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Improving Smart Work Zone Deployments in Texas

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16. Abstract

Smart work zones utilize technologies and strategies to enhance transportation safety, mobility, traveler satisfaction, and even construction/maintenance productivity through and around work zones. To date, there have been both positive and negative experiences with the technology. The objectives of this study were to determine why some smart work zone deployments in Texas have been more effective than others, and to determine how TxDOT's current processes for incorporating smart work zones into projects should be modified to improve how smart work zones are selected, procured, implemented, and maintained during construction.

Researchers interviewed TxDOT, contractor, and SWZ vendor staff, conducted operational and safety analyses of SWZ systems at a sample of projects, and reviewed contract management documentation related to SWZ deployments. Based on the information gathered, researchers identified potential improvements to TxDOT's project development and construction management workflows, bid specifications, and supporting resources to increase the likelihood of successful smart work zones on future projects.

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DISCLAIMER

This research was sponsored by the Texas Department of Transportation (TxDOT) and the Federal Highway Administration (FHWA). The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official view or policies of FHWA or TxDOT. This report does not constitute a standard, specification, or regulation. This report is not intended for construction, bidding, or permit purposes. The engineer(researcher) in charge of the project was Dr. Gerald Ullman, P.E. #66876.

The United States Government and the State of Texas do not endorse products or manufacturers. Trade or manufacturers' names appear herein solely because they are considered essential to the object of this report.

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INTRODUCTION

Work zone intelligent transportation systems (often referred to as smart work zones [SWZ]) utilize technologies and strategies to enhance transportation safety, mobility, traveler satisfaction, and even construction/maintenance productivity through and around work zones (*1, 2*). The systems are portable and temporary in most cases, although some deployments may use either existing fixed infrastructure or eventually become a permanent system.
SWZs generally include the following:

- Sensors and other components in the field to collect traffic information (traffic volumes, speeds, point-to-point travel times, video of traffic flow).
- Wireless communications links to transmit that data for processing and for disseminating instruction to other devices or systems (e.g., portable changeable message signs, agency websites, 3rd party navigation companies, etc.).
- Software that processes and analyzes the data, converting it to information that can be used by other components and various users of the information.
- Equipment to disseminate the processed information to end users of the information (motorists, other travelers, various agencies).

Information provided by smart work zones may be in the form of real-time traffic conditions, such as travel delays through a work zone or recommended diversion routes, which can be used by motorists to alter their travel behavior and by contractors and transportation agencies to alter traffic control strategies, traveler information, or work schedules (*1*). SWZs may also be used to provide immediate warnings, such as altering drivers that traffic is stopped ahead or that a slow truck is entering from a work zone or notifying workers that a vehicle is intruding into their work area. In many cases, the information and warnings generated by a SWZ system are disseminated autonomously without human intervention. The primary exceptions to autonomous operations are the SWZ systems that provide temporary video camera surveillance in and around the work zone for incident management purposes.

HISTORY OF SMART WORK ZONE SYSTEMS

SWZs have existed in various forms for over 20 years. Early systems focused primarily on overcoming technological limitations and were essentially proof-of-concept trials (e.g., *3, 4*). SWZ systems evolved significantly over time as technological limitations were overcome and as a range of functionalities were envisioned, designed, and implemented, such as:

- Real-time traveler information dissemination (travel times, delays, speeds) through the work zones and via alternative routes.
- Queue detection and warning.
- Dynamic lane merge.
- Incident management (detection, clearance, warning).
- Variable speed limits/speed advisories.
- Automated enforcement.
- Construction equipment alerts (workspace exiting/entering warnings).

Recently, temporary over-height vehicle warning has been added to the potential list of SWZ functionalities (*5, 6*).

Several evaluations of systems have been conducted over the years (see *1, 7-13* as examples). Collectively, these evaluations have concluded that when smart work zones are used where they are truly needed and are properly designed, deployed, tested/calibrated, operated, and maintained, they can provide important safety and mobility benefits. At the same time, the evaluations suggest that failures to attend to one or more of those key points typically resulted in systems that did not operate as expected and/or did not yield significant benefits (*12, 14, 15*). These results pointed to the importance of establishing appropriate decision-making steps and workflows within project development and contract management processes as critical to the successful use of SWZs as a tool for mitigating work zone transportation impacts.

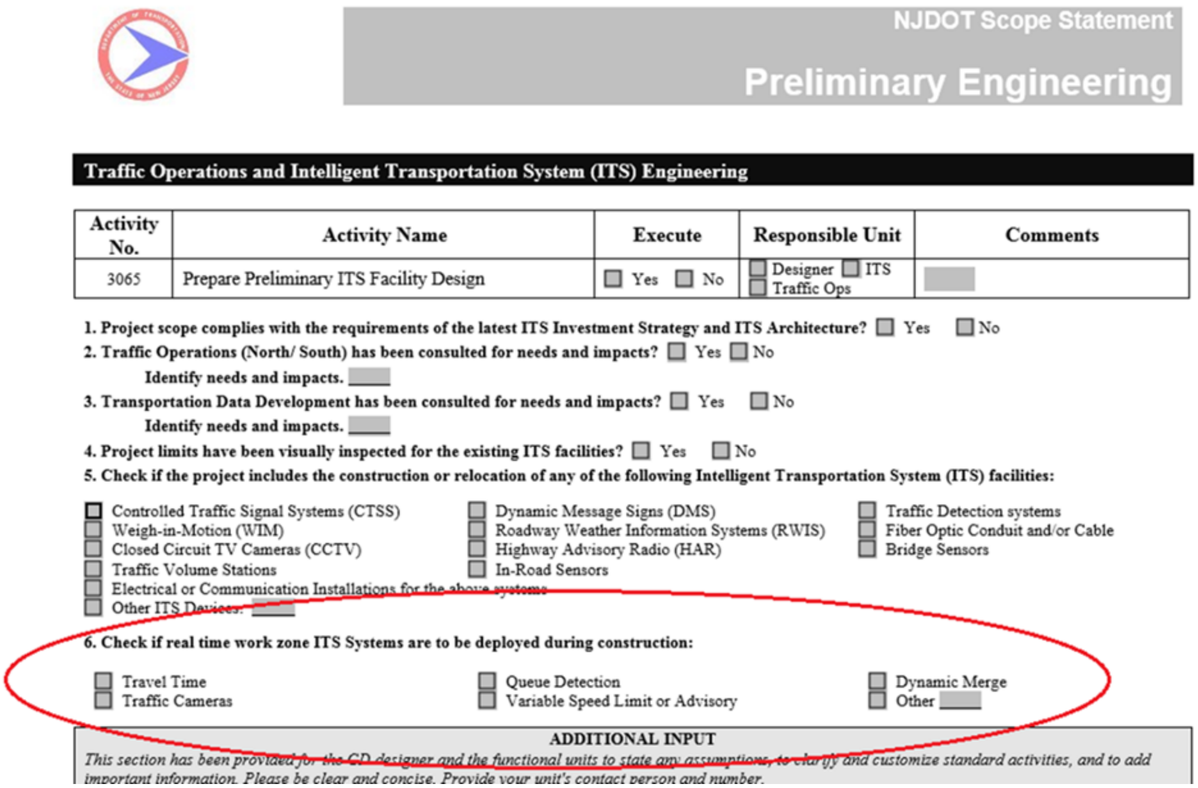
INCORPORATING SMART WORK ZONES INTO AGENCY PROJECT WORKFLOWS AND BUSINESS PROCESSES

In 2015, the third iteration of the FHWA Everyday Counts program (EDC-3) established its Smarter Work Zones initiative (*16*). The goal of the initiative was to have 35 state departments of transportation (DOTs) implement business processes for planning, designing, procuring, operating, and evaluating work zone ITS technologies as identified in the *Work Zone ITS Implementation Guide*, and/or utilize at least one work zone ITS technology application for dynamic management of work zone impacts such as speed and queue management (*17*). The *Work Zone ITS Implementation Guide* established six basic steps that consistently lead to successful SWZ deployments:

- Step 1: Assessment of Needs.
- Step 2: Concept Development and Feasibility.
- Step 3: Detailed System Planning and Design.
- Step 4: Procurement.
- Step 5: System Deployment.
- Step 6: System Operation Maintenance, and Evaluation.

These steps help lead project designers and other decision-makers through a series of questions and decisions in the SWZ selection and implementation process.

Although the *Work Zone ITS Implementation Guide* outlined a general approach to achieving good SWZ deployments, a key aspect of the EDC-3 initiative was supporting state DOT efforts to incorporate these steps into their own agency-specific project decision-making workflows and contracting mechanisms. Agencies participating in the EDC-3 initiative adopted a range of changes to their current project workflow and decision-making processes. As one example, the New Jersey DOT recognized that SWZs were not being incorporated into many of their projects even though such systems would have provided significant benefits to the traveling public. They traced the issue back to the inability to account for the increased costs of a smart work zone system during project scoping. As a result, the department added specific consideration of potential SWZ needs during construction into their preliminary project design workflow (see the screenshot of the process step in Figure 1).


