarily due to the short-term nature of the need. By the time TxDOT could display the information, the traffic disruption would likely be gone.

Another application might be where rolling terrain causes sight distance problems and formation of a queue would pose a potential hazard to high-speed motorists. The queue would not need to be lengthy to be a hazard, but short-term problems are more challenging in terms of providing timely warnings.

A weakness of work zones with alternate routes (to bypass a congested construction zone) is that motorists usually are unfamiliar with the alternate route and choose to stay on the primary route when the alternate might involve less travel time. Bluetooth readers along the alternate route could feed travel time data to drive PCMSs on the main line to tell motorists the travel time on the alternate route along with travel time on the main line through the construction zone.

Delays on the main line might force bypassing onto the frontage roads or alternate parallel routes, but there is no way for motorists to know the travel time on these alternate routes. By monitoring travel times on the alternate routes, a TMC could provide travel times on the main line as well as on the alternate route to give drivers a choice.

OPERATING AN EXISTING ITS IN COMBINATION WITH A WORK ZONE ITS

In this task, researchers developed recommendations for integrating, operationally and procedurally, construction-related ITS systems with permanent ITS systems to develop a comprehensive traffic management solution. Researchers developed recommendations for how TxDOT should use its permanent DMSs in the vicinity of work zones where these construction-related ITS systems have been deployed and are displaying traffic condition information. The other primary consideration was how TxDOT could use construction-related traffic monitoring systems to augment existing incident detection systems feeding data to a TMC. The use and integration of a construction-related video surveillance system within a TMC was also included.

Once again, the ITS solutions that were most appropriate for consideration in this task were:

- Dynamic congestion advisory.
- Dynamic merge (at work zones with lane closures).
- Dynamic queue warning system.
- Travel time/delay information.

Use of Permanent Dynamic Message Signs

In many cases, Smart Work Zones generate data/information for displays primarily on PDMSs within or near the work zone. However, similar data could be made available to be displayed on permanent DMSs strategically located well upstream of the work zone for traffic destined to pass through the work zone for the purpose of trip planning. The location of the DMS could be many miles away, so the message would need to be adapted based on this distance. This scenario suggests involvement of a TMC since the message would likely be different from the one displayed at or near the work zone. The work zone system might be designed to provide queue warning, but farther away from the problem area, the message would more likely pertain to the magnitude of the delay, the distance from the permanent DMS, and perhaps alternate route information.

The reverse situation of using PDMSs to warn or inform motorists of some situation beyond the limits of the work zone would likely depend upon the availability of the PDMS for this purpose. In other words, if the SWZ was not monitoring queues, congestion, or speeds within the work zone (e.g., off-peak period), it might become available to serve a secondary purpose. Again, this scenario suggests the involvement of a TMC, requiring an integrated architecture. The limitation of this alternate use is that the work zone would take priority and might, at any time, suddenly

require the system to stop performing the secondary role and resume its primary role. The other downside of having a dual role is the SWZ might fail its primary role or be sluggish in detection of critical conditions due to secondary demands.

Use of Vehicle Monitoring Systems

TxDOT could use construction-related traffic monitoring systems to augment existing incident detection systems feeding data to a TMC. In the case of the I-35 reconstruction through the Waco District, there could potentially be several SWZ systems deployed that would be available (assuming a TMC and use of the integrated architecture) to complement other permanent systems. For example, a major incident involving a complete closure of the interstate route could be detected initially by a rural system. This early detection would result in a tremendous payoff in reducing the freeway closure time, motorist delay, and secondary crashes that are likely to occur.

Use of Video Surveillance Systems

If a rural work zone employs video surveillance, TxDOT could use the imagery to verify conditions near the camera (assuming communications are in place). Bandwidth becomes an issue for high-quality video, but even reduced frame rates or resolution can still be helpful to both monitor and verify the situation.

Integration of Work Zone Website with Permanent Website (Speed Display)

Websites are another tool that might be useful to provide information on work zone conditions but also to provide information on incidents, weather, or perhaps other factors. Providing a link on the TMC's standard traffic map would be one way to get the information shared with motorists.

CHAPTER 9. SUMMARY AND CONCLUSIONS

INTRODUCTION

TxDOT's usage of ITSs in work zones has been relatively limited to date. The I-35 project near Hillsboro, which used an SWZ vendor to mitigate construction impacts, is an exception. A survey of TxDOT districts clearly indicates not only support for ITS applications within work zones but also an expectation of direct benefits. Some applications, such as Internet websites and speed advisory messages, appear to be almost standard practice based on the 10 district responses. It was therefore unnecessary for the project to focus on those areas since there would be little additional knowledge or information gained to promote their use.

The benefits, however, of focusing on the implementation of applications that are currently second-tier could be substantial. Given the information in the Chapter 2 literature and case study reviews, the benefits of applications such as queue warning, incident management, and merge control are real, measurable, and substantial. What is currently lacking, however, is a clear and consistent criteria-based methodology for assessing the benefits of their implementation. It is here that the project can make the largest advances in the state of the practice by the department. Chapter 6 presents guidance for application of ITS treatments. Table 8 in Chapter 4 summarizes some common SWZ treatments, the equipment used, and some typical decision criteria.

SUMMARY

Justification for Smart Work Zones

The following list indicates the justifications for choosing to use a Smart Work Zone:

- Crashes due to work zone.
- Excessive queuing.
- Excessive delay.
- Traffic volume above some minimum level.
- Project length over some value.
- Traffic impact on local business, etc.
- Site-specific issues such as sight distance limitations.

Using a single factor that can encompass most of these impacts seems to be a logical approach. This research and others before it propose the use of a benefit-cost analysis. The use of an alternate route appears to be more of a special case situation, predicated first and foremost by the availability of the route and second by the ability of the route to be safe, simple, and capable of handling the additional traffic volume.

Case Studies Illustrating the Effects of Smart Work Zones

Caltrans met its two critical traffic management goals by using an SWZ on its I-15 reconstruction project near Devore, California—reducing overall traffic volume through the work zones by 20 percent and reducing the maximum peak-hour delay by 50 percent. Early predictions placed delays for the extended closures at 90 minutes, but in reality, the maximum peak delay was measured at 45 minutes on weekdays.

Illinois DOT reported no significant traffic backups while its SWZ was in place on I-55, despite the relatively high traffic demand of about 41,000 vehicles per day. Of the two crashes known to occur during the construction activity, one resulted from driver fatigue and the other involved driving while impaired.

The NMSHTD purchased \$1.5 million in ITS equipment, including a series of cameras and sensors to monitor traffic conditions and detect incidents, electronic signs, highway advisory radios, a website, and other media to transmit traveler information. Three major benefit areas were mobility, safety, and cost savings. Pertaining to mobility was incident response and clearance time, which was reduced from 45 minutes (historically) to 25 minutes with the use of an ITS in the work zone. There was also a reduction of 15 percent in travel demand as a result of outreach efforts. There was a 7 percent increase in crashes over the first year of the project, but this increase was smaller than NMSHTD expected due to the complexity of the work zone.

At a cost of \$235,000, a Smart Work Zone in North Carolina reduced traffic queues on average to 2 miles or less, whereas before deployment, queues exceeded 5 miles. There were no recorded rear-end crashes and no fatalities. The delay information displayed by the system was accurate, although the available information did not give details. There was some utilization of alternate routes, but again, there were no specifics given on percentages or counts. There was significant positive response from the news media and from motorists

An SWZ system on I-35 near Hillsboro, Texas, demonstrated that it could detect congestion and display appropriate messages, although the minimum diversion message post time was likely too short in some cases. Specifically, it posted travel times for free-flow conditions, SLOW TRAFFIC AHEAD and similar messages when speeds dropped, and diversion messages when occupancy met the desired threshold. When the system posted messages recommending motorists use the signed alternate routes, reasonably large percentages of traffic diverted. During major incidents, for example, the system diverted an average of 10 percent of mainline traffic to alternate routes. The highest diversion was about 28 percent.

Smart Work Zone Architecture

The SWZ architecture should describe how a third-party ITS system might operate in a TxDOT work zone either with or without a TMC involved and provide the needed functions at the work zone. The local work zone functions might include operations where data collected within the work zone trigger actions defined by the traffic management plan. One example could be displaying messages on changeable message signs based on measured traffic statistics. The message might involve general delay information and/or it might direct motorists to an alternate route. The simpler systems would likely involve stand-alone architecture and would not involve a TMC. The second architecture would be for more complex environments and would likely involve a TMC.

Stand-alone architecture would involve:

- Vendor collecting Smart Work Zone data like speed and volume.
- Vendor controlling PDMSs deployed at the Smart Work Zone segment.
- Vendor providing alarms (based on speed thresholds and queue length thresholds) to Public Information Officer via text messages, email, or some other electronic format.
- Vendor providing data to a Public Information Officer through a web interface.

Integrated architecture would involve:

- Vendor collecting Smart Work Zone data like speed and volume.
- Vendor controlling PDMSs deployed at the Smart Work Zone segment.
- Vendor sharing speed (and possibly volume) data with TxDOT's LoneStar TSS subsystem.
- Vendor providing alarms (based on speed thresholds) via TSS subsystem.

