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Development of Design Guidance for Smart Work Zone Systems

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16. Abstract

Smart work zone (SWZ) systems are designed to provide real-time roadway information to better inform motorists, encourage them to take alternate routes, reduce their frustrations, reduce roadway congestion, and enhance safety for motorists and workers. These SWZ systems have been recommended by multiple federal agencies as part of the Intelligent Transportation Systems program with the overall goal to improve transportation safety, mobility, and efficiency. Despite these reported benefits, there is little guidance on standardizing the need for and deployment of SWZ systems to maximize safety and mobility. This report presents the findings of a research project funded by the Illinois Department of Transportation (IDOT) to provide additional research and recommendations to IDOT on standardizing the deployment of SWZ systems. The objectives of this project were to (1) conduct a comprehensive literature review to gather and analyze current practices and latest research studies on SWZ systems including their deployment on varying types of roadway projects, (2) perform a survey to gather and analyze feedback from other state DOTs on their experiences in utilizing SWZ systems, (3) develop a SWZ feasibility assessment tool that can be used by DOT planners to determine the need for deploying SWZ systems on roadway projects and generate layout designs for all recommended SWZ systems, and (4) create guidance for utilizing the developed SWZ feasibility assessment tool to illustrate its user-friendly interface and practical capabilities in identifying the need for deploying SWZ systems and generating their layout designs for IDOT projects.

17. Key Words

Smart Work Zone, Smart Work Zone Systems, Work Zone, Roadway Congestion, Traffic Safety, Traffic Mobility, Smart Work Zone Feasibility Tool, Intelligent Transportation Systems

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EXECUTIVE SUMMARY

Smart work zone (SWZ) systems are designed to provide real-time roadway information to better inform motorists, encourage them to take alternate routes, reduce their frustrations, reduce roadway congestion, and enhance safety for motorists and workers. These SWZ systems have been recommended by multiple federal agencies as part of the Intelligent Transportation Systems program with the overall goal to improve transportation safety, mobility, and efficiency. Despite these reported benefits, there is little guidance on standardizing the adoption and implementation of SWZ systems to maximize safety and mobility. Accordingly, a research project funded by the Illinois Department of Transportation (IDOT) was conducted to provide IDOT with recommendations on standardizing the specifications for SWZ systems. This report presents the findings of this research project. The objectives of this project were as follows:

- Conduct a comprehensive literature review to gather and analyze current practices and latest research studies on smart work zone systems, including their deployment on varying types of roadway projects. The conducted literature review focused on (1) 10 SWZ systems, (2) relevant federal and state SWZ guidelines, and (3) SWZ decision and design tools.

- Perform a survey to gather and analyze feedback from other state departments of transportation (DOTs) on their experiences in utilizing smart work zone systems. The survey was designed to collect data on the (1) uses of SWZ systems, (2) effectiveness of SWZ systems in reducing crashes, (3) effectiveness of SWZ systems in reducing delay and queue length, (4) project conditions for deploying SWZ systems, (5) cost of implementing SWZ systems, and (6) challenges of SWZ systems.

- Develop an SWZ feasibility assessment tool that can be used by DOT planners to determine the need for deploying SWZ systems on roadway projects and generate layout designs for all recommended SWZ systems, including queue warning systems, dynamic lane merge systems, variable speed advisory system, travel time information system, temporary incident detection system, and construction truck entry and exit detection system.

- Create guidance for utilizing the developed smart work zone feasibility assessment tool to illustrate its user-friendly interface and practical capabilities in identifying the need for deploying SWZ systems and generating their layout designs for IDOT projects.

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LIST OF ACRONYMS

- AADT: Average Annual Daily Traffic
- AAPOR: American Association for Public Opinion Research
- ADOT: Arizona Department of Transportation
- ARTBA: American Road and Transportation Builders Association
- ASE: Automated Speed Enforcement
- AVD: Average Vehicle Delay
- Caltrans: California Department of Transportation
- CCTV: Closed-Circuit Television
- CMF: Crash Modification Factors
- CMS: Changeable Message Sign
- CSL: Corridor Speed Limit
- CTEDS: Construction Truck Entry and Exit Detection System
- CTDOT: Connecticut Department of Transportation
- CTM: Cell Transmission Model
- DLMS: Dynamic Lane Merge System
- DMS: Dynamic Message Sign
- DOT: Department of Transportation
- EQWS: End-Of-Queue Warning System
- FDOT: Florida Department of Transportation
- FHWA: Federal Highway Administration
- GDOT: Georgia Department of Transportation
- GIS: Geographic Information System
- IDOT: Illinois Department of Transportation
- IDS: Incident Detection And Surveillance
- IIS: Incident Information System
- INDOT: Indiana Department of Transportation
- ITS: Intelligent Transportation System
- KSDOT: Kansas Department of Transportation
- MassDOT: Massachusetts Department of Transportation

- MDOT: Michigan Department of Transportation
- MnDOT: Minnesota Department of Transportation
- MoDOT: Missouri Department of Transportation
- MPH: Miles per Hour
- MSHA: Maryland State Highway Administration
- MwSWZDI: Midwest Smart Work Zone Deployment Initiative
- NASEM: National Academy of Science, Engineering, and Mathematics
- NHDOT: New Hampshire Department of Transportation
- NDDOT: North Dakota Department of Transportation
- NJDOT: New Jersey Department of Transportation
- NMSHTD: New Mexico State Highway and Transportation Department
- NYSDOT: New York State Department of Transportation
- ODOT: Ohio Department of Transportation
- OrDOT: Oregon Department of Transportation
- PCMS: Portable Changeable Message Sign
- PennDOT: Pennsylvania Department of Transportation
- PVMS: Portable Variable Message Sign
- QWS: Queue Warning System
- RCRS: Road Condition Reporting System
- SDLMS: Simplified Dynamic Lane Merge System
- SMS: Speed Monitoring System
- SNS: Speed Notification Systems
- SPF: Safety Performance Function
- SWZ: Smart Work Zone
- TIDS: Temporary Incident Detection System
- TMC: Traffic Management Center
- TNVD: Total Number of Vehicles Experiencing Delay
- TRP: Technical Review Panel
- TTIS: Travel Time Information System
- TVD: Total Vehicle Delay

- TxDOT: Texas Department of Transportation
- USDOT: United States Department of Transportation
- VDOT: Virginia Department of Transportation
- VMS: Variable Message Sign
- VPD: Vehicles per Day
- VPH: Vehicles per Hour
- VPHPL: Vehicle per Hour per Lane
- VSA: Variable Speed Advisory
- WSDOT: Washington Department of Transportation
- WisDOT: Wisconsin Department of Transportation
- WYDOT: Wyoming Department of Transportation
- WZL: Work Zone Length
- WZSL: Work Zone Speed Limit

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CHAPTER 1: INTRODUCTION

PROBLEM STATEMENT

Smart work zone (SWZ) systems are designed to predict travel time, delays, or speed in a roadway work zone; to implement traffic management strategies; and to enforce regulatory rules on a real-time basis. These systems are intended to better inform motorists, encourage them to take alternate routes, reduce their frustrations, reduce roadway congestion, and enhance safety for motorists and workers. SWZ systems can be used to provide real-time information to motorists during incidents, temporary closures, or any unexpected conditions on the roadway (FHWA, 2021). These systems have been recommended by multiple federal agencies as part of the Intelligent Transportation Systems program with the overall goal to improve transportation safety, mobility, and efficiency as well as enhance productivity of the nation’s transportation system (ITS, 2021). Smart work zone systems have been deployed by IDOT and other state DOTs for over 20 years and have experienced up to 70% reduction in rear-end collisions. A series of recent IDOT projects have examined mobility and safety impacts of SWZ systems. For example, the use of advanced sensor network systems for work zone traffic estimation was explored, and microsimulations and field data were used to measure the impacts of various traffic management strategies on traffic queue and delay (Li et al., 2016) as well as on vehicular energy consumption and emissions (Ghosh et al., 2015; Okte et al., 2019). The relationship between work zone system design, traffic exposure, and fatal/injury crashes have also been developed in the form of work zone–specific safety performance functions (SPFs) and crash modification factors (CMFs) (Schattler et al., 2020). Despite the benefits of SWZ systems, there is little guidance on standardizing their adoption and implementation to maximize safety. Accordingly, there is a pressing need for additional research to provide IDOT with recommendations on standardizing the specifications for SWZ systems.

RESEARCH OBJECTIVES AND METHODOLOGY

The main goal of this research project is to develop a guidance document for the design of smart work zone systems that can be incorporated into IDOT’s *Bureau of Design and Environment Manual*. To accomplish this, the objectives of the proposed research were as follows:

1. Conduct a comprehensive literature review on SWZ systems, including their deployment on varying types of projects, function, equipment, and components.
2. Perform a survey of other state DOTs to gather and analyze their experiences in utilizing various designs of smart work zone systems.
3. Develop a smart work zone feasibility assessment tool to determine the need for deploying SWZ systems for different types of roadway projects.
4. Create guidance to provide guidelines for the use of the developed SWZ feasibility assessment tool by IDOT planners.

Proposed Techniques and Methodology

The research team accomplished the objectives of this project by adopting a rigorous research methodology. The methodology breaks down the research work into six major tasks (see Figure 1) that are described in more detail in the following chapters and appendices.

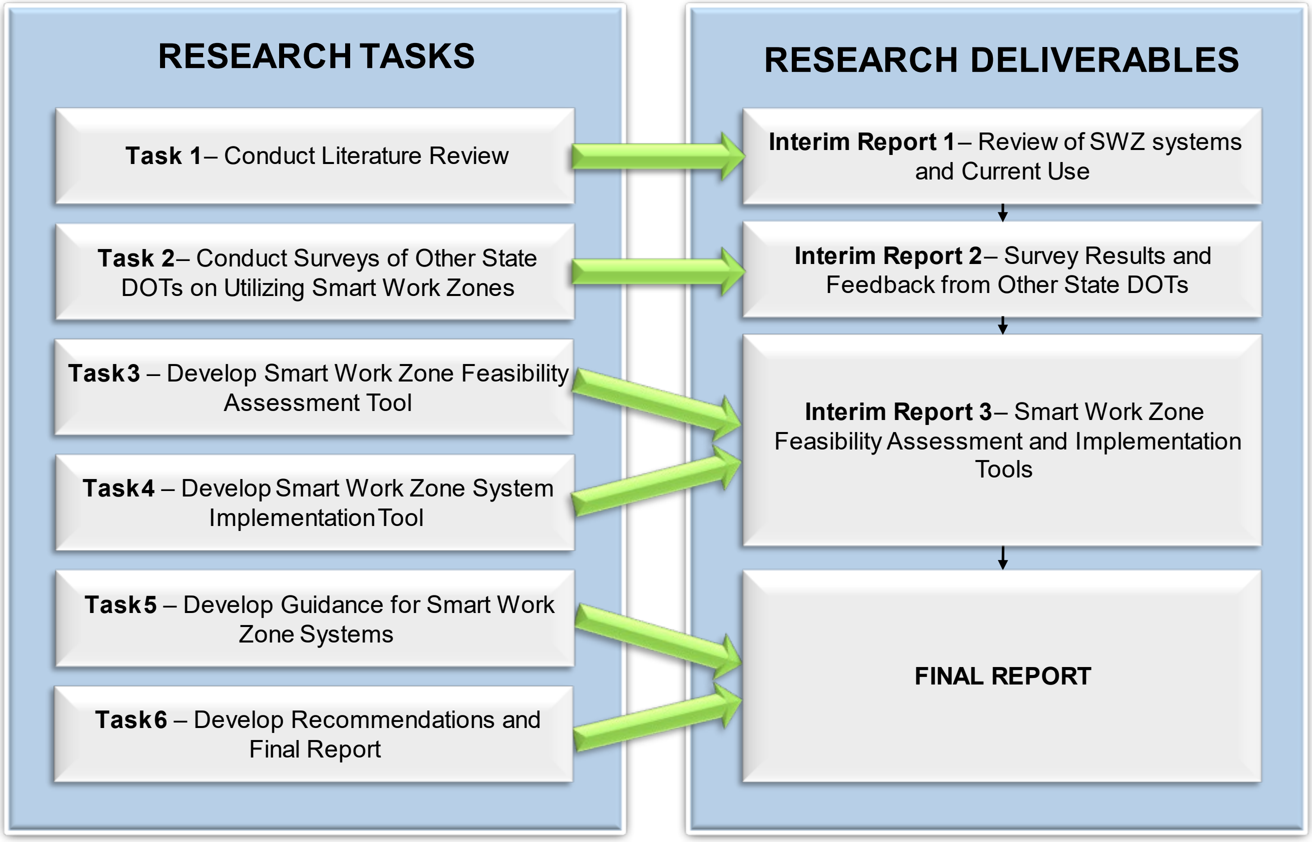


Figure 1. Diagram. Research tasks and deliverables.

CHAPTER 2: LITERATURE REVIEW

This chapter summarizes the findings of a comprehensive literature review that was conducted to gather and analyze current practices and latest research studies on smart work zone systems. The scope of the literature review focused on: (1) SWZ systems, (2) relevant federal and state SWZ guidelines, and (3) SWZ decision and design tools. A brief overview of the reviewed smart work zone systems is included in the following section. Appendix A includes a detailed literature review of these systems, relevant federal and state SWZ guidelines, and SWZ decision and design tools.

SMART WORK ZONE SYSTEMS

This section provides an overview of the reviewed smart work zone systems that are used by state DOTs. A total of 10 SWZ systems were analyzed in this literature review: (1) variable message signs, (2) queue warning systems, (3) dynamic lane merge systems, (4) speed feedback signs, (5) automated speed enforcement, (6) variable speed advisory systems, (7) travel time information systems, (8) smart arrow boards, (9) temporary incident detection and surveillance systems, and (10) construction truck entering and exiting systems, as shown in Table 1. A detailed literature review of each of these 10 systems is included in Appendix A.

Table 1. Smart Work Zone Systems

SWZ System	Description
Variable message signs (VMS)	Programmable electronic traffic control devices capable of displaying messages related to incidents, construction activities, travel times, detour information, road closures, and other messages related to changing traffic conditions.
Queue warning systems (QWS)	VMS used to alert drivers of upcoming traffic conditions. Capable of continuously monitoring the traffic on the approaches and within work zones to communicate whether queued traffic is expected ahead.
Dynamic lane merge systems (DLMS)	VMS placed upstream of expected bottlenecks caused by lane closures to direct traffic into either early merging or late merging strategies.
Speed feedback signs (SFS)	Dynamic signs placed on the side of the road with speed radars to measure the approaching speed of drivers and display it either via VMS or smaller LED display.
Automated speed enforcement (ASE)	A roadside system usually involving two radars, a display, and a camera. One of the radars is used to detect the speed of vehicles upstream of the enforcement point to display the speed to drivers and provide them with a chance to reduce their speeds before enforcement while the other is used for speed enforcement.
Variable speed advisory (VSA)	VMS used to display real-time downstream speeds to drivers so they can preemptively slow down before reaching the bottleneck.
Travel time information systems (TTIS)	Displays travel time through a work zone to motorists so they can make informed route choices accordingly.
Smart arrow boards	Illuminated arrow signs with data processing and sharing functionalities capable of sending real-time traffic data from the field to travelers.
Temporary incident detection and surveillance systems	Incident-detection systems monitor the work zone using cameras or sensors to alert traffic management centers (TMCs) or emergency response systems when traffic incidents occur in the work zone.
Construction truck entering & exiting systems	Construction truck alert systems automatically detects when slow-moving construction vehicles exit work zones and provide advance warning to motorists through VMS or flasher signs.

CHAPTER 3: SURVEY OF STATE DOTS

This chapter presents the findings of the online survey conducted to gather and analyze feedback from state DOT officials on their experiences utilizing smart work zone systems. This survey was designed to collect data organized in six sections, which focus on (1) uses of SWZ systems, (2) effectiveness of SWZ systems in reducing crashes, (3) effectiveness of SWZ systems in reducing delay and queue length, (4) project conditions for deploying SWZ systems, (5) cost of implementing SWZ systems, and (6) challenges of SWZ systems.

The survey was designed following the best practices provided by the American Association for Public Opinion Research (AAPOR, 2022). The survey was developed in collaboration with the Technical Review Panel of this project and was designed to take less than 15 minutes to complete. As shown in Table 3, the survey included 18 questions that were grouped into seven sections that focus on (1) background of survey respondents, (2) uses of SWZ systems, (3) effectiveness of SWZ systems in reducing crashes, (4) effectiveness of SWZ systems in reducing delay and queue length, (5) project conditions for deploying SWZ systems, (6) cost of implementing SWZ systems, and (7) challenges of SWZ systems, as shown in Table 2. The survey was developed using an online surveying platform (SurveyMonkey, https://www.surveymonkey.com/) to facilitate distribution and collection of survey data. A list of contacts for state DOT officials was compiled by the Technical Review Panel, and a link of the online survey was then emailed to each identified contact. The full list of survey questions that was emailed to state DOT officials is presented in Appendix A.

Table 2. Organization of State DOT Survey Questions

Section	Number of Question
1. Background Information	3
2. Use of SWZ Systems	2
3. Effectiveness of SWZ Systems in Reducing Crashes	3
4. Effectiveness of SWZ Systems in Reducing Delay and Queue Length	3
5. Projects Conditions for Deploying SWZ Systems	2
6. Cost of Implementing SWZ Systems	4
7. SWZ Systems Problems and Challenges	1

Table 3. Organization of State DOT Survey Questions

Survey Questions
1.1. What is your name?
1.2. What state do you represent?
1.3. What is your current job title?
2.1. Which of the following SWZ systems have been used by your state DOT? (full checklist in Appendix A)
2.2. If your state does not currently utilize any of the following SWZ systems, does your state have plans to consider it in the future? (full checklist in Appendix A)
3.1. Please report the impact of each SWZ system in reducing the frequency and/or severity of vehicle crashes (full checklist in Appendix A)
3.2. Has your state experienced a reduction in roadway crashes through utilizing SWZ systems?
3.3. If yes, please report experienced reduction in the frequency and/or severity of roadway crashes (%), or provide links to documented crash reduction if available.
4.1. Please report the impact of each SWZ system in reducing delay and queue length (full checklist in Appendix A)
4.2. Has your state experienced a reduction in delay and/or queue length through utilizing SWZ systems?
4.3. If yes, please report experienced reduction in travel time delay or queue length (%), or provide links to documented travel time and queue length reduction if available.
5.1. Please specify any project conditions that require the deployment of each of the following SWZ systems, or provide a link to your related DOT specifications.
5.2. If your DOT uses tools and/or design criteria to determine if a SWZ system is required on a project, please provide a link to this tool/design criteria.
6.1. Please indicate if your state DOT owns, leases or rents SWZ equipment? (Select all that apply: own; lease; rent)
6.2. Please provide the unit purchase cost of the following SWZ systems in $/unit, if they were purchased by your DOT. (full checklist in Appendix A)
6.3. Please provide the cost of the following SWZ systems as a percentage of the total project cost, if they were purchased by your DOT. (full checklist in Appendix A)
6.4. Please provide the monthly rental costs of the following SWZ systems, if they were leased by your DOT. (full checklist in Appendix A)
7.1. Please report the frequency of challenges encountered in operating and maintaining the following SWZ systems as None, Slight, Moderate, High, Very High or Inadequate Information and specify the type of challenges.

A total of 22 complete responses were received from 18 state DOTs, as shown in Table 4. Note that two responses were received from four state DOTs: Iowa, Ohio, Pennsylvania, and South Carolina. The remaining 14 state DOTs provided one response each: Arizona, Arkansas, Connecticut, Florida, Kansas, Michigan, Missouri, Montana, Nebraska, Nevada, North Carolina, South Dakota, Washington, and Wisconsin. The reported job titles of the 22 survey respondents were work zone engineers, traffic engineers or specialists, project managers, and transportation engineers, as shown in Figure 2.

Table 4. Number of State DOT Responses

State	Number of responses
Arizona	1
Arkansas	1
Connecticut	1
Florida	1
Iowa	2
Kansas	1
Michigan	1
Missouri	1
Montana	1
Nebraska	1
Nevada	1
North Carolina	1
Ohio	2
Pennsylvania	2
South Carolina	2
South Dakota	1
Washington	1
Wisconsin	1
Total	**22**

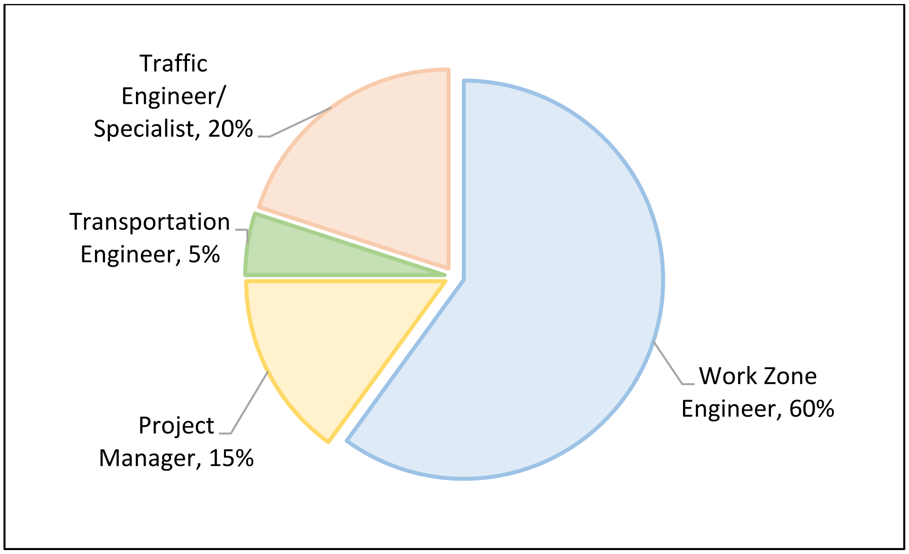


Figure 2. Chart. State DOT respondents' job titles.

USES OF SWZ SYSTEMS

State DOT officials were asked to identify the SWZ systems used or considered for future use in their state. The collected feedback from the survey respondents in this section is organized into two categories: SWZ systems utilized and future plans for utilizing SWZ systems.

SWZ Systems Utilized

State DOTs were asked to identify the SWZ systems utilized in their states from a list of 10 SWZ systems: variable message signs, queue warning systems, dynamic lane merge systems, speed feedback signs, automated speed enforcement, variable speed advisory travel time information systems, smart arrow boards, temporary incident detection and surveillance systems, and construction truck entering and exiting systems. The number of states reporting the use of each SWZ system and their percentages are summarized in Table 5 and Figure 3. In addition to these 10 systems, respondents reported the use of “other” systems, as shown in Table 5. The top five SWZ systems that were reported to be used the most by participating state DOTs are variable message signs, queue warning systems, travel time information systems, speed feedback signs, and construction truck entering and exiting systems respectively.

Table 5. SWZ Systems Utilized

SWZ System	States	Number of States Utilizing SWZ Systems	Percentage of Responding States
Variable message signs (VMS)	Arizona, Arkansas, Connecticut, Florida, Iowa, Kansas, Michigan, Missouri, Montana, Nebraska, Nevada, North Carolina, Ohio, Pennsylvania, South Carolina, South Dakota, Washington, Wisconsin	18	100.0%
Queue warning systems (QWS)	Arizona, Arkansas, Iowa, Kansas, Michigan, Missouri, Montana, Nebraska, North Carolina, Ohio, Pennsylvania, South Carolina, South Dakota, Washington, Wisconsin	15	83.3%
Dynamic lane merge systems (DLMS)	Arizona, Iowa, Kansas, Missouri, Montana, North Carolina, Washington, Wisconsin	8	44.4%
Speed feedback signs (SFS)	Arizona, Iowa, Kansas, Michigan, Missouri, Montana, Nevada, Pennsylvania, South Carolina, South Dakota, Washington, Wisconsin	12	66.7%
Automated speed enforcement (ASE)	Pennsylvania	1	5.6%
Variable speed advisory (VSA)	Iowa, Pennsylvania	2	11.1%
Travel time information systems (TTIS)	Arizona, Arkansas, Connecticut, Kansas, Michigan, Missouri, Montana, Nevada, North Carolina, Ohio, Pennsylvania, Washington, Wisconsin	13	72.2%
Smart arrow boards	Arizona, Iowa, Michigan, Missouri, North Carolina, Pennsylvania, Washington, Wisconsin	8	44.4%
Temporary incident detection and surveillance systems	Arkansas, Missouri, North Carolina, Pennsylvania, South Carolina	5	27.8%
Construction truck entering and exiting systems	Arizona, Iowa, Michigan, Missouri, North Carolina, Ohio, Pennsylvania, South Carolina, Wisconsin	9	50.0%
Other: Connected Lane Closure	North Carolina	3	16.7%
Other: Variable Speed Limit	Arizona, North Carolina, Ohio	3	16.7%

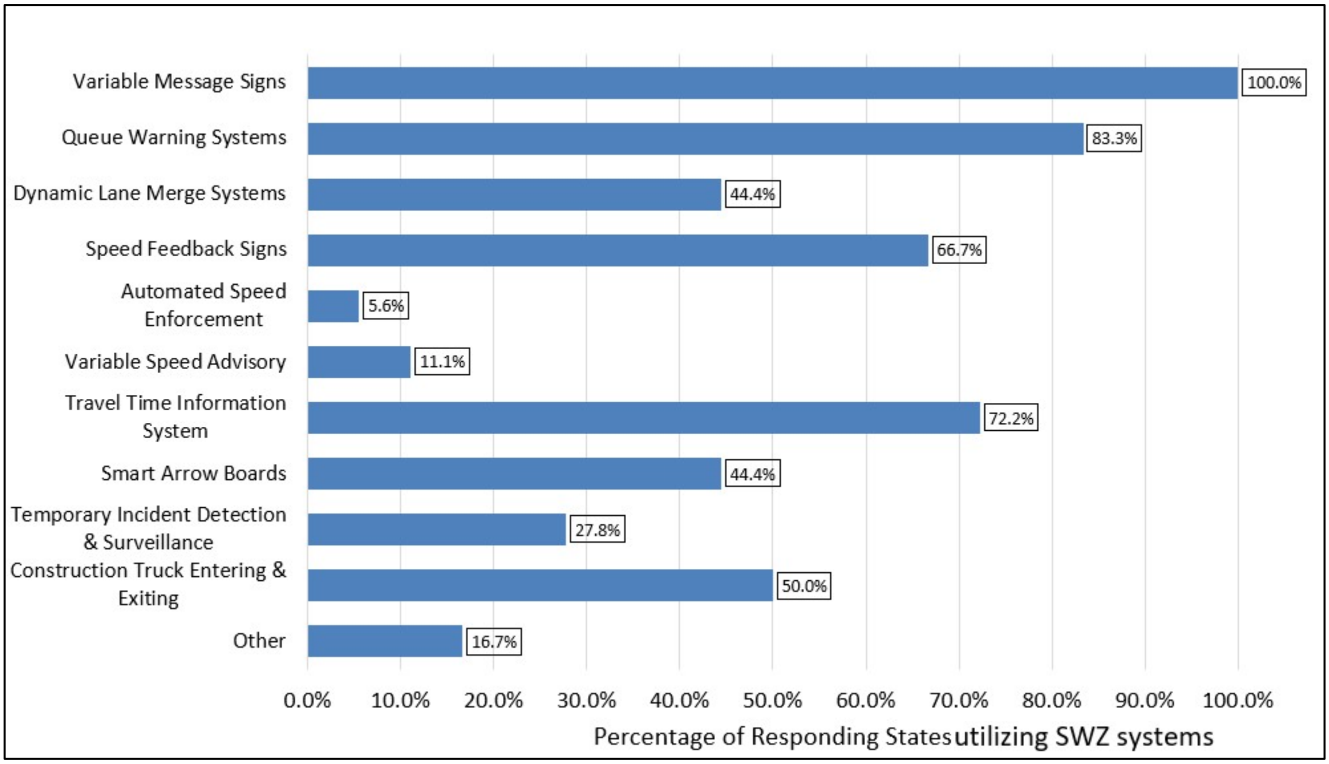


Figure 3. Chart. Percentage of responding state DOTs utilizing SWZ systems.

Future Plans for Utilizing SWZ Systems

State DOTs were asked to report if they have plans to utilize any of the aforementioned SWZ systems. The number of states reporting the future planned use of each SWZ system and their percentages are summarized in Table 6 and Figure 4. In addition to these 10 systems, three respondents reported that they plan to use “other” systems such as digital speed limit, lane reservation system, and variable speed limit. The top five SWZ systems that were reported to be considered the most for future use by participating state DOTs are smart arrow boards, queue warning systems, dynamic lane merge systems, automated speed enforcement, and construction truck entering and exiting systems, respectively.

Table 6. Future Plans to Utilize SWZ Systems

SWZ System	States	Number of Responding States	Percentage of Responding
No New Technologies Considered	Kansas	1	5.6%
Queue warning systems (QWS)	Arkansas, Florida, Nebraska, Nevada, Ohio	5	27.8%
Dynamic lane merge systems (DLMS)	Arkansas, Florida, Michigan, Montana, South Carolina	5	27.8%
Speed feedback signs (SFS)	Arkansas, Florida, Nebraska, Ohio	4	22.2%
Automated speed enforcement (ASE)	Connecticut, Michigan, North Carolina, Ohio, Washington	5	27.8%
Variable speed advisory (VSA)	Arkansas, Nevada, South Dakota	3	16.7%
Travel time information systems (TTIS)	Arkansas, Iowa	2	11.1%
Smart Arrow Boards	Arkansas, Florida, Montana, Nebraska, Ohio, Pennsylvania, South Carolina	7	38.9%
Temporary Incident Detection & Surveillance	Arkansas, Montana, Nevada, Pennsylvania	4	22.2%
Construction Truck Entering & Exiting	Arkansas, Nevada, Ohio, South Dakota, Washington	5	27.8%
Other: Digital Speed Limit	Nebraska	1	5.6%
Other: Lane Reservation System	Pennsylvania	1	5.6%
Other: Variable Speed Limit	Ohio	1	5.6%

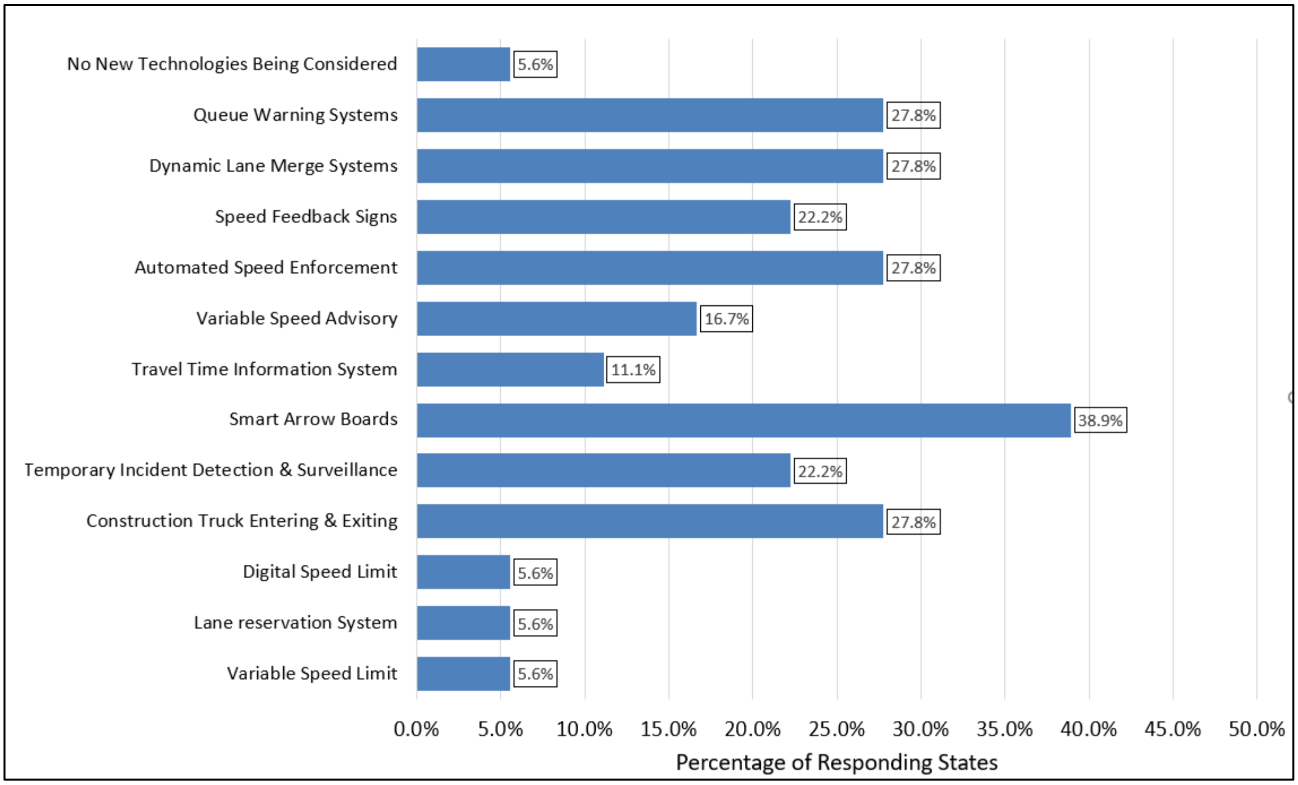


Figure 4. Chart. Percentage of state DOTs planning to utilize SWZ systems.

EFFECTIVENESS OF SWZ SYSTEMS IN REDUCING CRASHES

This section presents the reported effectiveness of SWZ systems in reducing crashes by state DOTs. The following two subsections summarize the collected and analyzed feedback from survey respondents on (1) impact of SWZ systems on reducing work zone crashes using a five-point scale that ranges from negative to very positive impact and (2) experienced percentage of reduction in work zone crashes because of the use of SWZ systems and the availability of any DOT-related studies or reports.

Impact of SWZ Systems in Reducing the Frequency and/or Severity of Crashes

Respondents were asked to report the impact of SWZ systems on reducing the frequency and/or severity of roadway crashes using a five-point scale: negative impact, no change, slightly positive impact, positive impact, or very positive impact. To identify the average impact of each SWZ system, each reported impact was represented numerically using a scale that ranges from 1 to 5, where 1 represents “negative impact” and 5 represents “very positive impact,” as shown in Table 7. A weighted average effectiveness of each SWZ system was calculated, as shown in Table 7 and Figure 5. The top five SWZ systems that were reported to have the highest weighted average positive impact in reducing crash frequency and severity by participating state DOTs are automated speed enforcement systems, variable speed advisory systems, queue warning systems, dynamic lane merge systems, and variable message signs, respectively.