NJDOT Scope Statement

Preliminary Engineering

Traffic Operations and Intelligent Transportation System (ITS) Engineering

Activity No.	Activity Name	Execute	Responsible Unit	Comments
3065	Prepare Preliminary ITS Facility Design	☐ Yes ☐ No	☐ Designer ☐ ITS ☐ Traffic Ops	

1. Project scope complies with the requirements of the latest ITS Investment Strategy and ITS Architecture? ☐ Yes ☐ No
2. Traffic Operations (North/ South) has been consulted for needs and impacts? ☐ Yes ☐ No
Identify needs and impacts.
3. Transportation Data Development has been consulted for needs and impacts? ☐ Yes ☐ No
Identify needs and impacts.
4. Project limits have been visually inspected for the existing ITS facilities? ☐ Yes ☐ No
5. Check if the project includes the construction or relocation of any of the following Intelligent Transportation System (ITS) facilities:

☐ Controlled Traffic Signal Systems (CTSS)
☐ Weigh-in-Motion (WIM)
☐ Closed Circuit TV Cameras (CCTV)
☐ Traffic Volume Stations
☐ Electrical or Communication Installations for the above systems
☐ Other ITS Devices:
☐ Dynamic Message Signs (DMS)
☐ Roadway Weather Information Systems (RWIS)
☐ Highway Advisory Radio (HAR)
☐ In-Road Sensors
☐ Traffic Detection systems
☐ Fiber Optic Conduit and/or Cable
☐ Bridge Sensors

6. Check if real time work zone ITS Systems are to be deployed during construction:

☐ Travel Time
☐ Traffic Cameras
☐ Queue Detection
☐ Variable Speed Limit or Advisory
☐ Dynamic Merge
☐ Other

ADDITIONAL INPUT

This section has been provided for the CD designer and the functional units to state any assumptions, to clarify and customize standard activities, and to add important information. Please be clear and concise. Provide your unit's contact person and number.

Figure 1. NJDOT addition of potential smart work zone funding needs during project scoping (*18*).

As another example, the Connecticut DOT (CTDOT) mapped the six implementation steps in the *Guide* to their own project development cycle and identified the agency leads with responsibilities for each of the steps Table 1 and Table 2). CTDOT also worked to incorporate SWZ decision-making into its existing ITS Projects – Systems Engineering Analysis FORM (SEAFORM) (*19*).

Table 1. Connecticut DOT SWZ Guideline Steps and Unit Responsibilities (*19*).

FHWA WORK ZONE ITS GUIDELINES SIX STEPS	CTDOT SWZ GUIDELINES	CTDOT UNIT
Step 1: Assessment of Needs	5.1 Design	Highway Operations, District, Construction, Traffic
Step 2: Concept Development and Feasibility	5.1 Design	Highway Operations, District, Construction, Traffic
Step 3: Detailed System Planning and Design	5.1 Design	Highway Operations, District, Construction, Traffic
Step 4: Procurement	5.2 Procurement	District, Construction, Contractor
Step 5: System Deployment	5.3 Deployment	District, Construction, Contractor
Step 6: System Operation, Maintenance, and Evaluation	5.4 Operations and Data Collection	Highway Operations, District, Construction, Contractor
Step 6: System Operation, Maintenance, and Evaluation	5.5 Security	District, Construction, Contractor
Step 6: System Operation, Maintenance, and Evaluation	5.6 Maintenance and Evaluation	District, Construction, Contractor
Step 6: System Operation, Maintenance, and Evaluation	5.7 Removal	District, Construction, Contractor

Table 2. Connecticut DOT Actions Assigned to Each Work Zone ITS Guidelines Step (*19*).

PROCESS	ACTIONS IN EACH PHASE
Assess Needs of the Project	• As part of the preliminary engineering and once MPT methods have been established, the SWZ feasibility determination committee shall evaluate applicability of SWZ for the project.
Feasibility Review and Concept Development	• SWZ feasibility determination committee conducts a review and makes recommendations on use of SWZ and SWZ application types to be deployed.
Detailed Planning and Design	• SWZ detailed plan is developed by the designer and included as part of TMP. TMP is reviewed as part of standard design review process. SWZ aspects are reviewed to ensure that SWZ objectives have been addressed.
Procurement	• Equipment is procured as items in project contract bid process. • Items for deployment, relocation, and operations are also included in the contract bid process.
System Deployment and Acceptance	• The Contractor deploys system under District oversight. • The Contractor is responsible for initial placement of equipment in work zones, calibration, testing, system demonstration and acceptance of system prior to commencement of construction activity.
System Operation	• The Contractor is responsible for operations, including maintaining security.
Maintenance	• The Contractor maintains equipment and websites as defined in the contract documents.
Data Collection	• Automated system collects field data and archives. • The Contractor has responsibility to collect and generate periodic work zone traffic performance reports for submittal to CTDOT

MPT = Maintenance and Protection of Traffic; TMP = Transportation Management Plan

As a third example, the Massachusetts DOT developed five separate documents to lead its staff through its SWZ decision-making and implementation processes (*20-24*):

- Scoring Criteria for Work Zone ITS.
- Work Zone ITS Application Matrix.
- Smart Work Zone Concepts of Operations.
- Smart Work Zone Design Standards.
- Smart Work Zone Standard Operating Procedures.

Guidance developed for the Texas Department of Transportation (TxDOT) also strives to tailor the implementation process in the *Guide* to the specific needs of agency staff (*5*). However, it is not clear whether the information in those guidelines is sufficiently detailed and integrated within the other parts of the TxDOT project development workflows to yield consistently effective deployments. It should be noted that TxDOT is not unique in that aspect. There have been few, if any, known efforts by agencies across the country to critique their existing smart work zone decision-making processes. In addition to the traditional challenges of evaluating the agency processes and procedures (such as the lack of sufficient staff and other resources to do so consistently), evaluating the effects of SWZ deployments themselves are particularly challenging.

CHALLENGES WITH EVALUATING SMART WORK ZONE EFFECTIVENESS

The benefits of strategies that mitigate the impacts (safety or operational) of a work zone are very challenging to quantify for several reasons. Some of these are summarized below.

- The effects of work zones upon safety and mobility depend extensively upon pre-work zone conditions in and around the work zone, the overall temporary traffic control (TCC) layout in place for the work zone, and day-to-day work activities themselves (e.g., when and how the work is performed, what short-duration or short-term temporary traffic control that may be required to supplement the overall TTC layout, etc.).
- There are symbiotic relationships between motorist decision-making and work zone impacts that complicate the prediction of those impacts. Specifically, greater work zone impacts generally lead to greater diversions by motorists from the work zone, which in

turn reduces the magnitude of those impacts. Unfortunately, this interdependence is still difficult to predict with any degree of accuracy for a given work zone.

- Meanwhile, the effect of any strategy implemented to mitigate work zone impacts should be based on what would have occurred if the strategy had not been implemented. However, given the complexities that influence work zone impacts as listed in the previous bullets, it is extremely difficult to predict what those impacts would have been without the strategy.

Failure to consider these external influences and challenges can lead to very different conclusions from an evaluation standpoint. For example, Table 3 summarizes the results of previous analyses of SWZ queue warning systems on crashes (*25-28*). The Illinois and Wisconsin analyses examined all crashes occurring before the smart work zone was deployed and after deployment. In comparison, the two Texas evaluations focused on times when queuing was expected or verified to be occurring. The Illinois and Wisconsin evaluations did not document when queues formed in the work zones either before or after the smart work zone deployment. As a result, the effect of the system is diluted by including crashes not associated with queuing in the overall analyses. In contrast, the evaluations of Texas SWZ deployments focused strictly on those times when queuing was expected based on an impact analysis or could be verified to be occurring using probe vehicle speed data in the work zone. In those instances, the effects of the queue warning system itself in reducing crashes was determined to be much more significant.

Table 3. Effect of Queue Warning Systems on Crashes.

State	Effect on Total Crashes	Effect on Severe Crashes	Analysis Methodology Used
Illinois (*27*)	-24%	-11%	Year-to-year comparisons of all crashes
Wisconsin (*28*)	-15%	-63%	Year-to-year comparisons of all crashes
Texas (*29*)	-44%	-61%	With/without queue warning present when queuing was expected
Texas (*30*)	-55%	-81%	With/without queue warning present when queuing was verified

These results point to the need for a strong analysis methodology that accounts for specific work zone activities and attributes of a project when attempting to perform an evaluation of the effectiveness of a smart work zone deployment.

STUDY OBJECTIVES

Smart work zones have been shown to have traffic safety and mobility benefits when and where they are truly needed, properly designed, implemented, and maintained. To date, however, there have been both positive and negative experiences as the technology migrates from research to implementation. The objectives of this study were as follows:

- Determine why some smart work zone deployments in Texas have been more effective than others.
- Evaluate TxDOT's current processes for incorporating smart work zones into projects and suggest enhancements to improve how smart work zones are selected, procured, implemented, and maintained during construction.

ORGANIZATION OF THIS REPORT

To achieve the above-stated objectives, the research team performed the following tasks:

- Identified a sample of projects across the state where SWZs have been deployed and interviewed TxDOT, contractor, and SWZ vendor staff to determine the decision-making processes of those SWZ deployments, challenges encountered, and perceptions about their effectiveness.
- Conducted operational and safety analyses of SWZ systems at a sample of projects to determine actual effects of the systems.
- Reviewed contract management documentation related to SWZ deployments.
- Identified potential improvements to TxDOT's project development and construction management workflows, bid specifications, and supporting resources to increase the likelihood of successful smart work zones on future projects.