At the stand-alone level, there would be no TMC involvement, but a local TxDOT Area Engineer would monitor the work zone. Table 11 in Chapter 5 summarizes some general characteristics of situations where each type of architecture might be appropriate. Integrated architecture would require the vendor to implement the TxDOT LoneStar interface defined by TxDOT's document entitled *Transportation Sensor Subsystem Protocol Document TSS-Protocol-1.0.6*, dated February 22, 2008 (69). For the vendor to be able to display messages on TxDOT DMSs, he or she needs to use the TxDOT C2C interfaces defined by the TxDOT document *Center-to-Center Communications Command/Control Interface Control Document C2C-CICD-4.3.0*, dated July 7, 2008 (69).

Proof-of-Concept Simulation

Queue monitoring and travel time monitoring services were the two ITS solutions simulated in this research. For queue monitoring, the SWZ utilized speed-based information to keep track of the queue status and inform drivers upstream of the approximate back-of-queue location via

portable DMSs. Travel time monitoring simulated Bluetooth technology to provide an estimate of segment travel time.

As with any probe-based travel time reporting system including Bluetooth, there is an issue with the time lag in reporting, as the travel delay incurred within the segment may prevent or delay probe vehicles from reaching their destination. This problem leads to differences in travel time estimates that the drivers see on the DMS versus what they actually experience. The problem worsens when the Bluetooth segment is long and the congestion location is relatively closer to the beginning of the segment.

To address the problem of probe-based travel time reporting in an SWZ, the research team proposed an algorithm to improve the travel time estimate using the real-time information from the queue monitoring system. The research team developed a simulation test bed to demonstrate such an approach, which required coding a segment of I-35. The simulated features included both queue monitoring and travel time information services. The queue monitoring system used speed sensors deployed at half-mile spacings upstream of the closure.

The results from simulation evaluation runs revealed that the proposed algorithm significantly improved the travel time (delay) estimate when the queue conditions existed ($v/c > 1$). When compared with the typical Bluetooth-based travel time reports, the proposed algorithm reduced the RMSE by values ranging from 6 percent to 54 percent.

Guidelines for Justifying Smart Work Zones

Determining the conditions for justifying an SWZ begins with simulation (see discussion above), specifically focusing on queue warning. Once the simulation determines an estimate of the maximum queue length, decision-makers are ready to design the Smart Work Zone, which will include the number of monitoring stations on the approach to the work zone and the number of PDMSs. Based on this design, one can develop a cost estimate to buy or lease the necessary equipment. Justifying the purchase or lease of the equipment depends on whether a desirable benefit-cost relationship exists. This research used reductions in crashes expected to result from use of an SWZ to represent the benefits side of the equation. One could also use delay reductions, although they are usually not as critical in rural work zones.

Research findings indicate that without relatively high traffic demand, long work zones, long queues, and projects lasting longer than 1 year, conditions are not likely to meet the desired B-C criterion exceeding 1.0. For rural areas, the conditions would not be likely except on high-volume interstate highways—possibly on segments near urban areas.

Integrating Smart Work Zones with Permanent ITS

The potential exists to integrate SWZs with permanent ITS, especially where a TMC is involved. There could be cases where TxDOT could more effectively manage traffic by providing advanced traveler information to motorists (e.g., long-haul motor carriers) before they enter a corridor covered by a smart work zone. This improved traffic management could result from integrating SWZ information into the traffic management operation of the nearest major cities.

A rural smart work zone system located on a major interstate route connecting two major urban areas could communicate critical work zone information to TMCs and be more proactive in managing traffic. For example, a work zone along the I-45 corridor between Houston and Dallas could provide delay information for operators at Houston TranStar and at DalTrans. If the delay reported by the SWZ system exceeds some predetermined threshold, TMC operators could use dynamic message signs in their respective urban areas at strategic points feeding the corridor to disseminate appropriate construction-related delay messages to motorists traveling in either direction on I-45. They might also use the information from the rural smart work zone system to provide web-based travel time and delay estimates for different segments along the I-45 corridor.

CONCLUSIONS

Rural Smart Work Zones clearly offer substantial benefits to an operating agency considering their use, but justifying SWZs with an anticipated low reduction in crashes (e.g., 5 or 10 percent over the life of the project) will be challenging without high traffic volume and long duration work zones. The Appendix offers several crash cost reduction curves for the use of TxDOT decision makers in determining when to use a Smart Work Zone.

Based on the simulation for queue warning, the number of detector stations depends on the expected maximum queue length. Once this length is established for a particular work zone, determining the number of detector stations is a function of the spacing of the stations. Based on simulation results and the experience of SWZ vendors, the maximum spacing is 1.0 mile and the desirable spacing is $\frac{1}{2}$ to $\frac{3}{4}$ mile. The SWZ cost is a function of the number of stations and PCMSs. The benefits depend on the AADT, whether the work zone is daytime or nighttime, and the length of the zone of influence (length of queue plus length of work zone) where crashes are likely to happen as a result of the work zone.

The lack of sufficient data to more accurately determine the expected crash reduction rates caused by SWZs is currently a limitation to the use of the methodology proposed in this report. Research is needed to investigate the difference in crashes before and after the installation of SWZs under a variety of conditions. Available information suggests that SWZs almost always reduce crashes and/or their severity, but the relationship is not well understood.

The research team recommends an Implementation Project Recommendation (IPR) be approved to focus on a deployment at TxDOT work zones where both types of architecture covered in this research—integrated and stand-alone architecture—would be appropriate. The IPR team would deploy (with TxDOT assistance) and demonstrate an operational SWZ system to communicate between the work zone and the local TxDOT office. Prior to these deployments, TTI would perform system tests and potential local test deployments to understand the nuances and application of at least two vendor-supplied data streams and their usefulness to the work zone management. Once the IPR team understands the data streams from vendor systems, it would also schedule a meeting with TxDOT Traffic Operations Division and others to examine the potential for including SWZ data into TxDOT systems for dissemination of traveler information.

REFERENCES

- 1 U.S. Department of Transportation, Intelligent Transportation Systems Joint Program Office, “Coordinating, Planning, and Managing the Effects of Roadway Construction with Technology,” Washington DC, April 30, 2009.
- 2 Texas Transportation Institute. 2009 Annual Urban Mobility Report: Media Information: Press Release. Urban Mobility Information. [Online] [Cited: January 23, 2010.] http://mobility.tamu.edu/ums/media_information/press_release.stm.
- 3 Research and Innovative Technology Administration. What is ITS. RITA | Intelligent Transportation Systems. [Online] [Cited: January 23, 2010.] http://www.its.dot.gov/its_overview.htm.
- 4 United States Department of Transportation. Intelligent Transportation Systems for Work Zones. Washington, DC: USDOT | Federal Highway Administration, 2007. FHWA-JPO-07-003.
- 5 Intelligent Infrastructure. “Roadway Operations and Maintenance,” ITS Benefits, Costs, Deployment, and Lessons Learned, Federal Highway Administration, U.S. Department of Transportation, Washington DC, 2008 Update.
- 6 Federal Highway Administration. Intelligent Transportation Systems in Work Zones. A Cross Cutting Study. Washington, DC: USDOT | Federal Highway Administration, 2002. FHWA-OP-02-025.
- 7 Federal Highway Administration. Manual on Uniform Traffic Control Devices. Washington, DC: U.S. DOT Federal Highway Administration, 2003.
- 8 Center for Urban Transportation Studies. Criteria for Portable ATIS in Work Zones. Milwaukee, MN: University of Wisconsin-Milwaukee, 2005.
- 9 Maryland State Highway Administration. Procedural Guidelines for Implementing Travel Time on DMS in CHART. Hanover MD: Maryland State Highway Administration, 2008.
- 10 Athey Creek Consultants. “Real-Time Traveler Information Systems.” NCHRP Synthesis 399. National Cooperative Highway Research Program. Washington, DC: Transportation Research Board. National Research Council, 2009. NCHRP Synthesis 399.
- 11 Lappin. Chapter 4. What have we learned about advanced traveler information systems and customer satisfaction? Washington, DC: United States Department of Transportation. Research and Special Programs Administration, 2000.

12 Lappin and Bottom. "Understanding and Predicting Traveler Response to Information: A Literature Review." Washington, DC: United States Department of Transportation. Research and Special Programs Administration; John A. Volpe National Transportation Center, 2001. FHWA-JPO-04-014.

13 Connecticut Academy of Science and Engineering. Information Technology Systems for Use in Incident Management and Work Zones. Newington, CT: Connecticut Department of Transportation, 2006. FHWA-CT-RD-222-39-06-1.

14 InterPlan Co. Variable Speed Limit Signs Effects on Speed and Speed Variation in Work Zones. Salt Lake City, UT: Utah Department of Transportation, 2008. UT-08.01.

15 Virginia Transportation Research Council. Work Zone Variable Speed Limit Systems: Effectiveness and System Design Issues. Springfield, VA: Virginia Department of Transportation, 2010. FHWA/VTRC 10-R20.

16 Nemeth Z.A., and N.M. Roupail. "Lane Closures at Freeway Work Zones: Simulation Study." Transportation Research Record, No. 869, TRB, National Research Council, Washington, DC, 1982.