Table 7. Effectiveness of SWZ Systems in Reducing Crash Severity and Frequency

SWZ System	Negative Impact	No Change	Slightly Positive	Positive Impact	Very Positive	Inadequate Information	Weighted Average
Five-point Scale	1	2	3	4	5	–	1 to 5
Variable Message Signs	0	1	2	9	1	7	3.69
Queue Warning Systems	0	0	0	4	7	8	4.64
Dynamic Lane Merge Systems	0	0	2	3	2	7	4.00
Speed Feedback Signs	0	2	2	5	1	9	3.30
Automated Speed Enforcement	0	0	0	0	2	10	5.00
Variable Speed Advisory Systems	0	0	0	0	1	11	5.00
Travel Time Information Systems	0	2	3	2	1	7	3.00
Smart Arrow Boards	0	2	1	2	1	9	3.00
Temporary Incident Detection & Surveillance	0	1	0	2	0	9	3.00
Construction Truck Entering & Exiting	0	1	2	4	1	7	3.50
Other	0	0	0	0	0	5	N/A

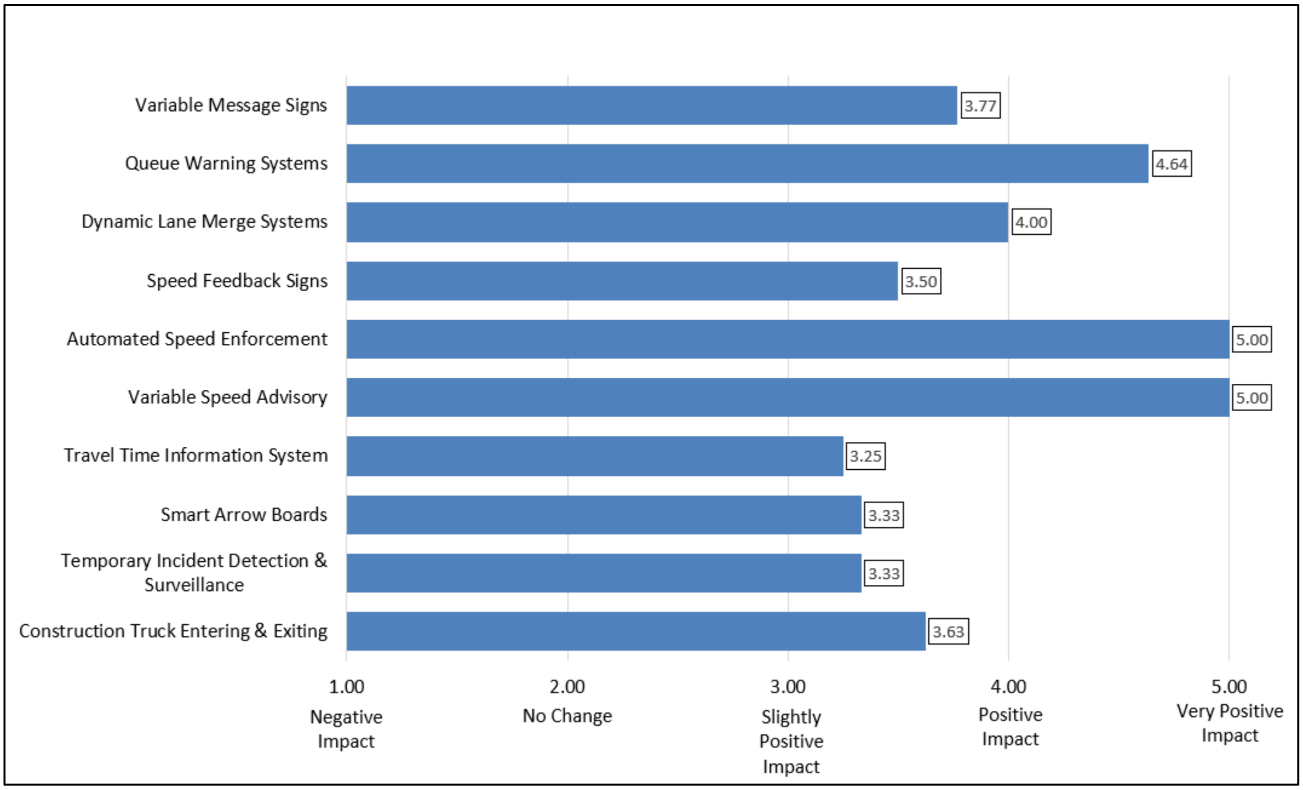


Figure 5. Chart. Average effectiveness of SWZ systems in reducing crash severity and frequency.

Experienced Crash Reductions

Respondents were asked to report if they have experienced a reduction in roadway crashes because of the use of SWZ systems. Eleven of the responding state DOTs (68.75%) reported that they have experienced a reduction in crashes because of utilizing SWZ systems, while five state DOTs (31.25%) reported they have not, as shown in Table 8 and Figure 6. In addition, respondents were asked to report the percentage reduction of roadway crashes or to provide a link to any available documented reduction. Pennsylvania DOT provided a link to a report documenting their experienced crash reduction due to automated speed enforcement systems, and nine additional state DOTs reported the effectiveness of SWZ systems in reducing crashes without providing links to related reports, as shown in Table 9. The Pennsylvania DOT report indicated that the use of the automated speed enforcement (ASE) system decreased the amount of crashes by an average of 100 crashes annually and fatal crashes by roughly 25%.

Table 8. State DOTs Experiencing Reduction in Roadways Crashes Because of SWZ Systems

Experienced Reduction in Crashes	States	Number of Respondents
Yes	Arizona, Arkansas, Iowa, Michigan, Montana, Nebraska, North Carolina, Pennsylvania (2), South Carolina, Wisconsin	11
No	Connecticut, Kansas, Missouri, Ohio, South Carolina	5

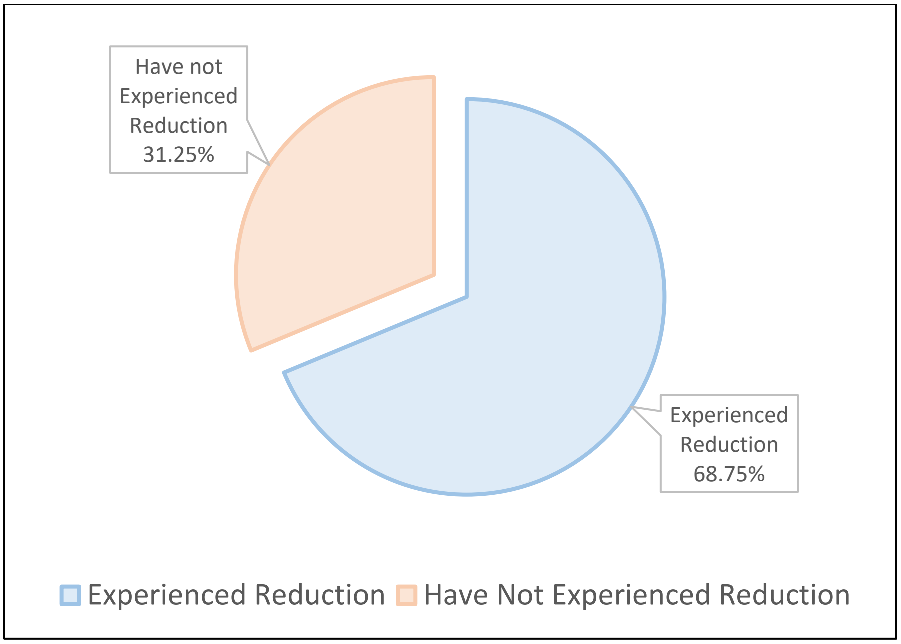


Figure 6. Chart. State DOTs experiencing reduction in roadways crashes because of SWZ systems.

Table 9. Responding States Experienced Reduction in Crashes with Related Report if Available

State	SWZ System	Answer/Link
Iowa	Other	We have not analyzed the data. Just a gut feel.
Michigan	Other	No officially documented results, but the numbers have been trending downward over the past 5 years with 2020 was an exception.
Missouri	Other	Distracted driving is still causing an increase in accidents even though we think that our smart work zone systems are working.
Nebraska	Other	no data to show, only anecdotal.
North Carolina	Other	I don't believe any of it has been quantified.
Pennsylvania	Automated Speed Enforcement	Pennsylvania's Automated Work Zone Speed Enforcement, Pennsylvania DOT ASE 2022 Report (PennDot 2022),
South Carolina	Queue Warning Systems	Haven't been able to isolate and compare data but by all appearances properly installed QWS on our interstates has been reducing back of queue crashes.
Washington	Other	First deployment of large queue warning system with queuing up to 9 miles during a 2-week continuous 1 or 2 lane closure on a 3-lane interstate had only two property damage collisions. In addition, some of our maintenance crews using connected devices felt that more drivers were moving over approaching their work areas.
Wisconsin	Other	We have not done a safety analysis, but work zone crashes appear to be trending down, but we have not attributed it to smart work zones.

EFFECTIVENESS OF SWZ SYSTEMS IN REDUCING DELAY AND QUEUE LENGTH

This section presents the reported effectiveness of SWZ systems in reducing delay and queue length by state DOTs. The following two subsections summarize the collected and analyzed feedback from survey respondents on (1) impact of SWZ systems on reducing work zone delay and queue length using a five-point scale that ranges from negative to very positive impact and (2) experienced percentage of reduction in work zone delays and queue lengths because of the use of SWZ systems and the availability of any DOT-related studies or reports.

Impact of SWZ Systems in Reducing Delay and Queue Length

Respondents were asked to report the impact of SWZ systems on reducing delay and queue length using a five-point scale: negative impact, no change, slightly positive impact, positive impact, or very positive impact. To identify the average impact of each SWZ system, each reported impact was represented numerically using a scale that ranges from 1 to 5, where 1 represents “negative impact” and 5 represents “very positive impact,” as shown in Table 10. A weighted average effectiveness of each SWZ system was calculated, as shown in Table 10 and Figure 7. The top five SWZ systems that were reported to have the highest weighted average positive impact in reducing delay and queue length by participating state DOTs are dynamic lane merge systems, temporary incident detection and surveillance systems, queue warning systems, variable message signs, and travel time information systems, respectively.

Table 10. Effectiveness of SWZ Systems in Reducing Delay and Queue Lengths

SWZ System	Negative Impact	No Change	Slightly Positive Impact	Positive Impact	Very Positive Impact	Inadequate Information	Weighted Average
Five-point Scale	1	2	3	4	5	–	1 to 5
Variable Message Signs	0	1	7	4	1	3	3.31
Queue Warning Systems	0	2	2	3	3	4	3.50
Dynamic Lane Merge Systems	0	0	3	2	1	4	3.67
Speed Feedback Signs	0	5	2	0	0	7	1.57
Automated Speed Enforcement	0	0	0	0	0	9	N/A
Variable Speed Advisory Systems	0	1	0	1	0	8	2.50
Travel Time Information Systems	0	1	5	3	1	3	3.30
Smart Arrow Boards	0	1	2	2	0	6	3.00
Temporary Incident Detection & Surveillance	0	0	1	2	0	7	3.67
Construction Truck Entering & Exiting	0	2	0	1	1	7	2.75
Other	0	0	0	0	0	4	N/A

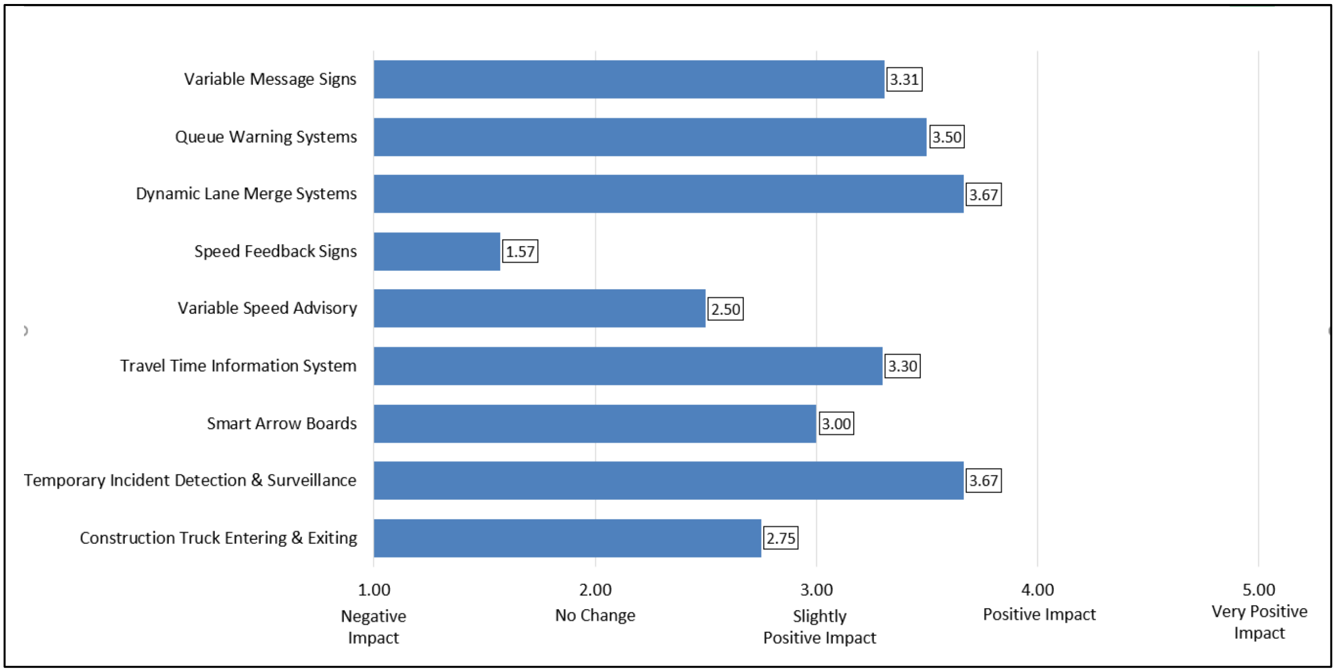


Figure 7. Chart. Average effectiveness of SWZ systems in reducing delay and queue length.

Experienced Reductions in Work Zone Delay and Queue Length

Respondents were asked to report if they have experienced a reduction in delay time and queue length because of the use of SWZ systems. Ten of the responding state DOTs (71.43%) reported that they have experienced a reduction in delay time and queue length because of utilizing SWZ systems, while four state DOTs (28.57%) reported they have not, as shown in Table 11 and Figure 8. In addition, respondents were asked to report the percentage reduction of roadway crashes or to provide a link to any available documented reduction. Four state DOTs reported the effectiveness of SWZ systems in reducing delay times and queue lengths without providing links to related reports, as shown in Table 12.

Table 11. State DOTs Experiencing Reduction in Delay and Queue Length Because of SWZ Systems

Experienced Reduction in Crashes	States	Number of Respondents	Percentage of Responding States
Yes	Arizona, Arkansas, Iowa, Kansas, Michigan, Missouri, North Carolina, Pennsylvania, South Carolina, Wisconsin	10	71.43%
No	Connecticut, Nebraska, Ohio, South Carolina	4	28.57%

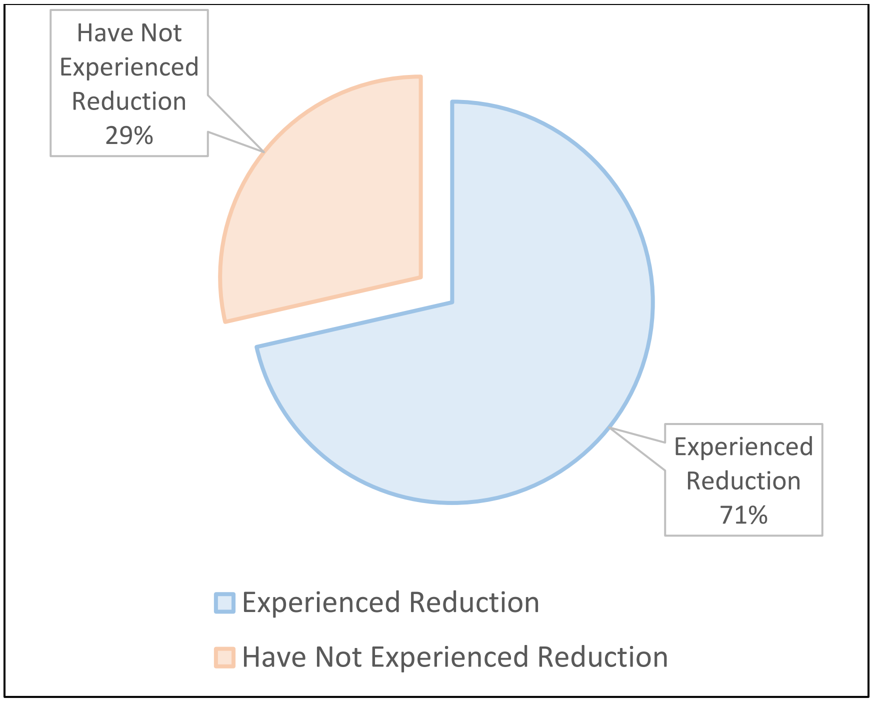


Figure 8. Chart. State DOTs experiencing reduction in delay and queue length because of SWZ systems.

Table 12. Responding States Experienced Reduction in Delay and Queue Length with Related Report, if Available

State	SWZ System	Answer or Link
Michigan	Other	Overall have seen less back-ups and motorist complaints
Missouri	Travel Time Information Systems	If an alternate route is 10 minutes longer, but the posted delay is 20 minutes, we see significant diversion as vehicles use the "longer" alternate route.
South Carolina	Queue Warning Systems	When QWS (and VMS) are used for lane closures there is greater utilization of both signed and unsigned alternate routes
Wisconsin	Other	No studies have been done to prove this. More of an observation when we implement these systems.

PROJECT CONDITIONS AND DESIGN CRITERIA FOR DEPLOYING SWZ SYSTEMS

This section presents the reported project conditions requiring the deployment of SWZ systems by state DOTs. The following two subsections summarize the collected and analyzed feedback from survey respondents on (1) project conditions requiring the deployment of SWZ systems by state DOTs and (2) tools or design criteria for deploying SWZ systems by state DOTs.

Project Conditions for Deploying SWZ Systems

Respondents were asked to specify project conditions that require the deployment of each SWZ system or to provide a link to related DOT specifications. Examples of project conditions include recurring queues, baseline crashes exceeding typical average in project location, or expected high truck volume. Two DOTs provided links to their related specifications/provisions while 14 state DOTs reported project conditions without providing a link, as shown in Table 13, Table 14, Table 15, Table 16, Table 17, Table 18, Table 19, Table 20, Table 21, Table 22, and Table 23. In addition, 16 state DOTs provided their specific project conditions that require the deployment of 11 SWZ systems. For example, the deployment of VMS was required by state DOTs based on a wide range of conditions including projects with road or lane closures, work on interstate highways, budgets over $300K, recurring queues, and increase in severe crashes, as shown in Table 13. Similarly, the deployment of QWS was required by state DOTs based on a wide range of conditions including projects with expected queues, work on interstate and freeway highways, road or lane closures, extended duration, and AADT greater than 25,000, as shown in Table 14. The deployment of DLMS was required by state DOTs for projects with expected queues and long-term lane closures, as shown in Table 15.

The deployment of SFS was required by state DOTs for projects with reduced or variable speed limits, lane closures, budgets over $200K, speed limits over 45 mph, and expected queues, as shown in Table 16. The deployment of ASE was required by state DOTs for interstate and freeway projects, as shown in Table 17. The deployment of VSA systems was required by state DOTs for projects with recurring queues, as shown in Table 18. The deployment of TTIS was required by state DOTs for projects with available alternate routes and expected queues, as shown in Table 19. The deployment of smart arrow boards was required by state DOTs for projects with lane closures, as shown in Table 20. The deployment of temporary incident detection and surveillance was required by state DOTs for projects with a lack of permanent CCTV to assist in traffic and incident management, as shown in Table 21. The deployment of construction truck entering and exiting systems was required by state DOTs for projects with set ingress and egress points that frequently have trucks entering and exiting the work zone and no road barriers, as shown in Table 22. The deployment of digital speed limits was required by state DOTs for projects with work on multi-lane highways, 55 mph speed limits, work zones 0.5 miles or longer that reduces existing functionality of travel lanes, and daily work duration of 3 hours, as shown Table 23.

Table 13. Project Conditions Requiring Deployment of VMS

State	Project Conditions/Link to Related Provisions
Connecticut	Smart Work Zone Special Provisions (CDOT, 2018)
Iowa	Used for real-time information
Michigan	Used in just about every project
Nevada	All projects over $300K
North Carolina	Relatively standard
Ohio	PCMS boards preceding interstate work zones Provided Links: (1) Traffic Engineering Manual: Part 6 (Sections 605-9, 642-41 Plan); (2) VMS Prequalification Procedure; (3) VMS Approved List (ODOT, 2022)
Pennsylvania	Enhance notification on long-term projects
South Carolina	Road closures/detours; lane closures during high volume periods; interstate lane closures; recurring queues, and more severe crashes

Table 14. Project Conditions Requiring Deployment of QWS

State	Project Conditions/Link to Related Provisions
Arkansas	ADT, speed, time of lane closure, number of lanes closed, sight distance, and facility
Iowa	Deployed when we expect queuing
Michigan	While there are no use statements for this and it is up to the design staff, it is usually used when there is freeway traffic or will be a queue on an extended duration project
Montana	All flagging and signal locations where there will be queues of 10 or more cars. Also required on interstates in areas where a lane reduction will create a queue outside of the lane closure
Nebraska	Rural interstate and freeway projects
North Carolina	Recurring queues expected >1 mile
Ohio	Used when required by the District or Central Office. Central Office may require in conjunction with a MOT Policy Exception approval where queues will be anticipated. Provided Links: (1) Traffic Engineering Manual: Part 6 (Sections 640-29.1, 642-57 Plan) (2) QWS Assembly Requirements, QWS Specifications; (3) QWS Approved List (ODOT, 2022)
Pennsylvania	Locations where recurring queues existed on previous projects
South Carolina	Predominantly interstate construction projects but also interstate maintenance projects with high volume lane closures; Recurring queues, and more severe crashes
South Dakota	The project must be in a location where we know traffic will back up due to the project
Washington	See “Queue Warning System” in General Special Provisions (starting on pg 38) (WDOT, 2022)
Wisconsin	Any freeway/expressway with an AADT greater than 25,000 is required to have some end of queue detection, regardless of queuing anticipated

Table 15. Project Conditions Requiring Deployment of DLMS

State	Project Conditions/Link to Related Provisions
North Carolina	Recurring queues expected > 1 mile
Wisconsin	Recommended to install with long-term lane closure with queuing expected, urban/ rural

Table 16. Project Conditions Requiring Deployment of SFS

State	Project Conditions/Link to Related Provisions
Iowa	Used for all lane closures on Interstate and expressways
Michigan	Required in projects with a traffic shift longer than 3 days and speed of 45 mph and above.
Nevada	Any project with temporary reduced speed limits
Ohio	Restriction on use in zones that have digital speed limit sign. Provided Links: Digital Speed Limit Sign Assembly Specifications (ODOT, 2022)
Pennsylvania	Any freeway project with an estimated cost over $200K
South Carolina	Recurring queues, and more severe crashes
South Dakota	The project must have a speed reduction and be in a location where we expect drivers to disregard the reduced speed.

Table 17. Project Conditions Requiring Deployment of ASE

State	Project Conditions/Link to Related Provisions
Pennsylvania	Program management team selects projects meeting certain criteria
South Carolina	Interstate construction projects

Table 18. Project Conditions Requiring Deployment of VSA

State	Project Conditions/Link to Related Provisions
Iowa	Deploy when expecting queuing

Table 19. Project Conditions Requiring Deployment of TTIS

State	Project Conditions/Link to Related Provisions
Michigan	Depends on the project level impact
North Carolina	Recurring queues expected, and viable alternate routes available
Ohio	Only added to location which will remain as permanent. May use work zone plaque during the temporary conditions and remove once work zone is done
Wisconsin	Recommended to install when there are viable alternate routes

Table 20. Project Conditions Requiring Deployment of Smart Arrow Boards

State	Project Conditions/Link to Related Provisions
Iowa	All lane closures
Michigan	Trying to add to all projects
North Carolina	Lane closures
Washington	Currently used by maintenance work zone traffic control specialty crews right now. A general special provision for freeway contract use will be published next month

Table 21. Project Conditions Requiring Deployment of Temporary Incident-Detection System

State	Project Conditions/Link to Related Provisions
North Carolina	lack of permanent CCTV to assist in traffic and incident management
Pennsylvania	Part of the department’s 511 and TMC operational procedures

Table 22. Project Conditions Requiring Deployment of Construction Truck Entering and Exiting

State	Project Conditions/Link to Related Provisions
Iowa	When we need to create gaps for merging construction equipment
Michigan	Used in roadway projects that have set access point of ingress and egress, no road barrier and work zone with drums. Trucks did not want to follow the path to set off system
Ohio	Used when use of Work Zone Egress Warning System are required by the District or Central Office. Should also be used on any project that has construction egress points as detailed in SCD Construction Truck Entering and Exiting Systems Layout Provided Links: (1) Traffic Engineering Manual: Part 6 (Sections 640-29.2, 642-59 Plan Note); (2) Construction Truck Entering and Exiting Systems Assembly Requirements, Construction Truck Entering and Exiting Systems Specifications; (3) Construction Truck Entering and Exiting Systems Specifications Approved List (ODOT, 2022)
Pennsylvania	Stopping sight distance concerns for projects with construction access points
Wisconsin	Recommended to install when there will be many trucks entering traffic from the work zone on a regular basis.

Table 23. Project Conditions Requiring Deployment of Other Systems Reported

State	Project Conditions/Link to Related Provisions
Arizona	It is all based on project "significance" as defined by the FHWA, and projects the department feels are "significant"
Ohio	The following conditions must be met: (1) multi-lane highway (2) 55 mph speed limit (3) work zone at least 0.5 miles and reduces existing functionality of travel lanes (4) work duration of 3 hours. Provided Links: (1) Traffic Engineering Manual: Part 6 (Sections 640-18.2, 641-34, 642-24 Plan Note), Part 12 (Sections 1203-2.9, Figures 1298-1a through 1298-1c, Table 1297-7, Forms 1296-6b, 1296-7b, 1296-17, 1296-18); (2) Digital Speed Limit Layout; (3) Digital Speed Limit Assembly Requirements, Digital Speed Limit Specifications; (4) Digital Speed Limit Approval List (ODOT, 2022)

Design Criteria for Deploying SWZ Systems

Respondents were asked to provide a link to their tool or design criteria that determines if a SWZ system is required on a project. As shown in Table 24, only Arizona, Connecticut, Michigan, Pennsylvania, Washington, and Wisconsin have submitted links to their design criteria. Arizona and Pennsylvania DOT have provided a link to a tool that assesses the feasibility of SWZ systems on a roadway project while Washington and Wisconsin DOT have provided a link to a manual for implementing and maintaining SWZ systems. Connecticut DOT provided a link to a document that describes project conditions for deployment, instructions on implementing, and layouts for SWZ systems.

Table 24. Design Criteria for Deploying SWZ Systems

State	Link to Design Criteria
Arizona	ADOT SWZ Feasibility Worksheet (ADOT, 2020a)
Connecticut	Smart Work Zone Matrix (CDOT, 2018)
Michigan	Work Zone Safety and Mobility Manual (MDOT, 2021)
Pennsylvania	FHWA Work Zone ITS Implementation Guide (FHWA, 2014)
Washington	General Special Provisions (WDOT, 2022)
Wisconsin	Facilities Development Manual (Chapter 11, Section 50): Transportation Management Plan

COST OF SWZ SYSTEMS

This section presents the reported costs of deploying SWZ systems by state DOTs. The following three subsections summarize the collected and analyzed feedback from survey respondents on (1) whether state DOTs own, lease, or rent their SWZ equipment; (2) cost of purchased SWZ systems in $/unit or as a percentage of project cost; and (3) monthly cost of rented SWZ systems.

State DOT Ownership of SWZ Equipment

State DOTs were asked to report if they purchase, lease, or rent the equipment used for SWZ systems. Note that survey respondents were allowed to select more than one ownership method such as rent and purchase. This enables state DOTs to report their specific ownership practices that may require the purchase of more frequently used equipment such as variable message signs and the rental of less used equipment such as automated speed enforcement systems. The percentages of responding state DOTs reporting that they purchase, lease, and rent their SWZ equipment were 43.75%, 6.25%, and 87.5%, respectively (see Table 25 and Figure 9). The results show that the top two methods used by state DOTs for acquiring and utilizing SWZ systems were renting and purchasing.

Table 25. Responding State DOTs SWZ Equipment Ownership Method

SWZ Ownership	States	Number of Respondents	Percentage of Responding States
Purchase	Iowa, Kansas, Michigan, Ohio, Pennsylvania, South Dakota, Washington	7	43.75%
Lease	Nebraska	1	6.25%
Rent	Arizona, Arkansas, Florida, Iowa, Kansas, Michigan, Missouri, Montana, Nevada, Ohio, Pennsylvania, South Carolina, South Dakota, Wisconsin	14	87.5%

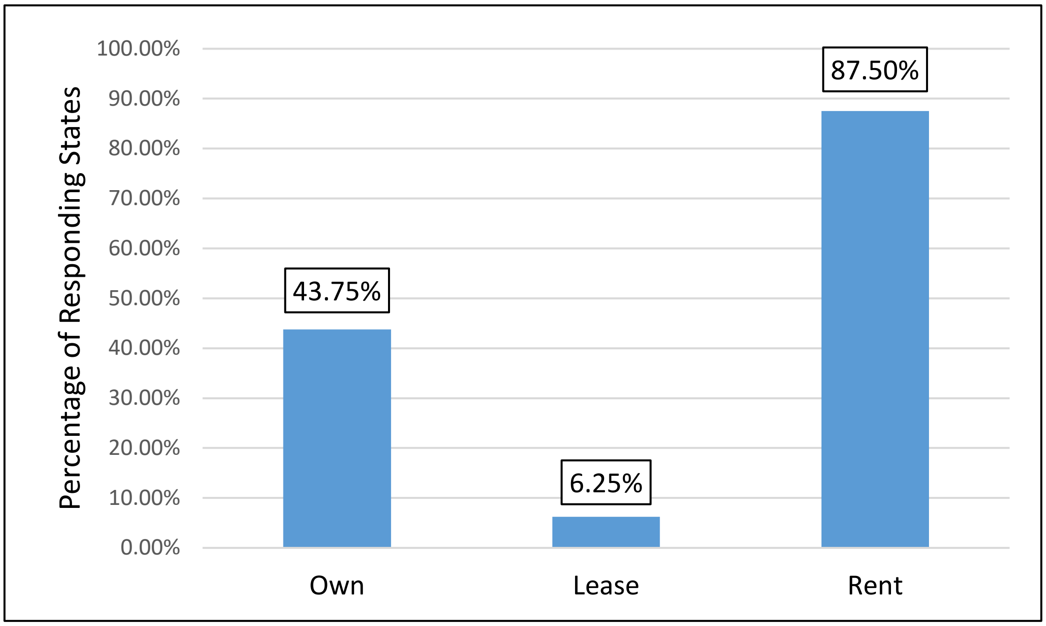


Figure 9. Chart. Percentage of state DOTs' SWZ system equipment ownership method.

Purchase Cost of SWZ Systems

State DOTs were asked to report the purchase cost of their SWZ systems. Three state DOTs reported the purchase unit cost of their VMS, SFS, and smart arrow boards, as shown in Table 26. For example, the purchase unit cost of VMS was reported by Iowa DOT and Pennsylvania DOT as $26,350 and $5,000–$8,000, respectively. The significant difference between the two reported VMS unit prices could be attributed to the wide range of VMS capabilities and features, which include an on-board dedicated NTCIP-compliant controller, automatic LED intensity control, a modem and radar for remote communication and recoding traffic patterns virtually, and solar panel assisted (Traffic Message Boards 3 lines, n.d.). The purchase unit cost of SFS was reported by Iowa DOT and

Pennsylvania DOT as $11,000 and $2,000–$5,000, respectively. The purchase unit cost of VSA systems was reported by Pennsylvania DOT as $2,000–$5,000, respectively. The purchase unit cost of smart arrow boards was reported by Washington DOT as $1,000. Note that all responding state DOTs were unable to provide the purchase cost of SWZ systems as a percentage of project cost.

Table 26. Reported Purchase Cost of SWZ Systems

SWZ System	States	Purchase Cost in $/Unit
Variable Message Signs	Iowa	$26,350.00 (2012 purchase) for DOT maintenance crews
Variable Message Signs	Pennsylvania	$5,000–$8,000
Speed Feedback Signs	Iowa	$11,000.00 (2015 purchase) for DOT maintenance crews
Speed Feedback Signs	Pennsylvania	$2,000–$5,000
Variable Speed Advisory	Pennsylvania	$5,000–$8,000
Smart Arrow Boards	Washington	Retrofit kits from iCone $1,000 each

Rental Cost of SWZ System Equipment

State DOTs were asked to report the rental cost of their SWZ systems. Three state DOTs reported the rental cost of their eight SWZ systems, shown in Table 27. For example, Iowa, Montana, and South Carolina DOT reported the rental cost of VMS as $950 per month, $300 per day, and $233 per month, respectively. Iowa DOT and Montana DOT reported the rental cost of QWS as $4,950 per month and $500 per day, respectively. Iowa DOT and Montana DOT reported the rental cost of DLMS as $7,237 per month and $1,000 per day, respectively. Iowa DOT and Montana DOT reported the rental cost of SFS as $2,250 per month and $15 per hour, respectively. Iowa DOT reported the rental cost of VSA systems as $9,027 per month. Iowa DOT and Montana DOT reported the rental cost of TTIS as $9,214 per month and $500 per day, respectively. Iowa DOT reported the rental cost of construction truck entering and exiting systems as $1,930 per month. South Carolina DOT reported the rental cost of CCTV cameras and smart traffic monitoring systems as $417 and $300 per month, respectively.

Table 27. Reported Rental Cost of SWZ Systems

State	SWZ System	Cost
Variable Message Signs	Iowa	$950 per month
Variable Message Signs	Montana	$300 per day
Variable Message Signs	South Carolina	$233 per month
Queue Warning Systems	Iowa	$4,950 per month
Queue Warning Systems	Montana	$500 per day
Dynamic Lane Merge Systems	Iowa	$7,237 per month
Dynamic Lane Merge Systems	Montana	$1000 per day
Speed Feedback Signs	Iowa	$2,250 per month
Speed Feedback Signs	Montana	$15 per hour
Variable Speed Advisory Systems	Iowa	$9,027 per month
Travel Time Information Systems	Iowa	$9,214 per month
Travel Time Information Systems	Montana	$500 per day
Construction Truck Entering and Exiting Systems	Iowa	$1,930 per month
Other: CCTV	South Carolina	$417 per month
Other: Smart Traffic Monitoring System	South Carolina	$300 per month

SWZ SYSTEM PROBLEMS AND CHALLENGES

This section presents the reported frequency of challenges encountered in operating and maintaining SWZ systems using a four-point scale that ranges from none to very high and the specified type of challenges encountered.

Challenges Encountered Utilizing SWZ Systems

State DOTs were asked to report the frequency of challenges encountered while operating or maintaining SWZ systems using a four-point scale: none, moderate, high, and very high. To identify the average frequency of challenges utilizing each SWZ system, each reported frequency was represented numerically using a scale that ranges from 0 to 3, where 0 represents “none” and 3 represents “very high,” as shown in Table 28. A weighted average was calculated for the frequency of encountered challenges for each SWZ system, as shown in Table 28 and Figure 10. The survey results show that the weighted averages for the frequency of encountered challenges by state DOTs for eight SWZ systems were none to moderate, while two SWZ systems were slightly higher than moderate. The top five SWZ systems that were reported to have the least weighted average frequency of challenges by participating state DOTs are variable speed advisory systems, speed feedback signs, travel time information systems, variable message signs, and queue warning systems, respectively.

In addition, respondents were asked to report the type of challenges encountered while operating or maintaining SWZ systems, as shown in Table 29 to Table 37. Thirteen state DOTs provided their encountered challenges while utilizing nine SWZ systems. For example, the reported challenges of VMS were replacing damaged equipment, equipment struck by traffic, equipment damaged by wind, equipment malfunctions, placement on roadways that are mostly on a structure or in fills adjacent to a guardrail, and poor communication connectivity. The reported challenges of QWS were false detections and messages, integration into ATMS software, queue extending into highway junctions, portraying relevant messages based on traffic conditions, moving the system along the project, coordinating detectors to VMS, and proper queue length estimates. The reported challenges of DLMS were lack of driver education on late/early merging and placing the “merge here” sign. The reported challenges of SFS were units struck by traffic, system being not cost effective, consistency in use, feedback programming, and moderate compliance. The reported challenge of ASE systems was noncompliance with state law. The reported challenges of TTIS were the number of available temporary devices, data communication issues, and occasional system malfunction. The reported challenges of smart arrow boards were sending data to servers, units struck by traffic, and moving the system along the project. The reported challenge of temporary incident detection and surveillance systems was units struck by traffic. The reported challenges of construction truck entering and exiting systems were finding equipment to detect entering/exiting vehicles and occasional system malfunction.