The results of these tasks are documented in the following chapters of this report:

- Interviews of TxDOT, Contractor, and Vendor Personnel
- SWZ Operational and Safety Analyses
- Critique of Contract Management Workflows and Documentation Related to SWZ Deployments
- Summary and Recommendations

INTERVIEWS OF TXDOT, CONTRACTOR, AND SWZ VENDOR PERSONNEL

DATA COLLECTION METHODOLOGY

The interviews themselves were conducted in a conversational format. The research team developed a list of questions regarding the planning/design, procurement, deployment, operation, maintenance, and evaluation of smart work zone systems for use when interviewing TxDOT staff and their designated representatives. Researchers interviewed a total of 26 individuals from 9 TxDOT districts. The team also reached out to three vendors and temporary traffic control subcontractors who have provided SWZ systems on various projects in Texas. The questions included the following topics:

- What smart work zone functionalities did you consider, if any, other than those ultimately deployed on the project? What was the decision-making process used for ultimately selecting the smart work zone functionality(ies) for the project (factors considered, past experiences, etc.)?
- When in the project development process did you decide whether to use a smart work zone system, and which smart work zone functionality(ies) to use?
- Were the *TxDOT Smart Work Zone Guidelines* and/or the Excel-based Go/No-Go tool used in the decision-making process? If so, were these tools helpful?
- Was any information regarding the smart work zone system proposed by the contractor used in the selection of the winning contractor for the project, or was it strictly the overall low bidder?
- Were there any challenges experienced during system deployment or calibration? If so, what do you think could be done to avoid those challenges in the future?
- Was a smart work zone operations plan developed for the project?
- Were there any challenges keeping the system maintained and operational? If so, what could have been done differently to avoid those challenges in the future?
- Were any comments from the public (positive or negative) received regarding the smart work zone system?

- How effective was the smart work zone system in improving safety, improving mobility, and/or public perceptions during the project?
- Were any evaluations performed of the effects of the smart work zone systems on traffic?

INTERVIEW RESULTS

The interviews yielded numerous insights and examples. These have been synthesized into several lessons learned which are discussed below.

Smart Work Zone Considerations and Decisions During Project Planning and Design

Queue warning is the most popular SWZ function being included in project bid requests. A few districts have begun expanding their comfort with, and use of, other SWZ functionalities as well (travel times, incident detection, construction equipment alert system). Most districts are specifying SWZ functions to be deployed, rather than simply indicating deployment of a generic SWZ system as was being done in previous years.

Although queue warning is the predominant SWZ functionality being specified, there typically is not an extensive analysis of queuing potential performed to assess the likelihood or magnitude of queues to be expected. Most urban districts expect enough incidents and short-term lane closures (even if at night) will cause queues to form to justify specifying a queue warning system on the project. In rural districts, prior queuing experiences with work zones on certain roadways is what justifies the perceived need for a system. In one district, consideration of the amount of truck traffic on the facility is used to assess whether they want a 3.5-mile queue warning system or a 7-mile queue warning system.

Most SWZ systems are deployed semi-permanently, moving them as needed for major phase changes. Daily or nightly deployments, while successfully used in one district in previous years, have not been as successful when attempted in other districts. The lack of success was due to confusion by the contractor and vendor about how the system was intended to be used and a lack of established business processes on how coordination between the contractor/vendor and TxDOT to properly manage their use would occur.

Each District has a slightly different approach to their consideration and incorporation of smart work zones into their projects. Staff in many districts are not aware of the TxDOT Smart Work Zone Guidelines or the Go/No Go spreadsheet tool the Traffic Safety Division has made available and also lack experience with specifying and using SWZ on projects. In these instances, these staff may simply include a SWZ system (usually queue detection) as a bid item because district leadership has specifically instructed them to do so. Since there is often a lack of understanding as to what is needed equipment-wise, the Plan 1 or Plan 2 WZ ITS standard plan sheets are simply downloaded from the Traffic Safety Division website and included in the plan set without realizing that those sheets are for a very specific application (i.e., a lane closure scenario where queue is expected to begin at the closure taper and propagate upstream). The contractor/subcontractor and TxDOT project staff must then decide on how best to use the technology that was procured on the project, even though it may be less than optimum. It should be noted that some urban districts have gone to more of an "always consider" the use of SWZ during design on their interstate or freeway projects, and do rely on the Guidelines, the Go/No Go spreadsheet tool, and experiences with SWZ on other projects in the District to decide on functionalities and such.

Design of a project specific SWZ implementation plan and incorporation into the bid package increases the likelihood of a successful deployment. Some districts have had good experiences with design consultants who developed the SWZ plan as part of the overall project design. Whether a plan is developed in house or by consultants, having a plan helps ensure that the system is deployed properly. Verifying that the SWZ components shown in the plans and SWZ bid items listed align also helps ensure that the system is deployed and will operate as intended. It is also beneficial if the location of the SWZ plan within the overall plan set is fairly consistent from project to project, as this helps ensure that contractors and vendors do not miss important details to consider when preparing the project bid.

Designing and deploying SWZ systems on a project-by-project basis may not always be the best approach. A few districts have had multiple projects abutting each other along a stretch of interstate. When a SWZ system is procured on a project-by-project basis, there is no guarantee that the same SWZ vendor will be used on all of the projects, even though the entire length would operate more efficiently as a single work zone. A lack of compatibility from one system to the next can inhibit their overall effectiveness. In these situations, it may be preferable to design and bid the SWZ system separately from the projects so that it will function as intended across all projects. Other states have utilized contracts for statewide, regional, district, and corridor-based SWZ deployments successfully. One district was able to get contractors to share SWZ equipment across multiple projects (although that was due primarily to almost all contractors in the corridor having the same temporary traffic control subcontractor).

Bidding and Procurement Considerations of Smart Work Zone Systems

Opinions differ as to the preferred approach to bidding and procuring SWZ systems. Depending on the district, lump sum bidding and per-day bidding have been used to procure SWZ. Lump sum bidding involves the least amount of work for TxDOT staff or their designee. However, once the contractor has been paid for the system, there is little incentive for the contractor to keep the system operating as intended. In addition, conflicts arise between the contractor, subcontractor/vendor, and TxDOT as to whose responsibility it is to pay for repairs to damaged equipment, relocation of equipment, or to otherwise keep the system operating as intended. Finally, a lump sum approach invokes additional risks to the contractor or SWZ vendor if the project experiences delays, since a part of the overall bid by a vendor or subcontractor is for cellular communications for the various devices, system software operation and maintenance, etc. If the project is delayed and the need continues for the SWZ system beyond the planned end date, the contractor or vendor then faces a choice of either requesting a change order to cover those ongoing costs for the system (assuming the project engineer continues to want the system in place) or simply absorbing those additional unexpected operating costs and lose money. Vendors advised that this project delay risk can result in major impacts to their revenues and even bankrupt smaller vendors or SWZ rental services.

Conversely, the newer SWZ specifications use a per-day payment basis based on specified performance metrics for each day. This approach gives TxDOT more day-to-day control and increases contactor/ vendor motivation to keep the system operating and repaired. This increased control comes at the expense of increased workload to monitor the system to ensure that it meets the performance specifications for each charged day of operation. One SWZ vendor suggested that a bid payment on a monthly rather than daily basis could work better and reduce monitoring burdens. However, since some type of acceptable performance threshold for payment would still be needed, it is not clear how much such an approach would reduce the monitoring burden.

Not all TxDOT staff are aware of all available SWZ bid specifications and bid items. The challenges of paying for relocation of SWZ system equipment was discussed during one of the interviews. In that instance, TxDOT was working through a change order to pay for the relocation. A discussion ensued about the availability of system "relocate" bid items that other districts were using, items that the interviewee did not know about.

Some SWZ providers would prefer more involvement in the pre-bidding process. From their perspective, the SWZ system bidding process would involve the initial release of a need for a SWZ system during project design, the ability of vendors to speak with the designer about the goals for the SWZ system prior to the request for bids being issued, the development of a bid by the vendors based on the understanding of the intended SWZ system goals, and then if awarded the contract, meet with the contractor/subcontractor and TxDOT to ensure that everyone understands the SWZ goal(s) for which the bid was prepared, how the equipment needs to be deployed to meet the goal, etc. However, it is believed that a well thought out and developed deployment plan for the system can achieve similar results.

SWZ system bids are not highly scrutinized as part of bid reviews. For the most part, SWZ system components are not scrutinized very heavily because they have little impact on the overall cost of the large projects where they are most commonly used. In addition, many districts do not have expertise available to be able to scrutinize whether a proposed SWZ system and vendor are bid appropriately. At least one urban district has established a designated SWZ champion and subject matter expert to help with system design, bid development, and bid review.

Some urban districts invoke additional specification requirements to connect SWZ systems with Transportation Management Center (TMC) operations. This allows TMC operators to access camera views, sensor data, and portable changeable message sign messages. In some cases, TMC staff serve as ITS subject matter experts to assist project staff in determining equipment needs and capabilities to include in the bid package and in getting the system implemented and connected to the TMC properly. TMC staff can also assist in monitoring the health and accuracy of the SWZ system.

Deployment and Calibration Considerations

Deployments of dynamic late merge (i.e., zipper merge) systems have not been consistently effective. Dynamic late merge, or zipper merge, systems encourage motorists to not vacate a lane closed downstream early but to remain in that lane in queue and take turns at the merge taper. Although successful deployments have been reported across the country, at least one district attempted to deploy it but ultimately abandoned it and went to a queue warning system instead.

SWZ system calibration is not typically a major issue. Most districts did not report any major issues encountered with calibration and verification of correct operation of SWZ system deployments. Some vendors provide dashboards and performance reports of system and traffic operations data. The use of these data by TxDOT staff varies significantly by district.