17 Tarko, A., and S. Venugopal. Safety and Capacity Evaluation of the Indiana Lane Merge System, FHWA/IN/JTRP-2000/19. Joint Transportation Research Program, Purdue University, sponsored by Indiana Department of Transportation, Indianapolis, IN, February 2001.

18 Tarko, A., S. Kanipakapatnam, and J. Wasson. Modeling and Optimization of the Indiana Lane Merge Control System on Approaches to Freeway Work Zones, FHWA/IN/JTRP-97/12. Joint Transportation Research Program, Purdue University, sponsored by Indiana Department of Transportation, Indianapolis, IN, May 1998.

19 McCoy, P.T., and G. Pesti. Alternative Driver Information to Alleviate Work-Zone-Related Delays. Final Report. NDOR SPR-PL-1(35)P513. Transportation Research Studies, February 1999.

20 Pesti, G., D.R. Jessen, P.S. Byrd, and P.T. McCoy. Traffic Flow Characteristics of the Late Merge Work Zone Control Strategy, Transportation Research Record, No. 1657, TRB, National Research Council, Washington, DC, 1999, pp. 1–9.

21 McCoy, P.T., and G. Pesti. Dynamic Late Merge Concept for Work Zones on Rural Interstate Highways, Transportation Research Record, No. 1745, TRB, National Research Council, Washington, DC, 2001, pp. 20–26.

- 22 Meyer, E. Construction Area Late Merge (CALM) System. Technology Evaluation Report. Midwest Smart Work Zone Deployment Initiative. FHWA Pooled Fund study. 2004.
- 23 Finley, M.D., G.L. Ullman, and C.L. Dudek. Sequential Warning-Light System for Work-Zone Lane Closures. Transportation Research Record 1745, TRB, National Research Council, Washington, DC, 2001, pp. 39–45.
- 24 National Transportation Safety Board. 2001. Vehicle- and Infrastructure-Based Technology for the Prevention of Rear-End Collisions. Special Investigation Report NTSB/SIR-01/01. Washington, DC [Online]. Available: <http://www.nts.gov/Publictn/2001/SIR0101.htm>.
- 25 Battelle Transportation Systems. Precursor Systems Analyses of Automated Highway Systems, AHS Roadway Analysis. Report No. FHWA-RD-95-043, October 1994.
- 26 Ullman, G.L., M.D. Fontaine, S.D. Schrock, and P.B. Wiles. A Review of Traffic Management and Enforcement Problems and Improvement Options at High-Volume, High-Speed Work Zones in Texas, Research Report 0-2137-1. Texas Transportation Institute, College Station, TX. February 2001.
- 27 Recommendations from CAA Ontario for Improving Safety—Highway 401 West of London. A report to the Honorable David Trumbull, Minister of Transportation, August 1999. [Online]. Available: http://www.caaontario.net/reports/highway_401_safety_99.htm.
- 28 Wiles, P.B., S.A. Cooner, C.H. Walters, and E.J. Pultorak. Advance Warning of Stopped Traffic on Freeways: Current Practices and Field Studies of Queue Propagation Speeds, Research Report 0-4413-1. Texas Transportation Institute, College Station, TX. June 2003.
- 29 National Transportation Safety Board. Safety Recommendation H-01-10 and H-01-11, May 25, 2001. [Online]. Available: http://www.nts.gov/Recs/letters/2001/H01_10_11.pdf.
- 30 Innovative Traffic Control Technology and Practice in Europe. Prepared by Study Tour Team (Tignor et al.), Federal Highway Administration, International Technology Exchange Program, August 1999. [Online]. Available: <http://www.international.fhwa.dot.gov/Pdfs/Innovtce.pdf>.
- 31 Middelham F. “Dynamic Traffic Management.” Ministry of Transport, Public Works and Water Management, Directorate-General of Public Works and Water Management, AVV Transport Research Centre, Rotterdam, The Netherlands, Presentation to PCM Scan Team, June 2006.

- 32 Maze, T., S.D. Schrock, and A. Kamyab. Capacity of Freeway Work Zone Lane Closures, Proc., Mid-Continent Transportation Symposium 2000, Center for Transportation Research and Education, Iowa State University, Ames, 2000.
- 33 Kujirai, S., and M. Matano. Introduction of Congestion Tail Display System into Metropolitan Expressway, OMRON Technics, 38 (2), Serial 126, 1998. [Online]. Available: http://www.omron.co.jp/omtec/E_126-10.html#UP.
- 34 Hellinga, B. Automated Freeway Queue Warning Systems: Optimizing Performance. Presentation at the INFORMS International Conference, Hawaii 2001 Cluster: Dynamic Optimization.
- 35 Pesti, G. Alternative Way of Using Speed Trailers: Evaluation of the D-25 Speed Advisory Sign System, Compendium of Papers CD-ROM, Paper 05-2735, 84th Annual Meeting of the Transportation Research Board, Washington, DC, January 9–13, 2005.
- 36 Kathmann, T. Assessment of the Effectiveness of Active Speed Warning Signs—Use of Inductive Loop Data or Empirical Data? Proceedings of International Conference: Traffic Safety on Three Continents, Moscow, 2001.
- 37 Deeter, D., and C.E. Bland. “Technology for Rural Transportation: Simple Solutions.” Report FHWA-RD-97-108, United States Department of Transportation, Eagan, MI, 1997.
- 38 Kaub, A.R., and T. Rawls. Automatic Speed Monitor. An Intelligent Vehicle Highway System Safespeed System for Advance Warning or Hazardous Speed Monitoring. Transportation Research Record, No. 1408, TRB, National Research Council, Washington, DC, 1993, pp. 6–10.
- 39 Hanscom, F.R. Weight-Specific Highway Sign Effects on Heavy Trucks. *Transportation Research Record*, No. 1114, TRB, National Research Council, Washington, DC, 1987, pp. 31–36.
- 40 McCoy, P.T., and G. Pesti. Effectiveness of Condition-Responsive Advisory Speed Messages in Rural Freeway Work Zones, Transportation Research Record, No. 1794, TRB, National Research Council, Washington, DC, 2002, pp. 11–18.
- 41 Sullivan, J.M., C. Winkler, and M.R. Hagan. Work-Zone Safety Intelligent Transportation Systems: Smart Barrel for an Adaptive Queue-Warning System. FHWA. Report Number: UMTRI-2005-3, Washington, DC, 2005.

- 42 Hoogen, V. and S. Smulders. "Control by Variable Speed Signs: Results of the Dutch Experiment." Institute of Electrical Engineers IEE. pp. 145–149. 1994.
- 43 Borrough, P. "Variable Speed Limits Reduce Crashes Significantly in the U.K." The Urban Transportation Monitor, March 14, 1997.
- 44 Hegyi, A., B. De Shutter, and H. Hellendoorn. "Optimal Coordination of Variable Speed Limits to Suppress Shockwaves." IEEE, December 2003.
- 45 Park, B.B., and S.S. Yadlapati. "Development and Testing of Variable Speed Limit Logics at Work Zones Using Simulation." Transportation Research Board, 82nd Annual Meeting, Washington, DC, 2003.
- 46 Zhicai J., X. Zhang, and H. Yao. "Simulation Research and Implemented Effect Analysis of Variable Speed Limits on Freeway." 2004 IEEE Intelligent Transportation Systems Conference Washington, DC, 2004.
- 47 Abdel-Aty M., J. Dilmore, and A. Dhindsa. Evaluation of Variable Speed Limits for Real-Time Freeway Safety Improvement, Accident Analysis and Prevention, Vol. 38, No. 2, 2006, pp. 335–345.
- 48 "Intelligent Transportation Systems in Work Zones, A Case Study; Reducing Congestion with the Use of a Traffic Management Contract Incentive During the Reconstruction of Arizona State Route 68." Federal Highway Administration, U.S. Department of Transportation, Washington, DC, October 2004.
- 49 Klashinsky, R. and R. Bushman. "Dynamic Work Zone Safety System," paper presented at the New Technologies in Traffic Engineering Session, Annual Conference of the Transportation Association of Canada, Edmonton, Alberta, 2000.
- 50 Lachhwani, V. and A.J. Horowitz. "Criteria for Portable ATIS in Work Zones," Midwest Smart Work Zone Deployment Initiative, October 2005.
- 51 Minnesota IWZ Toolbox, Guideline for Intelligent Work Zone System Selection, Minnesota Department of Transportation, Office of Traffic, Safety, and Operations, 2008.
- 52 Fontaine, M.D. and P. Edara. "Assessing the Benefits of Smart Work Zone Systems," Submitted to the Transportation Research Board, 2007 Annual Meeting CD-ROM, Washington, DC, 2007.