Table 28. Frequency of Challenges Encountered Utilizing SWZ Systems

SWZ System	None	Moderate	High	Very	Inadequate	Weighted
Four-point Scale	0	1	2	3	–	0 to 3
Variable Message Signs	7	11	0	0	0	0.61
Queue Warning Systems	6	8	3	0	1	0.82
Dynamic Lane Merge Systems	2	2	1	1	1	1.17
Speed Feedback Signs	7	7	0	0	1	0.50
Automated Speed Enforcement	2	0	0	1	2	1.00
Variable Speed Advisory	4	1	0	0	1	0.20
Travel Time Information System	5	2	2	1	1	0.90
Smart Arrow Boards	3	4	1	1	1	1.00
Temporary Incident Detection &	4	1	1	0	2	0.50
Construction Truck Entering & Exiting	4	2	3	1	1	1.10
Other	1	0	0	0	1	0.00

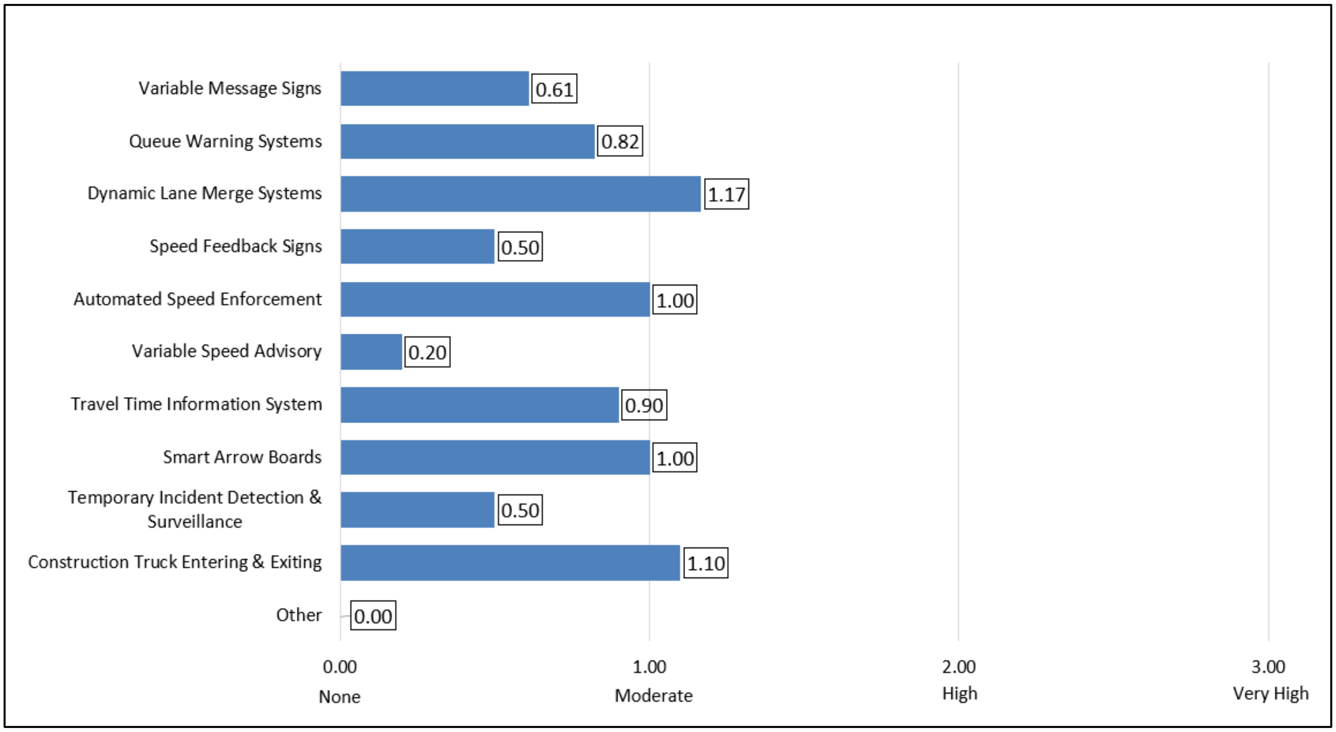


Figure 10. Chart. Average frequency of challenges encountered utilizing SWZ systems.

Table 29. Type of Challenges Encountered Utilizing VMS

State	Problems or Challenges Encountered
Iowa	Replacing damaged equipment
Montana	Communications connectivity
North Carolina	Getting hit by traffic
Ohio	Signs posted on construction projects sometimes malfunction
South Carolina	Some non-standard messages; placement on roadways that are mostly on structure or in fill adjacent to guardrail
South Dakota	Damage to equipment due to high winds.

Table 30. Type of Challenges Encountered Utilizing QWS

State	Problems or Challenges Encountered
Iowa	Could not integrate into our ATMS software
Kansas	When the queue extends into highway junctions
Montana	Keeping the message relevant based on the traffic conditions
Nebraska	Must be moved along with the project
South Carolina	Coordination of detectors to VMS; programming to reduce false queue messages; false detections of slow-moving construction vehicles that are not in travel way
Washington	Proper queue length estimates
Wisconsin	Only a few every so often with regards to the system activating when there is no slow or stopped traffic.

Table 31. Type of Challenges Encountered Utilizing DLMS

State	Problems or Challenges Encountered
Arizona	Placement of merge here signs
Kansas	Training drivers to utilize both lanes since early merge setups have been so commonly used
Missouri	There is significant confusion nationwide about late lane merge systems where some people consider it “butting in line” or cheating to late lane merge.
Washington	Driver education needed

Table 32. Type of Challenges Encountered Utilizing SFS

State	Problems or Challenges Encountered
Arizona	Effectiveness has been found to be not cost beneficial
Iowa	Maintaining units struck by traffic.
South Carolina	Consistency in use and their feedback programming
Washington	Due to moderate compliance, realistic speed limits are needed

Table 33. Type of Challenges Encountered Utilizing ASE

State	Problems or Challenges Encountered
Arizona	Against the law in Arizona

Table 34. Type of Challenges Encountered Utilizing TTIS

State	Problems or Challenges Encountered
Kansas	Number of temporary devices available when permanent devices are not available and the associated data communication issues in some areas
Pennsylvania	System occasionally down

Table 35. Type of Challenges Encountered Utilizing Smart Arrow Boards

State	Problems or Challenges Encountered
Iowa	Ensure they are sending data to servers
North Carolina	Getting hit by traffic
Washington	Need to be turned off in transport.

Table 36. Type of Challenges Encountered Utilizing Temporary Incident Detection and Surveillance

State	Problems or Challenges Encountered
North Carolina	Getting hit by traffic

Table 37. Type of Challenges Encountered Utilizing Construction Truck Entering and Exiting Systems

State	Problems or Challenges Encountered
Arizona	What is used to detect the entering or exiting vehicle
Pennsylvania	System down often

CHAPTER 4: SMART WORK ZONE SYSTEMS FEASIBILITY ASSESSMENT TOOL

This chapter summarizes the development of a user-friendly feasibility assessment tool that was designed to enable IDOT planners to determine the need for deploying six SWZ systems on roadway projects and generate layout designs for all recommended SWZ systems. The SWZ system feasibility assessment tool was developed in six phases that focused on (1) identifying all relevant work zone factors that affect traffic mobility and safety; (2) analyzing the mobility needs for each SWZ system based on quantitative and qualitative work zone factors; (3) assessing the safety needs for each SWZ system based on quantitative and qualitative work zone factors; (4) determining overall mobility and safety needs of each SWZ system; (5) designing a layout for the use of recommended SWZ systems in the work zone; and (6) developing a user-friendly interface for the feasibility tool and analyzing a case study to facilitate its use by DOT planners. The first five development phases are described in the following sections while the sixth phase is summarized in Appendix D, which presents a case study to illustrate the user-friendly interface of the developed tool and demonstrate its novel capabilities in predicting mobility and safety work zone factors to determine the need for deploying SWZ systems on different types of projects.

WORK ZONE FACTORS AFFECTING TRAFFIC MOBILITY AND SAFETY

This phase of model development was designed to consider all work zone factors that affect traffic mobility and safety in order to analyze the need for and feasibility of deploying six smart work zone systems: queue warning systems (QWS), dynamic lane merge systems (DLMS), variable speed advisory system (VSA), travel time information system (TTIS), temporary incident detection system (TIDS), and construction truck entry and exit detection system (CTEDS). A set of mobility and safety work zone factors were identified based on the literature review. The main sources of this identified list of mobility and safety work zone factors are FHWA's *Work Zone Intelligent Transportation Systems Implementation Guide* (FHWA, 2014), Arizona DOT SWZ Feasibility Worksheet (ADOT, 2020), Massachusetts DOT Scoring Criteria for Work Zone ITS (MassDOT, 2016) and Texas DOT Go/No-Go Decision Tool (TxDOT, 2018).

The identified work zone factors were organized into two subsets of mobility and safety factors, as shown in Table 38 and Table 39, respectively. The identified work zone mobility factors were then grouped into quantitative and qualitative categories based on their unit of measurement, which can be numerical or categorical, as shown in Table 38. The identified quantitative work zone mobility factors that can be represented by numerical values were max queue length in miles, average vehicle delay in hours, average vehicle delay in minutes, total delay of all vehicles in hours, queue duration in hours, and number of vehicles in max queue (all lanes), as shown in Table 38. The identified qualitative work zone mobility factors that can be represented by categories were work zone duration, highway function class, impact of a nearby roadway project, availability of alternate routes, impact of nearby traffic generator, existing traffic issues, presence of complex traffic layout, and sight distance from back of queue, as shown in Table 38.

Table 38. Work Zone Mobility Factors

Quantitative Factor	Numerical Unit of Measurement	Qualitative Factor	Categorical Unit of Measurement
Max Queue Length	Miles	Duration of Work Zone	Less than 1 month, 1–4 months, 5–10 months, larger than 1 year
Average Vehicle Delay	Minutes	Highway Function Class	Interstate, Freeway/Expressway, Major Arterial, Other
Total Delay of All Vehicles	Hours	Nearby Roadway Project	High Impact, Moderate Impact, Minimal Impact
Queue Duration	Hours	Availability of Alternate Routes	Yes, No
Number of Vehicles in Max Queue	Number of Vehicles	Nearby Traffic Generator Impact	High Impact, Moderate Impact, Minimal Impact
		Existing Traffic Issues	High Impact, Moderate Impact, Minimal Impact
		Presence of Complex Traffic Layout	Yes, No
		Sight Distance from Back of Queue	High Impact, Moderate Impact, Minimal Impact

Similarly, the identified work zone safety factors were grouped into quantitative and qualitative categories based on their unit of measurement, which can be numerical or categorical, as shown in Table 39. The identified quantitative work zone safety factors that can be represented by numerical values were average total number of crashes and average number of fatal/injury crashes, as shown in Table 39. The identified qualitative work zone safety factors that can be represented by categories were existing speeding issues, large speed variations, merging conflicts/hazards approaching the work zone, extreme weather conditions, percentage of heavy vehicles, constraints for emergency responders, and construction vehicle entering the roadway, as shown in Table 39.

Table 39. Work Zone Safety Factors

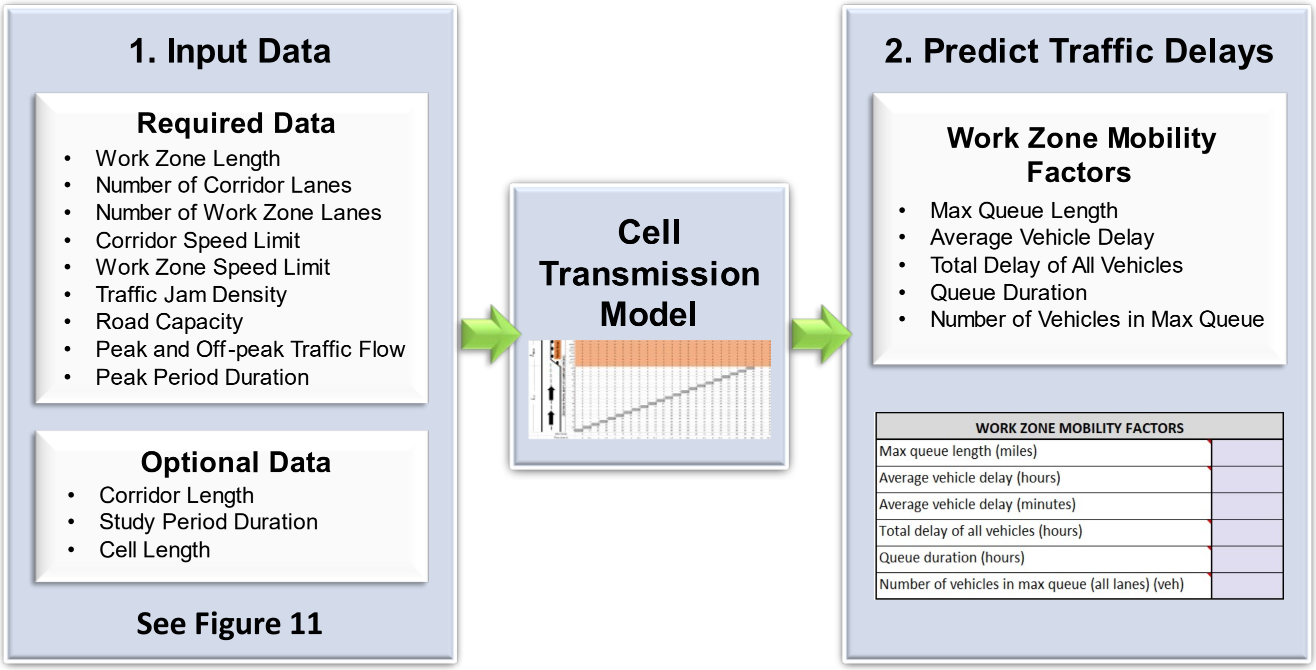
Quantitative Factor	Numerical Unit of Measurement	Qualitative Factor	Categorical Unit of Measurement
Average Total Number of Crashes	Number of Crashes	Existing Speeding Issues	Yes, No
Average Number of Fatal/Injury Crashes	Number of Crashes	Large Speed Variations	Yes, No
		Merging Conflicts/ Hazards Approaching the Work Zone	Yes, No
		Extreme Weather Conditions	High Impact, Moderate Impact, Minimal Impact
		Percentage of Heavy Vehicles	Less than 3%, 3%–6%, 6%–12%, Larger than 12%
		Constraint for Emergency Responders	High Impact, Moderate Impact, Minimal Impact
		Construction Vehicles Entering	Yes, No

WORK ZONE MOBILITY NEEDS FOR SWZ SYSTEMS

This phase was designed to analyze the mobility need for each SWZ system based on quantitative and qualitative work zone factors. This analysis was performed in three steps that are described in the following sections.

Predicting Impact of Work Zone Quantitative Mobility Factors on Traffic Delays

The developed tool was designed to integrate analytical models that provide the capability of predicting work zone traffic delays based on project-specific input data, as shown in Figure 11. The work zone traffic delays are predicted in the developed model in two steps that are designed to (1) collect all project-specific input data from DOT planners and (2) predict work zone traffic delays as well as queue length and duration based on project-specific input data, as shown in Figure 11.

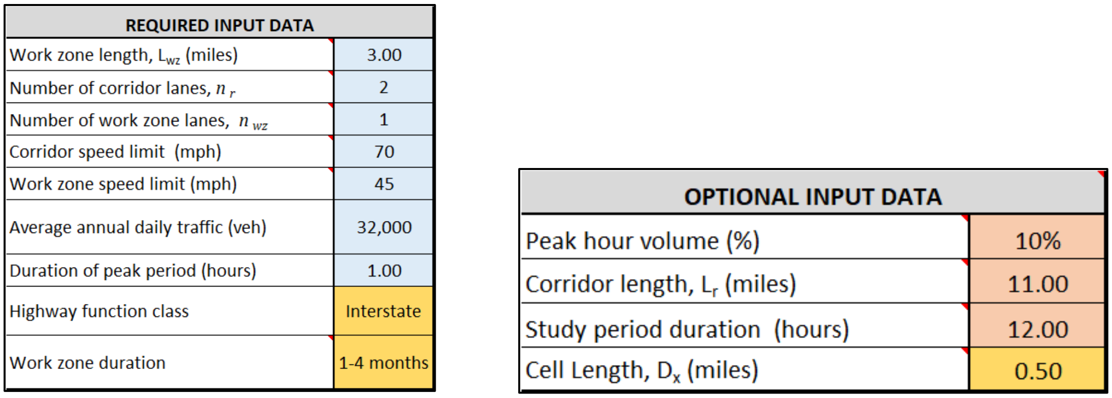


WORK ZONE MOBILITY FACTORS	
Max queue length (miles)	
Average vehicle delay (hours)	
Average vehicle delay (minutes)	
Total delay of all vehicles (hours)	
Queue duration (hours)	
Number of vehicles in max queue (all lanes) (veh)	

Figure 11. Diagram. Quantitative mobility factors scoring.

Input Project Data

The tool was designed to collect a set of required and optional input data, as shown in Figure 12. The required input data needed to calculate work zone traffic delays are work zone length in miles, number of roadway and work zone lanes, corridor and work zone speed limits in mph, average annual daily traffic in vehicles, peak period duration in hours, highway function class, and work zone duration in months, as shown in Figure 12-A. Similarly, the optional input data are peak hour volume in percentage, corridor length in miles, study period duration in hours, and cell length in miles, as shown in Figure 12-B. Note that study period duration in the developed model represents the total simulation time, which ranges from the duration of peak period + 1 hour to 24 hours. Furthermore, cell length represents the length of each discrete road segment in the simulation, which ranges from 0.1 to 0.5 miles.



REQUIRED INPUT DATA	
Work zone length, L_{wz} (miles)	3.00
Number of corridor lanes, n_r	2
Number of work zone lanes, n_{wz}	1
Corridor speed limit (mph)	70
Work zone speed limit (mph)	45
Average annual daily traffic (veh)	32,000
Duration of peak period (hours)	1.00
Highway function class	Interstate
Work zone duration	1-4 months

A. Required input data

OPTIONAL INPUT DATA	
Peak hour volume (%)	10%
Corridor length, L_r (miles)	11.00
Study period duration (hours)	12.00
Cell Length, D_x (miles)	0.50

B. Optional input data

Figure 12. Screenshot. Project specific input data.

Predict Work Zone Traffic Delays

The tool was designed to predict work zone mobility factors based on the project-specific input data. The predicted mobility factors include max queue length in miles, number of vehicles in max queue (all lanes), queue duration in hours, total delay of all vehicles in hours, average vehicle delay in hours, and average vehicle delay in minutes, as shown in Figure 15. These mobility factors were calculated in this tool using a state-of-the-art cell transmission model (CTM) (Ghosh et al., 2015, 2018). CTM is a macroscopic traffic flow model that predicts the progression of traffic conditions along a roadway by discretizing the roadway into segments (cells) whose length is equal to the free-flow travel distance corresponding to a small amount of time (Δt). CTM calculates the number of vehicles in the current cell during the next time step, $n_i(t+\Delta t)$ as equal to the number of vehicles in the current cell at time t, $n_i(t)$ plus the total inflow and minus the total outflow using Figure 13 and Figure 14.

$$n_i(t+\Delta t) = n_i(t) + y_i(t) - y_{i+1}(t)$$

Figure 13. Equation. Number of vehicles in the current cell $\boldsymbol{i}$ at time $(\boldsymbol{t}+\boldsymbol{\Delta t})$.

$$y_i(t) = \begin{cases} R_i(t) & R_i(t) \le (S_{i-1}(t)) \\ S_{i-1}(t) & Otherwise \end{cases}$$

Figure 14. Equation. Number of vehicles transferred from an upstream cell $\boldsymbol{i-1}$ to current cell, $\boldsymbol{i}$.

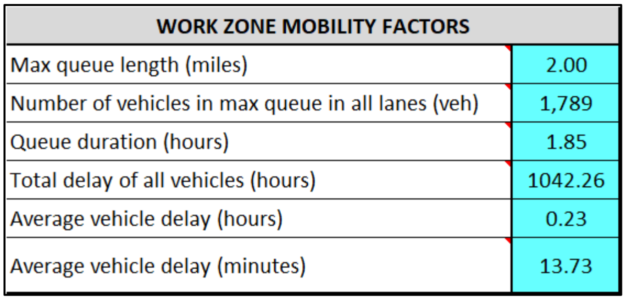
Where

$n_i(t)$: Number of vehicles in the current cell i at time t

$y_i(t)$: Number of vehicles transferred from an upstream cell, i – 1, to the current cell, i

$S_{i-1}(t)$: Number of vehicles that can be sent to cell i by the upstream cell, cell i – 1, during the time interval $[t, t+\Delta t]$, and can exceed neither the number of available vehicles nor the maximum flow rate of that cell

$R_i(t)$: Number of vehicles that can be received by cell i during the time interval $[t, t+\Delta t]$ and governs the equation when the number of vehicles that can be received by cell i is less than the combined number of vehicles to be sent from the upstream cell i – 1



WORK ZONE MOBILITY FACTORS	
Max queue length (miles)	2.00
Number of vehicles in max queue in all lanes (veh)	1,789
Queue duration (hours)	1.85
Total delay of all vehicles (hours)	1042.26
Average vehicle delay (hours)	0.23
Average vehicle delay (minutes)	13.73

Figure 15. Screenshot. Example work zone mobility factors.

The tool was designed to integrate a numerical and visual display of the changing traffic at and before the work zone using a grid of cells, where each cell represents the calculated number of vehicles $n_i(t)$ in cell i at time t using the aforementioned equations. Each cell in the grid represents a specific time and distance from the beginning of the corridor, as shown in Figure 24. Note that the grid of cells in this tool includes two types of cells: roadway corridor cells and work zone cells, which are represented by white and orange background colors, respectively (see Figure 24). The roadway corridor cell and work zone cell can accommodate a maximum number of vehicles N and N_{WZ} based on Figure 16, Figure 17, and Figure 18. For example, the maximum capacity of corridor and work zone cells in the illustrated example in Figure 25 are 136.67 and 13.33, respectively.

$$N = K_{jam} * D_x * NOL$$

Figure 16. Equation. Maximum number of vehicles a roadway cell can accommodate.

$$N_{WZ} = K_{jam} * D_{xwz} * NOWZL$$

Figure 17. Equation. Maximum number of vehicles a work zone cell can accommodate.

$$D_{xwz} = \Delta t * WZSL$$

Figure 18. Equation. Work zone cell length.

Where

N: Maximum number of vehicles a roadway cell can accommodate
N_{WZ}: Maximum number of vehicles a work zone cell can accommodate
K_{jam}: c in vehicle per mile per lane
D_x: Roadway corridor cell length in miles
D_{xwz}: Work zone cell length in miles
NOL : Number of roadway corridor lanes
$NOWZL$: Number of work zone lanes
$WZSL$: Work zone speed limit

The aforementioned grid of traffic cells developed in this tool is then used to calculate all required mobility factors including (1) max queue length in miles, (2) number of vehicles in max queue (all lanes), (3) queue duration in hours, (4) total delay of all vehicles in hours, (5) average vehicle delay in hours, and (6) average vehicle delay in minutes, as shown in Figure 15.

First, the maximum queue length is calculated by analyzing the formation of traffic queues resulting from lane closures in the work zone area. Based on the CTM calculations, a queue starts to form (see Figure 25) when the number of vehicles that can be sent to cell i ($S_{i-1}(t)$) by the upstream cell (i – 1) exceeds the number of vehicles that can be received by cell i, ($R_i(t)$). This indicates that the number of vehicles in cell i ($n_i(t)$) has reached the maximum number allowed for roadway corridor (N) and work zone (N_{WZ}) cells. The queue length is calculated as the distance from start to end of the queue, as shown in Figure 25. These calculated queue lengths at all time increments (t = 0 to T) are then analyzed to determine the maximum queue, as shown in Figure 26.

Second, the number of vehicles in the maximum queue is calculated by summing up the number of vehicles ($n_i(t)$) in all roadway corridor cells, which represent the entire length of the maximum queue, as shown in Figure 26. Third, the queue duration t_q is calculated by determining the queue start time t_{qstart}, which represents the first time t when the number of vehicles that can be sent to cell i ($S_{i-1}(t)$) by the upstream cell (i – 1) exceeds the number of vehicles that can be received by cell i, ($R_i(t)$), as shown in Figure 25. Similarly, the queue end time t_{qend} can be obtained by determining the time *t* when the number of vehicles that can be sent to cell i ($S_{i-1}(t)$) by the upstream cell (i – 1) are less than the number of vehicles that can be received by cell i, ($R_i(t)$), as shown in Figure 27. The queue duration t_q is then calculated by getting the difference between queue end time t_{qend} and queue start time t_{qstart}, as shown in Figure 19.

$$t_q = t_{qend} - t_{qstart}$$

Figure 19. Equation. Queue duration.

Where

t_q: Queue duration in hours

t_{qend}: Queue end time in hours

t_{qstart}: Queue start time in hours

Fourth, the total vehicle delay (*TVD*) is calculated as the difference between total vehicle hours travelled with queues (VHT_Q) and the total vehicle hours travelled without any queues (VHT_{NQ}), as shown in Figure 20. The total vehicle hours travelled with and without queues are calculated by summing up the number of vehicles $n_i(t)$ in all cells in the roadway corridor and work zone and multiplying it by the time increment Δt, as shown in Figure 21. Fifth, average vehicle delay in hours (*AVD*) is calculated as the total vehicle delay (*TVD*) divided by the total number of vehicles experiencing delays (*TNVD*), as shown in Figure 22. Sixth, average vehicle delay in minutes (AVD_m) is calculated as the average vehicle delay in hours (*AVD*) multiplied by 60, as shown in Figure 23 (Ghosh et al., 2015, 2018).

$$TVD = VHT_Q - VHT_{NQ}$$

Figure 20. Equation. Total vehicle delay.

$$VHT = \sum_{i=0}^{CL+WZL} n_i(t) * \Delta t$$

Figure 21. Equation. Total vehicle hours travelled.

$$AVD = \frac{VHT_Q - VHT_{NQ}}{TNVD}$$

Figure 22. Equation. Average vehicle delay in hours.

$$AVD_m = AVD * 60$$

Figure 23. Equation. Average vehicle delay in minutes.

Where

TVD: Total vehicle delay in hours
AVD: Average vehicle delay in hours
AVD_m: Average vehicle delay in minutes
VHT_Q: Total vehicle hours travelled with queue present in hours
VHT_{NQ}: Total vehicle hours travelled without queue present in hours
$TNVD$: Total number of vehicles experiencing delays

An example of the mobility factor calculations is included in Figure 28, which shows that the maximum queue length, the number of vehicles in the maximum queue, and the queue duration were calculated using Figure 28 as 2.00 miles, 1,789 vehicles, and 1.85 hours, respectively. These mobility factors were then used to calculate the total vehicle delay (*TVD*), the average vehicle delay in hours (*AVD*), and the average vehicle delay in minutes (AVD_m) as 2440.17 hours, 0.23 hours, and 13.73 minutes, respectively, using Figure 20, Figure 22, and Figure 23.

It should be noted that the estimated traffic queues and delays in this tool are used to analyze the need for deploying SWZ systems and is not meant to be used as a stand-alone computational tool for work zone performance measures. Accordingly, this tool is not intended to replace other detailed traffic analysis software such as Work Zone Q.

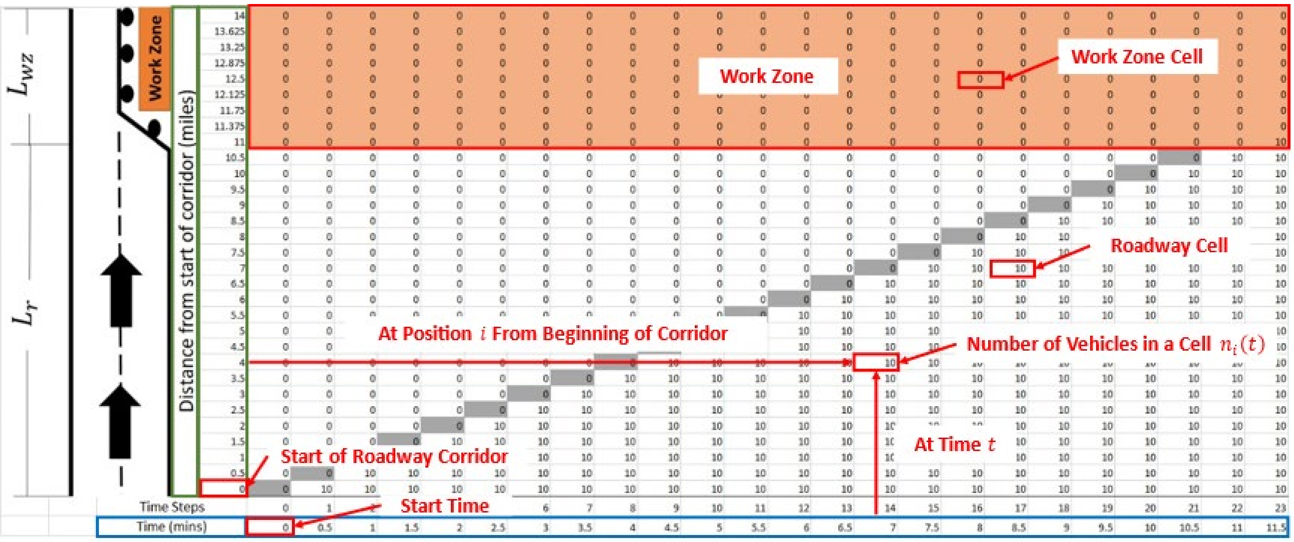


Figure 24. Screenshot. Visual display of start of peak hour.

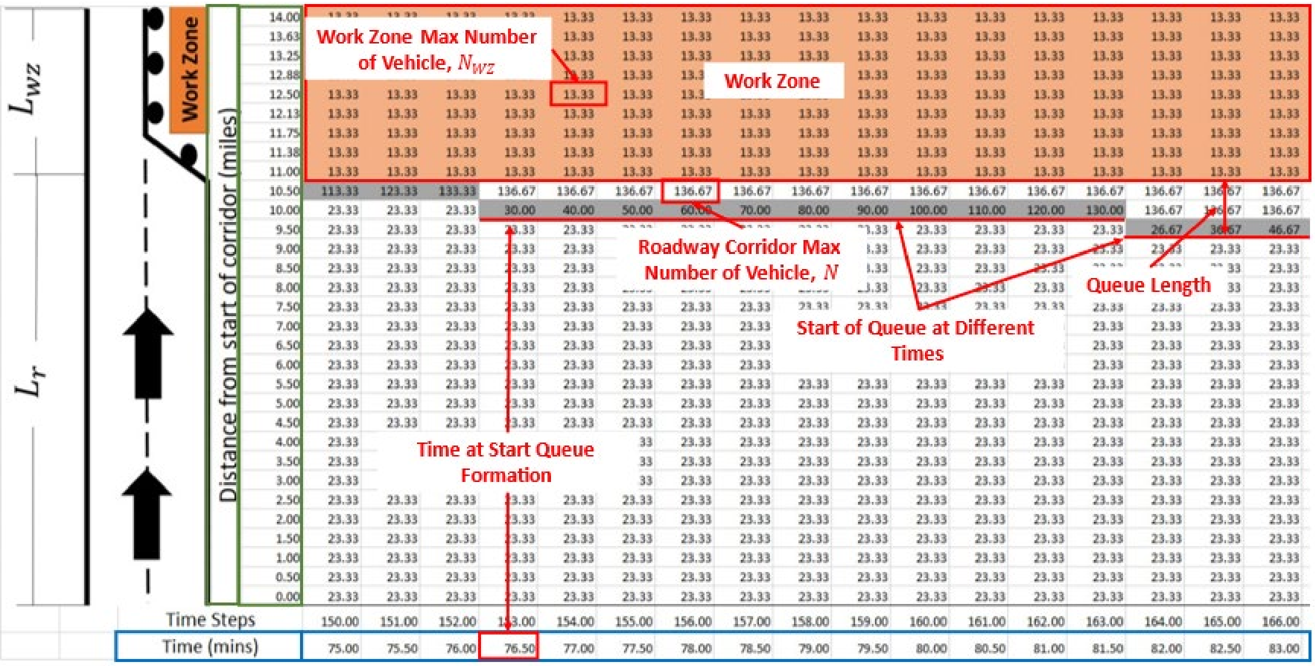
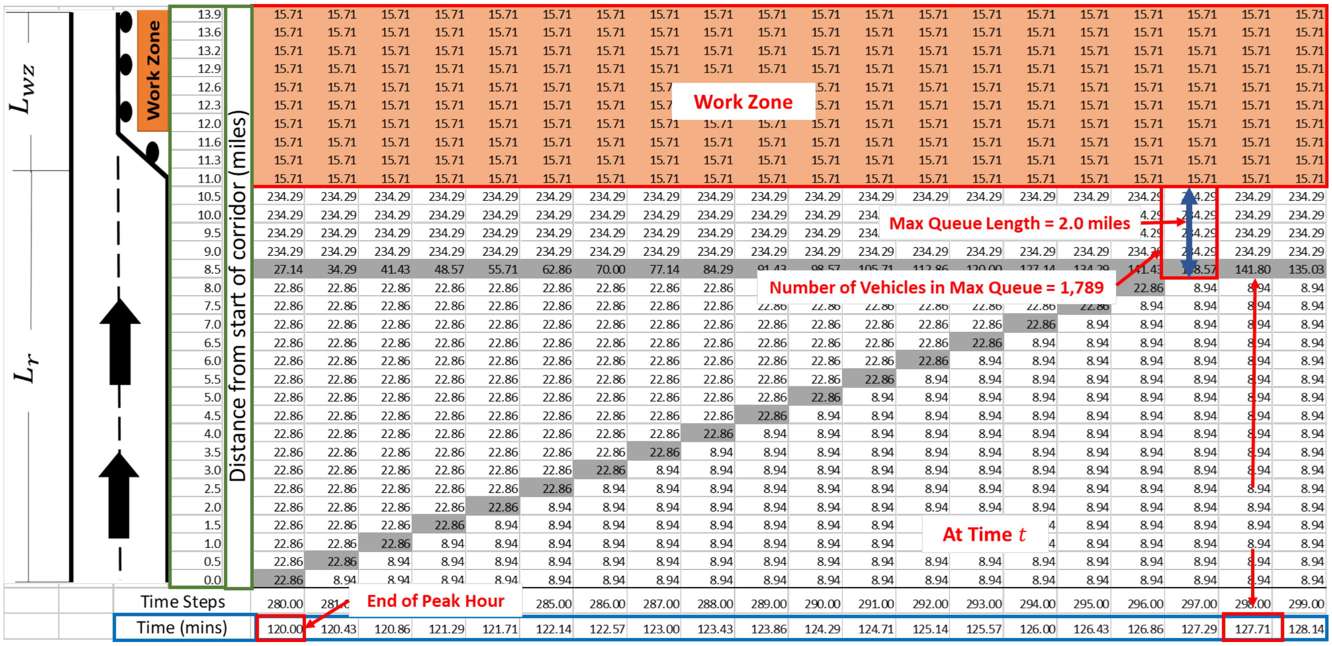


Figure 25. Screenshot. Visual display of queue formation.