Any issues that do arise during system deployment and calibration are often due to a lack of proper skill and expertise by those deploying the system. For example, if a contractor does their own temporary traffic control and decides simply to lease a system from a SWZ vendor, the contractor staff assigned to deploy the devices may not have the technical skill to accurately calibrate and verify correct operation. This occurred a few times in one district during the years of nightly SWZ queue warning deployments where the field crew deployed the SWZ devices, turned them on, and then left the scene without knowing they were supposed to verify that the device was detecting traffic properly and communicating correctly with the operating system.

Not all SWZ systems designed get bid, and not all bids are actually deployed, calibrated, and operated. In one urban district, a $250,000 SWZ system design did not meet criteria and need of the project manager and was later removed from going to bid. Outreach and coordination of purpose and need broke down in this case as a result of the designer focusing on equipment needs instead of safety goals and resulting location and duration details. In districts where the decision has been made to include SWZ functionality in the project bid package, a SWZ system may be bid but never actually deployed. These generally occur when the system is only needed for a fairly short period of time, and the costs and efforts to bring the equipment out and calibrate it are not deemed worth the expected benefits to be gained. These decisions appear to be based on engineering judgment and not any type of formal benefit-cost analyses. This approach has created challenges for SWZ subcontractors and vendors, requiring them to maintain an inventory of devices with the expectation that the system will be used without the ability to recoup any of the capital costs paid to have the system available. Theoretically, a vendor or subcontractor could wait to procure equipment until project staff determine that the system will indeed be deployed, but doing so would require more lead time notification before the system would need to be deployed and operational.

Some SWZ systems require significant field adjustments during deployment and relocation to ensure proper operation. Even when a well-thought-out SWZ deployment plan is included in the project plan set, field conditions (e.g., locations of work activities, barrier placements, and contractor equipment staging areas) can require changes to where system devices are deployed, decision algorithms used, and messages displayed.

Most SWZ system devices are not crashworthy. Designers need to make efforts to locate SWZ equipment behind barriers or guardrail or beyond the clear zone wherever possible. This can be challenging in some work zones with limited right-of-way available for such equipment.

Operations and Maintenance Considerations

Staff turnover can have significant adverse effects on ongoing SWZ system operations. SWZ vendors and TxDOT staff mentioned that staff turnover within TxDOT or within contractors sometimes causes difficulties in maintaining and operating a system. Although SWZ functionalities are fairly well standardized, site differences in the location of sensors, traffic behaviors, etc., affect how well a system operates. Replacing someone during the middle of a project may cause a lapse in performance until the new person is familiarized with those nuances and how they are affecting the deployed equipment. Similar issues are encountered when TxDOT staff turnover occurs on a project that has a SWZ system. In one case, a new TxDOT project manager taking over during the middle of the project lifecycle had difficulty obtaining documentation on the purpose, deployment locations and durations, and decision as to why the SWZ had or had not been deployed.

Other contractor activities can adversely affect SWZ performance over time. Because most SWZ equipment is portable, even after a system is initially calibrated and proper system operation is verified, the system must be monitored regularly to verify that it continues to operate as intended. Bumps by construction vehicles, vibrations, weather events, etc., can all move equipment slightly and degrade system operations. It helps to have someone who has history with the deployed system to monitor its output because one or more devices may still be providing an output but not accurate data. Someone familiar with the system can quickly spot these discrepancies, determine whether an explanation for the discrepancies exist, and if not, initiate remedial actions to get the system functioning properly again.

Equipment theft can be problematic for some SWZ systems. One district reported having a theft problem with system equipment (especially batteries) on a project where an adjacent frontage road made it convenient for thieves to park a vehicle and access the equipment. The SWZ subcontractor maintained a supply of spare batteries and other parts so it could quickly repair stolen or damaged equipment and ensure the system continued to operate correctly.

Smart Work Zone Effectiveness and Evaluation

Dynamic late merge (i.e., zipper merge) did not work well for one district. Eventually, the system was redone to be a queue warning system only. The reasons for the lack of performance were not known. Experiences in other states do show that it is more difficult to get drivers to comply with the concept in rural areas and on facilities with large percentages of truck traffic. Interestingly, drivers in urban areas often default to zipper merge behavior at bottleneck locations on their own.

Most districts perceive a safety benefit of SWZ (especially queue warning) systems. Although quantitative evaluations of actual safety performance are typically not done during or after a project, most project staff believe that SWZ systems are beneficial (this is why some urban districts now default to including SWZ systems in their bid packages). The perception is that other SWZ functionalities (e.g., travel time displays, incident detection, and construction equipment alert systems) also provide benefits and are viewed positively by the traveling public.

Data collected by SWZ systems have potential value beyond operation of the system. Project staff in several districts rely on performance reports and/or access to the system dashboard to regularly monitor the system and verify proper functioning. However, one SWZ vendor noted that the data generated by SWZ systems are typically not used to their full potential. For example, examination of traffic volume and speed trends during certain project activities could be beneficial when planning and designing future projects on similar roadways or when planning certain work activities.

SWZ OPERATIONAL AND SAFETY ANALYSES

DATA COLLECTION AND ANALYSIS METHODOLOGY

Operational Analyses

Researchers secured operational log data for recently deployed systems from two of the major vendors/providers of SWZ system in Texas (Street Smart Rental and Integrity Services of Texas). The primary data element of interest was the on and off times of messages presented on the system portable changeable message signs (PCMSs) to motorists about the presence of queues or, in a few instances, travel times. An initial request was made for records from 32 deployments across the state. The focus was primarily on queue warning systems because they are the predominant type of deployment occurring statewide. However, a few of the deployments were travel time systems. The vendors were able to provide partial log data for 20 projects. The other projects required access to archived data that the vendor contacts could not easily access. In addition, some of the log files for the projects that were provided did not contain sufficient detail, were limited to only a few days or weeks, or were otherwise unusable for an operational analysis. Ultimately, the researchers selected seven projects to use in the analysis. Table 4 summarizes the characteristics of those projects and available SWZ log data.

The research team examined the frequency and duration of queue warning messages based on the system logs. Efforts were then made to compare the accuracy of the activations against probe-based speed data from INRIX. For the systems that included travel time messages, researchers also attempted to assess how well the travel times themselves correlated with INRIX data.

Table 4. Projects Examined in Analyses.

District and Project Number	Location	2021 Roadway Annual Average Daily Traffic	Type of SWZ Deployment	Duration of Available Log Data
San Antonio 0025-02-219	I-10, Loop 1604 to Graytown Road	53,523	Travel time	2/21/2021-7/6/2022
Yoakum 0271-02-055	I-10, 0.85 miles west of FM 3538 to SH 36	40,458	Queue warning	4/26/2021-7/6/2022
San Antonio 0025-02-160	I-10, I-410 to Loop 1604	67,715	Queue warning, Travel time	1/1/2022-6/20/2022
Beaumont 0028-04-091	I-10, 0.5 miles east of FM3247 to Sabine River Bridge	50,395	Queue warning	2/21/2021-7/5/2022
Austin 0016-03-114	I-35, South of SH 80 to north of RM 12	120,875	Queue warning	2/21/2021-7/6/2022
Abilene 0005-07-058	I-20, FM 670 to Howard County Line	18,575	Queue warning	6/5/2021 - 4/6/2022
Waco 0048-09-029	I-35E, I-35W to Ellis County Line	34,510	Queue warning	5/9/2021-5/28/2022

Safety Analyses

The goal of the safety analysis was to estimate the effectiveness of the queue warning systems in reducing the frequency and severity of crashes that occur due to the presence of the queues. This requires an estimate of crash expectancies that would have occurred had the SWZ systems not been deployed at those sites. The difference between the crashes that would have been expected to occur and those crashes that did occur during queuing conditions would then reflect the benefits of the SWZ systems. Of course, the challenge is in estimating the number and severity of crashes that would have otherwise occurred.

For this analysis, the research team relied on the results of past research on the effects of queue warning systems deployed in the Waco District (*28*). That research indicated that queue warning systems were able to reduce the likelihood of a crash *during times when a queue was present* by 53.2 percent (i.e., a crash reduction factor of 0.468). In addition, the percentage of crashes that involve injuries or fatalities dropped from 50 percent without queue warning present to 16.1 percent with a queue warning system present. Thus, the team developed the following methodology for estimating the number of crashes that were avoided by the presence of the queue warning system:

1. For each project, determine the time periods and direction of travel when queues were present at each site.
2. Extract crash data occurring within the project limits (plus 0.5 miles upstream on each end to account for any queueing backups that may have occurred) during the time periods and direction of travel where queueing was reported.
3. Divide the number of crashes that did occur by 0.468 to estimate how many crashes would otherwise be expected if no SWZ system was used.
4. Multiply the results of step 3 by 0.50 to estimate the number of crashes that would have been severe (injury or fatal) if no SWZ system was used.
5. Subtract the actual total number of crashes that occurred during times when queues were present at each project from step 3 to estimate the total number of crashes that were likely avoided by using the SWZ system.
6. Subtract the number of severe (injury or fatal) crashes that occurred during times when queues were present from the results of step 4 to estimate the number of severe crashes that were likely avoided by using the SWZ system.

ANALYSIS RESULTS

Operational Analyses

Most of the SWZ deployments were designed to update their warning and/or travel time messages on a minute-by-minute basis. At several deployments, this resulted in significant oscillations between warning and default messages over very short periods of time. For example, Figure 2 presents the distribution of warning message activation durations for three of the projects listed in Table 4, based on an analysis of two-month samples of the log data for each. A significant percentage of queue warning message activations at two of the projects (0271-02-055 and 0048-09-029) were two minutes or less, and the majority of all activations at all three projects were five minutes or less in duration. Such short activation times indicates that the systems were responding to very transient reductions in detected speeds at one or more sensor locations rather than more extensive queuing conditions due to incidents or temporary lane closures at those projects. Such transient reductions could occur if a sensor was located too close to an exit ramp and detected periodic queue spillback from the downstream frontage road traffic signal during the red indication that cleared out during each green indication. Similarly, a sensor placed too close to an entrance ramp could detect slower-speed entering vehicles arriving periodically from the upstream frontage road signal.