- 53 Bushman, R., C. Berthelot, B. Taylor, and T. Scriba. "Probabilistic Evaluation of a Smart Work Zone Deployment," Submitted to the Transportation Research Board, 2008 Annual Meeting CD-ROM, Washington, DC, 2008.
- 54 Fontaine, M. "Guidelines for Application of Portable Work Zone Intelligent Transportation Systems," Transportation Research Record 1824, Transportation Research Board, Washington, DC, 2003.
- 55 ITS Work Zone Guidelines Draft (for ITS Council). Federal Highway Administration, Washington, DC, 2011.
- 56 Lou, J. "Network and Communication Design of a Work Zone Intelligent Transportation System," Transportation Research Record 1910, Transportation Research Board, Washington, DC, 2005.
- 57 "Intelligent Transportation Systems in Work Zones, A Case Study; Reducing Congestion with the Use of a Traffic Management Contract Incentive During the Reconstruction of Arizona State Route 68." Federal Highway Administration, U.S. Department of Transportation, Washington, DC, October 2004.
- 58 Tudor, L., A. Meadors, and R. Plant II. "Deployment of Smart Work Zone Technology in Arkansas," Transportation Research Record 1824, Paper No. 03-3115, Transportation Research Board, Washington, DC, 2003.
- 59 Lee, E., and D. Thomas, Public Roads, "Accelerated Reconstruction of I-15 Devore Corridor," January/February 2007, Vol. 70 No. 4.
- 60 Highway Capacity Manual Demand-Capacity Model, Transportation Research Board, Washington, DC, 2000.
- 61 Lee, E., C. Kim, and J. Harvey. "Traffic Demand Reduction Using an Automated Work Zone Information System for Urban Freeway Rehabilitation," Applications of Advanced Technologies in Transportation, 2006.
- 62 "Benefits of Using Intelligent Transportation Systems in Work Zones," A Summary Report, U.S. DOT, Federal Highway Administration, April 2008.
- 63 I-20/I-520 Interchange Brochure, Georgia Department of Transportation, June 2007.
- 64 "Intelligent Transportation Systems in Work Zones A Case Study, Real-Time Work Zone Traffic Control System," U.S. Department of Transportation, Washington, DC, October 2004.

65 “Intelligent Transportation Systems in Work Zones A Case Study, Work Zone Traffic and Incident Management System, Keeping Traffic Moving During Reconstruction of the Big I, a Major Interstate-Interstate Interchange in Albuquerque,” U.S. Department of Transportation, Washington, DC, January 2004.

66 Kite, S. “Smart Work Zones: Technology for Work Zone Management,” Presentation slides, North Carolina Department of Transportation, 2002.

67 Website for Work Zone and Safety Program, Federal Highway Administration. Accessed March 22, 2010, [www.http://WorkZoneITSIntegration\Literature\Case Studies\I-35 Hillsboro Benefits of Using ITS in WZ 11-19-09.htm](http://WorkZoneITSIntegration\Literature\Case Studies\I-35 Hillsboro Benefits of Using ITS in WZ 11-19-09.htm).

68 TxDOT Website for *Texas Manual on Uniform Traffic Control Devices*, http://www.txdot.gov/txdot_library/publications/tmutcd.htm, accessed August 19, 2011.

69 TxDOT Website for Engineering Software:
http://www.txdot.gov/business/contractors_consultants/engineering_software.htm,
Accessed May 19, 2011.

70 Ullman, G., M. Finley, J. Bryden, R. Srinivasan, and F. Council. *Traffic and Safety Evaluation of Nighttime and Daytime Work Zones*. National Cooperative Highway Research Program Report 627, Transportation Research Board, Washington, DC, 2008.

71 Council, F., E. Saloshnja, T. Miller, and B. Persaud. *Crash Cost Estimates by Maximum Police-Reported Injury Severity within Selected Crash Geometries*. Report No. FHWA-HRT-05-051. Federal Highway Administration, U.S. Department of Transportation, Washington, DC, October 2005.

APPENDIX A
CRASH COST GRAPHICS

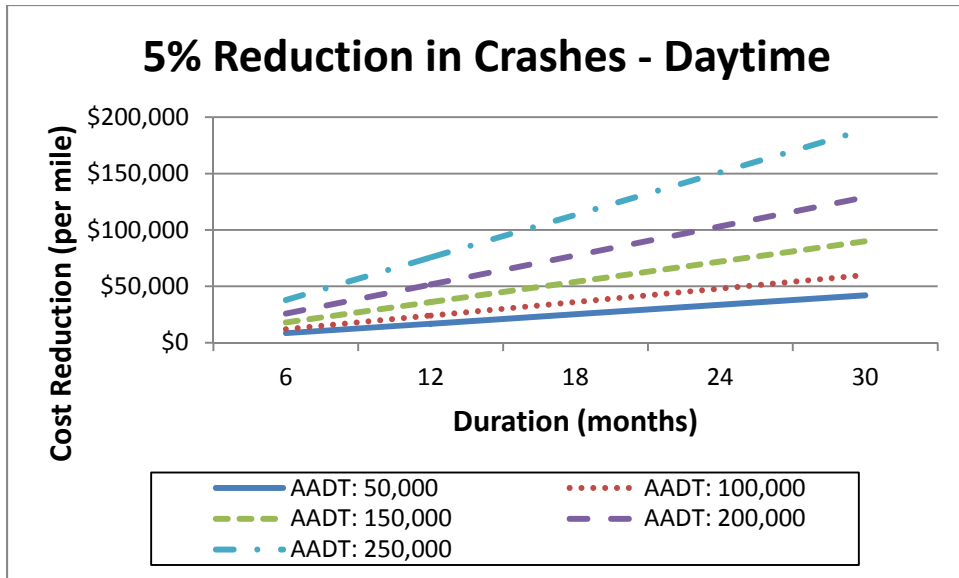


Figure 1. Crash Cost Reduction due to Daytime SWZ (5% assumed).

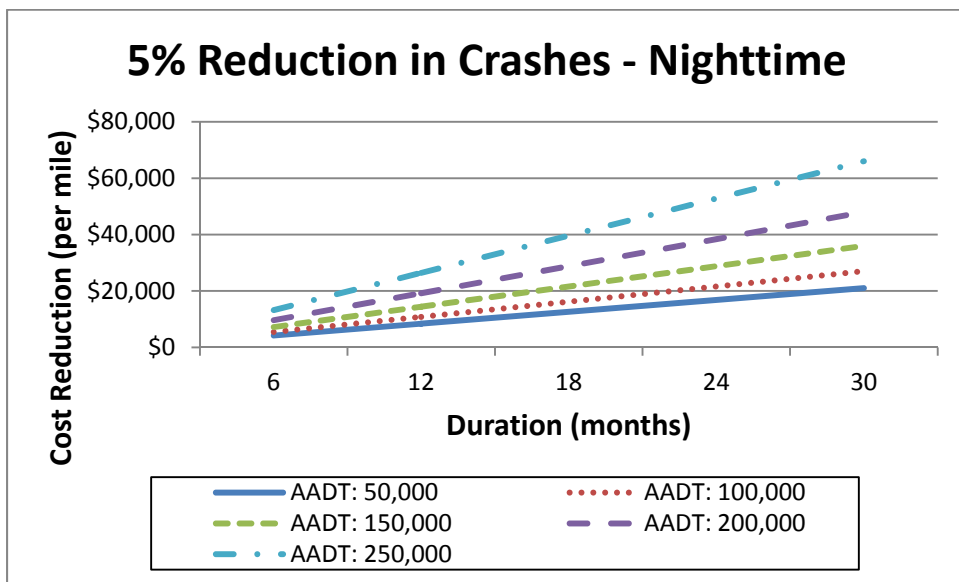


Figure 2. Crash Cost Reduction due to Nighttime SWZ (5% assumed).

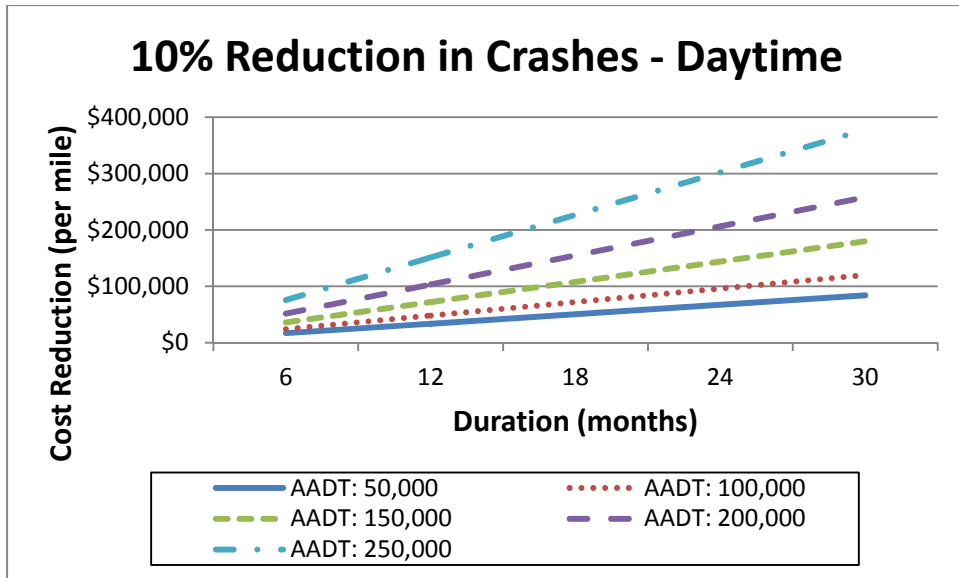


Figure 3. Crash Cost Reduction due to Daytime SWZ (10% assumed).