13.9	15.71	15.71	15.71	15.71	15.71	15.71	15.71	15.71	15.71	15.71	15.71	15.71	15.71	15.71	15.71	15.71	15.71	15.71	15.71	15.71
13.6	15.71	15.71	15.71	15.71	15.71	15.71	15.71	15.71	15.71	15.71	15.71	15.71	15.71	15.71	15.71	15.71	15.71	15.71	15.71	15.71
13.2	15.71	15.71	15.71	15.71	15.71	15.71	15.71	15.71	15.71	15.71	15.71	15.71	15.71	15.71	15.71	15.71	15.71	15.71	15.71	15.71
12.9	15.71	15.71	15.71	15.71	15.71	15.71	15.71	15.71	15.71	15.71	15.71	15.71	15.71	15.71	15.71	15.71	15.71	15.71	15.71	15.71
12.6	15.71	15.71	15.71	15.71	15.71	15.71	15.71	15.7			5.71	15.71	15.71	15.71	15.71	15.71	15.71	15.71	15.71	15.71
12.3	15.71	15.71	15.71	15.71	15.71	15.71	15.71	15.7			5.71	15.71	15.71	15.71	15.71	15.71	15.71	15.71	15.71	15.71
12.0	15.71	15.71	15.71	15.71	15.71	15.71	15.71	15.71	15.71	15.71	15.71	15.71	15.71	15.71	15.71	15.71	15.71	15.71	15.71	15.71
11.6	15.71	15.71	15.71	15.71	15.71	15.71	15.71	15.71	15.71	15.71	15.71	15.71	15.71	15.71	15.71	15.71	15.71	15.71	15.71	15.71
11.3	15.71	15.71	15.71	15.71	15.71	15.71	15.71	15.71	15.71	15.71	15.71	15.71	15.71	15.71	15.71	15.71	15.71	15.71	15.71	15.71
11.0	15.71	15.71	15.71	15.71	15.71	15.71	15.71	15.71	15.71	15.71	15.71	15.71	15.71	15.71	15.71	15.71	15.71	15.71	15.71	15.71
10.5	234.29	234.29	234.29	234.29	234.29	234.29	234.29	234.29	234.29	234.29	234.29	234.29	234.29	234.29	234.29	234.29	234.29	4.29	234.29	234.29
10.0	234.29	234.29	234.29	234.29	234.29	234.29	234.29	234.29	234.29	234.29	234.29	234.					4.29	2 4.29	234.29	234.29
9.5	234.29	234.29	234.29	234.29	234.29	234.29	234.29	234.29	234.29	234.29	234.29	234.					4.29	2 4.29	234.29	234.29
9.0	234.29	234.29	234.29	234.29	234.29	234.29	234.29	234.29	234.29	234.29	234.29	234.29	234.29	234.29	234.29	234.29	234.2	2 4.29	234.29	234.29
8.5	27.14	34.29	41.43	48.57	55.71	62.86	70.00	77.14	84.29	91.43	98.57	105.71	112.86	120.00	127.14	134.29	141.43	1 8.57	141.80	135.03
8.0	22.86	22.86	22.86	22.86	22.86	22.86	22.86	22.86	22.86								22.86	8.94	8.94	8.94
7.5	22.86	22.86	22.86	22.86	22.86	22.86	22.86	22.86	22.86	22.86	22.86	22.86	22.86	22.86	22.86	22.86	8.94	8.94	8.94	8.94
7.0	22.86	22.86	22.86	22.86	22.86	22.86	22.86	22.86	22.86	22.86	22.86	22.86	22.86	22.86	22.86	8.94	8.94	8.94	8.94	8.94
6.5	22.86	22.86	22.86	22.86	22.86	22.86	22.86	22.86	22.86	22.86	22.86	22.86	22.86	22.86	8.94	8.94	8.94	8.94	8.94	8.94
6.0	22.86	22.86	22.86	22.86	22.86	22.86	22.86	22.86	22.86	22.86	22.86	22.86	22.86	8.94	8.94	8.94	8.94	8.94	8.94	8.94
5.5	22.86	22.86	22.86	22.86	22.86	22.86	22.86	22.86	22.86	22.86	22.86	22.86	8.94	8.94	8.94	8.94	8.94	8.94	8.94	8.94
5.0	22.86	22.86	22.86	22.86	22.86	22.86	22.86	22.86	22.86	22.86	22.86	8.94	8.94	8.94	8.94	8.94	8.94	8.94	8.94	8.94
4.5	22.86	22.86	22.86	22.86	22.86	22.86	22.86	22.86	22.86	22.86	8.94	8.94	8.94	8.94	8.94	8.94	8.94	8.94	8.94	8.94
4.0	22.86	22.86	22.86	22.86	22.86	22.86	22.86	22.86	22.86	8.94	8.94	8.94	8.94	8.94	8.94	8.94	8.94	8.94	8.94	8.94
3.5	22.86	22.86	22.86	22.86	22.86	22.86	22.86	22.86	8.94	8.94	8.94	8.94	8.94	8.94	8.94	8.94	8.94	8.94	8.94	8.94
3.0	22.86	22.86	22.86	22.86	22.86	22.86	22.86	8.94	8.94	8.94	8.94	8.94	8.94	8.94	8.94	8.94	8.94	8.94	8.94	8.94
2.5	22.86	22.86	22.86	22.86	22.86	22.86	8.94	8.94	8.94	8.94	8.94	8.94	8.94	8.94	8.94	8.94	8.94	8.94	8.94	8.94
2.0	22.86	22.86	22.86	22.86	22.86	8.94	8.94	8.94	8.94	8.94	8.94	8.94	8.94	8.94	8.94	8.94	8.94	8.94	8.94	8.94
1.5	22.86	22.86	22.86	22.86	8.94	8.94	8.94	8.94	8.94	8.94	8.94	8.94			4	8.94	8.94	8.94	8.94	8.94
1.0	22.86	22.86	22.86	8.94	8.94	8.94	8.94	8.94	8.94	8.94	8.94	8.94			4	8.94	8.94	8.94	8.94	8.94
0.5	22.86	22.86	8.94	8.94	8.94	8.94	8.94	8.94	8.94	8.94	8.94	8.94	8.94	8.94	8.94	8.94	8.94	8.94	8.94	8.94
0.0	22.86	8.94	8.94	8.94	8.94	8.94	8.94	8.94	8.94	8.94	8.94	8.94	8.94	8.94	8.94	8.94	8.94	8.94	8.94	8.94
Time Steps	280.00	281.				285.00	286.00	287.00	288.00	289.00	290.00	291.00	292.00	293.00	294.00	295.00	296.00	297.00	298.00	299.00
Time (mins)	120.00	120.43	120.86	121.29	121.71	122.14	122.57	123.00	123.43	123.86	124.29	124.71	125.14	125.57	126.00	126.43	126.86	127.29	127.71	128.14

Work Zone

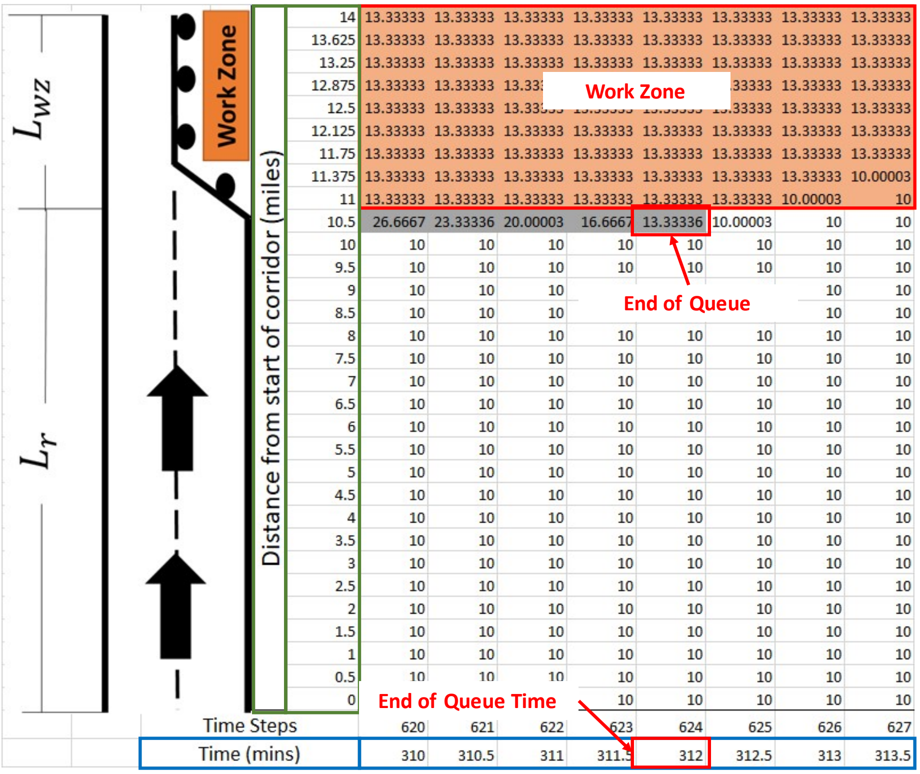
Max Queue Length = 2.0 miles

Number of Vehicles in Max Queue = 1,789

At Time *t*

End of Peak Hour

Figure 26. Screenshot. Visual display of max queue length and max number of vehicles.



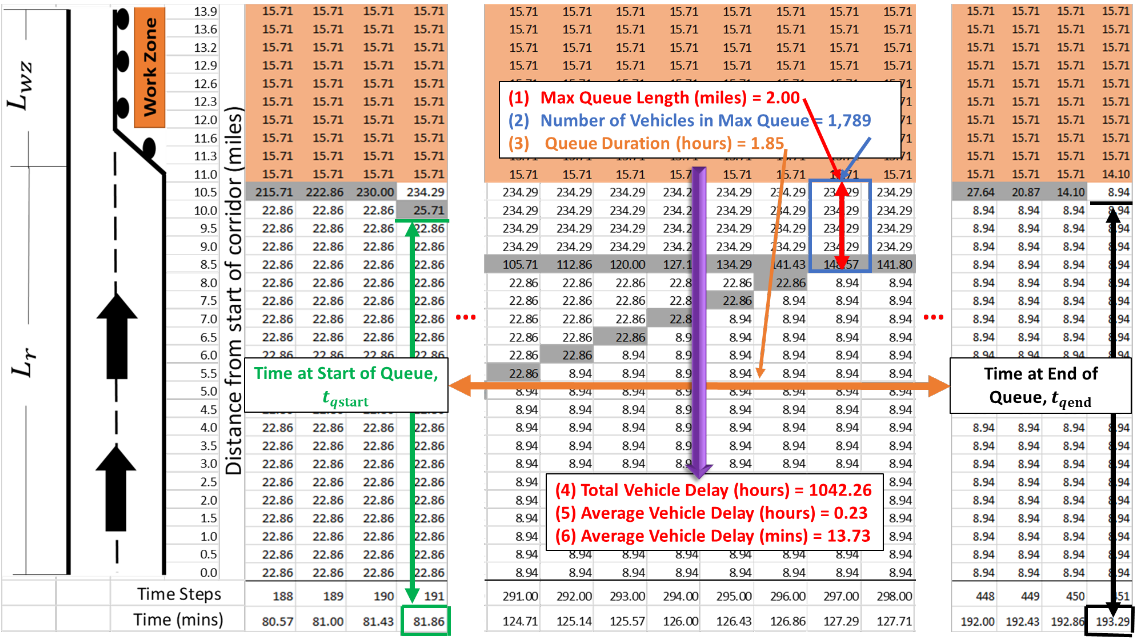
14	13.33333	13.33333	13.33333	13.33333	13.33333	13.33333	13.33333	13.33333
13.625	13.33333	13.33333	13.33333	13.33333	13.33333	13.33333	13.33333	13.33333
13.25	13.33333	13.33333	13.33333	13.33333	13.33333	13.33333	13.33333	13.33333
12.875	13.33333	13.33333	13.333			.33333	13.33333	13.33333
12.5	13.33333	13.33333	13.33333	13.33333	13.33333	13.33333	13.33333	13.33333
12.125	13.33333	13.33333	13.33333	13.33333	13.33333	13.33333	13.33333	13.33333
11.75	13.33333	13.33333	13.33333	13.33333	13.33333	13.33333	13.33333	13.33333
11.375	13.33333	13.33333	13.33333	13.33333	13.33333	13.33333	13.33333	10.00003
11	13.33333	13.33333	13.33333	13.33333	13.33333	13.33333	10.00003	10
10.5	26.6667	23.33336	20.00003	16.6667	13.33336	10.00003	10	10
10	10	10	10	10	10	10	10	10
9.5	10	10	10	10	10	10	10	10
9	10	10	10				10	10
8.5	10	10	10				10	10
8	10	10	10	10	10	10	10	10
7.5	10	10	10	10	10	10	10	10
7	10	10	10	10	10	10	10	10
6.5	10	10	10	10	10	10	10	10
6	10	10	10	10	10	10	10	10
5.5	10	10	10	10	10	10	10	10
5	10	10	10	10	10	10	10	10
4.5	10	10	10	10	10	10	10	10
4	10	10	10	10	10	10	10	10
3.5	10	10	10	10	10	10	10	10
3	10	10	10	10	10	10	10	10
2.5	10	10	10	10	10	10	10	10
2	10	10	10	10	10	10	10	10
1.5	10	10	10	10	10	10	10	10
1	10	10	10	10	10	10	10	10
0.5	10	10	10	10	10	10	10	10
0				10	10	10	10	10
Time Steps	620	621	622	623	624	625	626	627
Time (mins)	310	310.5	311	311.5	312	312.5	313	313.5

Work Zone

End of Queue

End of Queue Time

Figure 27. Screenshot. Visual display of end of queue.



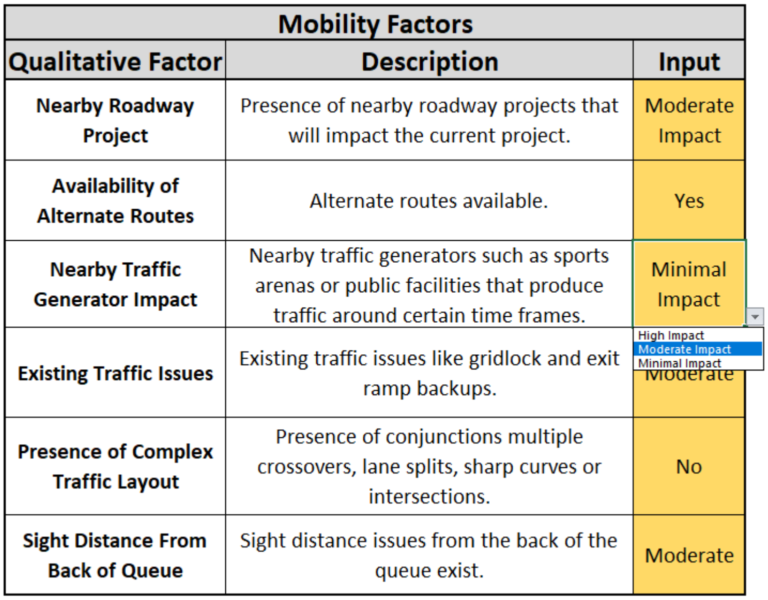
(1) Max Queue Length (miles) = 2.00
(2) Number of Vehicles in Max Queue = 1,789
(3) Queue Duration (hours) = 1.85

(4) Total Vehicle Delay (hours) = 1042.26
(5) Average Vehicle Delay (hours) = 0.23
(6) Average Vehicle Delay (mins) = 13.73

Figure 28. Screenshot. Visual display of quantitative work zone factors.

Specifying Work Zone Qualitative Mobility Factors

In addition to the quantitative mobility factors, the tool was designed to integrate a set of qualitative factors affecting work zone mobility that were identified in the first phase and listed in Table 38. For each qualitative factor, the tool was designed to enable DOT planners to select from a set of categories using dropdown lists based on work zone conditions. For example, the duration of the work zone is divided into four categories: < 1 month, 1 to 4 months, 5 to 10 months, and > 1 year, as shown in Figure 29.



Mobility Factors		
Qualitative Factor	**Description**	**Input**
Nearby Roadway Project	Presence of nearby roadway projects that will impact the current project.	Moderate Impact
Availability of Alternate Routes	Alternate routes available.	Yes
Nearby Traffic Generator Impact	Nearby traffic generators such as sports arenas or public facilities that produce traffic around certain time frames.	Minimal Impact
Existing Traffic Issues	Existing traffic issues like gridlock and exit ramp backups.	Moderate
Presence of Complex Traffic Layout	Presence of conjunctions multiple crossovers, lane splits, sharp curves or intersections.	No
Sight Distance From Back of Queue	Sight distance issues from the back of the queue exist.	Moderate

Figure 29. Screenshot. Work zone qualitative mobility factors.

Overall Mobility Score for SWZ Systems

The tool was designed to calculate an overall mobility score for each SWZ system that represents the need for deploying that system in the analyzed work zone. The calculated mobility score ranges from 0 to 100 points. For each SWZ system, the mobility score was calculated based on a newly developed scoring criteria that combine the impact of work zone quantitative and qualitative mobility factors as shown in Figure 30 for QWS. For each SWZ system, a new list of scoring criteria was developed in three main steps that were designed to (1) identify all work zone quantitative and qualitative mobility factors, (2) rank all identified mobility factors based on their relative importance, and (3) distribute the maximum 100 scoring points of each SWZ system among its identified mobility factors.

For example, the first step of developing the scoring criteria for the QWS system focused on identifying a complete list of quantitative and qualitative mobility factors that affect the need for deploying the QWS in work zones, as shown in Figure 30. This list of QWS mobility factors were identified based on a review of existing FHWA and state tools as well as related survey findings, as shown in Table 40 and Table 41. Existing FWHA and state DOT tools used in identifying the list of quantitative and qualitative mobility factors were the *FHWA Work Zone ITS Implementation Guide* (FHWA, 2014), Massachusetts DOT Scoring Criteria for Work Zone ITS (MassDOT, 2016) and Texas DOT Go/No-Go Decision Tool (TxDOT, 2018).

Table 1. Identified Quantitative Mobility Factors Based of Literature Review and Survey Findings

Quantitative Mobility Factors	FHWA	TxDOT	MassDot	ADOT	Survey	Identified Factors
Queue Length	●	●		●	●	●
Queue Duration	●		●	●	●	●
Average Delay	●		●	●	●	●

Table 2. Identified Qualitative Mobility Factors Based of Literature Review and Survey Findings

Qualitative Mobility Factors	FHWA	TxDOT	MassDot	ADOT	Survey	Identified Factors
Duration of the Work Zone	●		●	●	●	●
Highway Function Class					●	●
Availability of Alternate Routes	●	●	●	●		●
Nearby Traffic Generator Impact	●	●	●	●		●
Existing Traffic Issues	●	●	●	●	●	●
Presence of Complex Traffic Layout		●	●			●
Sight Distance from Back of Queue	●	●		●		●

The second step of developing the QWS scoring criteria focused on ranking its identified three quantitative and seven qualitative factors based on their reported relative importance by existing FHWA and state DOT tools and related survey findings, as shown in Table 42 and Table 43. The third step of developing the QWS scoring criteria distributed the 100 scoring points among all its identified work zone factors based on their rankings while assigning a collective higher weight (70%) for all quantitative factors while distributing the remaining weight (30%) among all qualitative factors, as shown in Table 44. A similar methodology was used to develop individual scoring criteria for the remaining SWZ systems: DLMS, VSA, TTIS, TIDS, CTEDS, as shown in Figure 31, Figure 32, Figure 33, Figure 34, and Figure 35.

Table 3. Ranking of QWS Quantitative Mobility Factors

	FHWA	FHWA	FHWA	TxDOT	TxDOT	TxDOT	MassDot	MassDot	MassDot	ADOT	ADOT	ADOT	Survey Findings
Factor	Max Score	Weight*	Rank	Max Score	Weight*	Rank	Max Score	Weight*	Rank	Max Score	Weight*	Rank	Rank
Queue Length	10	13.2%	1	130	52.2%	1				10	13.2%	1	1
Queue Duration	10	13.2%	1				10	28.6%	1	10	13.2%	1	1
Average Delay	10	13.2%	1				10	28.6%	1	10	13.2%	1	2

* Weight is calculated as a percentage of the maximum total score.

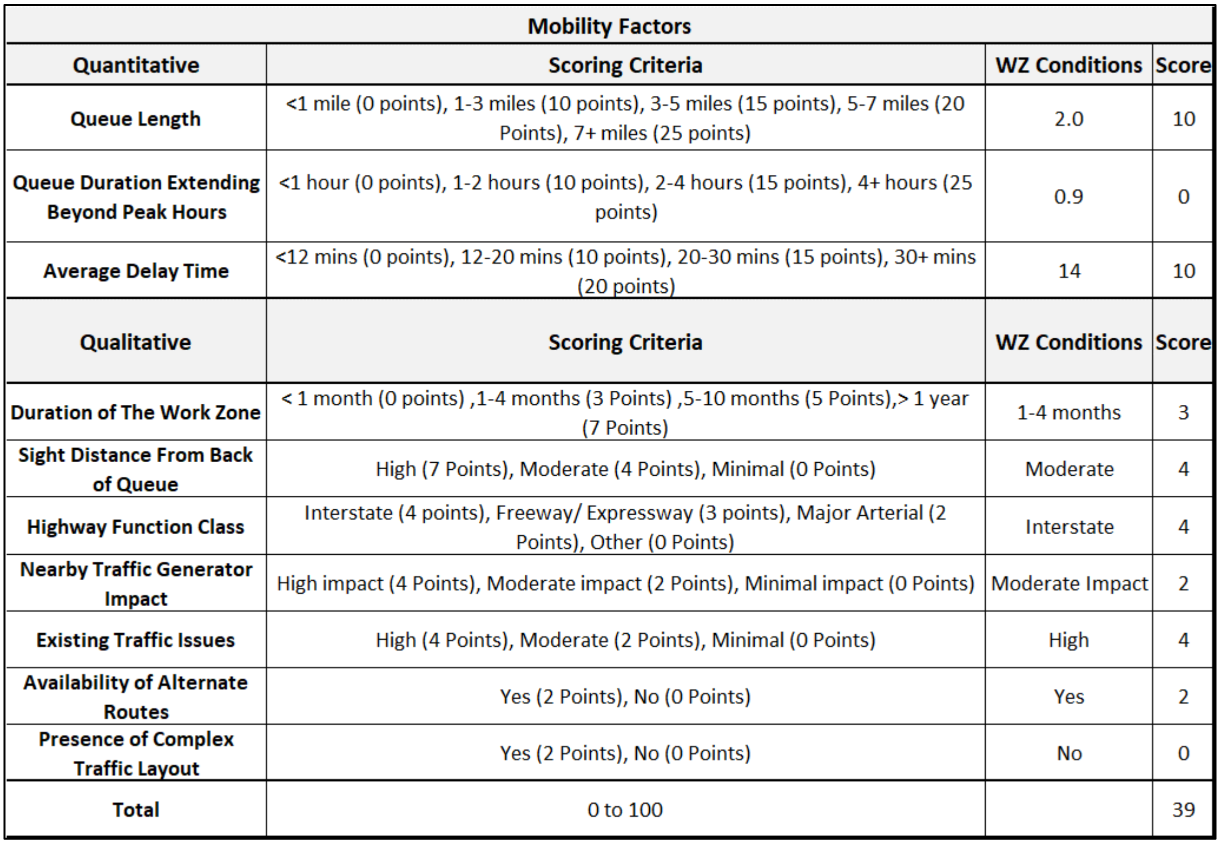
Table 4. Ranking of QWS Qualitative Mobility Factors

	FHWA	FHWA	FHWA	TxDOT	TxDOT	TxDOT	MassDot	MassDot	MassDot	ADOT	ADOT	ADOT	Survey Findings
Factor	Max Score	Weight*	Rank	Max Score	Weight*	Rank	Max Score	Weight*	Rank	Max Score	Weight*	Rank	Rank
Duration of the Work Zone	10	13.2%	1				8	22.9%	1.0	10	13.2%	1	3
Highway Function Class				50	20.1%	1							1
Availability of Alternate Routes	3	3.9%	2	3	1.2%	1	4	11.4%	2.0	3	3.9%	2	
Nearby Traffic Generator Impact	3	3.9%	2	20	8.0%	3	1	2.9%	3.0	3	3.9%	2	
Existing Traffic Issues	10	13.2%	1	30	12.0%	2	1	2.9%	3.0	10	13.2%	1	2
Presence of Complex Traffic Layout	3	3.9%	2	3	1.2%	1	1	2.9%	3.0	3	3.9%	2	
Sight Distance from Back of Queue	3	3.9%	2	30	12.0%	2				3	3.9%	2	
Duration of the Work Zone	10	13.2%	1				8	22.9%	1.0	10	13.2%	1	3

Table 5. QWS Mobility Factors Ranking and Scoring Criteria

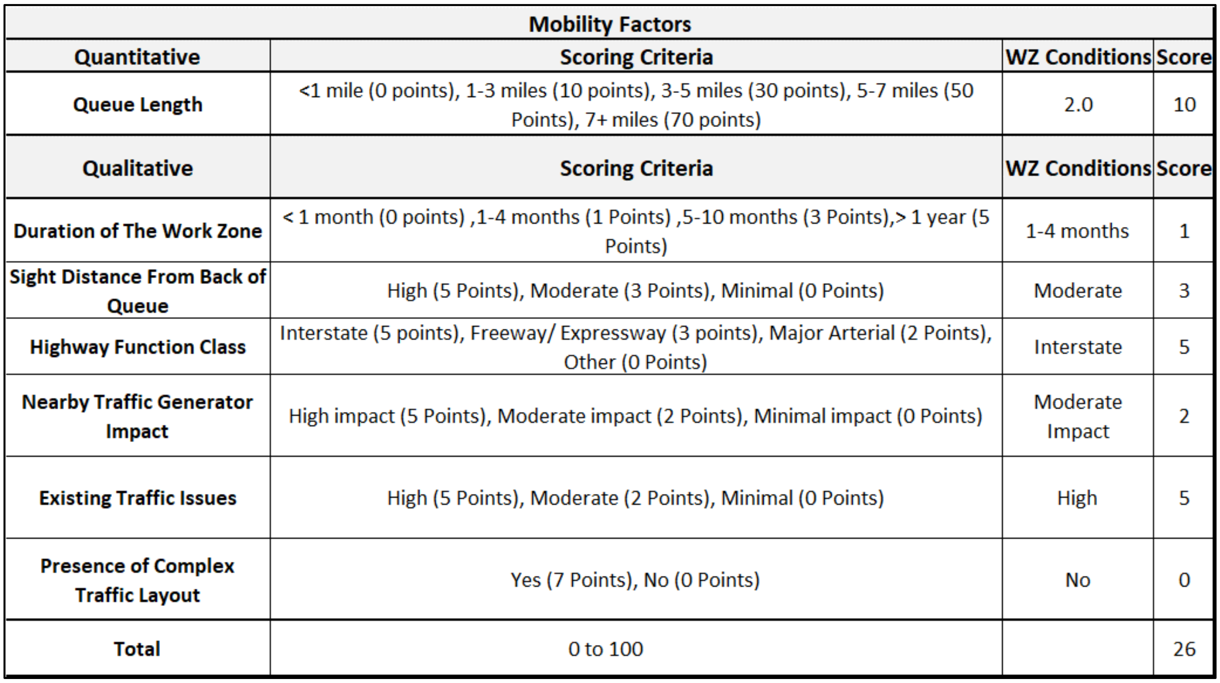
Quantitative Factors	Rank	Maximum Score
Queue Length	1	25
Queue Duration	1	25
Average Delay	2	20
Total	–	70
Qualitative Factors	**Rank**	**Maximum Score**
Duration of the Work Zone	1	7
Sight Distance from Back of Queue	1	7
Highway Function Class	2	4
Nearby Traffic Generator Impact	2	4
Existing Traffic Issues	2	4
Availability of Alternate Routes	3	2
Presence of Complex Traffic Layout	3	2
Total	–	30

For each SWZ system, the developed tool was then used to calculate an individual mobility score for each identified mobility factor based on its assigned criteria points and its related work zone conditions. For example, the QWS mobility score for the queue length factor was calculated by the tool as 20 points based on its predetermined scoring criteria and its estimated queue length of 5 miles, which was calculated using the earlier described CTM in the Predicting Work Zone Traffic Delay section, as shown in Figure 30. Note that the mobility score of each factor is automatically calculated by the developed tool based on the user-input data. The calculated mobility scores of individual quantitative and qualitative factors are then summed up to identify the overall mobility score of each SWZ system. For example, the calculated overall mobility score for the deployment of QWS in an example work zone was 39, as shown in Figure 30.



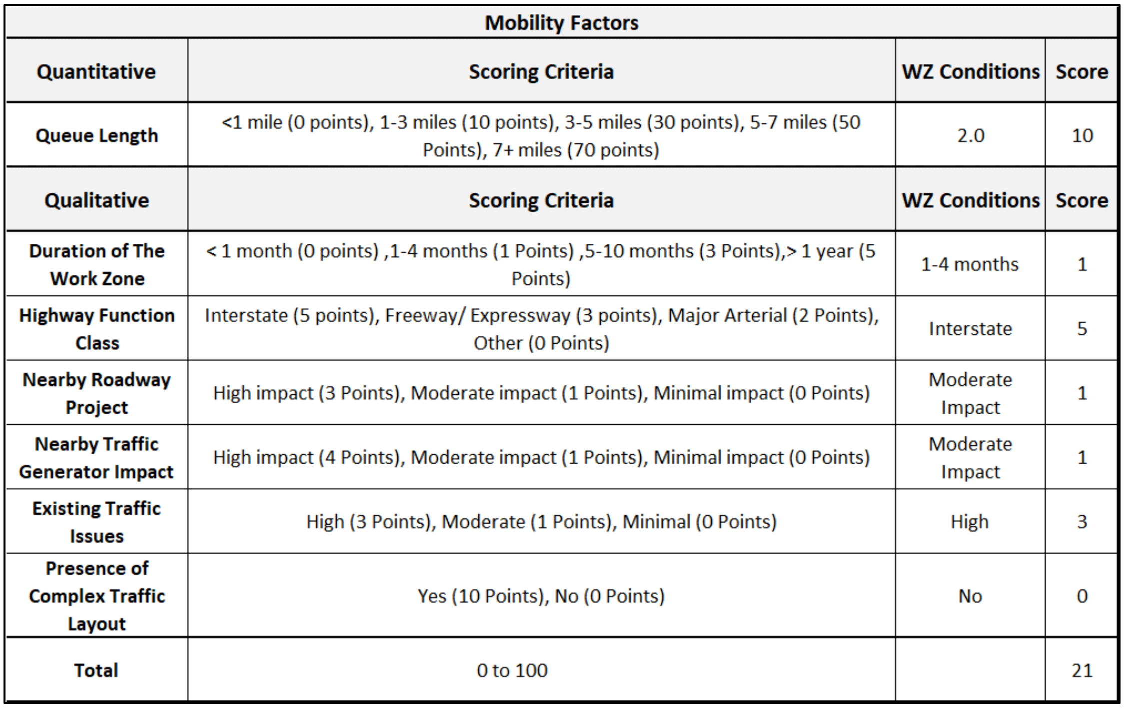
Mobility Factors			
Quantitative	**Scoring Criteria**	**WZ Conditions**	**Score**
Queue Length	<1 mile (0 points), 1-3 miles (10 points), 3-5 miles (15 points), 5-7 miles (20 Points), 7+ miles (25 points)	2.0	10
Queue Duration Extending Beyond Peak Hours	<1 hour (0 points), 1-2 hours (10 points), 2-4 hours (15 points), 4+ hours (25 points)	0.9	0
Average Delay Time	<12 mins (0 points), 12-20 mins (10 points), 20-30 mins (15 points), 30+ mins (20 points)	14	10
Qualitative	**Scoring Criteria**	**WZ Conditions**	**Score**
Duration of The Work Zone	< 1 month (0 points) ,1-4 months (3 Points) ,5-10 months (5 Points),> 1 year (7 Points)	1-4 months	3
Sight Distance From Back of Queue	High (7 Points), Moderate (4 Points), Minimal (0 Points)	Moderate	4
Highway Function Class	Interstate (4 points), Freeway/ Expressway (3 points), Major Arterial (2 Points), Other (0 Points)	Interstate	4
Nearby Traffic Generator Impact	High impact (4 Points), Moderate impact (2 Points), Minimal impact (0 Points)	Moderate Impact	2
Existing Traffic Issues	High (4 Points), Moderate (2 Points), Minimal (0 Points)	High	4
Availability of Alternate Routes	Yes (2 Points), No (0 Points)	Yes	2
Presence of Complex Traffic Layout	Yes (2 Points), No (0 Points)	No	0
Total	0 to 100		39

Figure 30. Screenshot. QWS mobility scores.



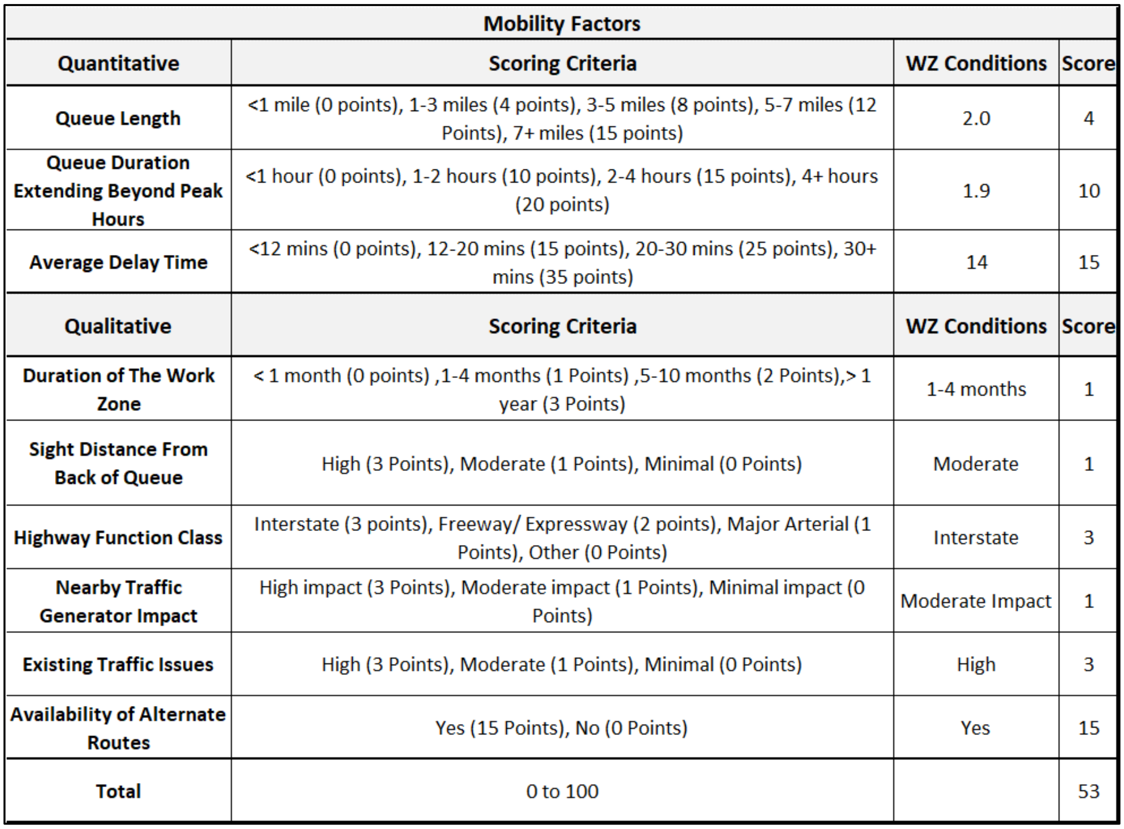
Mobility Factors			
Quantitative	**Scoring Criteria**	**WZ Conditions**	**Score**
Queue Length	<1 mile (0 points), 1-3 miles (10 points), 3-5 miles (30 points), 5-7 miles (50 Points), 7+ miles (70 points)	2.0	10
Qualitative	**Scoring Criteria**	**WZ Conditions**	**Score**
Duration of The Work Zone	< 1 month (0 points) ,1-4 months (1 Points) ,5-10 months (3 Points),> 1 year (5 Points)	1-4 months	1
Sight Distance From Back of Queue	High (5 Points), Moderate (3 Points), Minimal (0 Points)	Moderate	3
Highway Function Class	Interstate (5 points), Freeway/ Expressway (3 points), Major Arterial (2 Points), Other (0 Points)	Interstate	5
Nearby Traffic Generator Impact	High impact (5 Points), Moderate impact (2 Points), Minimal impact (0 Points)	Moderate Impact	2
Existing Traffic Issues	High (5 Points), Moderate (2 Points), Minimal (0 Points)	High	5
Presence of Complex Traffic Layout	Yes (7 Points), No (0 Points)	No	0
Total	0 to 100		26

Figure 31. Screenshot. DLMS mobility scores.