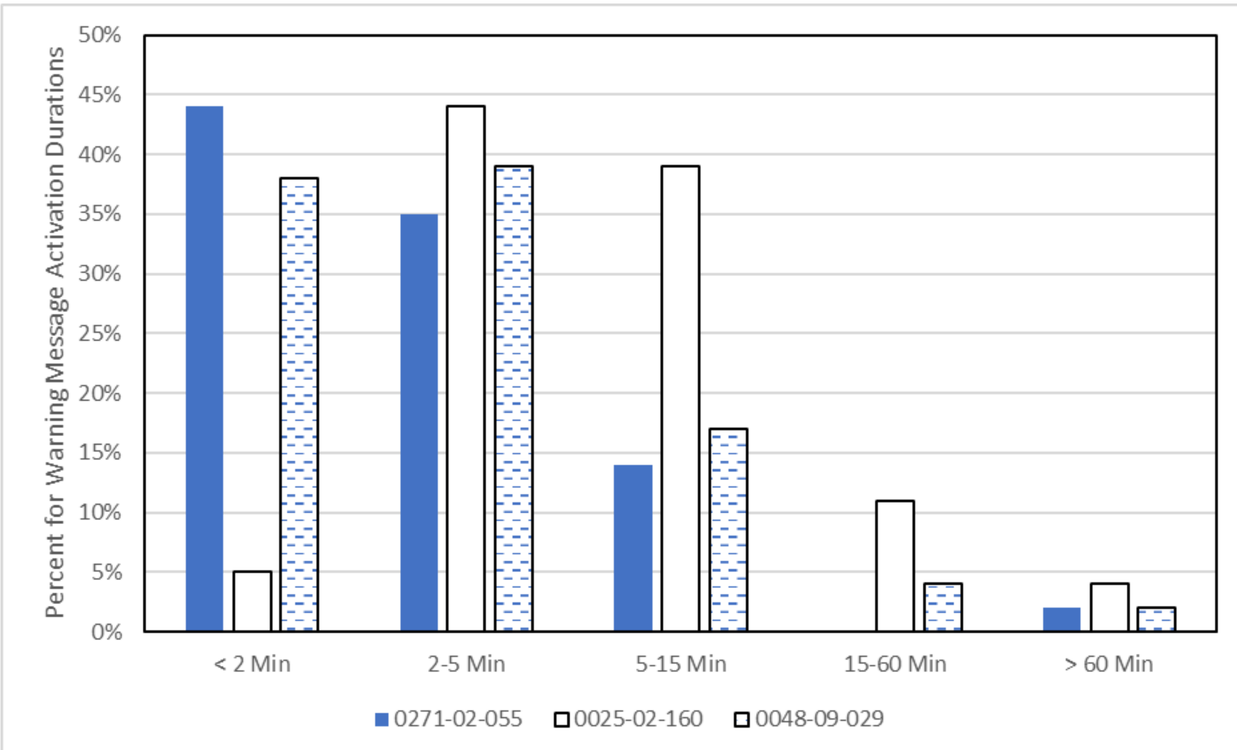


Figure 2. Distribution of queue warning message activation durations.

Table 5 presents similar data, this time presented in terms of the frequency of queue warning activations per month as a function of the duration of the activation. Message activations less than five minutes in duration were very frequent, between 131 and 287 times per month (or between approximately four and nine times per day). Message activations of between 5 and 15 minutes were also relatively frequent, ranging between 31.8 and 113 times per month (or about one to four times per day). Message activations greater than 15 minutes in duration only occurred between 15.7 and 45.0 times per month.

Table 5. Queue Warning Message Activation Frequency by Duration.

Project	Average Number of Activations per Month				
	Total	< 5-Minute Duration	5- to 15-Minute Duration	15- to 60-Minute Duration	> 60-Minute Duration
0271-02-055	227.2	180.0	31.8	11.5	4.2
0025-02-160	289.0	131.0	113.0	32.0	13.0
0048-09-029	373.5	287.0	64.5	14.5	7.5

The research team attempted to correlate the actual on and off times of the message activations with probe-based speed data obtained from minute-by-minute INRIX data for the same dates, times, and locations. However, the researchers found very poor correlation between the log data and the INRIX data. This was quite evident when attempting to correlate the travel time messages being displayed by the SWZ systems. Travel times displayed by the SWZ system on project 0025-02-219, for example, agreed with travel times during the same minute calculated from INRIX travel times slightly less than 50 percent of the minutes examined. Furthermore, most of the agreement between the SWZ and INRIX data occurred during free-flow travel conditions. Once congestion and queuing developed, the SWZ and INRIX estimates of travel times tended to diverge. In multiple instances, the travel time displayed by the SWZ was 20 minutes or more higher than what the INRIX data indicated. Given how the SWZ system uses the speed from a point sensor to extrapolate across a travel distance versus the INRIX probe-based data that measures elapsed travel times across roadway segments and computes an average speed over that segment, such differences are not surprising. In addition, the lag time between data collection and the updating of both the SWZ messages and the INRIX speed values may have been different enough to also adversely affect the correlation of the two data sources on a minute-by-minute basis.

Because of the lack of agreement between the SWZ and INRIX data on a minute-by-minute basis, a decision was made to target only longer-duration periods of slow speeds and queuing messages. Specifically, efforts were made to associate queue warning messages with 15-minute aggregated probe-based speed data. The segment lengths (or traffic message channels) of the probe dataset within each project were deemed to be sufficiently granular to provide a good estimate of actual queuing times and locations within each project. The research team compared times when the probe data indicated the presence of a queue with the SWZ log activations of queue warning messages. Table 6 provides the results of the analysis. On average, the 15-minute aggregated INRIX data suggested a queue was present between 24 to 116 times per month, depending on the project. Also, the average duration of those queues ranged between 20 minutes and about 1.5 hours per event. The last two columns in Table 6 represent the extent to which SWZ queue warning messages aligned with times when 15-minute average INRIX speeds in one or more segments within the work zone were 45 mph or less. The last two columns suggest poor correlation between the SWZ warnings and the INRIX data. The lack of agreement with INRIX data when SWZ warning messages were issued (the second to last column in Table 6) can again be explained by the large number of very short warning message durations. As indicated previously, most of the SWZ warning message durations were five minutes or less, suggesting that many of those activations were not associated with significant queuing events. Consequently, it is not surprising that many of those warning message activations did not align with any segments within the work zone where average INRIX speeds were below 45 mph over a 15-minute period

Table 6. Correlation of Queuing Based on 15-Minute Aggregated INRIX Data and SWZ Queuing Messages.

Project Number	Frequency of Queues * per Month Based on INRIX Data	Average Duration of INRIX "Queues"	Percent of Time	
			SWZ Warning Messages Align with INRIX "Queues"	INRIX "Queues" Align with SWZ Warning Messages
0271-02-055	43	43 Minutes 45 Seconds	30	56
0025-02-160	103	52 Minutes 16 Seconds	31	35
0028-04-091	34	35 Minutes 46 Seconds	46	36
0016-03-114	116	84 Minutes 59 Seconds	69	34
0005-07-058	24	20 Minutes 38 Seconds	16	33
0048-09-029	43	40 Minutes 55 Seconds	32	23

* Average INRIX link travel speeds < 45 mph

On the other hand, the poor correlation of SWZ warning messages to times when the INRIX data indicated the average speeds below 45 mph existed in one or more of the continuous segments within each project (the last column in Table 4) can be explained in how the data from INRIX and data collected by the SWZ differ. As shown in Figure 3, SWZ systems utilize multiple point sources of speed to detect queue presence, spaced at some distances apart (generally 0.5 to 1 mile). In contrast, INRIX data is collected continuously along a roadway section, measured across sequential segments. The length of these segments can vary significantly, often ranging between 0.2 miles and 1.5 miles or longer. If a small area of congestion develops away from SWZ sensor locations, it could be detected in one or two INRIX segments but not in the SWZ sensor detection zones. In addition, INRIX probe data varies temporally in quantity and quality as tracked through confidence interval metrics. This analysis of SWZ performance based on INRIX speeds and SWZ messaging alerts accounts for whether SWZ incidents were more weighted toward late PM and early AM hours.