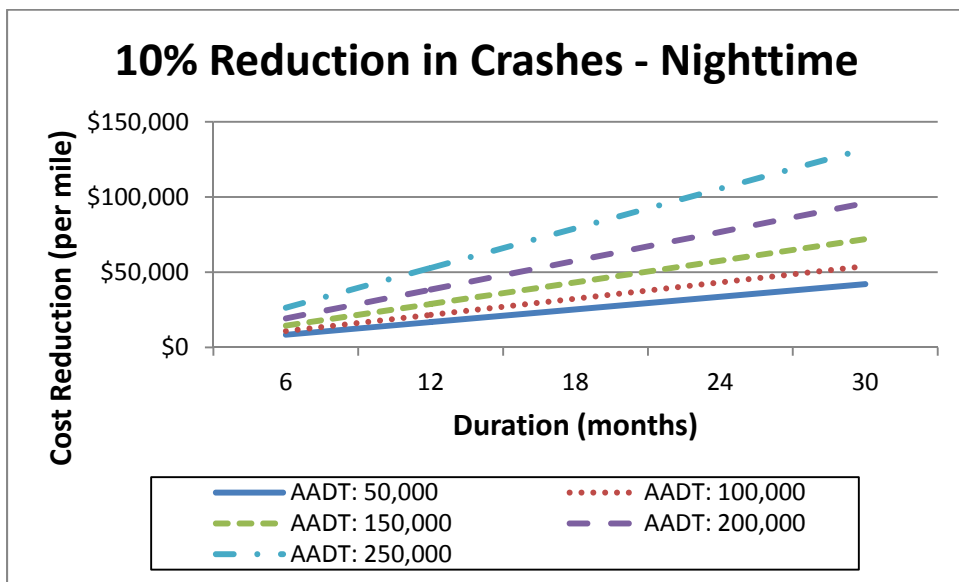


Figure 4. Crash Cost Reduction due to Nighttime SWZ (10% assumed).

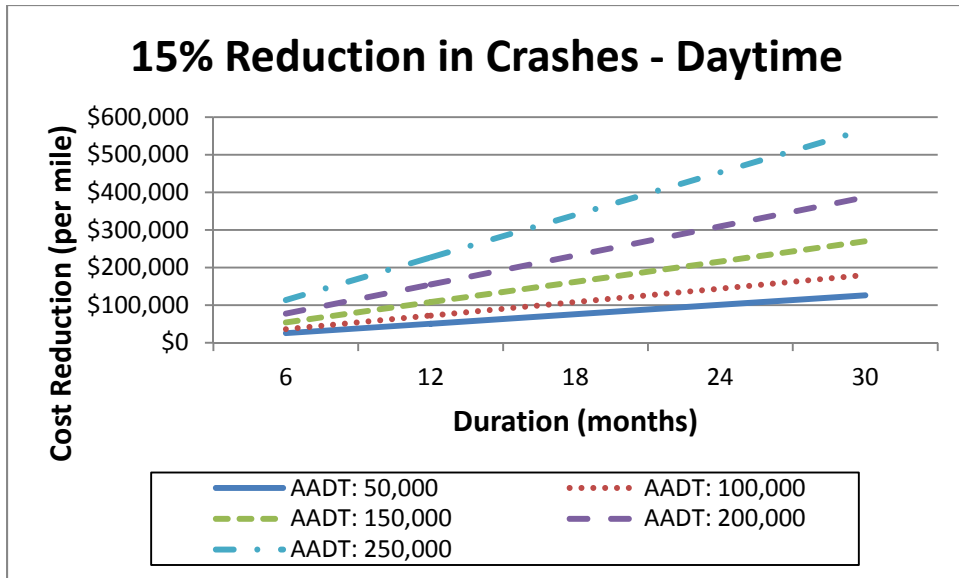


Figure 5. Crash Cost Reduction due to Daytime SWZ (15% assumed).

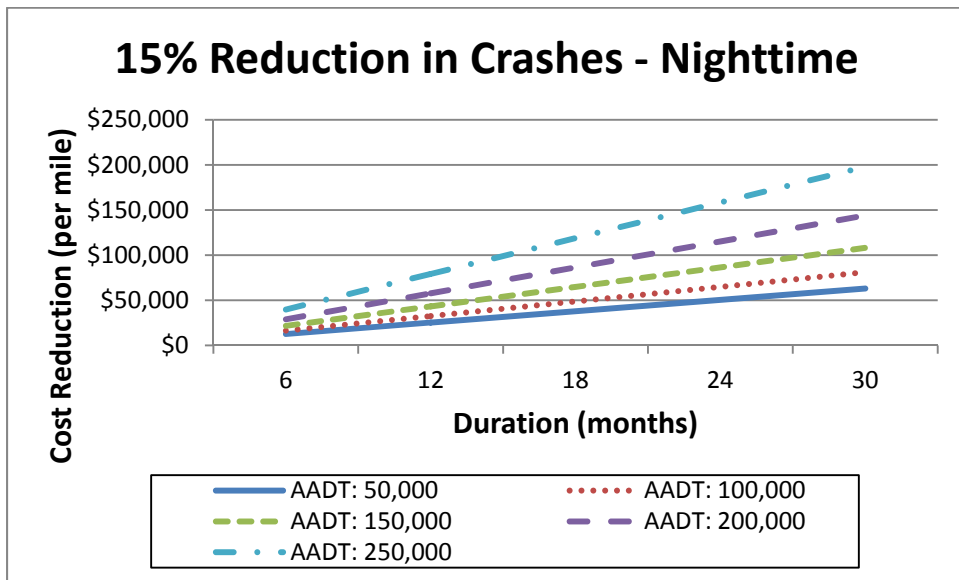


Figure 6. Crash Cost Reduction due to Nighttime SWZ (15% assumed).

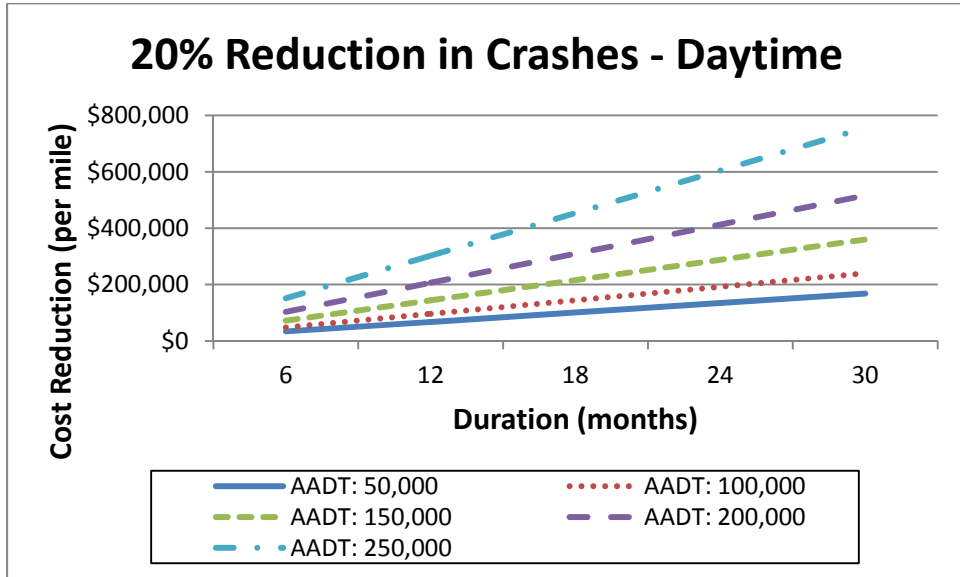


Figure 7. Crash Cost Reduction due to Daytime SWZ (20% assumed).

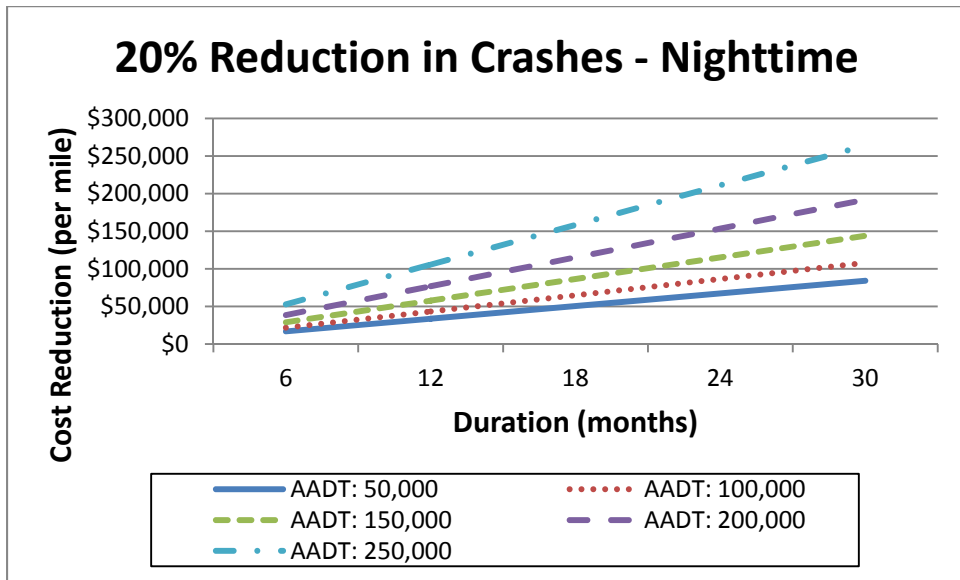


Figure 8. Crash Cost Reduction due to Nighttime SWZ (20% assumed).