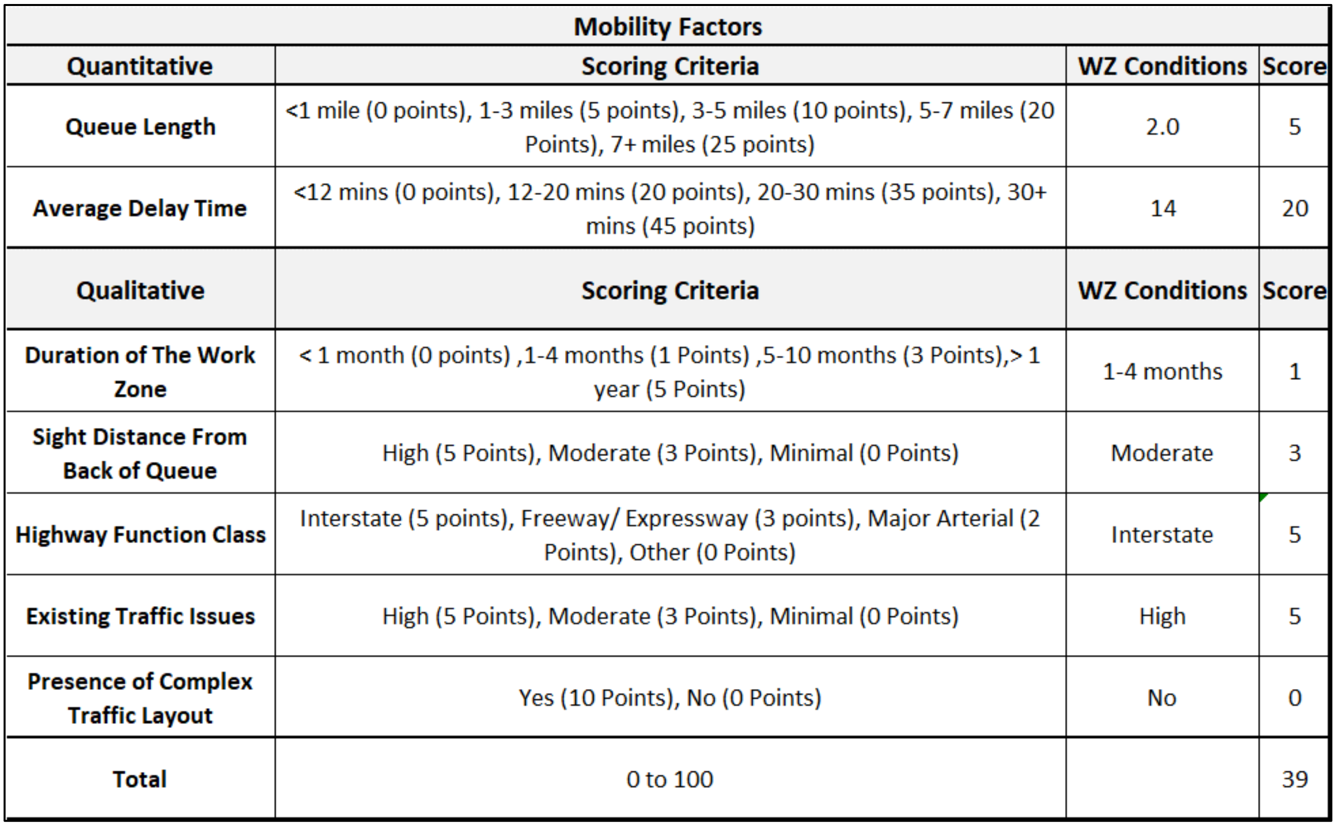
Mobility Factors			
Quantitative	**Scoring Criteria**	**WZ Conditions**	**Score**
Queue Length	<1 mile (0 points), 1-3 miles (10 points), 3-5 miles (30 points), 5-7 miles (50 Points), 7+ miles (70 points)	2.0	10
Qualitative	**Scoring Criteria**	**WZ Conditions**	**Score**
Duration of The Work Zone	< 1 month (0 points) ,1-4 months (1 Points) ,5-10 months (3 Points),> 1 year (5 Points)	1-4 months	1
Highway Function Class	Interstate (5 points), Freeway/ Expressway (3 points), Major Arterial (2 Points), Other (0 Points)	Interstate	5
Nearby Roadway Project	High impact (3 Points), Moderate impact (1 Points), Minimal impact (0 Points)	Moderate Impact	1
Nearby Traffic Generator Impact	High impact (4 Points), Moderate impact (1 Points), Minimal impact (0 Points)	Moderate Impact	1
Existing Traffic Issues	High (3 Points), Moderate (1 Points), Minimal (0 Points)	High	3
Presence of Complex Traffic Layout	Yes (10 Points), No (0 Points)	No	0
Total	0 to 100		21

Figure 32. Screenshot. VSA mobility scores.



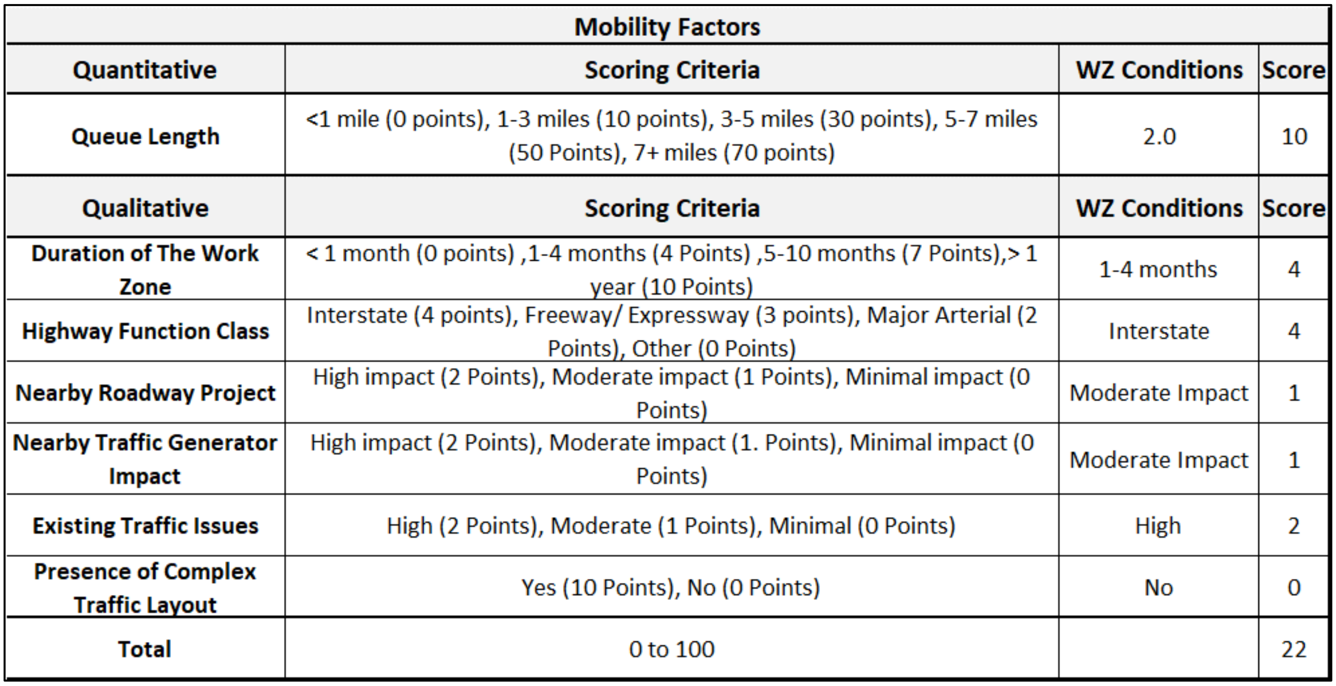
Mobility Factors			
Quantitative	**Scoring Criteria**	**WZ Conditions**	**Score**
Queue Length	<1 mile (0 points), 1-3 miles (4 points), 3-5 miles (8 points), 5-7 miles (12 Points), 7+ miles (15 points)	2.0	4
Queue Duration Extending Beyond Peak Hours	<1 hour (0 points), 1-2 hours (10 points), 2-4 hours (15 points), 4+ hours (20 points)	1.9	10
Average Delay Time	<12 mins (0 points), 12-20 mins (15 points), 20-30 mins (25 points), 30+ mins (35 points)	14	15
Qualitative	**Scoring Criteria**	**WZ Conditions**	**Score**
Duration of The Work Zone	< 1 month (0 points) ,1-4 months (1 Points) ,5-10 months (2 Points),> 1 year (3 Points)	1-4 months	1
Sight Distance From Back of Queue	High (3 Points), Moderate (1 Points), Minimal (0 Points)	Moderate	1
Highway Function Class	Interstate (3 points), Freeway/ Expressway (2 points), Major Arterial (1 Points), Other (0 Points)	Interstate	3
Nearby Traffic Generator Impact	High impact (3 Points), Moderate impact (1 Points), Minimal impact (0 Points)	Moderate Impact	1
Existing Traffic Issues	High (3 Points), Moderate (1 Points), Minimal (0 Points)	High	3
Availability of Alternate Routes	Yes (15 Points), No (0 Points)	Yes	15
Total	0 to 100		53

Figure 33. Screenshot. TTIS mobility scores.



Mobility Factors			
Quantitative	**Scoring Criteria**	**WZ Conditions**	**Score**
Queue Length	<1 mile (0 points), 1-3 miles (5 points), 3-5 miles (10 points), 5-7 miles (20 Points), 7+ miles (25 points)	2.0	5
Average Delay Time	<12 mins (0 points), 12-20 mins (20 points), 20-30 mins (35 points), 30+ mins (45 points)	14	20
Qualitative	**Scoring Criteria**	**WZ Conditions**	**Score**
Duration of The Work Zone	< 1 month (0 points) ,1-4 months (1 Points) ,5-10 months (3 Points),> 1 year (5 Points)	1-4 months	1
Sight Distance From Back of Queue	High (5 Points), Moderate (3 Points), Minimal (0 Points)	Moderate	3
Highway Function Class	Interstate (5 points), Freeway/ Expressway (3 points), Major Arterial (2 Points), Other (0 Points)	Interstate	5
Existing Traffic Issues	High (5 Points), Moderate (3 Points), Minimal (0 Points)	High	5
Presence of Complex Traffic Layout	Yes (10 Points), No (0 Points)	No	0
Total	0 to 100		39

Figure 34. Screenshot. TIDS mobility scores.



Mobility Factors			
Quantitative	**Scoring Criteria**	**WZ Conditions**	**Score**
Queue Length	<1 mile (0 points), 1-3 miles (10 points), 3-5 miles (30 points), 5-7 miles (50 Points), 7+ miles (70 points)	2.0	10
Qualitative	**Scoring Criteria**	**WZ Conditions**	**Score**
Duration of The Work Zone	< 1 month (0 points) ,1-4 months (4 Points) ,5-10 months (7 Points),> 1 year (10 Points)	1-4 months	4
Highway Function Class	Interstate (4 points), Freeway/ Expressway (3 points), Major Arterial (2 Points), Other (0 Points)	Interstate	4
Nearby Roadway Project	High impact (2 Points), Moderate impact (1 Points), Minimal impact (0 Points)	Moderate Impact	1
Nearby Traffic Generator Impact	High impact (2 Points), Moderate impact (1. Points), Minimal impact (0 Points)	Moderate Impact	1
Existing Traffic Issues	High (2 Points), Moderate (1 Points), Minimal (0 Points)	High	2
Presence of Complex Traffic Layout	Yes (10 Points), No (0 Points)	No	0
Total	0 to 100		22

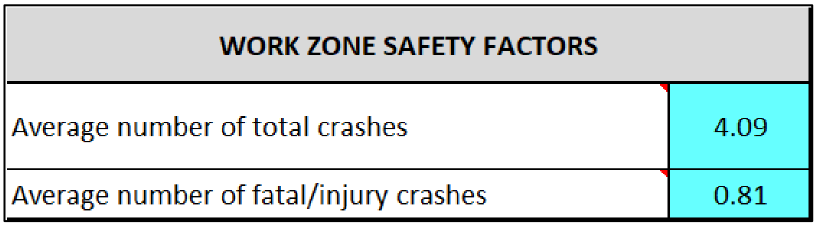
Figure 35. Screenshot. CTEDS mobility scores.

WORK ZONE SAFETY NEEDS FOR SWZ SYSTEMS

This phase was designed to assess the safety needs for each SWZ system based on quantitative and qualitative work zone factors. This assessment was performed in three steps that are described in the following sections.

Predicting Impact of Work Zone Quantitative Safety Factors on Crashes

The developed tool was designed to integrate analytical models that provide the capability of predicting work zone crashes based on project-specific input data. These work zone crashes include average number of total work zone crashes (fatal; A-, B- and C-injury crashes; and property damage only crashes) and average number of fatal/injury crashes (fatal, A-, B- and C-injury crashes), as shown in Figure 36. These work zone crashes were calculated in this tool using work-zone safety performance functions (SPFs) and crash modification factors (CMFs) that were developed in other IDOT research projects (Tegge et al., 2010; Schattler et al., 2020).



WORK ZONE SAFETY FACTORS	
Average number of total crashes	4.09
Average number of fatal/injury crashes	0.81

Figure 36. Screenshot. Work zone safety factors.

First, the average number of total work zone crashes (μ_{Total}) is calculated based on the work zone duration (*D*), work zone length (*WZL*), average annual daily traffic (*AADT*), corridor speed limit (*CSL*), and work zone speed limit (*WZSL*), as shown in Figure 37. The AADT is calculated by summing up the user-specified peak-hour traffic and the off-peak hour traffic in the roadway corridor, as shown in Figure 38. Second, the average number of fatal/injury crashes work zone crashes ($\mu_{Fatal/Injury}$) is calculated based on the work zone duration (*D*), work zone length (*WZL*), corridor speed limit (*CSL*), and work zone speed limit (*WZSL*), as shown in Figure 39.

$$\mu_{Total} = e^{-7.049} * D^{0.904} * WZL^{0.317} * AADT^{0.486} * e^{-0.0004(CSL*WZSL)}$$

Figure 37. Equation. Average number of total work zone crashes.

$$AADT = (PF * NOL * PD) + \big(OPF * NOL * (24 - PD)\big)$$

Figure 38. Equation. Annual average daily traffic.

$$\mu_{Fatal/Injury} = e^{-2.872} * D^{0.812} * WZL^{0.323} * e^{-0.0005(CSL*WZSL)}$$

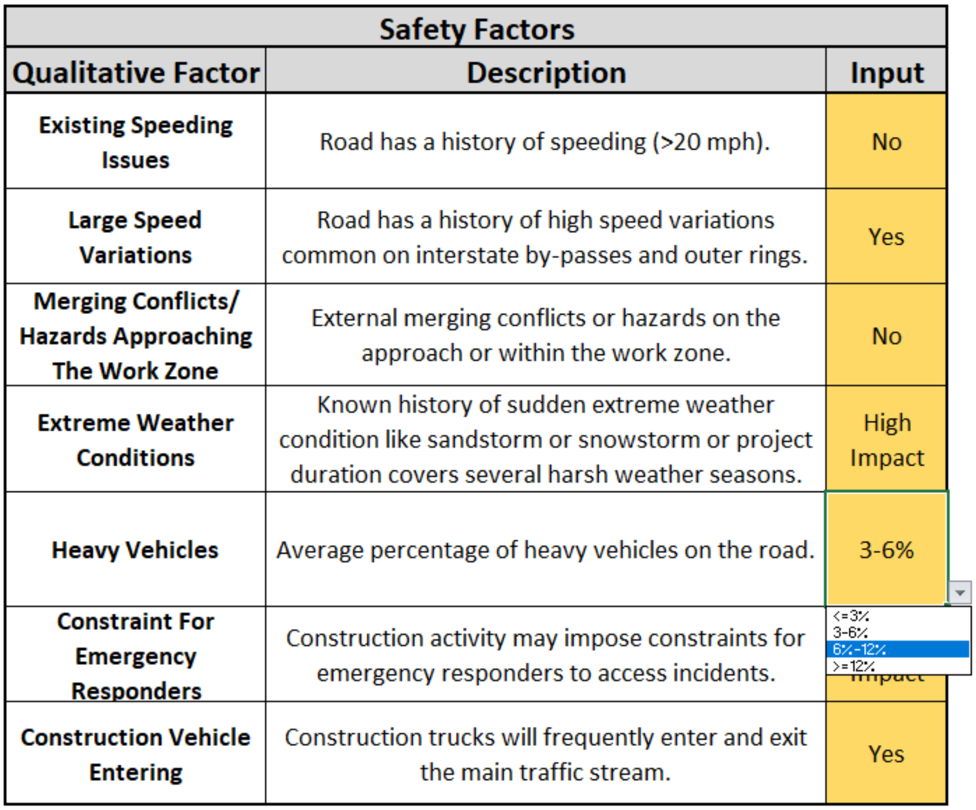
Figure 39. Equation. Average number of fatal/injury crashes.

Where

μ_{Total}: Average number of total work zone crashes
$\mu_{Fatal/Injury}$: Average number of fatal/injury crashes work zone crashes
D: Work zone duration, in days
WZL: Work zone length, in miles
AADT: Annual average daily traffic, in vehicles per day (VPD)
CSL: Corridor speed limit, in mph
WZSL: Work zone speed limit, in mph
PF: Peak-hour traffic flow, in VPHPL
NOL: Number of lanes
PD: Peak duration, in hours
OPF: Off-peak traffic flow, in VPHPL

Impact of Qualitative Factors

In addition to the aforementioned analysis of quantitative safety factors, the tool was designed to integrate a set of qualitative factors affecting work zone safety that were identified in the first phase of the model development and listed in Table 39. For each qualitative factor, the tool was designed to enable DOT planners to select from a set of categories using dropdown lists based on work zone conditions. For example, the impact of extreme weather conditions is divided into three categories: high impact, moderate impact, and minimal impact, as shown in Figure 40.

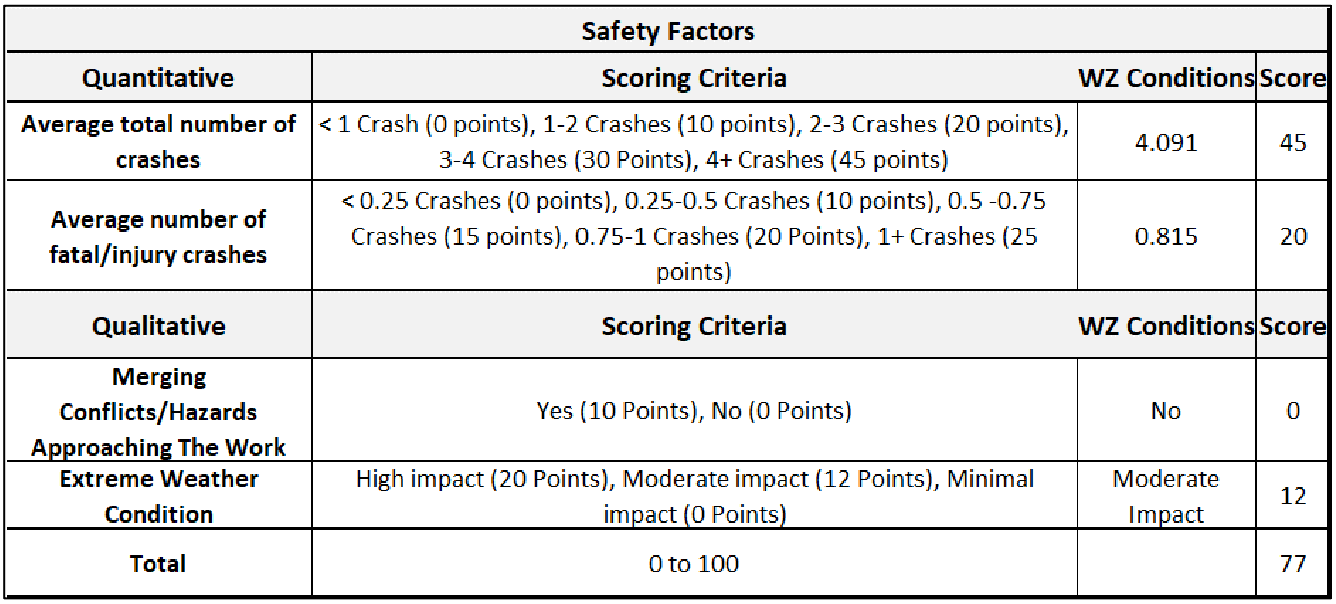


Safety Factors		
Qualitative Factor	**Description**	**Input**
Existing Speeding Issues	Road has a history of speeding (>20 mph).	No
Large Speed Variations	Road has a history of high speed variations common on interstate by-passes and outer rings.	Yes
Merging Conflicts/ Hazards Approaching The Work Zone	External merging conflicts or hazards on the approach or within the work zone.	No
Extreme Weather Conditions	Known history of sudden extreme weather condition like sandstorm or snowstorm or project duration covers several harsh weather seasons.	High Impact
Heavy Vehicles	Average percentage of heavy vehicles on the road.	3-6%
Constraint For Emergency Responders	Construction activity may impose constraints for emergency responders to access incidents.	Impact
Construction Vehicle Entering	Construction trucks will frequently enter and exit the main traffic stream.	Yes

Figure 40. Screenshot. Work zone qualitative safety factors.

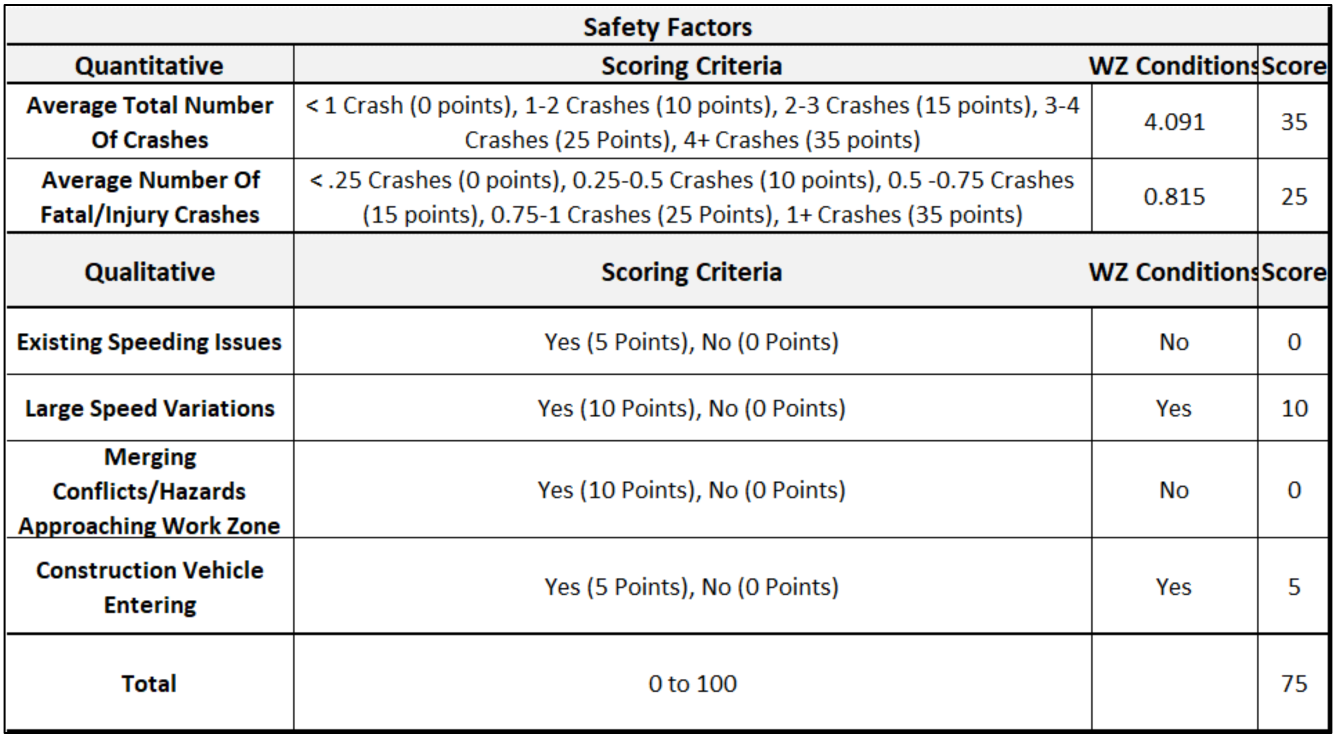
Overall Safety Score for SWZ Systems

The tool was designed to calculate an overall safety score for each SWZ system that represents the need for deploying that system in the analyzed work zone. The calculated safety score ranges from 0 to 100 points. For each SWZ system, the safety score was calculated based on a new list of scoring criteria which was developed using a similar methodology described in the Overall mobility Score for SWZ Systems section, as shown in Figure 41, Figure 42, Figure 43, Figure 44, Figure 45, and Figure 46. For example, the QWS safety score for the average total number of crashes was calculated by the tool as 20 points based on its predetermined scoring criteria and its estimated average total number of crashes of 2.617, which was calculated using the earlier described SPF in the Predicting Impact of Work Zone Quantitative Safety Factors on Crashes section, as shown in Figure 41. Note that the safety score of each factor is automatically calculated by the developed tool based on the user input data. The calculated safety scores of individual quantitative and qualitative factors are then summed up to identify the overall safety score of each SWZ system. For example, the calculated overall safety score for the deployment of QWS in an example work zone was 52, as shown in Figure 41.



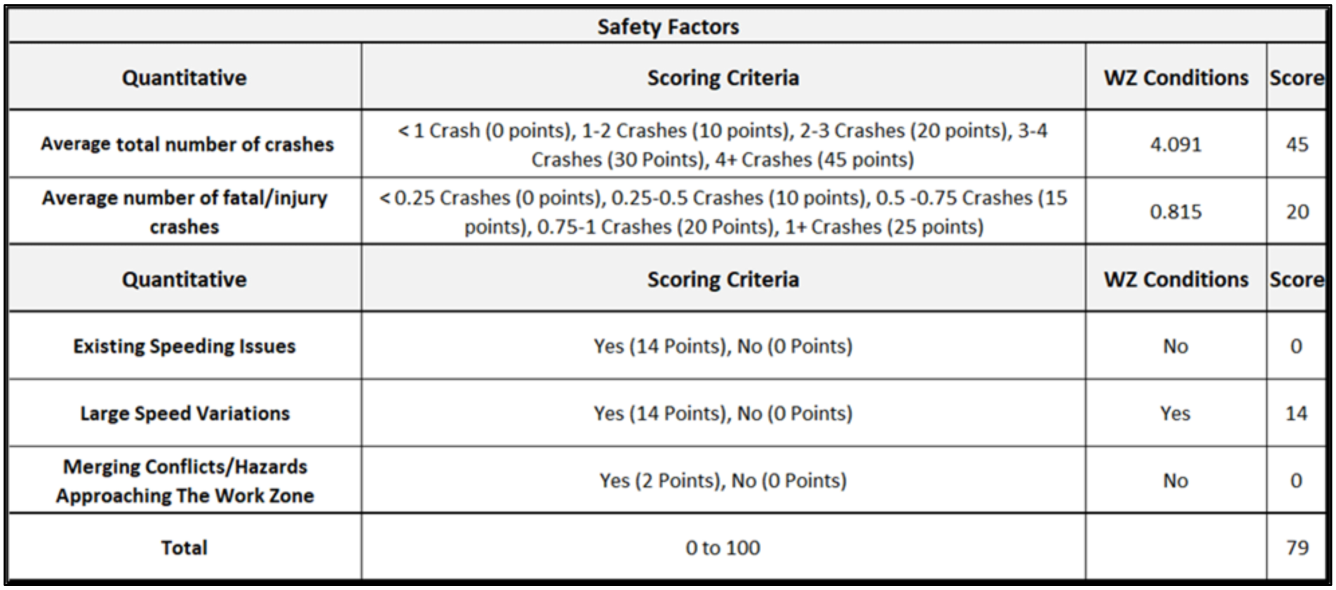
Safety Factors			
Quantitative	**Scoring Criteria**	**WZ Conditions**	**Score**
Average total number of crashes	< 1 Crash (0 points), 1-2 Crashes (10 points), 2-3 Crashes (20 points), 3-4 Crashes (30 Points), 4+ Crashes (45 points)	4.091	45
Average number of fatal/injury crashes	< 0.25 Crashes (0 points), 0.25-0.5 Crashes (10 points), 0.5 -0.75 Crashes (15 points), 0.75-1 Crashes (20 Points), 1+ Crashes (25 points)	0.815	20
Qualitative	**Scoring Criteria**	**WZ Conditions**	**Score**
Merging Conflicts/Hazards Approaching The Work	Yes (10 Points), No (0 Points)	No	0
Extreme Weather Condition	High impact (20 Points), Moderate impact (12 Points), Minimal impact (0 Points)	Moderate Impact	12
Total	0 to 100		77

Figure 41. Screenshot. QWS safety score.



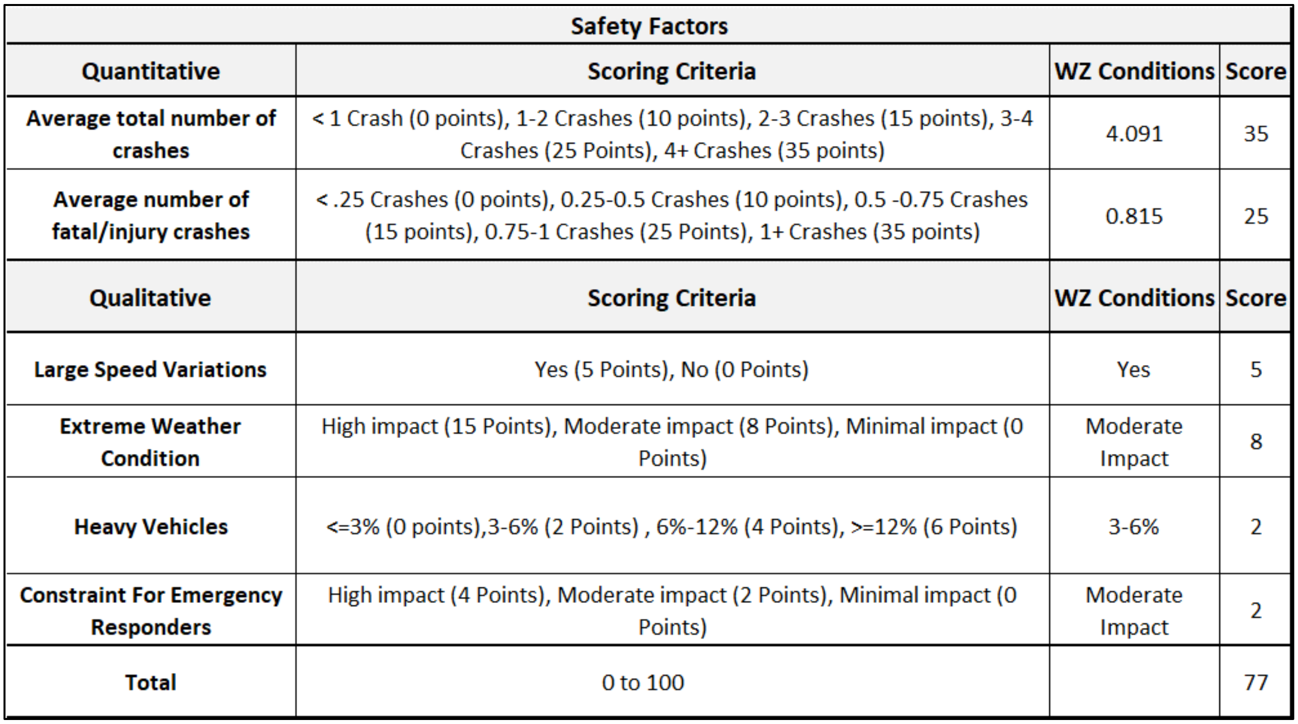
Safety Factors			
Quantitative	**Scoring Criteria**	**WZ Conditions**	**Score**
Average Total Number Of Crashes	< 1 Crash (0 points), 1-2 Crashes (10 points), 2-3 Crashes (15 points), 3-4 Crashes (25 Points), 4+ Crashes (35 points)	4.091	35
Average Number Of Fatal/Injury Crashes	< .25 Crashes (0 points), 0.25-0.5 Crashes (10 points), 0.5 -0.75 Crashes (15 points), 0.75-1 Crashes (25 Points), 1+ Crashes (35 points)	0.815	25
Qualitative	**Scoring Criteria**	**WZ Conditions**	**Score**
Existing Speeding Issues	Yes (5 Points), No (0 Points)	No	0
Large Speed Variations	Yes (10 Points), No (0 Points)	Yes	10
Merging Conflicts/Hazards Approaching Work Zone	Yes (10 Points), No (0 Points)	No	0
Construction Vehicle Entering	Yes (5 Points), No (0 Points)	Yes	5
Total	0 to 100		75

Figure 42. Screenshot. DLMS safety score.



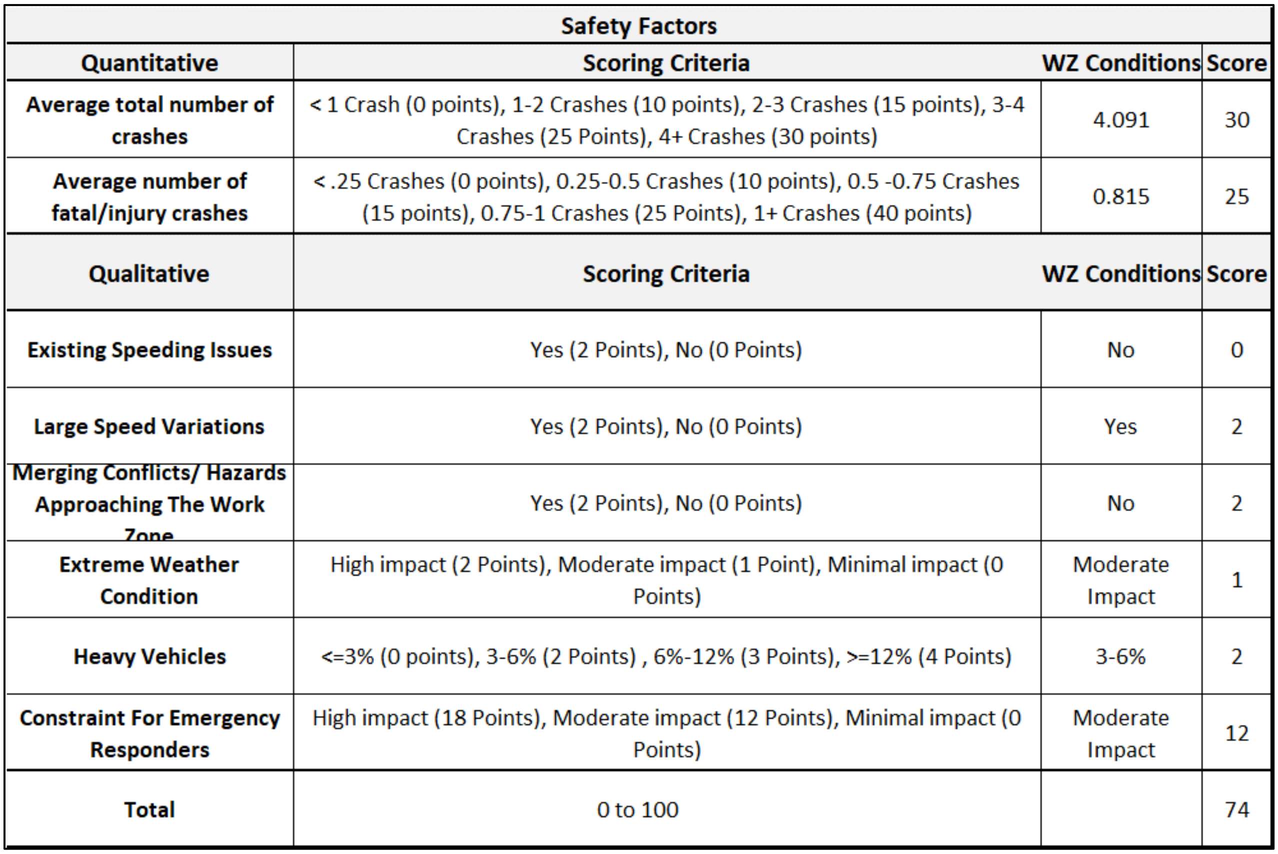
Safety Factors			
Quantitative	**Scoring Criteria**	**WZ Conditions**	**Score**
Average total number of crashes	< 1 Crash (0 points), 1-2 Crashes (10 points), 2-3 Crashes (20 points), 3-4 Crashes (30 Points), 4+ Crashes (45 points)	4.091	45
Average number of fatal/injury crashes	< 0.25 Crashes (0 points), 0.25-0.5 Crashes (10 points), 0.5 -0.75 Crashes (15 points), 0.75-1 Crashes (20 Points), 1+ Crashes (25 points)	0.815	20
Quantitative	**Scoring Criteria**	**WZ Conditions**	**Score**
Existing Speeding Issues	Yes (14 Points), No (0 Points)	No	0
Large Speed Variations	Yes (14 Points), No (0 Points)	Yes	14
Merging Conflicts/Hazards Approaching The Work Zone	Yes (2 Points), No (0 Points)	No	0
Total	0 to 100		79

Figure 43. Screenshot. VSA safety score.