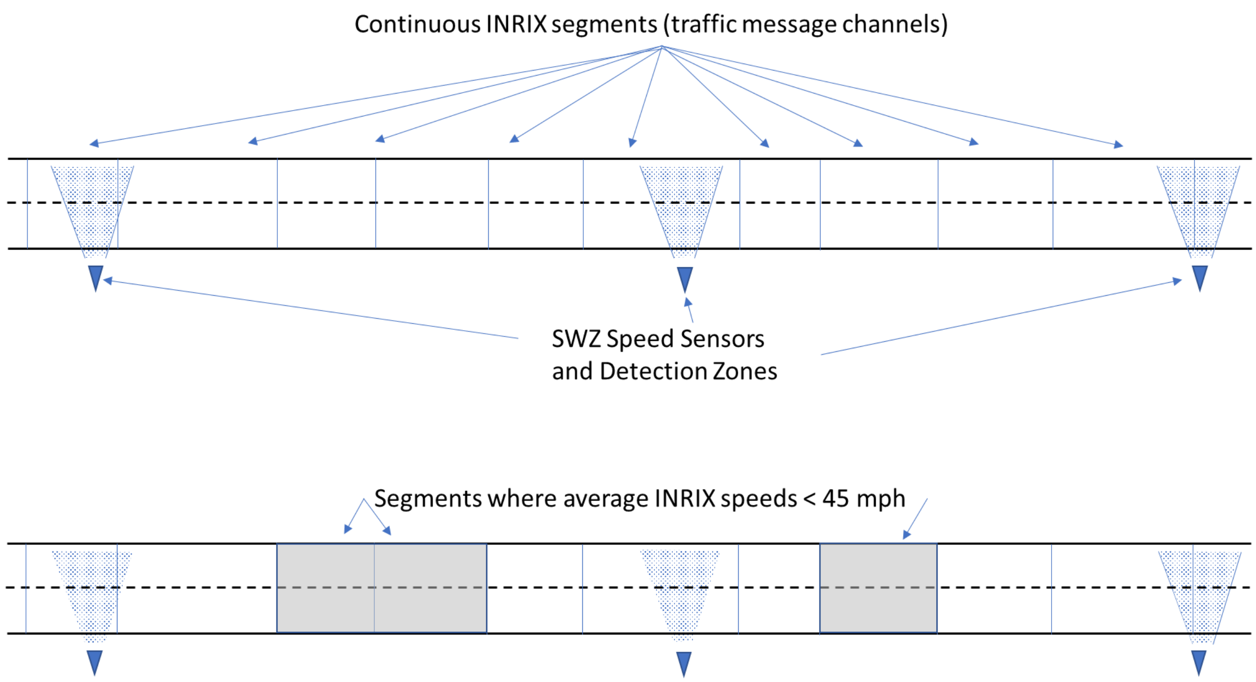


Figure 3. Illustration of how INRIX and SWZ system sensor data can differ.

Safety Analysis

Although the two data sources do not correlate particularly well for transient or very localized congestion events (as indicated in Table 5), researcher perusals of times during each project when longer-duration and longer-length queues and congestion (as indicated by INRIX data) did show better agreement with SWZ warning message times. Therefore, the safety analysis focused on times when the INRIX data (15-minute aggregate segment speeds) indicated queuing and congestion present. Researchers extracted crash data from the TxDOT Crash Records Information System (CRIS) for several months at each project and correlated crash times with times when INRIX indicated queue presence. These data were then used to estimate the number of crashes that were likely avoided by the use of the SWZ as described in the Study Methodology section. The results, shown in Table 7, indicate that between 0.1 and 5.0 crashes per month (1.0 and 60.5 per year) were likely avoided by deploying and operating the SWZ systems. Perhaps more importantly, the data suggest that the systems avoided between 0.1 and 2.8 injury or fatal crashes per month per project (1.0 and 33.2 per year).

Table 7. Estimates of Crashes Avoided Through the Display of SWZ Queue Warning Messages

Project Number	Crashes Experienced during Times When Queues Were Present (Based on INRIX Data)		Analysis Period (Months)	Estimated Crashes Avoided per Month through Use of SWZ Queue Warning	
	Total	Injury + Fatal Crashes		Total	Injury + Fatal Crashes
0271-02-055	15	5	13.0	1.3	0.9
0025-02-160	19	8	13.0	1.7	1.0
0028-04-091	12	5	16.5	0.8	0.5
0016-03-114	43	19	9.7	5.0	2.8
0005-07-058	1	0	13.0	0.1	0.1
0048-09-029	14	5	12.5	1.3	0.8

The frequency of crashes (and thus, the frequency of crashes likely avoided) is related to the amount of traffic passing through the work zone. Figure 4 illustrates the estimates of crashes (total, injury + fatal) avoided per month against the 2021 roadway annual average daily traffic (AADT) associated with each project. Linear regression trend lines are also shown. Based on the trend lines, it appears that SWZ would be expected to have little effect on queue crashes in locations where the AADT is below 20,000 vehicles per day. Above that threshold, however, it does appear that the systems could have measurable crash-reducing benefits.

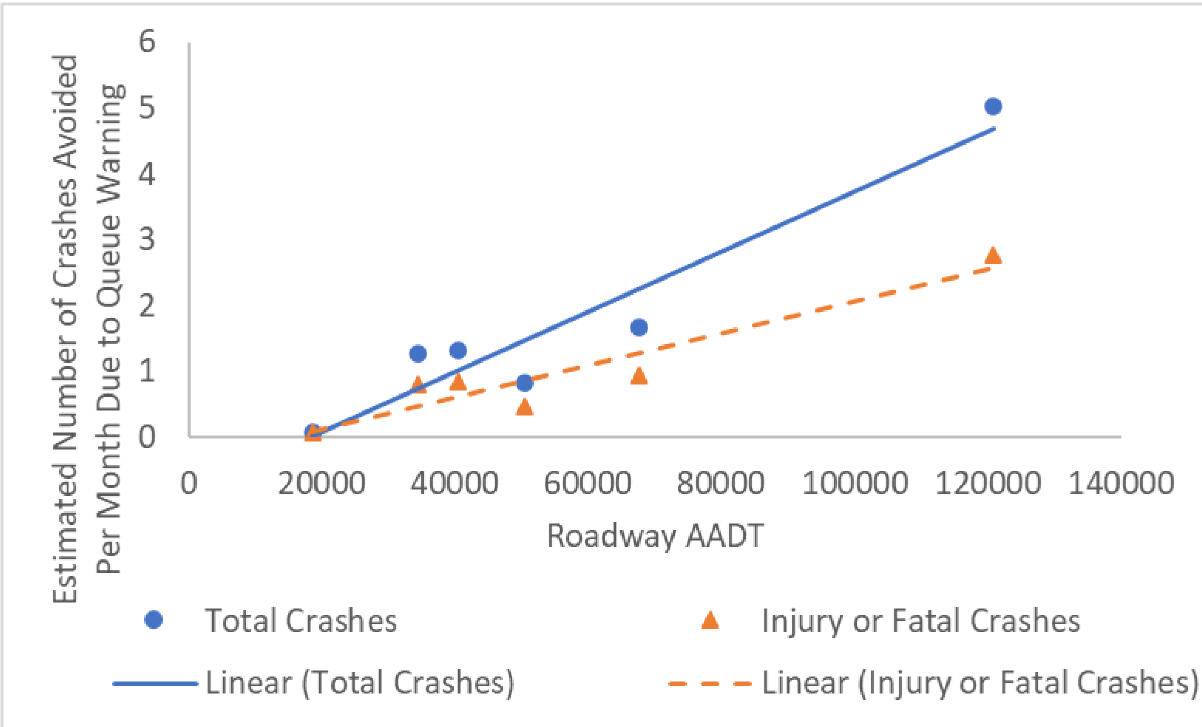


Figure 4. Relationship between roadway AADT and the frequency of crashes likely avoided by deploying SWZ queue warning systems.

CRITIQUE OF CONTRACT MANAGEMENT WORKFLOWS AND DOCUMENTATION RELATED TO SMART WORK ZONE DEPLOYMENTS

The interviews of TxDOT, contractor, and SWZ vendor personnel identified a number of challenges and issues encountered when procuring, deploying, and maintaining SWZ systems. Researchers examined the manuals pertaining to TxDOT's project development and contract administration processes, SWZ special specifications, work zone ITS standard sheets, and its *Smart Work Zone Guidelines Design Guidelines for Deployment of Work Zone Intelligent Transportation Systems (ITS)*. This section summarizes recommendations for how these various documents could be modified to address these issues.

PROJECT DEVELOPMENT PROCESS MANUAL

The *Project Development Process Manual* (*29*) "… provides task information for the transportation engineering practitioner to begin with a project concept and move forward to a complete PS&E [plans, specifications, and estimates] project approved for work authorization." Currently, nothing related to the scoping, design, or procurement of SWZs is included in the manual. For example, no reference is made in the manual about the *Smart Work Zone Guidelines Design Guidelines for Deployment of Work Zone Intelligent Transportation Systems (ITS)* or the G0/No Go spreadsheet tool on the TxDOT Smart Work Zone website (*5, 30*).

The consideration of the potential need for SWZ during construction should be identified very early in the planning and programming tasks for a project. Therefore, reference to the potential consideration of SWZ needs could be listed under "*Chapter 1: Planning and Programming, Section 4: Study Requirements Determination, Task 10430: Obtain Traffic Data*," and reference the availability of the SWZ Go/No Go spreadsheet tool (*30*). The impact of including the potential need for SWZ in initial cost estimates is likely to be negligible for large projects. However, for smaller projects, consideration of the potential need for a higher allocation of funds to cover the potential for including a SWZ system should be encouraged early in the planning and programming process. Furthermore, example SWZ costs located within the Go/No Go tool should be pointed out for reference.

Under "*Chapter 1: Planning and Programming, Section 5: Design and Construction Funding Identification, Task 10510: Prepare and Execute Project Funding Agreements*," a statement should be included instructing the project designer to assess whether multiple projects located consecutively along a roadway corridor will be established with SWZ needs. If it is, consideration should be given to establishing a corridor approach to SWZ design and implementation across the various projects to promote continuity of operations. Discussions should occur with the district engineer on how best to design and fund a corridor SWZ deployment across the multiple projects.