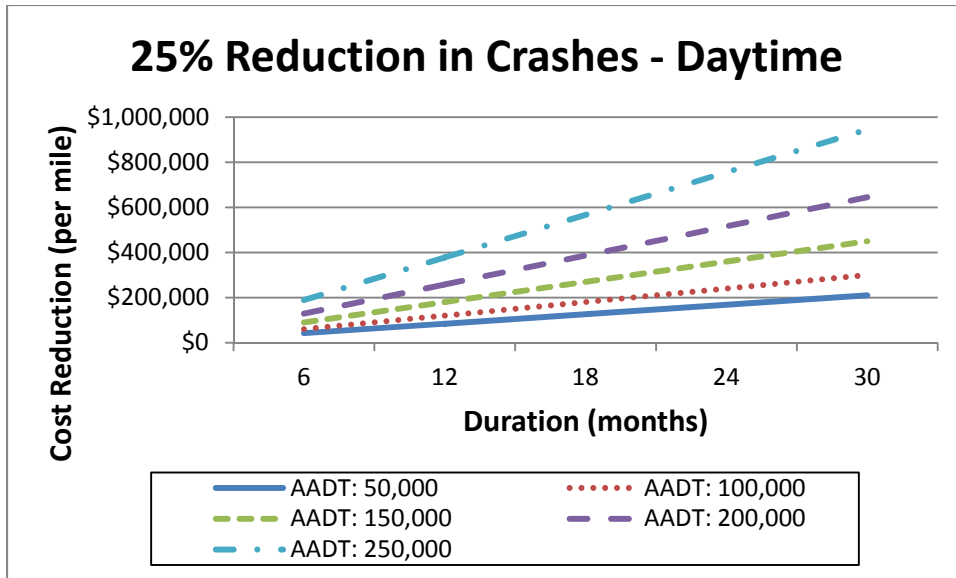


Figure 9. Crash Cost Reduction due to Daytime SWZ (25% assumed).

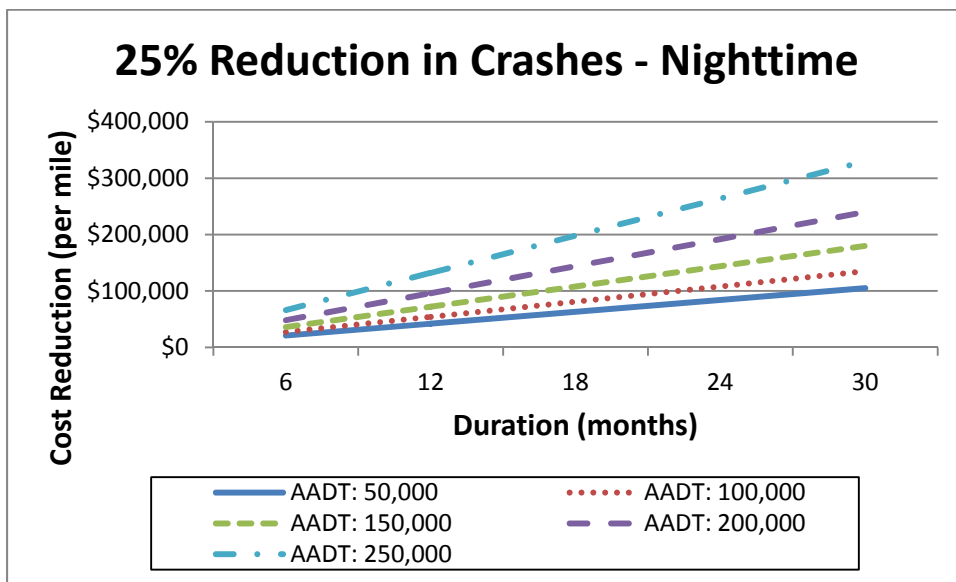


Figure 10. Crash Cost Reduction due to Nighttime SWZ (25% assumed).

APPENDIX B

CRASH COST REDUCTION TABLES FOR NIGHTTIME WORK ZONES

AADT: 50,000

Cost Savings/100 hr/mi due to 5% Reduction in Crashes—Nighttime					
Time	Per Mile	% of the Day with Queue			
Length (mo)	Savings	0.2	0.4	0.6	0.8
6	4200	840	1680	2520	3360
12	8400	1680	3360	5040	6720
18	12600	2520	5040	7560	10080
24	16800	3360	6720	10080	13440
30	21000	4200	8400	12600	16800

AADT: 100,000

Cost Savings/100 hr/mi due to 5% Reduction in Crashes—Nighttime					
Time	Per Mile	% of the Day with Queue			
Length (mo)	Savings	0.2	0.4	0.6	0.8
6	5400	1080	2160	3240	4320
12	10800	2160	4320	6480	8640
18	16200	3240	6480	9720	12960
24	21600	4320	8640	12960	17280
30	27000	5400	10800	16200	21600

AADT: 150,000

Cost Savings/100 hr/mi due to 5% Reduction in Crashes—Nighttime					
Time	Per Mile	% of the Day with Queue			
Length (mo)	Savings	0.2	0.4	0.6	0.8
6	7200	1440	2880	4320	5760
12	14400	2880	5760	8640	11520
18	21600	4320	8640	12960	17280
24	28800	5760	11520	17280	23040
30	36000	7200	14400	21600	28800

AADT: 200,000

Cost Savings/100 hr/mi due to 5% Reduction in Crashes—Nighttime					
Time	Per Mile	% of the Day with Queue			
Length (mo)	Savings	0.2	0.4	0.6	0.8
6	9600	1920	3840	5760	7680
12	19200	3840	7680	11520	15360
18	28800	5760	11520	17280	23040
24	38400	7680	15360	23040	30720
30	48000	9600	19200	28800	38400

AADT: 250,000

Cost Savings/100 hr/mi due to 5% Reduction in Crashes—Nighttime					
Time	Per Mile	% of the Day with Queue			
Length (mo)	Savings	0.2	0.4	0.6	0.8
6	13200	2640	5280	7920	10560
12	26400	5280	10560	15840	21120
18	39600	7920	15840	23760	31680
24	52800	10560	21120	31680	42240
30	66000	13200	26400	39600	52800

AADT: 50,000

Cost Savings/100 hr/mi due to 10% Reduction in Crashes—Nighttime					
Time	Per Mile	% of the Day with Queue			
Length (mo)	Savings	0.2	0.4	0.6	0.8
6	8400	1680	3360	5040	6720
12	16800	3360	6720	10080	13440
18	25200	5040	10080	15120	20160
24	33600	6720	13440	20160	26880
30	42000	8400	16800	25200	33600

AADT: 100,000

Cost Savings/100 hr/mi due to 10% Reduction in Crashes—Nighttime					
Time	Per Mile	% of the Day with Queue			
Length (mo)	Savings	0.2	0.4	0.6	0.8
6	10800	2160	4320	6480	8640
12	21600	4320	8640	12960	17280
18	32400	6480	12960	19440	25920
24	43200	8640	17280	25920	34560
30	54000	10800	21600	32400	43200

AADT: 150,000

Cost Savings/100 hr/mi due to 10% Reduction in Crashes—Nighttime					
Time	Per Mile	% of the Day with Queue			
Length (mo)	Savings	0.2	0.4	0.6	0.8
6	14400	2880	5760	8640	11520
12	28800	5760	11520	17280	23040
18	43200	8640	17280	25920	34560
24	57600	11520	23040	34560	46080
30	72000	14400	28800	43200	57600

AADT: 200,000

Cost Savings/100 hr/mi due to 10% Reduction in Crashes—Nighttime					
Time	Per Mile	% of the Day with Queue			
Length (mo)	Savings	0.2	0.4	0.6	0.8
6	19200	3840	7680	11520	15360
12	38400	7680	15360	23040	30720
18	57600	11520	23040	34560	46080
24	76800	15360	30720	46080	61440
30	96000	19200	38400	57600	76800

AADT: 250,000

Cost Savings/100 hr/mi due to 10% Reduction in Crashes—Nighttime					
Time	Per Mile	% of the Day with Queue			
Length (mo)	Savings	0.2	0.4	0.6	0.8
6	26400	5280	10560	15840	21120
12	52800	10560	21120	31680	42240
18	79200	15840	31680	47520	63360
24	105600	21120	42240	63360	84480
30	132000	26400	52800	79200	105600

AADT: 50,000

Cost Savings/100 hr/mi due to 15% Reduction in Crashes—Nighttime					
Time	Per Mile	% of the Day with Queue			
Length (mo)	Savings	0.2	0.4	0.6	0.8
6	8400	1680	3360	5040	6720
12	16800	3360	6720	10080	13440
18	25200	5040	10080	15120	20160
24	33600	6720	13440	20160	26880
30	42000	8400	16800	25200	33600

AADT: 100,000

Cost Savings/100 hr/mi due to 15% Reduction in Crashes—Nighttime					
Time	Per Mile	% of the Day with Queue			
Length (mo)	Savings	0.2	0.4	0.6	0.8
6	10800	2160	4320	6480	8640
12	21600	4320	8640	12960	17280
18	32400	6480	12960	19440	25920
24	43200	8640	17280	25920	34560
30	54000	10800	21600	32400	43200