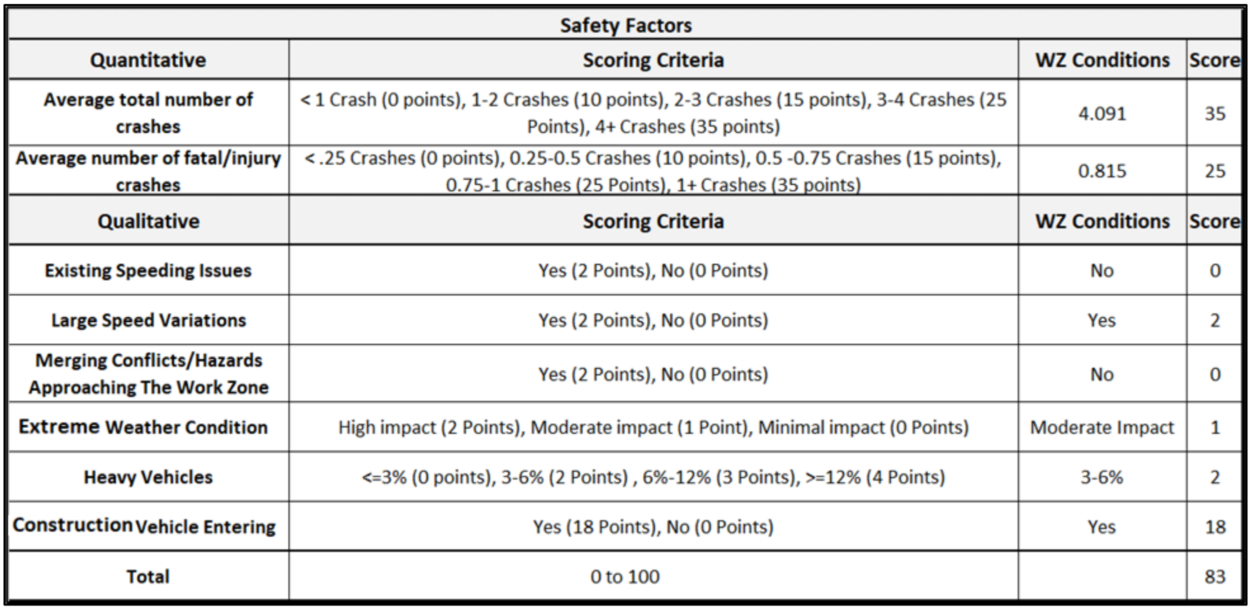
Safety Factors			
Quantitative	**Scoring Criteria**	**WZ Conditions**	**Score**
Average total number of crashes	< 1 Crash (0 points), 1-2 Crashes (10 points), 2-3 Crashes (15 points), 3-4 Crashes (25 Points), 4+ Crashes (35 points)	4.091	35
Average number of fatal/injury crashes	< .25 Crashes (0 points), 0.25-0.5 Crashes (10 points), 0.5 -0.75 Crashes (15 points), 0.75-1 Crashes (25 Points), 1+ Crashes (35 points)	0.815	25
Qualitative	**Scoring Criteria**	**WZ Conditions**	**Score**
Large Speed Variations	Yes (5 Points), No (0 Points)	Yes	5
Extreme Weather Condition	High impact (15 Points), Moderate impact (8 Points), Minimal impact (0 Points)	Moderate Impact	8
Heavy Vehicles	<=3% (0 points),3-6% (2 Points) , 6%-12% (4 Points), >=12% (6 Points)	3-6%	2
Constraint For Emergency Responders	High impact (4 Points), Moderate impact (2 Points), Minimal impact (0 Points)	Moderate Impact	2
Total	0 to 100		77

Figure 44. Screenshot. TTIS safety score.



Safety Factors			
Quantitative	**Scoring Criteria**	**WZ Conditions**	**Score**
Average total number of crashes	< 1 Crash (0 points), 1-2 Crashes (10 points), 2-3 Crashes (15 points), 3-4 Crashes (25 Points), 4+ Crashes (30 points)	4.091	30
Average number of fatal/injury crashes	< .25 Crashes (0 points), 0.25-0.5 Crashes (10 points), 0.5 -0.75 Crashes (15 points), 0.75-1 Crashes (25 Points), 1+ Crashes (40 points)	0.815	25
Qualitative	**Scoring Criteria**	**WZ Conditions**	**Score**
Existing Speeding Issues	Yes (2 Points), No (0 Points)	No	0
Large Speed Variations	Yes (2 Points), No (0 Points)	Yes	2
Merging Conflicts/ Hazards Approaching The Work Zone	Yes (2 Points), No (0 Points)	No	2
Extreme Weather Condition	High impact (2 Points), Moderate impact (1 Point), Minimal impact (0 Points)	Moderate Impact	1
Heavy Vehicles	<=3% (0 points), 3-6% (2 Points) , 6%-12% (3 Points), >=12% (4 Points)	3-6%	2
Constraint For Emergency Responders	High impact (18 Points), Moderate impact (12 Points), Minimal impact (0 Points)	Moderate Impact	12
Total	0 to 100		74

Figure 45. Screenshot. TIDS safety score.



Safety Factors			
Quantitative	**Scoring Criteria**	**WZ Conditions**	**Score**
Average total number of crashes	< 1 Crash (0 points), 1-2 Crashes (10 points), 2-3 Crashes (15 points), 3-4 Crashes (25 Points), 4+ Crashes (35 points)	4.091	35
Average number of fatal/injury crashes	< .25 Crashes (0 points), 0.25-0.5 Crashes (10 points), 0.5 -0.75 Crashes (15 points), 0.75-1 Crashes (25 Points), 1+ Crashes (35 points)	0.815	25
Qualitative	**Scoring Criteria**	**WZ Conditions**	**Score**
Existing Speeding Issues	Yes (2 Points), No (0 Points)	No	0
Large Speed Variations	Yes (2 Points), No (0 Points)	Yes	2
Merging Conflicts/Hazards Approaching The Work Zone	Yes (2 Points), No (0 Points)	No	0
Extreme Weather Condition	High impact (2 Points), Moderate impact (1 Point), Minimal impact (0 Points)	Moderate Impact	1
Heavy Vehicles	<=3% (0 points), 3-6% (2 Points) , 6%-12% (3 Points), >=12% (4 Points)	3-6%	2
Construction Vehicle Entering	Yes (18 Points), No (0 Points)	Yes	18
Total	0 to 100		83

Figure 46. Screenshot. CTEDS safety score.

MOBILITY AND SAFETY NEEDS FOR SWZ SYSTEMS

This phase of model development was designed to determine overall mobility and safety needs for each SWZ system. The tool was designed to calculate an overall score for each SWZ system based on user-specified relative weights that represent the relative importance of mobility and safety in the analyzed work zone, as shown in Figure 48. These user-specified relative weights are then used by the tool to calculate a SWZ feasibility score that ranges from 0 to 100 points, representing absolutely no need to maximum need for deploying the SWZ system in the work zone, respectively (see Figure 47).

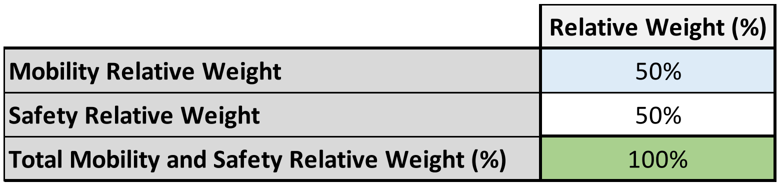
$$SWZFS = (MS * MRW) + (SS * SRW)$$

Figure 47. Equation. Feasibility score for SWZ system.

Where

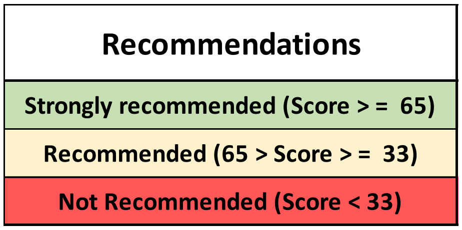
SWZFS: Feasibility score for SWZ system
MS: Mobility score for SWZ system
MRW: Relative weight of mobility
SS: Safety score for SWZ system
SRW: Relative weight of safety

This calculated feasibility score is then used by the tool to provide a recommendation for the deployment of each SWZ system using a set of normalized FHWA and Texas DOT thresholds, as shown in Figure 49 (FHWA, 2014; TxDOT, 2018). The FHWA and Texas DOT normalized thresholds provide three alternate recommendations for SWZ deployment: (1) not recommended (when the score is less than 33), (2) recommended (when the score is between 33 and 65), and (3) strongly recommended (when the score is greater than 65), as shown in Figure 49.



	Relative Weight (%)
Mobility Relative Weight	50%
Safety Relative Weight	50%
Total Mobility and Safety Relative Weight (%)	100%

Figure 48. Screenshot. Relative weight of mobility and safety.



Recommendations
Strongly recommended (Score > = 65)
Recommended (65 > Score > = 33)
Not Recommended (Score < 33)

Figure 49. Screenshot. Recommendation to deploy SWZ system.

SWZ SYSTEMS LAYOUT

This phase of model development was designed to integrate a layout for the use of SWZ systems in the work zone. For each SWZ system, a layout design was adapted based on a comprehensive literature review and the survey results in two main steps that were designed to (1) identify all required SWZ system components for deployment and (2) distribute the SWZ system components according to their technical requirements. For example, the first step of designing a layout for the QWS system focused on identifying a complete list of equipment needed for deploying the QWS in work zones, as shown in Figure 50. This list of QWS equipment was identified based on a review of existing FHWA and state guidelines and related survey findings, as shown in Table 45. Existing FWHA and guidelines used in identifying the list of QWS equipment in this tool were FHWA Work Zone ITS Implementation Guide (FHWA, 2014), Georgia DOT ITS Guidelines (GDOT,2020), Mass DOT SWZ Design Standards (MassDOT, 2016), Connecticut DOT SWZ Guide (CTDOT, 2017), Minnesota DOT IWZ Toolbox (MnDOT, 2020), Ohio Travel Engineering Manual (ODOT, 2022), Arizona DOT SWZ Quantity Tools (ADOT, 2020b), and Texas WZ ITS Design Guidelines (TxDOT, 2018). The second step of designing the QWS layout was to distribute its identified three components based on their reported locations by existing FHWA and state DOT guidelines/standards, as shown in Table 46. A similar analysis was conducted for each of the remaining five SWZ systems (DLMS, VSA, TTIS, TIDS, CTEDS), which is summarized in Table 76 to Table 80, respectively in Appendix C. The recommended design layouts for these five SWZ systems (DLMS, VSA, TTIS, TIDS, CTEDS) are shown in Figure 51, Figure 52, Figure 53, Figure 54, and Figure 55, respectively.

Table 45. List of QWS Equipment Required by FHWA and State DOTs

Equipment	FHWA	GDOT	MassDOT	CTDOT	MnDOT	ODOT	ADOT	TxDOT	SCDOT
VMS	●	●	●	●	●	●	●	●	●
Traffic Sensor	●	●	●	●	●	●	●	●	●
CCTV			●	●			●		●

Table 46. QWS Designed Equipment Location

State	System	Roadway Corridor Location	Activity Area Location
MassDOT	VMS	• End of queue • Before alternative route exit	• Start of activity area
MassDOT	Detectors	• Middle of queue • End of queue • Before and after alternative route exit	• Start of activity area • Middle of activity area • End of activity area
MassDOT	CCTV	None	• Start of activity area (optional) • End of activity area (optional)
CTDOT	VMS	• End of queue • Before alternative route exit	• Start of activity area
CTDOT	Detectors	• Full distance of the queue with spacing specified based on each project	• Full distance of the activity area with spacing specified based on each
CTDOT	CCTV	None	• Start of activity area (optional)
ADOT	VMS	• Every 1 mile until end of queue	None
ADOT	Detectors	• Every 0.5 mile until end of queue	• Start of activity area • Middle of activity area • End of activity area
ADOT	CCTV	None	• Start of activity area (optional)
MnDOT	VMS	• End of queue • Before alternative route exit	• Start of activity area
MnDOT	Detectors	• Every 0.5 or 1 mile until end of queue	• Every 0.5 or 1 mile until end of queue
TxDOT	VMS	• End of queue	• Start of activity area
TxDOT	Detectors	• Every 1 mile until end of queue	None
Recommended Design Layout	VMS	• End of queue • Before alternative route exit	• Start of activity area
Recommended Design Layout	Detectors	• Every 1 mile until end of queue	• Start of activity area • Middle of activity area • End of activity area
Recommended Design Layout	CCTV	None	• Start of activity area (optional)

For each SWZ system, the developed tool was designed to visually illustrate the work zone layout for each component. For example, the QWS layout was designed to have two VMS, eight traffic sensors, and one optional CCTV camera, as shown in Figure 50. Note that the layout of each system is automatically displayed by the developed tool when the SWZ system feasibility score is above 33, which indicates it is either recommended or strongly recommended.

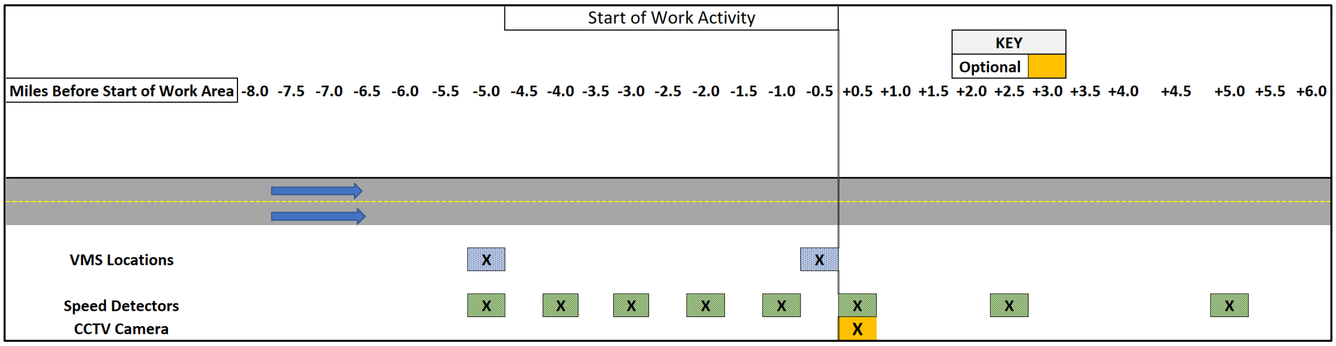


Figure 50. Screenshot. QWS layout design.

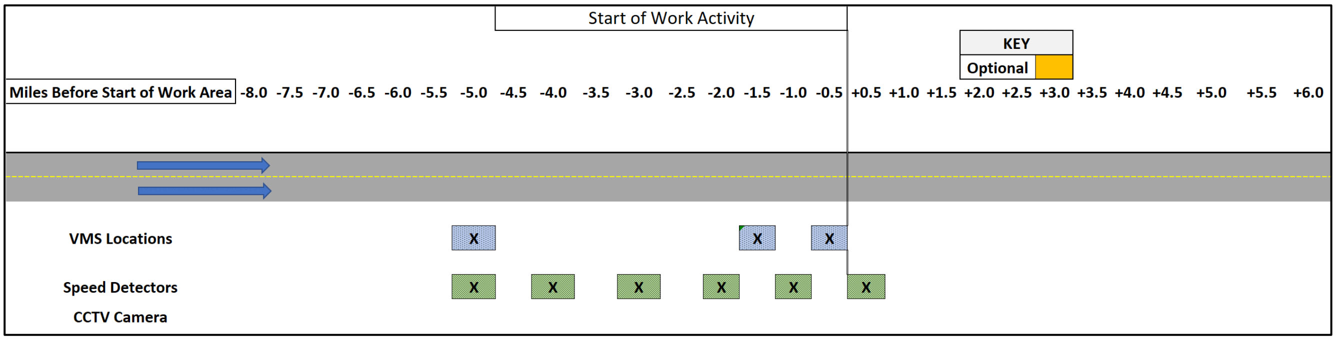


Figure 51. Screenshot. DLMS layout design.

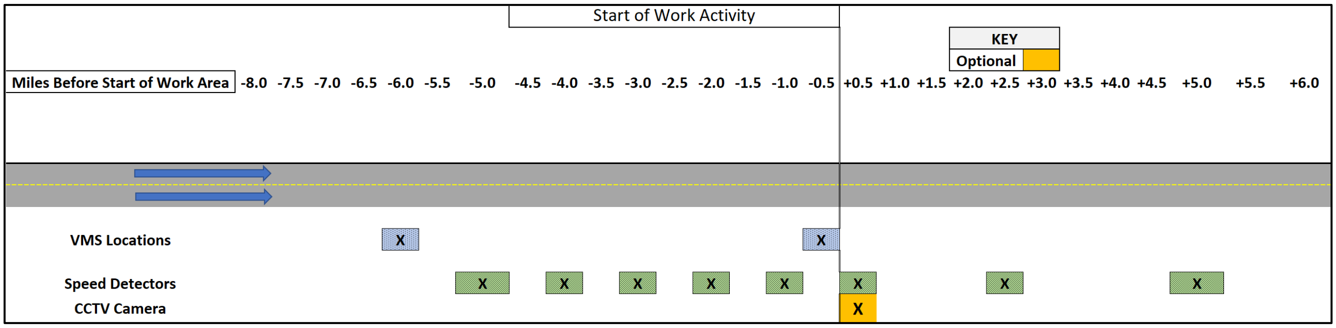


Figure 52. Screenshot. VSA layout design.

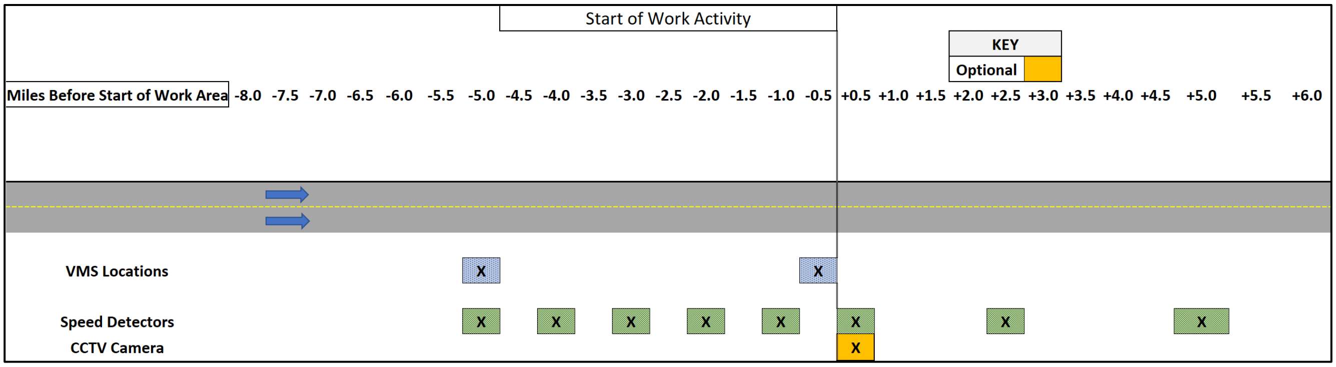


Figure 53. Screenshot. TTIS layout design.

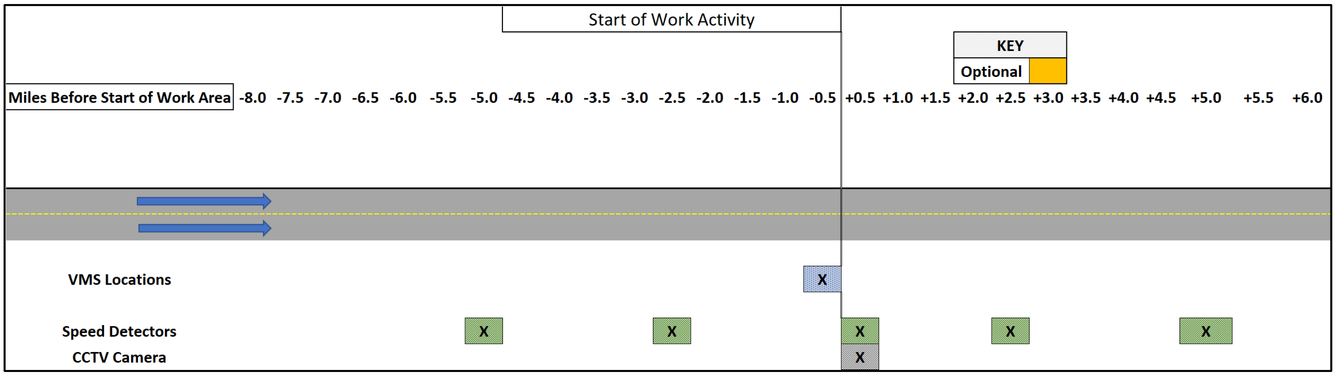


Figure 54. Screenshot. TIDS layout design.

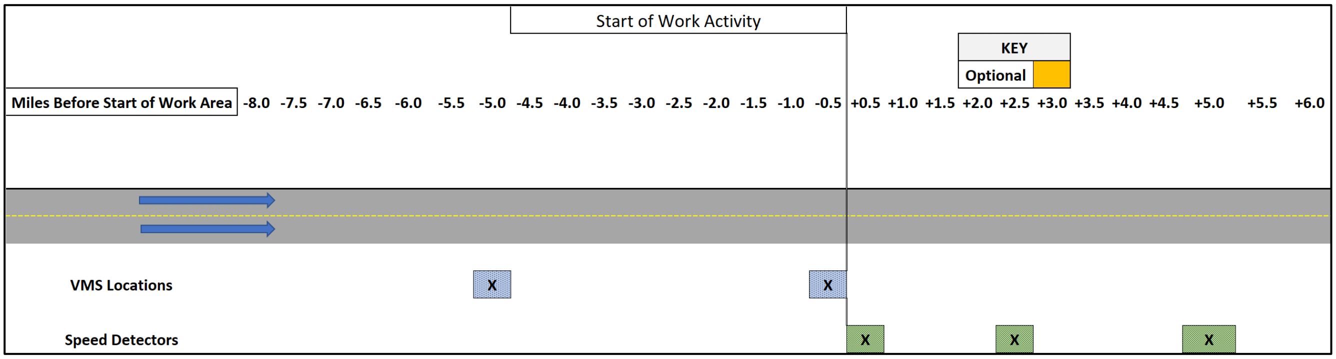


Figure 55. Screenshot. CTEDS layout design.

CHAPTER 5: GUIDANCE FOR DESIGN OF SMART WORK ZONE SYSTEMS

This chapter provides guidance for utilizing scoresheets to assess the feasibility of deploying SWZ systems that can be used in Phase 1 or as early in the project development process as feasible for any roadway project where its impacts may be mitigated by the use of smart work zone systems. Smart work zone systems should be incorporated in the traffic control plan (TCP) which may be either part of the transportation management plan (TMP) or may be the whole transportation management plan. The scoresheets can be used to determine the need for utilizing one or more of the following six SWZ systems:

1. Queue Warning Systems (QWS). QWS are used to alert drivers of upcoming traffic conditions and are capable of continuously monitoring the traffic on the approaches and within work zones to communicate whether queued traffic is expected ahead.

2. Dynamic Lane Merge Systems (DLMS). DLMS are placed upstream of expected bottlenecks caused by lane closures to direct traffic into either early merging or late merging strategies.

3. Variable Speed Advisory Systems (VSA). VSA are used to display real-time downstream speeds to drivers so they can preemptively slow down before reaching the bottleneck.

4. Travel Time Information Systems (TTIS). TTIS are used to display travel time through a work zone to motorists so they can make informed route choices accordingly.

5. Temporary Incident Detection Systems (TIDS). TIDS are used to monitor the work zone using cameras or sensors to alert traffic management centers (TMCs) or emergency response systems when traffic incidents occur in the work zone.

6. Construction Truck Entry and Exit Detection Systems (CTEDS). CTEDS are used to automatically detect when slow-moving construction vehicles exit work zones and provide advance warning to motorists through VMS or flasher signs.

Table 47 to Table 52 provide scoresheets for these six systems to evaluate the need for deploying them in work zones based on a set of scoring criteria. When using the scoresheet, assign a score based on the scoring criteria listed for each work zone factor then calculate the total score for each system by summing up all the assigned scores of all factors. If the total score is greater than 65, the SWZ system is “recommended.” If the score is between 33 and 65, the SWZ system should be “feasible,” and if the score is below 33, the SWZ system is “not recommended.” In addition to the scoresheets, this research project developed a tool that uses project information to assist in the calculation of the feasibility scores.

Table 47. QWS Feasibility Scoresheet

Work Zone Factors	QWS Scoring Criteria	Score
Queue Length	< 1 mile (0 points), 1–3 miles (5 points), 3–5 miles (10 points), 5–7 miles (15 Points), 7+ miles (20 points)	
Queue Duration	< 1 hour (0 points), 1–2 hours (3 points), 2–4 hours (7 points), 4+ hours (10 points)	
Average Delay Time	< 12 mins (0 points), 12–20 mins (3 points), 20–30 mins (7 points), 30+ mins (10 points)	
Duration of Work Zone	< 1 month (0 points), 1–4 months (3 Points), 5–10 months (7 Points), > 1 year (10 Points)	
Average Total Number of Crashes	< 1 Crash (0 points), 1–2 Crashes (2 points), 2–3 Crashes (5 points), 3–4 Crashes (8 Points), 4+ Crashes (10 points)	
Average Number of Fatal/Injury Crashes	< 0.25 Crashes (0 points), 0.25–0.5 Crashes (2 points), 0.5–0.75 Crashes (5 points), 0.75–1 Crashes (8 Points), 1+ Crashes (10 points)	
Sight Distance from Back of Queue	Minimal (0 Points), Moderate (5 Points), High (8 Points)	
Highway Function Class	Other (0 Points), Major Arterial (2 Points), Freeway/ Expressway (3 points), Interstate (4 points)	
Nearby Traffic Generator	Minimal impact (0 Points), Moderate impact (2 Points), High impact (4 Points)	
Existing Traffic Issues	Minimal (0 Points), Moderate (2 Points), High (4 Points)	
Availability of Alternate Routes	No (0 Points), Yes (4 Points)	
Presence of Complex Traffic Layout	No (0 Points), Yes (2 Points)	
Merging Conflicts/Hazards Approaching the Work Zone	No (0 Points), Yes (2 Points)	
Extreme Weather Condition	Minimal impact (0 Points), Moderate impact (1 Points), High impact (2 Points)	
QWS Total Feasibility Score	0 to 100	

QWS is recommended if the total score is greater than 65.

QWS is feasible if the total score is between 33 and 65.

QWS is not recommended if the total score is below 33.

Table 48. DLMS Feasibility Scoresheet

Work Zone Factors	DLMS Scoring Criteria	Score
Queue Length	< 1 mile (0 points), 1–3 miles (5 points), 3–5 miles (10 points), 5–7 miles (15 Points), 7+ miles (20 points)	
Merging Conflicts/Hazards Approaching the Work Zone	No (0 Points), Yes (10 Points)	
Average Total Number of Crashes	< 1 Crash (0 points), 1–2 Crashes (2 points), 2–3 Crashes (5 points), 3–4 Crashes (8 Points), 4+ Crashes (10 points)	
Average Number of Fatal/Injury Crashes	< 0.25 Crashes (0 points), 0.25–0.5 Crashes (2 points), 0.5–0.75 Crashes (5 points), 0.75–1 Crashes (8 Points), 1+ Crashes (10 points)	
Sight Distance from Back of Queue	Minimal (0 Points), Moderate (6 Points), High (10 Points)	
Duration of Work Zone	< 1 month (0 points), 1–4 months (3 Points), 5–10 months (6 Points), > 1 year (8 Points)	
Large Speed Variations	No (0 Points), Yes (8 Points)	
Highway Function Class	Other (0 Points), Major Arterial (2 Points), Freeway/ Expressway (3 points), Interstate (4 points)	
Nearby Traffic Generator	Minimal impact (0 Points), Moderate impact (2 Points), High impact (4 Points)	
Existing Traffic Issues	Minimal (0 Points), Moderate (2 Points), High (4 Points)	
Presence of Complex Traffic Layout	No (0 Points), Yes (4 Points)	
Existing Speeding Issues	No (0 Points), Yes (4 Points)	
Construction Vehicle Entering	No (0 Points), Yes (4 Points)	
DLMS Total Feasibility Score	0 to 100	

DLMS is recommended if the total score is greater than 65.

DLMS is feasible if the total score is between 33 and 65.

DLMS is not recommended if the total score is below 33

Table 49. VSA Feasibility Scoresheet

Work Zone Factors	VSA Scoring Criteria	Score
Large Speed Variations	No (0 Points), Yes (15 Points)	
Existing Speeding Issues	No (0 Points), Yes (15 Points)	
Average Total Number of Crashes	< 1 Crash (0 points), 1–2 Crashes (2 points), 2–3 Crashes (5 points), 3–4 Crashes (8 Points), 4+ Crashes (10 points)	
Average Number of Fatal/Injury Crashes	< 0.25 Crashes (0 points), 0.25–0.5 Crashes (2 points), 0.5–0.75 Crashes (5 points), 0.75–1 Crashes (8 Points), 1+ Crashes (10 points)	
Highway Function Class	Other (0 Points), Major Arterial (3 Points), Freeway/ Expressway (7 points), Interstate (10 points)	
Existing Traffic Issues	Minimal (0 Points), Moderate (6 Points), High (10 Points)	
Presence of Complex Traffic Layout	No (0 Points), Yes (10 Points)	
Queue Length	< 1 mile (0 points), 1–3 miles (2 points), 3–5 miles (4 points), 5–7 miles (6 Points), 7+ miles (8 points)	
Merging Conflicts/Hazards Approaching the Work Zone	No (0 Points), Yes (4 Points)	
Duration of Work Zone	< 1 month (0 points), 1–4 months (2 Points), 5–10 months (3 Points), > 1 year (4 Points)	
Nearby Traffic Generator	Minimal impact (0 Points), Moderate impact (1 Points), High impact (2 Points)	
Nearby Roadway Project	Minimal impact (0 Points), Moderate impact (1 Points), High impact (2 Points)	
VSA Total Feasibility Score	0 to 100	

VSA is recommended if the total score is greater than 65.

VSA is feasible if the total score is between 33 and 65.

VSA is not recommended if the total score is below 33.

Table 50. TTIS Feasibility Scoresheet

Work Zone Factors	TTIS Scoring Criteria	Score
Average Delay Time	< 12 mins (0 points), 12–20 mins (7 points), 20–30 mins (13 points), 30+ mins (18 points)	
Queue Duration	< 1 hour (0 points), 1–2 hours (6 points), 2–4 hours (10 points), 4+ hours (14 points)	
Availability of Alternate Routes	No (0 Points), Yes (10 Points)	
Queue Length	< 1 mile (0 points), 1–3 miles (3 points), 3–5 miles (6 points), 5–7 miles (8 Points), 7+ miles (10 points)	
Average Total Number of Crashes	< 1 Crash (0 points), 1–2 Crashes (2 points), 2–3 Crashes (4 points), 3–4 Crashes (6 Points), 4+ Crashes (8 points)	
Highway Function Class	Other (0 Points), Major Arterial (3 Points), Freeway/ Expressway (6 points), Interstate (8 points)	
Existing Traffic Issues	Minimal (0 Points), Moderate (3 Points), High (6 Points)	
Average Number of Fatal/Injury Crashes	< 0.25 Crashes (0 points), 0.25–0.5 Crashes (4 points), 0.5–0.75 Crashes (3 points), 0.75–1 Crashes (4 Points), 1+ Crashes (5 points)	
Sight Distance from Back of Queue	Minimal (0 Points), Moderate (2 Points), High (4 Points)	
Nearby Traffic Generator	Minimal impact (0 Points), Moderate impact (2 Points), High impact (4 Points)	
Duration of Work Zone	< 1 month (0 points), 1–4 months (2 Points), 5–10 months (3 Points), > 1 year (4 Points)	
Constraint For Emergency Responders	Minimal impact (0 Points), Moderate impact (1 Points), High impact (2 Points)	
Heavy Vehicles	<=3% (0 points), 3–6% (1 Points), 6%–12% (2 Points), >=12% (3 Points)	
Large Speed Variations	No (0 Points), Yes (2 Points)	
Extreme Weather Condition	Minimal impact (0 Points), Moderate impact (1 Points), High impact (2 Points)	
TTIS Total Feasibility Score	0 to 100	

TTIS is recommended if the total score is greater than 65.
TTIS is feasible if the total score is between 33 and 65.
TTIS is not recommended if the total score is below 33.

Table 51. TIDS Feasibility Scoresheet

Work Zone Factors	TIDS Scoring Criteria	Score
Average Total Number of Crashes	< 1 Crash (0 points), 1–2 Crashes (3 points), 2–3 Crashes (7 points), 3–4 Crashes (10 Points), 4+ Crashes (14 points)	
Average Number of Fatal/Injury Crashes	< 0.25 Crashes (0 points), 0.25–0.5 Crashes (3 points), 0.5–0.75 Crashes (7 points), 0.75–1 Crashes (10 Points), 1+ Crashes (14 points)	
Constraint for Emergency Responders	Minimal impact (0 Points), Moderate impact (9 Points), High impact (14 Points)	
Average Delay Time	< 12 mins (0 points), 12–20 mins (3 points), 20–30 mins (7 points), 30+ mins (10 points)	
Large Speed Variations	No (0 Points), Yes (8 Points)	
Highway Function Class	Other (0 Points), Major Arterial (3 Points), Freeway/ Expressway (6 points), Interstate (8 points)	
Heavy Vehicles	<=3% (0 points), 3–6% (2 Points), 6%–12% (4 Points), >=12% (6 Points)	
Existing Traffic Issues	Minimal (0 Points), Moderate (3 Points), High (6 Points)	
Queue Length	< 1 mile (0 points), 1–3 miles (1 points), 3–5 miles (2 points), 5–7 miles (3 Points), 7+ miles (4 points)	
Duration of Work Zone	< 1 month (0 points), 1–4 months (2 Points), 5–10 months (3 Points), > 1 year (4 Points)	
Sight Distance from Back of Queue	Minimal (0 Points), Moderate (2 Points), High (4 Points)	
Merging Conflicts/ Hazards Approaching the Work Zone	No (0 Points), Yes (2 Points)	
Presence of Complex Traffic Layout	No (0 Points), Yes (2 Points)	
Existing Speeding Issues	No (0 Points), Yes (2 Points)	
Extreme Weather Condition	Minimal impact (0 Points), Moderate impact (1 Points), High impact (2 Points)	
TIDS Total Feasibility Score	0 to 100	

TIDS is recommended if the total score is greater than 65.
TIDS is feasible if the total score is between 33 and 65.
TIDS is not recommended if the total score is below 33.