Once the project has moved to the detailed design stage, it is appropriate to flesh out specific SWZ functionality needs in concurrence with traffic control plan development. The addition of a statement to refer to the *Design Guidelines* would be appropriate to include as a separate task under "*Chapter 5: PS&E Development, Section 9: Traffic Control Plan.*" Guidance included in the task description should specifically note that the Work Zone ITS Standard Sheets (WZ-ITS [1,2, or 3]-19) are only appropriate for projects where:

- Queue detection and warning is deemed necessary based on the Go/No Go tool or other factors.
- A single location of expected queuing will exist (such as at a lane closure merging taper) (*31*).

If queues are anticipated to possibly occur at multiple locations within and at the upstream ends of the project, a detailed design for the SWZ system and deployment/operations plans will need to be developed, with details appropriate for each phase or stage of the project.

Another statement will be needed in Section 9 that indicates the designer will decide whether to develop the deployment/operations plan for inclusion in the PS&E package or to require the contractor to develop the plan as part of its bid. If the latter, the statement should instruct the designer to describe the SWZ functionality(ies) required and the required extent of SWZ coverage in the general notes.

Likewise, a statement should be added indicating that projects with other SWZ functionality needs (e.g., a construction equipment alert system, a temporary travel time system, an incident surveillance system, or over-height warning system) will also need a detailed design and deployment/operations plan developed. The statement should also say that the deployment/operations plan needs to describe the anticipated location of all equipment during each phase or stage of the project.

A final statement that should be added pertains to guidance on the specification of lump sum versus per-day bidding of SWZ costs. Specifically, projects that are shorter in duration and are unlikely to require project extensions may be suitable for lump sum bidding. Conversely, more complex projects that are larger and longer in duration and thus more susceptible to time delays and subsequent time extensions should consider using per-day bidding for the SWZ. If lump-sum bidding is still preferred, the designer should indicate that safety contingency funds will be used to cover system operations costs if delays arise that will significantly extend the duration of the project.

PS&E PREPARATION MANUAL

The *PS&E Preparation Manual* provides specific guidance on how the PS&E package should be prepared for submission to the Design Division to complete the processes required prior to letting (*32*). Whereas guidance regarding SWZ scoping and design is recommended for inclusion in several locations within the *Project Development Process Manual*, the suggestions are intended to remind designers to incorporate the SWZ decisions appropriately into the PS&E package. These items would be added to "*Chapter 5: PS&E Submissions and Processing, Section 4: PS&E Checklists, Pre-Submission Checklist*."

- A statement should be added to ensure that the special specifications included in the package for SWZs are appropriate for the SWZ deployment/operations plan and are included in the specifications list.
- A statement should be added to the checklist that reminds the designer to include an estimate for the number of SWZ system relocations that are anticipated to be needed over the duration of the project.
- A statement should be added to instruct the designer to check whether the contractor will be required to develop the SWZ deployment/operations plans, and if so, to include information about the functionality(ies) required and the extent of SWZ coverage.

- If an SWZ system is being specified but there is still some question about whether it will be needed on the project, a statement should be included in the general notes indicating that and specifying that an adequate time be allowed between the determination of need on the project and its required deployment to allow the contractor to procure the necessary equipment once notification of need is provided.

CONSTRUCTION CONTRACT ADMINISTRATION MANUAL

The *Construction Contract Administration Manual* provides policy for district staff on the elements required for successfully administering a contract (*33*). Once a project is under way and an SWZ system will or has been deployed, the following action should be included in the manual: monitor the system to ensure that it operates as desired when initially deployed and continues to do so throughout the duration for which it is needed. Specifically, under "*Chapter 9: Legal Relations and Responsibilities, Section 2: Employee Responsibilities, Public Safety and Convenience*," the researchers suggest including the following bullet items:

- Where used, monitor the operation of smart work zone systems to ensure they are activating correctly and are providing accurate, credible information to the motoring public.

- At a minimum, correct smart work zone system operations should be verified when first deployed and after each relocation of one or more system components.

SWZ SPECIAL SPECIFICATION 6302, TEMPORARY QUEUE DETECTION SYSTEM

In addition to the proposed bullet item in the *Construction Contract Administration Manual*, the researchers also recommend more specific language be considered for incorporation into the Temporary Queue Detection System Special Specification (*34*) under "*Section 4, Construction, Subsection 4.3 Performance*." Specifically, the researchers suggest that additional language be inserted stating that "If the system oscillates repeatedly between queue warning and non-queue (default messages) at 5-minute intervals or less, a field inspection of the location of each sensor in the system shall be performed to determine the reason for the oscillations (e.g., exit ramp spillback traffic, slow-moving entering traffic, etc.). The contractor shall adjust the location of the sensors to alleviate the conditions causing the oscillations."

TRAFFIC ENGINEERING STANDARD PLAN SHEETS

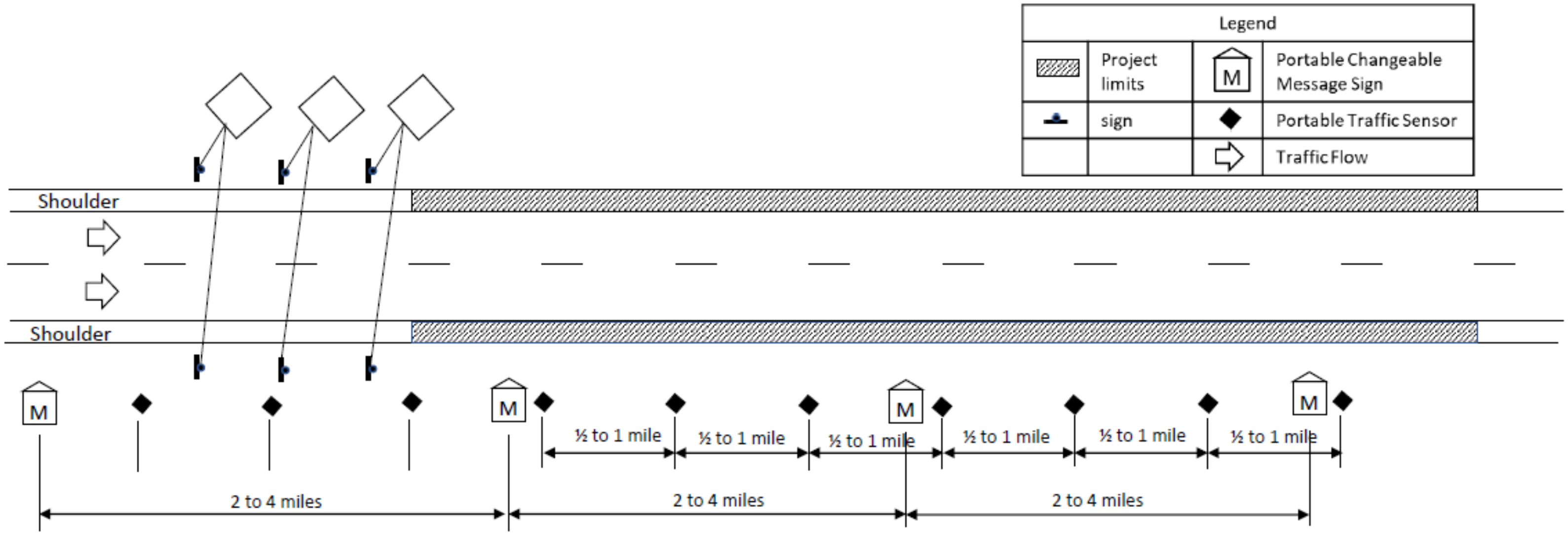
TxDOT has developed and published one set of SWZ standard sheets (*31*). As noted in the discussion for the *Construction Contract Administration Manual*, these standard sheets are intended specifically for a lane closure bottleneck location where queues are expected to develop at the merge point and propagate upstream. Consequently, traffic sensor locations and the PCMS locations are shown relative to that merge point.

However, many work zones where SWZ systems are needed do not have a single lane-closure merge-point location. Rather, temporary lane closures occur periodically throughout the project limits over the duration of the project. In addition, the temporary loss of shoulders causes more frequent queues to form due to vehicle stalls or fender benders that cannot be moved to the shoulder and instead block a travel lane. For these types of applications, deploying sensors and PCMS approaching and also distributed throughout the project limits that remain in place for significant periods of time (e.g., an entire project phase) is more efficient. The researchers recommend an additional work zone ITS standard sheet be developed that illustrates this type of deployment. Figure 5 depicts how such a standard sheet might look.

SWZ TRAINING AND MENTORING

Many of the issues identified during the interviews of TxDOT personnel pointed to a limited understanding of SWZ systems regarding how they should be designed, deployed, and operated, along with the tools developed by TxDOT to assist in those areas. The researchers suggest that TxDOT offer training, either internally developed or procured from training organizations such as the American Traffic Safety Services Association, about SWZ systems to project engineers.

Another option would be to establish an SWZ mentorship program within TxDOT. Several districts that use SWZ systems extensively have well-developed expertise in designing and procuring SWZ systems. Individuals in those districts could be a valuable resource to other districts where such expertise has not yet developed.



Semi-Permanent Queue Detection System

GENERAL NOTES

1. The number of PCMS, static signs, and spacing of sensors will be as shown in the plans.
2. Refer to TCP and BC Traffic Engineering Standard sheets for additional information regarding the type and placement of temporary traffic control devices.
3. The viewing angle of the sensors should not be blocked and should be measuring mainlane traffic unless project conditions and manufacturers specifications dictate otherwise.
4. Operational logic of the system shall be as dictated in the plans or as manufacturers specifications indicate.

Figure 5. Suggested Depiction of a Standard Sheet for a Semi-Permanent Queue Detection System.