AADT: 150,000

Cost Savings/100 hr/mi due to 15% Reduction in Crashes—Nighttime					
Time	Per Mile	% of the Day with Queue			
Length (mo)	Savings	0.2	0.4	0.6	0.8
6	14400	2880	5760	8640	11520
12	28800	5760	11520	17280	23040
18	43200	8640	17280	25920	34560
24	57600	11520	23040	34560	46080
30	72000	14400	28800	43200	57600

AADT: 200,000

Cost Savings/100 hr/mi due to 15% Reduction in Crashes—Nighttime					
Time	Per Mile	% of the Day with Queue			
Length (mo)	Savings	0.2	0.4	0.6	0.8
6	19200	3840	7680	11520	15360
12	38400	7680	15360	23040	30720
18	57600	11520	23040	34560	46080
24	76800	15360	30720	46080	61440
30	96000	19200	38400	57600	76800

AADT: 250,000

Cost Savings/100 hr/mi due to 15% Reduction in Crashes—Nighttime					
Time	Per Mile	% of the Day with Queue			
Length (mo)	Savings	0.2	0.4	0.6	0.8
6	26400	5280	10560	15840	21120
12	52800	10560	21120	31680	42240
18	79200	15840	31680	47520	63360
24	105600	21120	42240	63360	84480
30	132000	26400	52800	79200	105600

AADT: 50,000

Cost Savings/100 hr/mi due to 20% Reduction in Crashes—Nighttime					
Time	Per Mile	% of the Day with Queue			
Length (mo)	Savings	0.2	0.4	0.6	0.8
6	16800	3360	6720	10080	13440
12	33600	6720	13440	20160	26880
18	50400	10080	20160	30240	40320
24	67200	13440	26880	40320	53760
30	84000	16800	33600	50400	67200

AADT: 100,000

Cost Savings/100 hr/mi due to 20% Reduction in Crashes—Nighttime					
Time	Per Mile	% of the Day with Queue			
Length (mo)	Savings	0.2	0.4	0.6	0.8
6	21600	4320	8640	12960	17280
12	43200	8640	17280	25920	34560
18	64800	12960	25920	38880	51840
24	86400	17280	34560	51840	69120
30	108000	21600	43200	64800	86400

AADT: 150,000

Cost Savings/100 hr/mi due to 20% Reduction in Crashes—Nighttime					
Time	Per Mile	% of the Day with Queue			
Length (mo)	Savings	0.2	0.4	0.6	0.8
6	28800	5760	11520	17280	23040
12	57600	11520	23040	34560	46080
18	86400	17280	34560	51840	69120
24	115200	23040	46080	69120	92160
30	144000	28800	57600	86400	115200

AADT: 200,000

Cost Savings/100 hr/mi due to 20% Reduction in Crashes—Nighttime					
Time	Per Mile	% of the Day with Queue			
Length (mo)	Savings	0.2	0.4	0.6	0.8
6	38400	7680	15360	23040	30720
12	76800	15360	30720	46080	61440
18	115200	23040	46080	69120	92160
24	153600	30720	61440	92160	122880
30	192000	38400	76800	115200	153600

AADT: 250,000

Cost Savings/100 hr/mi due to 20% Reduction in Crashes—Nighttime					
Time	Per Mile	% of the Day with Queue			
Length (mo)	Savings	0.2	0.4	0.6	0.8
6	52800	10560	21120	31680	42240
12	105600	21120	42240	63360	84480
18	158400	31680	63360	95040	126720
24	211200	42240	84480	126720	168960
30	264000	52800	105600	158400	211200

AADT: 50,000

Cost Savings/100 hr/mi due to 25% Reduction in Crashes—Nighttime					
Time	Per Mile	% of the Day with Queue			
Length (mo)	Savings	0.2	0.4	0.6	0.8
6	21000	4200	8400	12600	16800
12	42000	8400	16800	25200	33600
18	63000	12600	25200	37800	50400
24	84000	16800	33600	50400	67200
30	105000	21000	42000	63000	84000

AADT: 100,000

Cost Savings/100 hr/mi due to 25% Reduction in Crashes—Nighttime					
Time	Per Mile	% of the Day with Queue			
Length (mo)	Savings	0.2	0.4	0.6	0.8
6	27000	5400	10800	16200	21600
12	54000	10800	21600	32400	43200
18	81000	16200	32400	48600	64800
24	108000	21600	43200	64800	86400
30	135000	27000	54000	81000	108000

AADT: 150,000

Cost Savings/100 hr/mi due to 25% Reduction in Crashes—Nighttime					
Time	Per Mile	% of the Day with Queue			
Length (mo)	Savings	0.2	0.4	0.6	0.8
6	36000	7200	14400	21600	28800
12	72000	14400	28800	43200	57600
18	108000	21600	43200	64800	86400
24	144000	28800	57600	86400	115200
30	180000	36000	72000	108000	144000

AADT: 200,000

Cost Savings/100 hr/mi due to 25% Reduction in Crashes—Nighttime					
Time	Per Mile	% of the Day with Queue			
Length (mo)	Savings	0.2	0.4	0.6	0.8
6	48000	9600	19200	28800	38400
12	96000	19200	38400	57600	76800
18	144000	28800	57600	86400	115200
24	192000	38400	76800	115200	153600
30	240000	48000	96000	144000	192000

AADT: 250,000

Cost Savings/100 hr/mi due to 25% Reduction in Crashes—Nighttime					
Time	Per Mile	% of the Day with Queue			
Length (mo)	Savings	0.2	0.4	0.6	0.8
6	66000	13200	26400	39600	52800
12	132000	26400	52800	79200	105600
18	198000	39600	79200	118800	158400
24	264000	52800	105600	158400	211200
30	330000	66000	132000	198000	264000

APPENDIX C

CRASH COST REDUCTION TABLES FOR DAYTIME WORK ZONES

AADT: 50,000

Cost Savings/100 hr/mi due to 5% Reduction in Crashes—Daytime					
Time	Per Mile	% of the Day with Queue			
Length (mo)	Savings	0.2	0.4	0.6	0.8
6	8400	1680	3360	5040	6720
12	16800	3360	6720	10080	13440
18	25200	5040	10080	15120	20160
24	33600	6720	13440	20160	26880
30	42000	8400	16800	25200	33600

AADT: 100,000

Time	Per Mile	% of the Day with Queue			
Length (mo)	Savings	0.2	0.4	0.6	0.8
6	12000	2400	4800	7200	9600
12	24000	4800	9600	14400	19200
18	36000	7200	14400	21600	28800
24	48000	9600	19200	28800	38400
30	60000	12000	24000	36000	48000

AADT: 150,000

Time	Per Mile	% of the Day with Queue			
Length (mo)	Savings	0.2	0.4	0.6	0.8
6	18000	3600	7200	10800	14400
12	36000	7200	14400	21600	28800
18	54000	10800	21600	32400	43200
24	72000	14400	28800	43200	57600
30	90000	18000	36000	54000	72000

AADT: 200,000

Time	Per Mile	% of the Day with Queue			
Length (mo)	Savings	0.2	0.4	0.6	0.8
6	25800	5160	10320	15480	20640
12	51600	10320	20640	30960	41280
18	77400	15480	30960	46440	61920
24	103200	20640	41280	61920	82560
30	129000	25800	51600	77400	103200

AADT: 250,000

Time	Per Mile	% of the Day with Queue			
Length (mo)	Savings	0.2	0.4	0.6	0.8
6	37800	7560	15120	22680	30240
12	75600	15120	30240	45360	60480
18	113400	22680	45360	68040	90720
24	151200	30240	60480	90720	120960
30	189000	37800	75600	113400	151200

AADT: 50,000

Cost Savings/100 hr/mi due to 10% Reduction in Crashes—Daytime					
Time	Per Mile	% of the Day with Queue			
Length (mo)	Savings	0.2	0.4	0.6	0.8
6	16800	3360	6720	10080	13440
12	33600	6720	13440	20160	26880
18	50400	10080	20160	30240	40320
24	67200	13440	26880	40320	53760
30	84000	16800	33600	50400	67200

AADT: 100,000

Cost Savings/100 hr/mi due to 10% Reduction in Crashes—Daytime					
Time	Per Mile	% of the Day with Queue			
Length (mo)	Savings	0.2	0.4	0.6	0.8
6	24000	4800	9600	14400	19200
12	48000	9600	19200	28800	38400
18	72000	14400	28800	43200	57600
24	96000	19200	38400	57600	76800
30	120000	24000	48000	72000	96000

AADT: 150,000

Cost Savings/100 hr/mi due to 10% Reduction in Crashes—Daytime					
Time	Per Mile	% of the Day with Queue			
Length (mo)	Savings	0.2	0.4	0.6	0.8
6	36000	7200	14400	21600	28800
12	72000	14400	28800	43200	57600
18	108000	21600	43200	64800	86400
24	144000	28800	57600	86400	115200
30	180000	36000	72000	108000	144000

AADT: 200,000

Cost Savings/100 hr/mi due to 10% Reduction in Crashes—Daytime					
Time	Per Mile	% of the Day with Queue			
Length (mo)	Savings	0.2	0.4	0.6	0.8
6	51600	10320	20640	30960	41280
12	103200	20640	41280	61920	82560
18	154800	30960	61920	92880	123840
24	206400	41280	82560	123840	165120
30	258000	51600	103200	154800	206400