Table 52. CTEDS Feasibility Scoresheet

Work Zone Factors	CTEDS Scoring Criteria	Score
Construction Vehicle Entering	Minimal impact (0 Points), Moderate impact (12 Points), High impact (20 Points)	
Average Total Number of Crashes	< 1 Crash (0 points), 1–2 Crashes (2 points), 2–3 Crashes (5 points), 3–4 Crashes (8 Points), 4+ Crashes (10 points)	
Average Number of Fatal/Injury Crashes	< 0.25 Crashes (0 points), 0.25–0.5 Crashes (2 points), 0.5–0.75 Crashes (5 points), 0.75–1 Crashes (8 Points), 1+ Crashes (10 points)	
Highway Function Class	Other (0 Points), Major Arterial (3 Points), Freeway/ Expressway (6 points), Interstate (8 points)	
Merging Conflicts/ Hazards Approaching Work Zone	No (0 Points), Yes (8 Points)	
Existing Speeding Issues	No (0 Points), Yes (8 Points)	
Heavy Vehicles	<=3% (0 points), 3–6% (2 Points), 6%–12% (4 Points), >=12% (6 Points)	
Queue Length	< 1 mile (0 points), 1–3 miles (1 points), 3–5 miles (2 points), 5–7 miles (4 Points), 7+ miles (6 points)	
Duration of Work Zone	< 1 month (0 points), 1–4 months (2 Points), 5–10 months (4 Points), > 1 year (6 Points)	
Presence of Complex Traffic Layout	No (0 Points), Yes (4 Points)	
Existing Traffic Issues	Minimal (0 Points), Moderate (2 Points), High (4 Points)	
Extreme Weather Condition	Minimal impact (0 Points), Moderate impact (2 Points), High impact (4 Points)	
Nearby Traffic Generator Impact	Minimal impact (0 Points), Moderate impact (1 Points), High impact (2 Points)	
Nearby Roadway Project	Minimal impact (0 Points), Moderate impact (1 Points), High impact (2 Points)	
Large Speed Variations	No (0 Points), Yes (2 Points)	
CTED Total Feasibility Score	0 to 100	

CTEDS is recommended if the total score is greater than 65.
CTEDS is feasible if the total score is between 33 and 65.
CTEDS is not recommended if the total score is below 33.

CHAPTER 6: FUTURE RESEARCH

During this study, the research team identified two promising research areas that need further in-depth analysis and investigation. Building on the accomplishments in this project, the research team foresees an opportunity to further improve the safety and mobility of work zones on Illinois roads by studying (1) the effectiveness of individual and collective deployments of SWZ systems and (2) the effectiveness of alternative displayed messages on variable message signs.

FUTURE RESEARCH 1: EFFECTIVENESS OF SWZ SYSTEMS IN IMPROVING SAFETY AND MOBILITY

Problem Statement

According to the survey results in this study, state DOT officials reported a lack of field data on the impact and benefits of deploying SWZ systems in reducing the number of roadway crashes, queue length, and delay times. The lack of data makes it difficult to quantify the impact of individual and collective deployments of SWZ systems on safety and mobility. Accordingly, there is a pressing need to collect, document, and analyze this data to refine the developed SWZ feasibility assessment tool and ensure that its recommended deployments of SWZ systems provide the highest possible safety and mobility performance, especially when there are limited budgets for SWZ systems.

Objective and Scope of Proposed Research

The objectives of this proposed research are to (1) collect work zone mobility and safety data, including number of roadway crashes, queue length, and delay times from IDOT projects with multiple, individual, and no SWZ systems; (2) compare the collected data to quantify the individual and collective impact of deploying SWZ systems; (3) refine SWZ system deployment recommendations by the developed tool based on the quantified individual and collective impact of SWZ systems; and (4) develop and integrate an optimization model in the developed tool to maximize safety and mobility for work zones with limited budgets for SWZ systems.

Expected Outcome

The deliverables of this proposed research would enable IDOT to (1) create a detailed work zone mobility and safety data set from IDOT projects with multiple, individual, and no SWZ systems; (2) quantify the individual and collective impact of deploying SWZ systems; (3) enhance the performance of the developed SWZ feasibility assessment tool; and (4) optimize the deployment of SWZ systems to maximize safety and mobility for Illinois work zones while considering limited budgets.

FUTURE RESEARCH 2: EFFECTIVENESS OF ALTERNATIVE DISPLAYED MESSAGES ON VARIABLE MESSAGE SIGNS

Problem Statement

Twenty-seven state DOTs were reported to display highway death toll statistics on variable message signs to alert drivers about driving hazards to improve safety compliance (Hall & Madsen, 2022). A recent study, however, reported that alarming messages caused an increase in the number of crashes on Texas roads. It reported that displaying a fatality message increased the number of crashes by 4.5% and suggested that these types of messages may weigh down drivers' "cognitive loads," temporarily impacting their ability to respond to changes in traffic conditions (Hall & Madsen, 2022). On the other hand, several state DOTs use funny messages to improve safety compliance. For example, Illinois DOT highway signs displayed "Got the munchies? Get food delivered. Don't drive high!" after legalizing marijuana in 2020 (IDOT, 2020). In 2021, Virginia DOT used a brain mapping helmet to measure 300 drivers' reactions to 80 different messages and reported that funny messages caused the highest increase in brain activity. After implementing top-performing messages on Virginia roads, VDOT experienced more social media exposure with over 33,000 Facebook impressions, retweets up 336%, and over 35,000 Instagram impressions (VDOT, 2021). Accordingly, there is a pressing need for IDOT to conduct research to (1) determine whether the message displayed on variable message signs promotes a higher increase in safety compliance and (2) evaluate the safety effectiveness of different types of messages (funny, serious, etc.) on Illinois roads. This proposed research will enable IDOT to improve roadway safety and mobility for the travelling public by providing effective messages on its variable message signs to alert drivers and encourage them to exercise safe driving.

Objective and Scope of Proposed Research

The objective of this proposed research is to evaluate the effectiveness of different types of messages displayed on variable message signs in improving drivers' safety compliance. To accomplish this, the project scope will focus on (1) conducting a comprehensive literature review of all related studies; (2) performing a national survey of state DOTs to gather and analyze their experiences in utilizing effective safety messages; (3) performing field tests to analyze the effectiveness of top-performing messages in the previous task that will be displayed on IDOT variable message signs; and (4) providing recommendations on the most effective messages displayed on variable message signs to increase safety compliance on Illinois roads.

Expected Outcome

The expected outcomes of this proposed research include (1) a comprehensive literature review of the latest research on the effectiveness of different messages on variable message signs in improving roadway safety; (2) survey results of other state DOTs on their best practices for implementing messages on variable message signs to improve safety compliance; (3) field test results that identify the most effective messages based on their collected and analyzed crash data; and (4) recommendations on the most effective messages to increase safety compliance on Illinois roads.

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APPENDIX A: LITERATURE REVIEW

APPENDIX A1: SMART WORK ZONE SYSTEMS

Variable Message Signs

Variable message signs (VMS) are also referred to as dynamic message signs (DMS), changeable message signs (CMS), or dynamic message boards. These variable message signs are traffic control devices capable of displaying one or more alternative messages (FHWA, 2009). These programmable electronic signs are usually composed of alphanumeric characters which display information related to road incidents, construction activities, travel times, detour information, road closures, and other messages related to changing traffic conditions. There are three main types of VMS: permanent, portable, and truck mounted (NYSDOT, 2018; MnDOT, 2012). Permanent VMS are usually installed on overhead structures spanning the entire road or on the side of the road. One advantage of permanent VMS is that agencies can typically display longer messages compared to portable VMS, eliminating many challenges regarding abbreviations and limited space. However, due to their fixed structure they cannot be transported to specific sites, so they may not be available where needed relative to the work zone area (Caltrans, 2021). Additionally, they need to be integrated to allow the SWZ system provider to post messages on agency-owned signs, which presents logistical challenges. On the other hand, portable VMS (PVMS) are common in work zones because of their lower costs and portability. PVMS can be easily transported to locations as needed, but they are limited in the amount of information that can be displayed. Although less common, the more limited in size truck-mounted VMS can also be deployed in work zones typically to communicate to motorist an action that should immediately be taken (NYSDOT, 2018).

In order to be effective in informing drivers, VMS must provide timely, reliable, accurate, relevant, concise, and clear information (ODOT, 2018; King and McCrea, 2012). Many states have strict guidelines for the information that cannot be displayed which may include advertisements, flashing animations, general weather information, among others (Roelofs and Schroeder, 2016).

Benefits

VMS have been implemented in numerous DOT projects in the past decades. They are usually coupled with sensors to produce travel time information systems (TTIS), speed monitoring systems (SMS), queue warning systems (QWS), or incident information systems (IIS). In general, they are the main way to communicate critical messages to motorist upstream of areas of concern or alternate routes. The use of VMS on DOT projects has been reported to provide many benefits including reduction in average speeds, as shown in Table 53.

Table 53. VMS Deployments

Agency	Year	Location	Application	Reported Safety and Mobility Benefits	Reference
FDOT	2016-2018	I-75	IIS	6% reduction in average speeds when VMSs displayed crash information.	Alluri et al., 2020
MSHA	2009-2011	I-95	QWS and TTIS	Average traffic diversion of 5-20% to alternative roads. Speed in the majority of cases studied was unaffected.	Haghani et al., 2013
Missouri DOT	2010	I-55, I-57	TTIS	Average speed decreases if 3.64 mph and 1.25 mph in two sites. 41% of drivers relied solely on DMS for detour information	Edara et al., 2012
KSDOT	2010	K-13	QWS	Reduction in average speed of 13%, 10% 17% for text, graphic aided, and graphic PVMS	Bai et al., 2011
SCDOT	2007	I-585, SC72, SC290, SC 101	SMS	Significant reductions in the 85th percentile mean speeds of up to 14 mph	Sorrell et al., 2007
Caltrans	2004	I-15	TTIS	ADT decreased by 19%. Traffic in two main detour roads, I-215 and I-10, increased by 15% and 10% respectively, indicating effective diversion.	Lee and Kim, 2006
GDOT	2003	-	SMS	Reduction of 7-8 mph for approaching traffic	Wang et al., 2003
CSHI	2001	I-90	QWS and DLM	Reduction of vehicle speeds by approximately 3 to 7 mph.	Zech et al., 2008
IDOT	1990	I-57	SMS	Speed reduction of cars and trucks by 4.6 mph and 2.6 mph, respectively, when two VMSs were used within WZ.	Benekohal and Shu, 1992
TxDOT	1985	I-10, I-35, FM 1960	SMS	Mean speed reduction 3-5 mph	Richards et al., 1985

Work Zone Application

VMS can be used to display non-work zone related information such as adverse weather conditions, special events, abducted child alerts, and traffic safety campaigns (MnDOT, 2012). This literature review however, focuses on work zone related applications. According to the FHWA *Portable Changeable Message Sign Handbook*, PVMS in work zones can be used to provide specific messages for: (1) speed reduction; (2) advance notice of lane closures and shifts; (3) diversion to a different route; (4) advance notice of ramp closures; (5) expected reopening of existing closed lane; (6) crash or other incidents; and (7) changes in alignment or surface conditions (FHWA, 2003).

A Pooled Fund Study titled *Planning Guidance for Intelligent Transportation System (ITS) Devices* provided guidelines for the use of VMS for 'Changing Traffic Control or Conditions'. The stated purpose of this guideline is to "notify drivers in advance of special changing traffic conditions and roadway configuration changes associated with road construction or maintenance in order to reduce driver confusion that could result in a crash". This guideline recommends that VMS should be considered if the following three conditions are satisfied (1) candidate location is upstream of an area with construction or maintenance activities that are expected to cause at least 15 minutes of delay to the mainline traffic; (2) candidate location is upstream of traffic control or construction/maintenance activities that are expected to change more frequently than once every 60 days; and (3) posted work zone speed limit is greater than 45 MPH (Enterprise, 2014a).

VMS is also integrated into other SWZ systems to provide information to drivers. Other SWZ systems that utilize VMS as an integral component include: (a) queue warning system; (b) dynamic lane merge system; (c) speed monitoring system; (d) travel time or delay information system; (e) incident detection and surveillance; and (f) construction truck alert systems. These SWZ systems that utilize VMS are described in detail in the following sections of this chapter.

Technical Requirements

There is a wide range of VMS technologies and technical requirements that can be used in SWZ including (1) lighting display technology; (2) matrix display type; and (3) power source. First, the most commonly used lighting display technology is light-emitting diodes (LEDs) that are listed in the FHWA *Guidance for the Use of Portable Changeable Message Signs in Work Zones* (FHWA, 2013). They are typically capable of automatic dimming for nighttime operations, so they provide consistent visibility for many light conditions. Additionally, LED bulbs are rated for 100,000 hours of service which makes them reliable. Second, VMS matrix display types represents the arrangements of the light bulbs. The three main display types are character matrix, line matrix (less common in portable VMS) and full matrix, as shown in Figure 56. The character matrix is used for messages with a small number of characters, while full matrices can be used for longer messages and can replicate typical road signs, if allowed (WisDOT, 2009; FHWA, 2013).

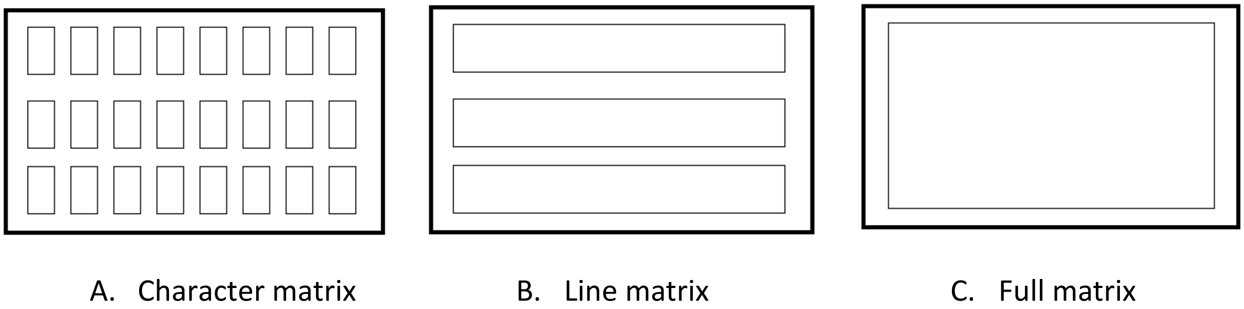

A. Character matrix B. Line matrix C. Full matrix

Figure 56. Photo. VMS matrix display types.

Third, the main power sources of VMS are solar and battery, depending on the conditions of the site and the length of the project (FHWA, 2013). Solar panels can be installed to provide energy to the VMS in the long term, but typically requires sunny environments. If this is a limitation, solar powered systems can be equipped with batteries to store energy and power the VMS for prolonged periods. Alternatively, VMS can be battery-powered which can last up to a week. Generally, this is used in less sunny environments and requires less up-front cost. However, proper planning must be done for recharging and replacing the battery. The recharging duration can last up to a day.

Cost

According to *the Illinois Statewide Intelligent Transportation Systems (ITS) Strategic Plan* Appendix H, portable VMS are estimated to cost $25,000/sign plus $5,000 for the hardware and configuration of the connected roadside unit, and $2,000/sign/year in operations and maintenance costs. The permanent VMS range from $25,000 to $100,000 per sign depending on the size and color plus $5,000 for hardware and configuration, and maintenance and operations cost varying from $2,000 to $5,000/sign/year (IDOT, 2019). Other historical cost estimates can be found in the FHWA *Guidance for Use of Portable Changeable Message Signs in Work Zones* (FHWA, 2013).

Queue Warning Systems

Queue warning systems (QWS), also called end-of-queue warning systems (EQWS), are technologies used in smart work zones to alert drivers ahead of time of upcoming traffic conditions (ADOT, 2019). Specifically, the system is capable of continuously monitoring the traffic on the approaches and within work zone to communicate whether queued traffic is expected ahead (MassDOT, 2016; Enterprise, 2014). Typically, QWS are used to reduce the number and severity of back-of-queue rear-end crashes as well as to help inform drivers of alternative routes (NASEM, 2020).

The QWS setup consists of sensors placed upstream (and within the work zone and termination area if there is a specific need) where queues are expected to form. Then, thresholds in the data collected by the sensors (e.g., specific vehicle speeds, flow, and lane occupancy) are used to broadcast messages to the drivers according to the distance from queue, sensor, or work zone, as shown in Figure 57. The typical messages include "BE PREPARED TO STOP", "STOPPED TRAFFIC AHEAD", and "SLOW TRAFFIC AHEAD" (Hallmark et al., 2020; NASEM, 2020).

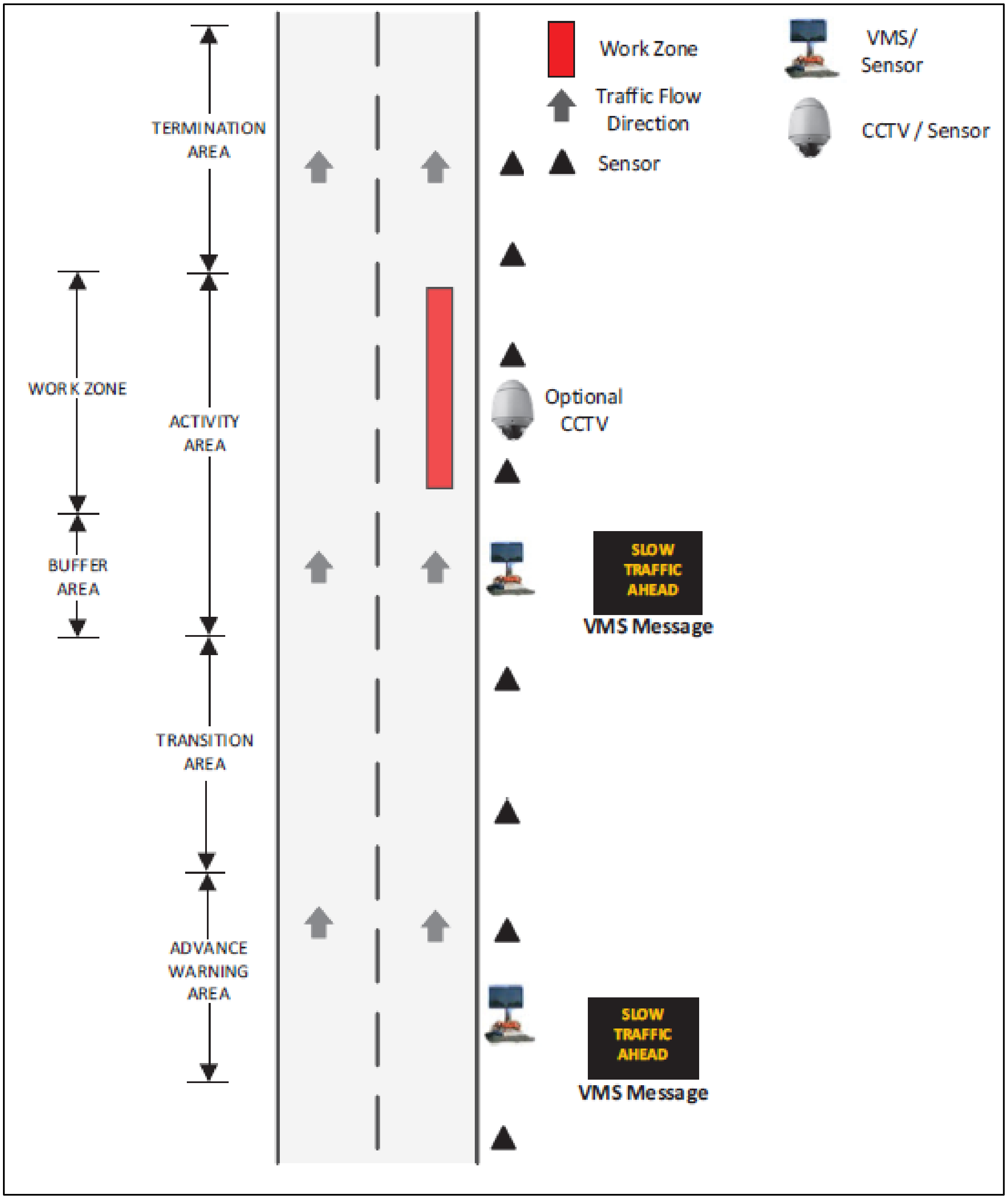


Figure 57. Photo. Queue warning system conceptual layout (CTDOT, 2017).

Benefits

A number of recent studies have reported the safety and/or mobility benefits of implementing QWS in smart work zones in multiple states, as shown in Table 54

Table 54. Reported Benefits of QWS

Agency	Year	Location	Reported Safety and Mobility Benefits	Reference
WisDOT	2017	I-43	15% reduction in crashes and 63% reduction in injury crashes.	Stone, 2018
MnDOT	2016	I-35W	Reduction in the speed variance near the queue locations.	Hourdos, 2017
MnDOT	2016	I-94	22% decrease in crashes, and 54% decrease in near crashes.	Hourdos, 2017
CalTrans	2012-2013	Holiday traffic around a mall	66% reduction in incidents.	Roelofs et al., 2014
IDOT	2010-2012	I-55	13.8% reduction in rear-end queuing crashes.	Roelofs et al., 2014
TxDOT	2013-2016	I-35W	44.1% reduction in crashes.	Ullman et al., 2016
IDOT	2011-2013	I-70/I-57 and I-57/I-64	14% decrease in queuing crashes, 11% reduction in injury crashes.	Ullman and Schroeder, 2014
TxDOT	2006-2007	US59	Reduction in speed variance.	Pesti et al., 2008
TxDOT	2006-2007	IH610	6% reduction in vehicle conflicts and reduction in speed variance.	Pesti et al., 2008
AHTD	2000-2001	I-40	35% reduction in fatal crash rates compared to similar work zones.	Tudor et al., 2003

Work Zone Application

QWS are often deployed in smart work zones when drivers may have limited reaction times due to unexpected changes in traffic conditions or poor visibility. Typical applications of QWS in smart work zones were reported by state DOTs and recent studies to include the following road and traffic conditions (NASEM, 2020; Roelofs et al., 2014; Ullman et al., 2014):

- Physical road characteristics, such as curves, steep grades, or poor lighting that may limit the drivers' reaction time.
- Queue lengths are expected to vary greatly either day by day (e.g., weekday vs weekend) or hour by hour (e.g., peak vs off-peak).
- Project reduces road capacity due to lane closures, shoulder closures, or narrow lanes in which queues and significant speed differentials are expected.
- History of high crash frequencies on the site.

Technical Requirements

Several state DOTs provide technical requirements for the use of QWS in smart zones to ensure the quality and reliability of the system. For example, the information displayed to the motorist may depend on the quality of data collected, so minimum data collection standards are expected for the system's success. For example, the Minnesota Department of Transportation's (MnDOT's) technical requirements for implementing QWS include (MnDOT, 2015):

- QWS shall be capable of detecting the full range of traffic speeds including stopped traffic, low speeds (less than 30 MPH), and high speeds (over 30 MPH).
- QWS vehicle detector system shall be 95% accurate regarding speed of vehicles at any speed, including stopped vehicles.
- Location of the slowed or stopped traffic shall be accurate to within ½ mile.
- Message shall include the distance to the end of the queue.
- End of queue location shall be updated at intervals no greater than one minute.
- Message shall be capable of being sent in a variety of formats compatible with VMS.
- System shall be able to send the notifications of device failures to specified contacts through the most effective format including email, phone, or text message.
- Central System logic shall recommend standards-compliant messaging to display on all VMS in the system.
- All failures including maintenance and wireless communications shall have 98% uptime over the project life.

The technical requirements specified by Michigan Department of Transportation (MDOT) for the use of QWS in smart work zones requires the use of PVMS, sensors, and a server to store data and process traffic data. Additionally, MDOT reported that additional cameras can enhance the deployment of QWS by monitoring the end of the queue as well (Roelofs et al., 2014).

Cost

The cost of implementing a QWS varies according to the project needs based on the number of sensors, cameras, message boards, and the duration of the project. For example, NASEM (2020) reported that the cost per unit of individual QWS components such as PVMS, traffic sensors, and cameras is approximately $1000 per week per unit. The Texas Department of Transportation (TxDOT) provides a guideline stating that, in general, SWZ costs can be expected to range between 1% to 5% of the total project cost (TxDOT, 2018). In addition, several state DOTs have reported the costs of implementing QWS in smart work zones on the following completed projects:

- TxDOT completed a project in 2017 which continuously monitored traffic on the approaches and within the work zone to detect slow or stopped traffic. The project included the lease of 1 PVMS and 4 doppler radars for 70 days. The cost per equipment setup was a total of $104,160 or $1,488/day (TxDOT, 2018).

- TxDOT project located in I-35 spanned a length of 96 miles through Central Texas. Two main setups were deployed depending on the queue length expected in each closure. For shorter queues, a speed sensor was placed 0.5, 1.5, and 2.5 miles upstream of the taper, and a PVMS was placed 3.5 mi upstream of the taper. For lane closures with longer queues, additional sensors were placed 3.5, 4.5, 5.5, and 6.5 miles upstream of the taper, and a second PVMS was placed at 7.5 mi upstream. The QWS was deployed for 216 nights, and the estimated cost ranged from $3,700 to $5,000 per night which included the maintenance, labor, and deployment (Ullman, 2016).

- In 2013, the Kansas Department of Transportation (KSDOT) completed a project in a 1.48-mile stretch of I-35 at the Homestead Lane interchange. The ITS, which included 21 Wavetronics sensors, 18 PVMS, and 6 CCTV cameras, were deployed for approximately 150 days (April-Sept 2013). The total cost was $1.6M, or approximately $305 per equipment per day (Bledsoe et al., 2014).

- The Illinois Department of Transportation (IDOT) completed a project for 25 months from 2010-2012 which included the deployment of VMS, 25 portable traffic sensors, 20 video cameras, and 1 central base station. The initial mobilization and deployment cost of the system components was a total of $1.5M and the traffic management system operations and maintenance was $1,800 per month for 25 months (Ullman, 2014).

- The Iowa Department of Transportation (Iowa DOT) posted a per-device cost in the 2017 *Traffic Critical Projects Program*. The cost for PVMS, detectors with cellular modems, and monitoring cameras were, on average, $2,844 per deployment plus $23 per day for maintenance and operations and a cost of $480 per equipment relocation (Falero et al., 2017).

Additional project examples of QWS applications and costs can be found on the U.S. Department of Transportation (USDOT) ITS Deployment Evaluation website (USDOT, 2022).

Dynamic Lane Merge Systems

Dynamic lane merge systems (DLMS) use variable message signs (VMS) that are placed upstream of expected bottlenecks caused by lane closures to direct traffic into either early merging or late merging strategies. Early merging advises drivers to switch lanes before the “merging point” in which traffic is forced to merge due to tapers. Alternatively, the late merging strategy instructs drivers to remain in their respective lanes until they are forced to switch lanes by the lane closure, in which drivers are expected to alternate turns at the taper (i.e., “zipper merge”) (FHWA, 2012). The early merge strategy is usually preferred in low traffic conditions while the late merging is used in high traffic to maximize the full capacity of the road. These merging strategies can be used dynamically and alternated when needed. For instance, the message "MERGE AHEAD / USE ALL LANES" can be displayed on a VMS to encourage late merging (e.g., see Figure 58), and can be turned off when needed to allow early merging. Additionally, traffic detecting sensors can be used to monitor traffic conditions with automated thresholds to display instructive messages on the VMS. Examples of these messages are: "USE BOTH LANES / TO MERGE POINT," "MERGE HERE", "TAKE TURNS", among others (FHWA, 2012; Radwan et al., 2009; Kang et al., 2006; Grillo et al., 2008).

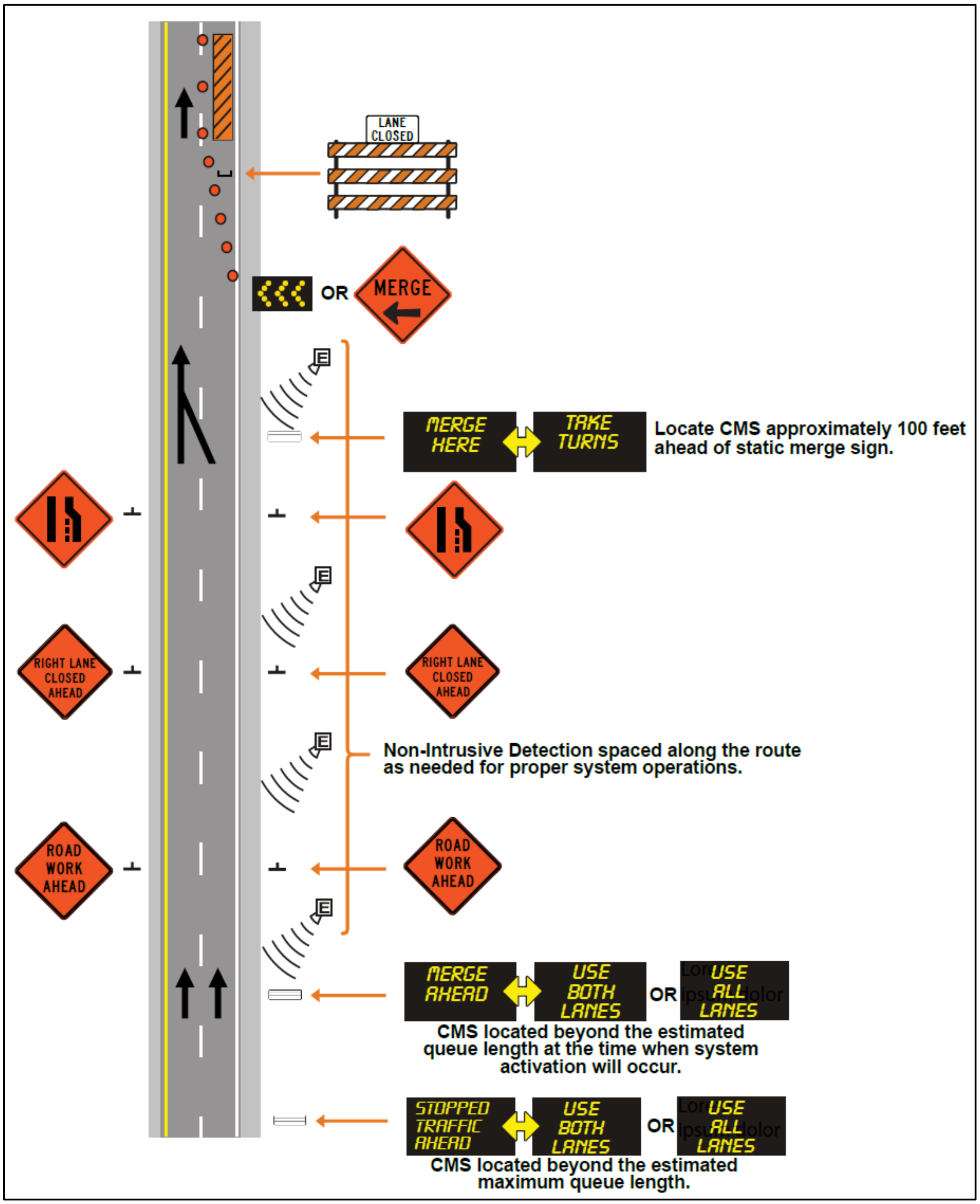


Figure 58. Photo. Example dynamic lane merge system (MnDOT, 2020).

Benefits

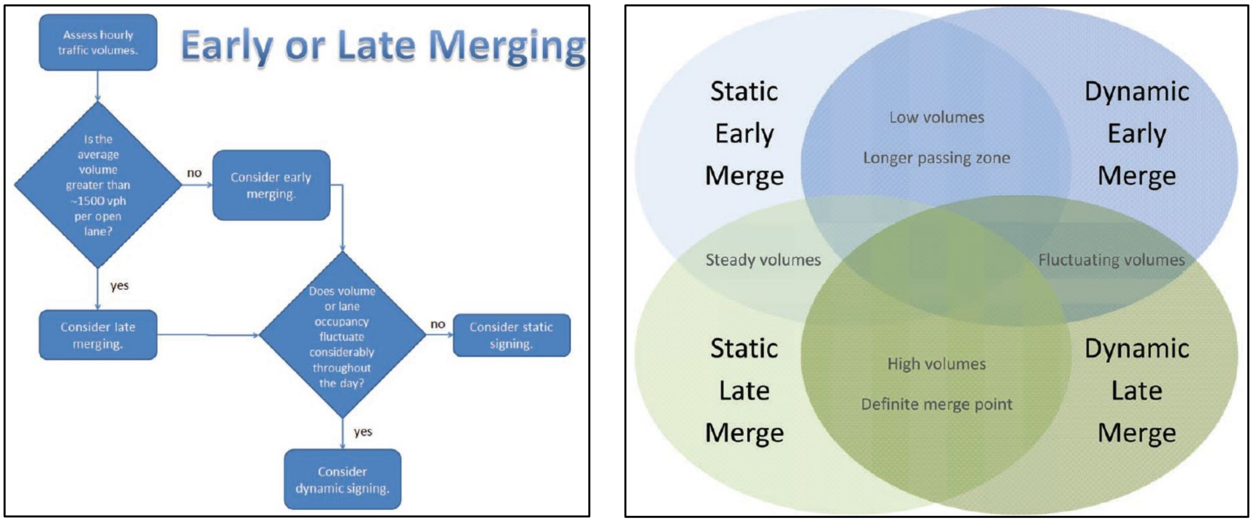
According to a MnDOT study, DLMS have the potential to reduce the length of upstream queues by 40% and greatly reduce the speed differentials between lanes (MnDOT, 2020). These queue and speed reductions also help smooth traffic conditions, reduce aggressive driving, and reduce dangerous merging maneuvers. Consequently, these benefits result in a reduction of rear-end crashes. The use of DLMS has also been reported to provide additional benefits such as increased average speeds, decreased delay, and increased traffic flow in work zones, as shown in Table 55

Table 55. Reported Benefits of DLMS.

Agency	Year	Location	Reported Safety and Mobility Benefits	Reference
NCDOT	2016	I-85	Increased lane utilization from 15% to 17%. Significantly decreased the percentage of dangerous merges from 40% to 7%. Average travel time decreased by 1 min. and increased average speed by 11.3 mph.	Vaughan et al., 2018
FDOT	2008	I-95	Increased roadway capacity compared to regular motorist awareness system. Reduced speed fluctuations	Radwan et al., 2009
Iowa DOT	2008	I-80	No significant changes in merging behavior due to low volumes, and unreliable equipment	Sperry et al., 2009
MDOT	2006	I-94	Increased average speed, decreased delay, and increased throughput	Grillo et al., 2008
MnDOT	2004	I-494, US-52, I-35	Minimal queue lengths Throughput did not change	URS Corporation, 2004
MDOT	2004	I-131	Reduced forced merges when system was activated. Dangerous merges were three times higher when the system was off. Forced merges were 7 times higher when the system was off.	FHWA, 2008
KDOT	2003	I70	Reduced queue lengths. Drivers occupied the lanes more efficiently once the late merge message was activated.	Meyer, 2004
MDOT	2003	I-94	Reduced travel time delays. Reduced number of stops per vehicle. Reduced aggressive driving maneuvers	Datta et al., 2004
MSHA	2003	I-83	Increased overall throughput by up to 11% More uniformly distributed volumes between open lane and closed lane Reduced maximum queue length by up to 33%	Kang et al., 2006

Work Zone Application

The FHWA provides guidelines on the use of dynamic lane merging systems to encourage either early or late merging using static or dynamic approaches based on several factors including traffic volumes and length of merging area, as shown in Figure 59-A and Figure 59-B (FHWA, 2012). In general, static merging is recommended for steady traffic volumes, while dynamic merging is recommended for fluctuating traffic volumes. FHWA reported that DLMS are most effective when traffic volumes range between 1200 to 1800 vehicles per hour (vph) with the most common implementations using a 1500 vph threshold. Other recent studies identified significant benefits when using DLMS on roadways where the percentage of heavy vehicles is greater than 20% due to the slow acceleration of heavy trucks (Datta et al., 2007; Grillo et al., 2008, Sperry et al., 2009; URS Corporation, 2004). Furthermore, Minnesota Department of Transportation (MnDOT) *IWZ Toolbox* recommended that dynamic late (zipper) merge should be considered when: (1) two or more lanes of traffic must merge when one or more lanes are closed to traffic; (2) traffic volume exceeds 1500 vehicles/hour; (3) estimated queue lengths may encroach beyond an upstream intersection or interchange operations; and (4) speeds and lane occupancy volumes are anticipated to vary unpredictably causing the motorist to have trouble identifying the best lane usage practice. MnDOT further advice that DLMS may be used in combinations with QWS, travel time information systems, and congestion warning systems to enhance its effectiveness (MnDOT, 2020). This may typically require only one extra PCMS on site.