SUMMARY AND RECOMMENDATIONS

SUMMARY

SWZs have been shown to have traffic safety and mobility benefits when and where they are truly needed, properly designed, implemented, and maintained. To date, however, there have been both positive and negative experiences as the technology migrates from research to implementation. The objectives of this study were to determine why some SWZ deployments in Texas have been more effective than others and how TxDOT's current processes for incorporating SWZs into projects should be modified to improve how SWZs are selected, procured, implemented, and maintained during construction. Researchers accomplished these objectives through the following tasks:

- Identified a sample of projects across the state where SWZs have been deployed, and interviewed TxDOT, contractor, and SWZ vendor staff to determine the decision-making processes of those SWZ deployments, challenges encountered, and perceptions about their effectiveness.
- Conducted operational and safety analyses of SWZ systems at a sample of projects to determine the actual effects of the systems.
- Reviewed contract management documentation related to SWZ deployments.
- Identified potential improvements to TxDOT's project development and construction management workflows, bid specifications, and supporting resources to increase the likelihood of successful SWZs in future projects.

The interviews provided the following insights about the issues encountered when designing, procuring, deploying, and operating SWZ systems in Texas work zones:

- Each district has a slightly different approach to their consideration and incorporation of SWZs into its projects.
- Not all uses of SWZs on projects include a project-specific deployment plan. However, the design of a project-specific SWZ implementation plan and its incorporation into the bid package increases the likelihood of a successful deployment.

- Designing and deploying SWZ systems on a project-by-project basis may not always be the best approach. Specifically, when work activity on a roadway segment is divided and let as several projects that back up on to the next, it may be preferable to design and bid the SWZ system separately from the projects so that it will function as intended across all of the projects to the benefit of the entire corridor.
- Different approaches to bidding SWZ systems (lump sum versus per-day billing) each have their advantages and disadvantages.
- Not all TxDOT staff are aware of all available SWZ resources that TxDOT has developed (i.e., the Go/No Go Tool, the *Smart Work Zone Guidelines: Design Guidelines for Deployment of Work Zone Intelligent Transportation Systems (ITS*), SWZ bid specifications, and work zone ITS standard plan sheets).
- SWZ system bids are not highly scrutinized as part of bid reviews.
- Deployments of dynamic late merge (i.e., zipper merge) systems have not been consistently effective.
- Issues that arise during system deployment and calibration are often due to a lack of proper skill and expertise by those deploying the system.
- Including an SWZ in project plans but not ultimately deploying it on a project has an adverse effect on a vendor's bottom line and ability to provide competitive pricing on subsequent projects.
- Some SWZ systems require significant field adjustments during deployment and relocation to ensure proper operation.
- Although most SWZ system devices are not crashworthy, it can be challenging to locate SWZ equipment behind barriers or guardrail in some work zones due to limited roadside space available.
- Staff turnover can have significant adverse effects on ongoing SWZ system operations.
- Bumps by construction vehicles, vibrations created by construction equipment operations, weather events, etc. can all move equipment slightly and degrade system operations.
- Equipment theft can be problematic for some SWZ systems when equipment is located where it is easy for thieves to stop and quickly break into and remove components.

The research team analyzed SWZ system operations at a sample of projects statewide. The researchers found that several of the temporary queue detection deployments suffered from frequent oscillations between queue warning messages and default (roadwork ahead) messages. It appears that the systems were responding to very transient reductions in detected speeds at one or more sensor locations rather than more extensive queuing conditions due to incidents or temporary lane closures at those projects. Such transient reductions could occur if a sensor was located too close to an exit ramp and detected periodic queue spillback from the downstream frontage road traffic signal during the red indication that cleared out during each green indication. Similarly, a sensor placed too close to an entrance ramp could detect slower-speed entering vehicles arriving periodically from the upstream frontage road signal.

The issues with SWZ system oscillation notwithstanding, the research team evaluated the possible crash reduction effects of a sample of SWZ deployments. The researchers estimated that the evaluated deployments likely achieved a net reduction of between 0.1 and 5.0 total crashes per month, most of which would have resulted in injuries or fatalities. Researchers also showed that the likely reductions in crashes due to SWZ deployments were correlated with roadway AADT.

Finally, the research team reviewed and critiqued the following TxDOT manuals and other documents to determine where and how current project workflows could be changed to improve how SWZ systems were designed, procured, deployed, and maintained:

- *Project Development Process Manual.*
- *PS&E Preparation Manual.*
- *Construction Contract Administration Manual.*
- SWZ special specifications.
- Traffic Engineering Standard Plan Sheets.

RECOMMENDATIONS

Based on the results of the various analyses performed, the research team developed recommendations to improve SWZ design, procurement, deployment, and operations. Several of these recommendations pertain to TxDOT documents:

- *Project Development Process Manual*:
    - Add a statement to use the SWZ Go/No Go spreadsheet tool to help determine if a SWZ should be considered for a particular project.
    - Add a statement that encourages consideration of a corridor-based approach to SWZ design and deployment when construction on a roadway segment will be divided into multiple projects.
    - Add language to differentiate between SWZ deployments that are dependent on a specific lane-closure location and deployments of a semi-permanent SWZ system in advance of and through the project.
    - Add language to either develop a project-specific SWZ deployment plan for inclusion in the set of plans sent out for bids, or require the contractor to develop the plan as part of the bid package.
    - Add language to assist project designers in determining whether to use lump sum versus per-day bidding of the SWZ system.
- *PS&E Preparation Manual*:
    - Add a statement to ensure that the special specifications included in the package for SWZ are appropriate for the SWZ deployment/operations plan and are included in the specifications list.
    - Add a statement to the checklist that reminds the designer to include an estimate for the number of SWZ system relocations that are anticipated to be needed over the duration of the project.
    - Add a statement to instruct the designer to check whether the contractor will be required to develop the SWZ deployment/operations plans, and if so, to include information about the functionality(ies) required and extent of SWZ coverage.
    - Add a statement noting that if an SWZ system is being specified but there is still some question about whether it will be needed on the project, the general notes should state this and an adequate time should be allowed between the determination of SWZ need in the project and its required deployment date in the project.

- *Construction Contract Administration Manual*:
    - Add a statement that indicates project engineers should monitor the operation of SWZ systems to ensure they are activating correctly and are providing accurate, credible information to the motoring public.
    - Add a statement that indicates, at a minimum, that correct SWZ system operations should be verified when first deployed and after each relocation of one or more system components.
- Add a statement in SWZ special specifications that indicates the following: "If the system oscillates repeatedly between queue warning and non-queue (default messages) at 5-minute intervals or less, a field inspection of the location of each sensor in the system shall be performed to determine the reason for the oscillations (e.g., exit ramp spillback traffic, slow-moving entering traffic, etc.). The contractor shall adjust the location of the sensors to alleviate the conditions causing the oscillations."
- Create a new Traffic Engineering Standard Plans Sheet to illustrate how a semi-permanent SWZ system should be deployed in advance of and through a project.

Finally, the researchers recommend that TxDOT offer training about SWZ systems to project engineers and/or establish an SWZ mentorship program within TxDOT.

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APPENDIX—VALUE OF RESEARCH ANALYSIS

OVERVIEW

Researchers performed a value of research (VoR) analysis of TxDOT Research Project 0-7118 to produce an estimate of the benefit that the project will possibly provide for TxDOT. The primary objectives of TxDOT Research Project 0-7118 were to determine why some smart work zone deployments in Texas have been more effective than others, and to evaluate TxDOT's current processes for incorporating smart work zones into projects and suggest enhancements to improve how smart work zones are selected, procured, implemented, and maintained during construction. Implementing the results of the research are expected to result in the following:

- Improved operations of a portion of SWZ deployments that would otherwise operate sub-optimally. This would yield benefits to the motoring in terms of improved operations and safety as drivers receive more accurate information and warnings (e.g., fewer instances of stop-and-go traffic conditions, better re-routing decisions that could yield slightly less motorist delay, and fewer crashes).
- Increase the proper utilization of SWZ at the subset of projects where deployment of such technology would be expected to yield operational and safety benefits, but where would not be included in the project due to a lack of appropriate steps in project development workflows to guide project designers in determining what type of SWZ functionalities are needed and how to properly incorporate SWZ requirements into the overall project bid package.
- Decrease the deployment of SWZ at the subset of projects where planned work activities and roadway conditions do not justify the deployment and operation of a SWZ system but where a system is included in the project bid package anyway, again because of a lack of appropriate steps in project development workflows to properly guide project designers.

Unfortunately, the research team was not able to accurate estimate the number of Texas work zones in any of the above three scenarios. However, the results of the safety and operational analysis performed strongly indicate that SWZ systems can be highly effective in reducing crashes. For sake of simplicity, the researchers conservatively assumed that implementation of the research findings would result in one less work zone fatal or injury crash per year. The researchers assumed that increased costs of SWZ deployments at additional work zones where they are justified would be offset by not deploying systems in locations where they are not actually needed. The effects of the research findings on reduced motorist delays were not considered, nor were any possible improvements in SWZ bid costs that may be achieved through the improvement of SWZ requirements included in project bid packages.

Crash cost values from the TxDOT Highway Safety Improvement Program guidelines places the economic value of fatalities and incapacitating injuries at $4,000,000 in 2022 dollars. Over the next eight years, reduction of a single fatal or incapacitating injury crash statewide per year due to improved SWZ deployments are expected to yield a net present value of $33,045,960 in societal crash cost benefits. Compared to the cost of the research project ($199,978), this implies that the cost-benefit ratio for the research would be 165:1. The payback period for the research would be 0.05 years.