AADT: 250,000

Cost Savings/100 hr/mi due to 10% Reduction in Crashes—Daytime					
Time	Per Mile	% of the Day with Queue			
Length (mo)	Savings	0.2	0.4	0.6	0.8
6	75600	15120	30240	45360	60480
12	151200	30240	60480	90720	120960
18	226800	45360	90720	136080	181440
24	302400	60480	120960	181440	241920
30	378000	75600	151200	226800	302400

AADT: 50,000

Cost Savings/100 hr/mi due to 15% Reduction in Crashes—Daytime					
Time	Per Mile	% of the Day with Queue			
Length (mo)	Savings	0.2	0.4	0.6	0.8
6	25200	5040	10080	15120	20160
12	50400	10080	20160	30240	40320
18	75600	15120	30240	45360	60480
24	100800	20160	40320	60480	80640
30	126000	25200	50400	75600	100800

AADT: 100,000

Cost Savings/100 hr/mi due to 15% Reduction in Crashes—Daytime					
Time	Per Mile	% of the Day with Queue			
Length (mo)	Savings	0.2	0.4	0.6	0.8
6	36000	7200	14400	21600	28800
12	72000	14400	28800	43200	57600
18	108000	21600	43200	64800	86400
24	144000	28800	57600	86400	115200
30	180000	36000	72000	108000	144000

AADT: 150,000

Cost Savings/100 hr/mi due to 15% Reduction in Crashes—Daytime					
Time	Per Mile	% of the Day with Queue			
Length (mo)	Savings	0.2	0.4	0.6	0.8
6	54000	10800	21600	32400	43200
12	108000	21600	43200	64800	86400
18	162000	32400	64800	97200	129600
24	216000	43200	86400	129600	172800
30	270000	54000	108000	162000	216000

AADT: 200,000

Cost Savings/100 hr/mi due to 15% Reduction in Crashes—Daytime					
Time	Per Mile	% of the Day with Queue			
Length (mo)	Savings	0.2	0.4	0.6	0.8
6	77400	15480	30960	46440	61920
12	154800	30960	61920	92880	123840
18	232200	46440	92880	139320	185760
24	309600	61920	123840	185760	247680
30	387000	77400	154800	232200	309600

AADT: 250,000

Cost Savings/100 hr/mi due to 15% Reduction in Crashes—Daytime					
Time	Per Mile	% of the Day with Queue			
Length (mo)	Savings	0.2	0.4	0.6	0.8
6	113400	22680	45360	68040	90720
12	226800	45360	90720	136080	181440
18	340200	68040	136080	204120	272160
24	453600	90720	181440	272160	362880
30	567000	113400	226800	340200	453600

AADT: 50,000

Cost Savings/100 hr/mi due to 20% Reduction in Crashes—Daytime					
Time	Per Mile	% of the Day with Queue			
Length (mo)	Savings	0.2	0.4	0.6	0.8
6	33600	6720	13440	20160	26880
12	67200	13440	26880	40320	53760
18	100800	20160	40320	60480	80640
24	134400	26880	53760	80640	107520
30	168000	33600	67200	100800	134400

AADT: 100,000

Cost Savings/100 hr/mi due to 20% Reduction in Crashes—Daytime					
Time	Per Mile	% of the Day with Queue			
Length (mo)	Savings	0.2	0.4	0.6	0.8
6	48000	9600	19200	28800	38400
12	96000	19200	38400	57600	76800
18	144000	28800	57600	86400	115200
24	192000	38400	76800	115200	153600
30	240000	48000	96000	144000	192000

AADT: 150,000

Cost Savings/100 hr/mi due to 20% Reduction in Crashes—Daytime					
Time	Per Mile	% of the Day with Queue			
Length (mo)	Savings	0.2	0.4	0.6	0.8
6	72000	14400	28800	43200	57600
12	144000	28800	57600	86400	115200
18	216000	43200	86400	129600	172800
24	288000	57600	115200	172800	230400
30	360000	72000	144000	216000	288000

AADT: 200,000

Cost Savings/100 hr/mi due to 20% Reduction in Crashes—Daytime					
Time	Per Mile	% of the Day with Queue			
Length (mo)	Savings	0.2	0.4	0.6	0.8
6	103200	20640	41280	61920	82560
12	206400	41280	82560	123840	165120
18	309600	61920	123840	185760	247680
24	412800	82560	165120	247680	330240
30	516000	103200	206400	309600	412800

AADT: 250,000

Cost Savings/100 hr/mi due to 20% Reduction in Crashes—Daytime					
Time	Per Mile	% of the Day with Queue			
Length (mo)	Savings	0.2	0.4	0.6	0.8
6	151200	30240	60480	90720	120960
12	302400	60480	120960	181440	241920
18	453600	90720	181440	272160	362880
24	604800	120960	241920	362880	483840
30	756000	151200	302400	453600	604800

AADT: 50,000

Cost Savings/100 hr/mi due to 25% Reduction in Crashes—Daytime					
Time	Per Mile	% of the Day with Queue			
Length (mo)	Savings	0.2	0.4	0.6	0.8
6	42000	8400	16800	25200	33600
12	84000	16800	33600	50400	67200
18	126000	25200	50400	75600	100800
24	168000	33600	67200	100800	134400
30	210000	42000	84000	126000	168000

AADT: 100,000

Cost Savings/100 hr/mi due to 25% Reduction in Crashes—Daytime					
Time	Per Mile	% of the Day with Queue			
Length (mo)	Savings	0.2	0.4	0.6	0.8
6	60000	12000	24000	36000	48000
12	120000	24000	48000	72000	96000
18	180000	36000	72000	108000	144000
24	240000	48000	96000	144000	192000
30	300000	60000	120000	180000	240000

AADT: 150,000

Cost Savings/100 hr/mi due to 25% Reduction in Crashes—Daytime					
Time	Per Mile	% of the Day with Queue			
Length (mo)	Savings	0.2	0.4	0.6	0.8
6	90000	18000	36000	54000	72000
12	180000	36000	72000	108000	144000
18	270000	54000	108000	162000	216000
24	360000	72000	144000	216000	288000
30	450000	90000	180000	270000	360000

AADT: 200,000

Cost Savings/100 hr/mi due to 25% Reduction in Crashes—Daytime					
Time	Per Mile	% of the Day with Queue			
Length (mo)	Savings	0.2	0.4	0.6	0.8
6	129000	25800	51600	77400	103200
12	258000	51600	103200	154800	206400
18	387000	77400	154800	232200	309600
24	516000	103200	206400	309600	412800
30	645000	129000	258000	387000	516000

AADT: 250,000

Cost Savings/100 hr/mi due to 25% Reduction in Crashes—Daytime					
Time	Per Mile	% of the Day with Queue			
Length (mo)	Savings	0.2	0.4	0.6	0.8
6	189000	37800	75600	113400	151200
12	378000	75600	151200	226800	302400
18	567000	113400	226800	340200	453600
24	756000	151200	302400	453600	604800
30	945000	189000	378000	567000	756000

APPENDIX D
ITS IN WORK ZONE SURVEY



Research Project 0-6427
"Integration of Work Zone ITS into the Statewide ITS Architecture"

GENERAL INFORMATION

Name:

TxDOT District:

Position:

Telephone:

Email:

1. Which of the following "ITS" components do you currently use in work zones? *Select all that apply.*

a. Real-time traffic information for motorists

- Speed Advisory Messages
- Speed display trailers
- Variable Message Signs (VMS)
- Travel time information:
 - Specific travel time
 - General travel time (e.g., expect delays) – Specify:
- Delay warnings:
 - Smart system to predict x minutes
 - Categorize as moderate delays, long delays, etc.
- Dynamic queue warning for slowing or stopped vehicles
- Incident detection
- Internet web site to disseminate WZ information to the public
- Other (specify):

b. Merge Control

- Early merge
- Late merge
- Dynamic Merge

c. Alternate route information

What are the conditions when you use alternate route information?

- Never
- When travel time > minutes
- When average speed < mph
- Other (specify):

2. Would your typical work zones benefit from the deployment of ITS technologies?

- YES NO

If yes, what are the expected benefits? *Select all that apply.*

- Reduced congestion
- Shorter travel times and delays
- Improvement in traffic safety (less crashes)
- Other (please specify):

3. What are the conditions that you believe warrant the use of the following ITS applications?

Provision of real-time motorist information is warranted when

- Daily traffic volume (AADT) > vehicles/day
- Length of work zone > miles
- Other (Specify):

Use of queue detection and warning system is warranted when

- Daily traffic volume (AADT) > vehicles/day
- Length of work zone > miles
- Other (Specify):

Provision of alternate route information is warranted when

- Daily traffic volume (AADT) > vehicles/day
- Length of work zone > miles
- Other (Specify):

4. Do you know of candidate work zone sites where this research project could install one or more ITS components during FY 2011 (summer)?

- YES NO

If Yes, please provide the following information:

Roadway	Number of Lanes	Speed limit (mph)	Work zone type	Expected Duration
<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>
<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>
<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>
<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>
<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>
<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>

Thank you for completing the survey. Please return it using the "Submit by Email" button below:

Submit by Email