A.

B.

Figure 59. Photo. FHWA decision diagram and conditions for use of DLMS (FHWA, 2012).

Technical Requirements

In general, DLMS require the basic layout of a typical SWZ system including traffic sensors which detect dynamic traffic conditions, and VMS to display the merging strategy. To accomplish this, the SWZ system may need an automated traffic system that stores the data and uses algorithms to automatically control the VMS (NASEM, 2020). For instance, Radwan (2009) reported that a simplified DLMS (SDLMS) should provide the capabilities of: (1) storing all displayed messages along with time and date stamps; (2) displaying default and advisory messages that are automatically selected based on traffic conditions that are monitored using traffic sensors; (3) programming default and advisory message content and related thresholds from the central base station; (4) storing messages created by an authorized user to override any default or automatic advisory message; (5) incorporating an error detection/correction mechanism to ensure the integrity of the system; and (6) independent communication between central computer base station and any individual PCMS or traffic sensor station through the full range of deployed locations (Radwan, 2009).

Cost

The cost of implementing a DLMS varies according to the project needs. Several state DOTs have reported the costs of implementing DLMS in smart work zones, but according to an Illinois official, it is important to note that prices have significantly decreased industry-wide in the period of 2017-2022. The following are historical records of completed project, along with updated costs estimates from 2019-2020:

- MDOT reported the use of early merging DLMS for two construction seasons (2002 and 2003) for a total of about 4 months. Their total cost for both seasons was $111,134.50, which included dynamic lane merge trailer and its operating cost, relocation cost of the trailer, PCMS and its operating costs, and cost of police enforcement on site (Datta et al. 2004).
- MDOT reported the use of DLMS for a period of approximately 7 months which included 4 PCMS for a total cost of $57,108 in 2006 (Datta et al. 2007; and Grillo et al., 2008).
- FDOT reported the costs for a 1-year rental of a one-direction DLMS to be between $40,000 to $43,000 (Radwan et al., 2009).
- KDOT implemented DLMS coupled with a QWS which included a CMS and 8 CCTV cameras for monitoring. The total cost of the deployment was $5,000 per month. In addition, KDOT reported the rental of three radar for an extra cost of $1,500 per month. The total project cost was $99,970 which equated to approximately $840 per day (ADOT, 2019).
- MnDOT reported a cost for active zipper merge systems using two PCMS and six sensors to be $58,000 per 6 months based on 2018 rental prices (NASEM, 2020).

Speed Feedback Signs

Speed feedback signs are dynamic signs placed on the side of the road with speed radars to measure the approaching speed of drivers and display it either via VMS or a smaller LED display (e.g., on a trailer or truck-mounted), as shown in Figure 60. This technology is also referred to as dynamic speed display, radar speed display, speed display trailers, speed monitoring devices, or “your speed is” signs. Speed feedback signs have been shown to decrease the speed of approaching drivers as well as increase speed limit compliance, especially when posted work zone speed limits are reasonable as reported by an IDOT official. The drivers’ speed are usually shown besides the speed limit sign to inform drivers of any speeding behavior. Speed feedback signs are usually deployed with reduced speed limit signs or other standard work zone warning signage. VMS applications of this technology can also be programmed to show specific messages according to speed thresholds such as: “YOUR SPEED XX MPH/ SLOW DOWN,” “REDUCE SPEED IN WORK ZONE,” “EXCESSIVE SPEED/FINES DOUBLE”, “REDUCE SPEED TO XX MPH”, or “XX MPH SPEED ZONE” (NASEM, 2020; Fisher et al., 2021, FHWA, 2013).

A. Speed feedback sign with LED display

B. Speed feedback sign with VMS

Figure 60. Photo. Speed feedback signs examples (Fisher et al., 2021; NASEM, 2020).

Benefits

A number of recent studies have reported the safety and/or mobility benefits of implementing speed feedback signs in smart work zones in multiple states as shown in Table 56 (Fisher et al., 2021). However, according to an IDOT official, this system may provide mobility and safety benefits only when the posted speed limits are reasonable for the conditions of the work zone. Otherwise, if speed limits are too low, the signs are usually ignored, and no benefits are observed.

Table 56. Reported Benefits of SFS

Organization	Year	Location	Reported Safety and Mobility Benefits	Reference
Oregon DOT	2013-2014	I-5	Reduction of vehicle speeds	Gambatese, 2014
ADOT	2012	SR-89	4 mph reduction in vehicle speeds More than 25% reduction of speeding over the limit by 5 mph and more.	Roberts, 2012
IDOT	2006-2007	I-64 and I-55	5 to 7 mph reduction in vehicle speed but is less effective than the SPE system.	Hajbabai, 2011
NDOT	2007	CR-215 and I-15	8 to 9 mph reduction in vehicle speed.	Teng, 2009
SCDOT	2006	I-585, SC-72, SC-290 and SC-101	3 to 10 mph reduction in vehicle speed.	Sorrel, 2007
SCDOT	2005-2006	SC-101, US-278, SC-121, SC-295 and SC-292	Reduction in vehicle speed. Reduction of speeding.	Sarasua, 2006
WisDOT	2005-2006	STH-29 and STH-64	Significant reduction in both the average speed and percent of speeding during nighttime hours.	Chen, 2007
SCDOT	2005	SC-219, SC-290 and SC-72	3 mph reduction in vehicle speed. 4 mph reduction in vehicle speed during period of excessive speeding.	Mattox, 2007
KSDOT	2002	K-10	5 mph reduction in vehicle speed. 40% reduction of speeding Increase in speed uniformity.	Meyer, 2002
Oregon DOT	2002	I-205, I-84 and US-97	27% to 48% reduction of speeding, and 5% to 23% reduction of 85th percentile speed.	Gambatese, 2015
UDOT	2002	I-215, SR-89 and I-80	4 mph reduction in vehicle speed	Bowie, 2003
MwSWZDI	2001	I-80	3 mph reduction in vehicle speed. 10% to 20% increase in speed limit compliance.	Pesti, 2001
TxDOT	2000	US-83 and US-62	2 to 9 mph reduction in vehicle speed and 3 to 10 mph reduction in truck speed. Reduction of speeding.	Fontaine, (2001)

Work Zone Application

In 2013, the FHWA developed speed management strategies for work zones on roadway projects. These speed management strategies were recommended in areas that observed: high incidence of speeding drivers, high speed variance between vehicles, high incidence of rear-end crashes, and/or work zone design that includes a pattern change, lane closure, or flagging operation as these would tend to increase the speed variance within the work zone (FHWA, 2013).

A research study recommended that the aforementioned speed management strategies can be expanded to include work zones with: posted speed limits of 35 mph or more, observed mean speeds that exceed the posted speed limit by 10 mph or more, observed 85th percentile speeds that exceed the posted speed limit by 10 mph or more (provided the speed limit is appropriate for the circumstance), and history of speed-related accidents (Veneziano et al., 2012).

Similarly, MnDOT also recommended deploying speed feedback signs in work zones with hazardous roadway conditions that require extra driving precautions such as a temporary unusually tight curve or rough road surfaces; workers adjacent to travel lanes without protection of positive barrier; and/or used with advisory speed or regulatory speed limits (MnDOT, 2020).

IDOT officials also consider the implementation of speed feedback signs ¼ to ½ mile in advance of exposed workers. This increases drivers' awareness to reduce the risk of incident with workers and increase the overall safety of the site.

Technical Requirements

Speed feedback signs require a speed detector and either a VMS or a trailer/truck-mounted LED display to show the drivers' speed limits as well as data collection and storage capabilities, if needed. Illinois Department of Transportation recently revised the special provisions for speed feedback signs which include the following (Elston, 2021):

- The speed display trailer shall consist of an LED speed indicator display with self-contained, one-direction radar mounted on an orange trailer. The height of the display and radar shall be such that it will function and be visible when located behind concrete barrier.
- The speed measurement shall be by radar and provide a minimum detection distance of 1000 ft (300 m). The radar shall have an accuracy of ±1 mile per hour.
- The speed indicator display shall face approaching traffic and shall have a sign legend of "YOUR SPEED" immediately above or below the speed display.
- The sign letters shall be between 5 and 8 in. (125 and 200 mm) in height.
- The digital speed display shall show two digits (00 to 99) in mph.
- The color of the changeable message legend shall be an amber legend on a black background.
- The minimum height of the numerals shall be 18 in. (450 mm), and the nominal legibility distance shall be at least 750 ft (250 m).

- The speed indicator display shall be equipped with a violation alert that flashes the displayed detected speed when the work zone posted speed limit is exceeded (typically above 5mph).

- The speed indicator shall have a maximum speed cutoff. On roadway facilities with a normal posted speed limit greater than or equal to 45 mph, the detected speeds of vehicles traveling more than 25 mph over the work zone speed limit shall not be displayed. On facilities with normal posted speed limit of less than 45 mph, the detected speeds of vehicles traveling more than 15 mph over the work zone speeds limit shall not be displayed.

- On any roadway facility if detected speeds are less than 25 mph, they should not be displayed.

- The display shall include automatic dimming for nighttime operation.

These provisions are consistent with those used by other state DOTs such as MnDOT *IWZ Toolbox* (2020) and NASEM (2020). Additionally, Iowa DOT (2016) special provisions include detailed requirements for the power system, display behavior, LEDs requirements, controls, operating modes, radars, and regulatory signs.

Cost

The cost of speed feedback signs vary based on the display type VMS or LED. The VMS are estimated to be \$10,000 to \$12,000, while the smaller LED speed displays are estimated to be \$7,000 to \$10,000 (NASEM, 2020). Data collection storage capabilities may add an additional cost of about \$5,000. From specific projects, the Maryland State Highway Administration (MSHA) reported a cost of \$3,000 per sign per month which included two PCMS rentals (MSHA, 2005). Additionally, the South Carolina DOT reported an approximate cost of VMS with radar of \$20,000 (Mattox et al., 2007). The Iowa DOT also reported costs between \$2,000 to \$11,000 (Hallmark and Hawkings, 2014).

Automated Speed Enforcement

Automated speed enforcement (ASE) is a roadside SWZ system usually involving two radars, a display (e.g., VMS or small LED display), and the capability of capturing images (Benekohal et al., 2008; NASEM, 2020). Typically, one of the radars is used to detect the speed of vehicles upstream of the enforcement point to display the speed to drivers and provide them with a chance to reduce their speeds before enforcement, as shown in Figure 61. The purpose of the ASE is to increase speed compliance, improve safety, and support law enforcement by reducing their roadway exposure and allowing officers to focus on other duties.

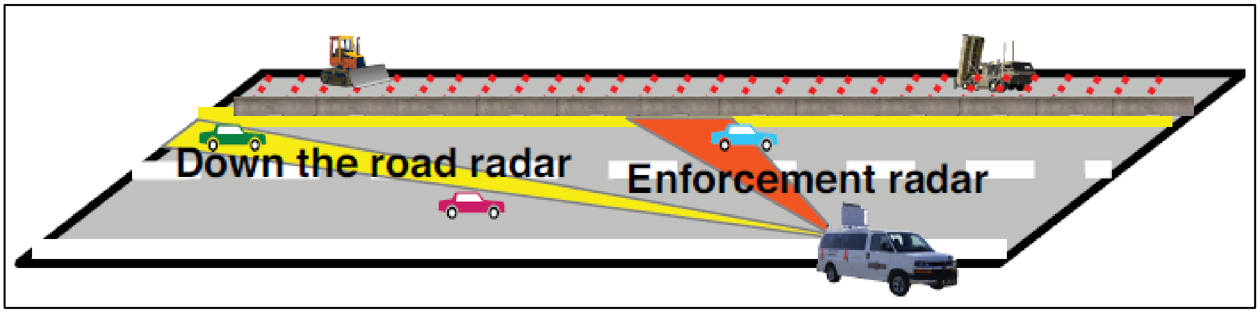


Figure 61. Photo. ASE operation setup (Benekohal et al., 2008).

Benefits

The Illinois Department of Transportation (IDOT) pioneered the deployment of ASE in work zones in 2006 (Benekohal et al., 2008). Since then, other State DOTs have started to adopt ASE as it has been shown to significantly reduce speeds, improve safety, and increase compliance. Due to the legal requirements however, the adoption has been slower compared to other systems. Table 57 presents a summary of deployments in the United States, along with their reported benefits.

Table 57. Reported Benefits of ASE System Deployments

DOT	Year	Location	Reported Safety and Mobility Benefits	Reference
PennDOT	2020-2021	I-76, I-276, I-476	Reduced number of crashes by 19%.	PennDOT, 2022
CalTrans	2012-2015	SR-99, I-210	60% of speeding vehicles were captured by the ASE.	Ravani et al., 2015
MnDOT	2010-2020	Hwy 169	Increased drivers' visual attention. Increased glances to speed meter.	Morris, 2016
MnDOT	2008-2009	I-695, I-95	Reduced number of aggressive motorists.	Franz and Chang, 2011
MSHA	2007-2009	98 enforcement locations	Decrease in violation percentage Reduced speeding of 12 mph above the speed limit (or more) by 90%.	MSHA, 2021
ODOT	2009	US-30	Reduced speeding by 27.3%.	Joerger, 2010
WSDOT	2008-2009	I-5	Decreased number of vehicles traveling above 70 mph in a 60-mph work zone.	WSDOT, 2009
IDOT	2007	I-55	6.8 mph reduction in free flow speed.	Avrenli et al., 2012
IDOT	2006	I-64, I-55	Reduced speeds by 5 mph to 7 mph Reduced frequency and degree of speeding. Increased mean headway.	Benekohal et al. (2009, 2011)

Work Zone Applications

The deployment of ASE often requires legislation permitting its use. It also requires active participation of state DOT, state or local police, state department of motor vehicles, and courts. Typical applications of ASE in smart work zones were reported by state DOTs and recent studies to include the following road and traffic conditions (NASEM, 2020):

- Active work zones on expressways or controlled-access highways (speed limit of 45 mph or higher).
- Workers are exposed or there are motorist hazards (e.g., lane shifts, lane splits, reduced lane widths, closed shoulders, rough pavements, etc.).
- Work zones remain active over a long period of time.
- 24-hour speed enforcement is desired.
- Law enforcement availability is limited.

Technical Requirements

The technical requirements of deploying ASE include: (1) speed detection equipment approved by the International Association of Chiefs of Police; (2) image-capturing equipment triggered by the speed detection radars or lasers with sufficient resolution to capture license plates at different environmental and lighting conditions; (3) database storing all information related to the citations; and (4) work zone warning signs which communicate the use of ASE to the drivers ahead of the enforcement point (PennDOT, 2022; Ravani et al., 2015; Morris, 2016; Franz and Chang, 2011; MSHA, 2021; Joerger, 2010; WSDOT, 2009; Avrenli et al., 2012; Benekohal et al., 2009 and 2011).

Cost

The estimated cost of ASE deployment was reported to be \$150,000-\$250,000 including system hardware and software costs (NASEM, 2020). In 2006, the monthly estimated cost was reported to be \$2,950 per month per enforcement van that includes the cost of van, equipment, maintenance, upgrades, and training, plus a \$15 processing fee per citation (Benekohal et al., 2010).

Variable Speed Advisory Systems

Variable speed advisory (VSA) systems or speed notification systems (SNS) use VMS to display real-time downstream speeds to drivers so they can preemptively slow down before reaching the bottleneck. This system potentially reduces aggressive driving as drivers are always aware of the slower upcoming traffic (FHWA, 2013). An example of variable message signs (VMS) messages displayed ahead of the work zone are presented in Figure 62.

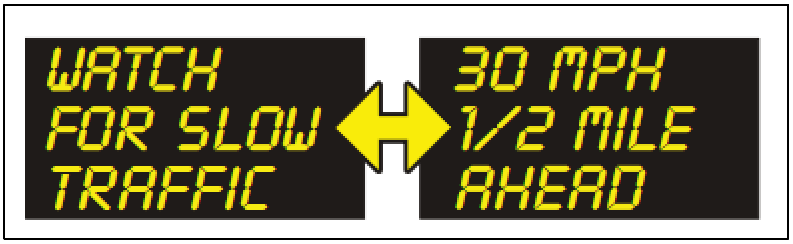


Figure 62. Photo. Example of VSA messages (MnDOT, 2020).

Benefits

A number of recent studies have reported the safety and/or mobility benefits of implementing VSA in smart work zones in multiple states, as shown in Table 58.

Table 58. Reported Benefits of VSA Deployments

Organization	Year	Location	Reported Safety and Mobility Benefits	Reference
MnDOT	2016-2017	I-94	Reduction of more than 30% in the selected deceleration rates were observed.	Hourdos, 2019
MoDOT	2017	I-270	Effective in slowing down drivers gradually as they approached the work zone bottleneck and reducing any sudden speed changes.	Edara et al., 2017
UDOT	2010	Beck Street, Salt Lake City	During slow traffic conditions, the system was in general effective at increasing mean speeds and decreasing speed variances, thus providing smooth traffic flow to drivers.	Wilson and Saito, 2012
MnDOT	2006	I-494	25% to 35% speed reduction 7% increase in total throughput 20% to 60% compliance level with the speed advisory	Kwon et al., 2007
MwSWZD	2003	US-41	Only one incident in the work zone duration in the spring and summer of 2003. Drivers expressed satisfaction with the sign. Delay was approximately the same for diverted and non-diverted drivers.	Horowitz and Notbohm, 2003
MoDOT	2002	I-70	63% of drivers slowed down and 3.6% of drivers diverted to alternate routes. Reduced speeds by 7 mph on average.	King et al., 2004
MwSWZD	2002	I-680	Due to low levels of demand, the system did not significantly decrease speeds, increase diversion, or decrease demand.	Pesti et al., 2002
MwSWZD	2000	I-80	Maximum of 4% diversion.	McCoy, 2000.

Work Zone Application

Typical applications of VSA in smart work zones were reported by a FHWA pooled fund study and MnDOT to include the following road and traffic conditions (Enterprise, 2015 and MnDOT, 2020):

- Schedule of the construction activities being performed AND the design of the work zone is such that the vehicles are not required to be slowed to the same speed 24 hours per day. For example, if vehicles are slowed to a speed during the day when workers are present, but when work is not occurring the absence of workers and layout of the construction zone (lane width, geometries, structure) would allow higher speeds.
- Construction zone already exists and there is a noticeable differential in the speed of vehicles as they progress through the work zone (where travelers would benefit from slowing earlier).
- Queue lengths are estimated to vary greatly, day-by-day and hour-by-hour such that a suitable location for a traditional fixed work zone signage cannot be predicted.
- Roadway geometry (e.g. terrain) may cause poor visibility of end of traffic queues, causing short reaction times and panic stopping.
- Alternate routes available prior to the queue must have the capacity to accept vehicles that may deviate based upon the information displayed on the VMS. Accurately assessing the current capacity and traffic conditions of road conditions is important, otherwise no benefit may be gained.
- Queue is estimated to stop downstream of the first occurring VMS in the system.

Technical Requirements

The VSA system usually requires at least one VMS and one speed detection technology. Most commonly, the system is deployed with multiple VMS to gradually advise lower speed limits as the vehicle approaches the intersection (Edara et al., 2017). Furthermore, the VMS must be programmable to show speed advisories according to downstream detection thresholds. The technical requirements are often similar to those of the queue warning system or travel time information system including: (1) the system should alert drivers of an upcoming traffic slow-down or stopped traffic, providing time to determine possible route alternates, and to be prepared to stop safely; and (2) the system should provide current traffic status information to drivers so that drivers can choose to divert to avoid the situation, to reduce driver anxiety, and to reduce crashes involving drivers encountering unexpected stopped traffic (MnDOT, 2020).

Cost

The estimated cost of VSA deployment was reported by several state DOTs. For example, UDOT reported the VSA deployment cost to include equipment rental costs of $173 to $329 per day, equipment mobilization, training, software configuration, and ½ full-time field operator cost. Similarly, CDOT reported VSA deployment cost of $550 per unit per month, with a one-time mobilization fee of $10,000. Furthermore, SDDOT reported a VSA deployment cost of $5,700 per unit along with a monthly maintenance fee of $1,700 for software and modems (NASEM, 2020).

Travel Time and Delay Time Information Systems

Travel time information systems (TTIS) continuously monitor travel time through a work zone and display this information to the motorists ahead of time so they can make informed route choices accordingly. These systems may also display the delay ahead which is the current travel time minus the regular free-flow travel time on the road, usually rounded to the nearest 5-minute mark. TTIS may also refer to systems which provide travel time estimation for alternative routes, so motorist can make informed decisions based on other routes' travel time as well. This generally requires knowledge on the alternative routes travel time which is only cost effective if third party probe data is available (e.g., from Google, HERE, INRIX, etc.) instead of installing sensors on every advised alternative route. Motorists tend to overestimate the additional (often unexpected) travel time caused by work zones, and this could lead to dangerous driving behavior. Therefore, informing motorists of actual travel time may also decrease aggressive driving maneuvers (TxDOT, 2018). A typical TTIS layout is presented in Figure 63.

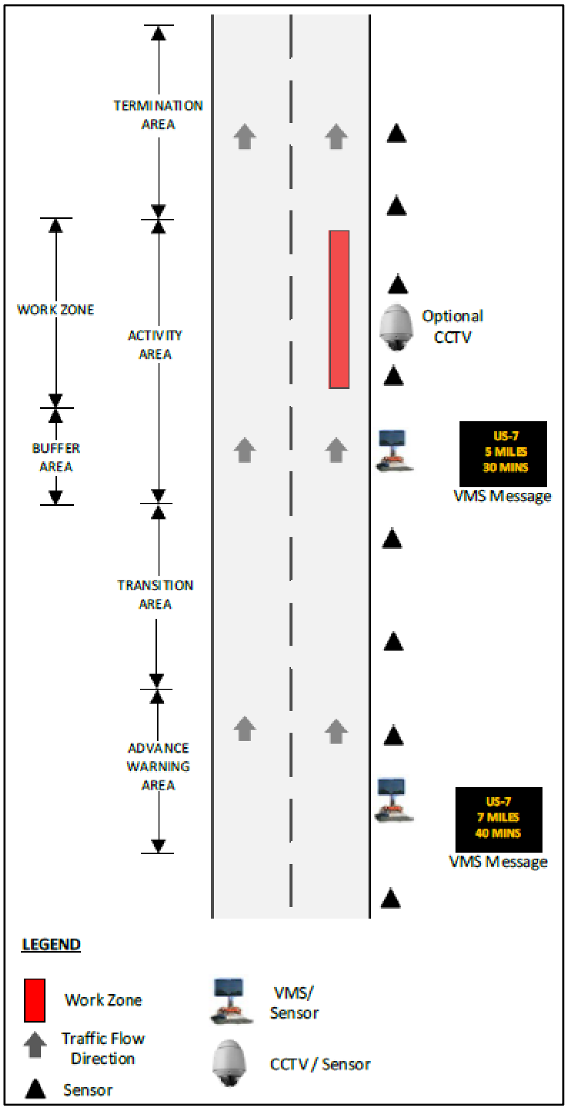


Figure 63. Photo. TTIS typical layout (CTDOT, 2017).

Benefits

A number of recent studies have reported the safety and/or mobility benefits of implementing TTIS in smart work zones in multiple states, as shown in Table 59.

Table 59. Reported Benefits of TTIS

Agency	Year	Location	Reported Safety and Mobility Benefits	Reference
INDOT	2009	I-65	Help facilitate more flexible innovative contracting methods 30% increase of observed probes diverting along the trail-blazed route	Haseman, 2010
CalTrans	2008	I-5	5.3% to 8.7% diversion was observed, Travel time savings of 3 to 4 minutes reported.	Chu et al., 2005
SCDOT	2004	I-15	18% reduction of traffic demand through the SWZ during peak hour Significant volume increases to detour freeways. 40 minutes reduction in peak time maximum delay	Lee, 2006
KYTC	2003	I-64	The difference between predicted travel times and actual travel times was less than 4 minutes. Increase in traffic on US 60, which is a parallel route to I-64.	Pigman, 2004
NCDOT	2003	I-95	85% of survey respondents changed route in response to CMS travel time display	Bushman and Berthelot, 2005
IDOT	2001-2002	I-55	No significant traffic backups despite being a busy interstate. Safety benefits due to the decreased number of moving violations and small number of crashes in work zone	FHWA, 2004
WisDOT	2001	I-94	Diversion with or without TTIS is about equal. No evidence of significantly increased safety, low number of crashes	Horowitz, 2003, Notbohm, 2001
ODOT	2000	I-75	The travel time prediction was accurate. The information was helpful for the drivers	Pant, 2001
Ohio DOT	2000	I-17	88% of travel times shown on the CMS were within 4 minutes accuracy.	Zwahlen and Russ, 2001

Work Zone Application

Typical applications of TTIS in smart work zones were reported by state DOTs and recent studies to include work zones that cause (1) ten minutes or more of additional travel time; and (2) more than five miles of delay beyond the PVMS location and preferably ten miles or more if multiple alternate routes are available (NASEM, 2020). FHWA *Work Zone Operations Best Practices Guidebook* recommended that TTIS be implemented when there is unreliability of travel times for construction projects which may delay commuters (FHWA, 2013). TTIS helps commuters compensate their departure times and routing according to the expected delays to improve the reliability of their travel times. Moreover, the guidebook states that projects benefiting from TTIS usually incorporate complex staging. TTIS may also be considered when easily accessible alternate routes can accommodate long-distance, regional travelers (Enterprise, 2014).

Furthermore, New Jersey DOT developed a scoring system that can be used to determine the need for TTIS in work zones, as shown in Table 60 (NASEM 2020). This scoring system requires designers to provide answers and numerical scores for ten work zone related questions/conditions based on specified criteria. These individual scores are then summed up to determine the need for TTIS deployment. NJDOT's guideline states that if the total score is less than 35, the system should not be deployed. If the total score is between 35 and 45, it should be reviewed by the executive manager of mobility and systems engineering. Otherwise, if the total score is above 45, the system should be deployed (NJDOT, 2013).

Table 60. NJDOT Scoring System to Determine Need for TTIS (NJDOT, 2013).

No.	Condition	Scoring Criteria
1	Based on proposed work zone, will there be a long-term loss of traveled lane continuously for 3 or more months? [a]	Yes: 10 points No: 0 points
2	Based on proposed work zone, will there be a temporary loss of traveled lane continuously for 3 or more months? [b]	Yes: 10 points for 6 hours of the day 9 points for 5 hours of the day, etc. No: 0 points
3	Does section of the highway containing proposed work zones include parallel local and express lanes?	Yes: 10 No: 0
4	Are viable alternative routes available so motorists can avoid work zone?	Freeway: 10 US route: 7 State route: 5 Local road: 3 No: 0
5	Does one-way AADT or ADT exceed 60,000 in the direction of proposed work zone? [c]	Yes: 1 × each 10,000 above 60,000
6	Does traffic volume per lane exceed 1,500 vphpl in the remaining lanes if answer to question 1 is an affirmative? [d]	Yes: 1 × each 100 above 1,500
7	Will traffic volume exceed 1,500 vphpl in the remaining lanes if answer to question 1 is an affirmative? [e]	Yes: 1 × each 100 above 1,500
8	Is highway section containing proposed work zone a known location of congestion for the congestion management system?	Makes top 10: 10 Makes top 20: 9 Makes top 30: 8, etc.
9	Is section of the work zone near major traffic generators?[f]	Based on severity: 0-5 Seasonal: 10
10	Is work zone proposing temporary bridge, contraflow lanes, or cattle chute?	Based on complexity: 0-5
	Total Score	

Note:

[a] This includes the conditions in which a traveled lane is lost permanently from the proposed work zone and continuously for an extended period of time (Loss of highway lane continuously for 3 months).

[b] This includes the condition where the loss of highway lane is temporary, limited to peak periods of the day, and only for an extended period of time (Loss of highway lane only during certain hours of the day for an extended period of time).

[c] If AADT is not available, determine ADT based on the nearest section of the highway where 24-hour volume was recorded. The information needs to be based on an average of at least three regular weekdays during the months when schools are in session. If the information is not available, use 10.

[d] If per-lane volume information is not available, divide the highest volume of any peak hour during the day (6:00 a.m., - 8:00 p.m.) by the number of highway lanes in the section of the work zone.

[e] If the proposed work zone will reduce the number of lanes, divide the highway volumes through the work zone by the number of remaining available lanes.

[f] If the roadway section is near major traffic generators, such as shopping malls, office complexes, etc. For recreational or seasonal traffic generators, use 10.

Technical Requirements

The TTIS system requires sensors to record traffic data and a VMS to provide real-time information to drivers. The characteristics to be specified in the design documentation and specification by TxDOT includes the following (TxDOT, 2018):

- A system that should include at least two sensors placed at either end of the segment if using Bluetooth, 2 PCMS, and an operating system.
- Selected locations for sensors to ensure comprehensive coverage of the work zone and the approach.
- Automated continuous data acquisition if performance measures are needed or TMC desires situational awareness.
- Real time data transfer connectivity to various agencies or TMC.
- Format and frequency requirements for archive data transmission to TMC.
- Error detection-correction mechanisms.
- Travel time/delay sampling rates.

An IDOT official further stated that Bluetooth is not used for real-time data and instead uses a point-to-point system. If the points are too far apart, the data obtained may be late or no data can accurately be recorded due to vehicles exiting before the second radar. Regarding the frequency of data, the industry standard is once per minute, while daily and weekly reports are also an option.

Cost

It is important to note that the cost for TTIS vary widely depending on the scope and duration and amount of field devices. Nonetheless, a number of state DOTs reported the cost required for travel time information systems. For example, WisDOT reported the leasing cost of TTIS for 5-months in 2017 to be $113,000 ($22,600/month) which included 14 PCMS and 2 camera trailers with 16 sensors and wireless communications. Similarly, TxDOT reported the leasing cost of TTIS for 24-months in 2016 to be $410,000 ($17,083/month) which included 4 PCMS, 4 CCTV cameras, 8-lane side-fire radar, and 4 trailers. Additionally, TxDOT reported the leasing cost of TTIS for 34-months in 2016 to be $835,690 ($24,579/month) which included 8 PCMS, 8 CCTV cameras, 8-lane side-fire radar, and 8 trailers (TxDOT, 2018). Furthermore, MnDOT reported the cost of TTIS without alternate routes as approximately $140,000 and double this cost for a system with alternate routes (MnDOT, 2019).

Smart Arrow Boards

Smart arrow boards are illuminated arrow signs with data processing and sharing functionalities capable of sending real-time traffic data from the field so it can be shared with the travelling public, as shown in Figure 64 (NASEM, 2020). This real-time traffic data can be shared with the public through 511, transportation management center systems, upstream VMS, social media, and even GPS apps such as Google maps or Waze. To add connective capabilities to these traveler information systems, an "arrow board kit" or smart location beacon is added to a regular arrow board (Ver-Mac, 2022).

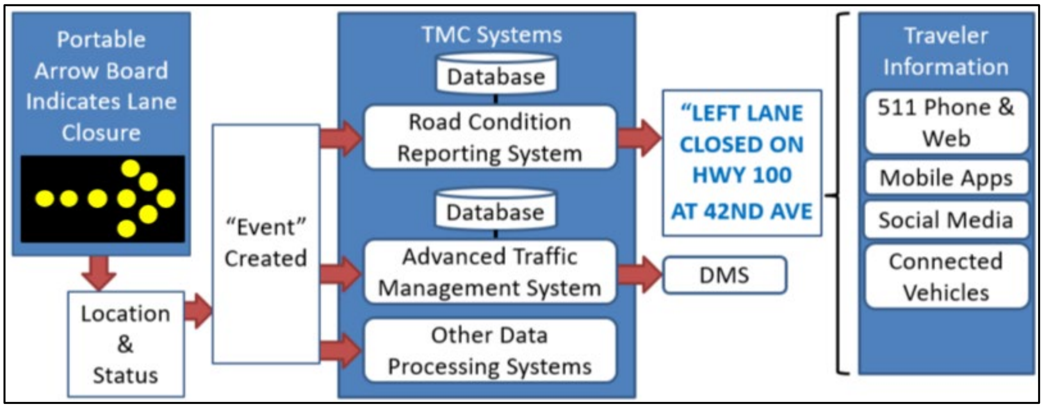


Figure 64. Diagram. Smart arrow board system (Enterprise, 2017).

Smart arrow boards can be used in all work zones, however they are specially recommended for fast-changing, shorter duration work zones. Work zones are typically updated through a road condition reporting system (RCRS), however these systems take a considerable amount of time to update, and drivers may travel on roads unaware of work zones' up-to-date locations. Smart arrow boards solve these problems by automatically reporting their location and status to traveler information systems so drivers can make informed decisions.

Benefits

MnDOT deployed 20 smart arrow boards in 2018 and reported the following benefits: (1) detailed, consistent, reliable, and automated real-time information about lane closures disseminated to travelers upstream of the closure through DMS, traveler information mediums, and connected and automated vehicle applications; (2) improved situational awareness by Regional Traffic Management Center operators of real-time lane closures in the field; (3) increased archived data available for evaluation, performance management, and research to better understand mobility impacts of maintenance activities, plan for future efforts, and develop performance-based specifications; and (4) broadcast display status and lane closure-related information to connected and automated vehicles (MnDOT, 2018). Michigan DOT is currently in the process of deploying smart arrow board systems and evaluating their benefits (NASEM, 2020).

Work Zone Application

Smart arrow boards are often used to improve sharing information on lane closures and their applications are similar to those of traditional arrow boards including their use to notify drivers of closed lanes or shoulders. Furthermore, work zones of any duration were reported to benefit from their implementation (NASEM, 2020). Currently, Iowa DOT requires smart arrow boards for any interstate or State highway lane closure (IowaDOT, 2020; IowaDOT, 2022).

Technical Requirements

The FHWA Enterprise Transportation Pooled Fund Study specified the technical requirements for the arrow boards reporting system and traffic management center as follows (Enterprise, 2017b):

- Arrow boards reporting system: the functional requirements of the system includes (a) periodically (ideally real-time every 1 minute or instantaneous) preparing data messages when the device is active; (b) providing status messages when the device is inactive; (c) periodically communicating messages; (d) automatically sending notification messages to DOT staff, if the TMC system does not; and (e) indicating that it is no longer active. The non-functional requirements of the system includes independent operation that does not require additional work from field staff; and comprehensive use of the system on all arrow boards in a single work zone.

- Traffic Management Center system: the functional requirements of the system includes providing the capability of (1) receiving Arrow Board Reporting System status data; (2) processing received Arrow Board Reporting System data; (3) preparing processed Arrow Board Reporting System data for ingest to the RCRS, when an RCRS is present; (4) preparing processed Arrow Board Reporting System data to be ingested by the ATMS, when an ATMS is present; (5) preparing processed Arrow Board Reporting System data for present traveler information systems; (6) automatically providing notification messages to DOT staff; (7) providing the most recent Arrow Board device updates to DOT staff on demand; (8) determining when an Arrow Board is no longer active; and (9) storing and providing historical data when queried. The non-functional requirements of the system includes flexibility in how automatic messages are transmitted, if sent from TMC Systems; and allowing staff to access historical Arrow Board data.

Cost

A recent study reported that the cost for a trailer-based smart arrow board ranged from $10,000 to $12,000, while the cost for a truck mounted arrow board ranged from $6,000 to $8,000 (NASEM, 2020). Furthermore, the MnDOT reported the estimated annual operation and maintenance costs for their recent deployment of smart arrow boards, as shown in Table 61 (MnDOT, 2018). Nonetheless, the estimates may be lower today as the presented costs are based on the first purchase of the technology.

Table 61. Operations and Maintenance Costs of Smart Arrow Boards (MnDOT 2018).

Cost Item	Hours of Staff Time	Annual Estimated Cost
20 arrow board reporting systems (device and system/server rental that includes communications, and maintenance)	-	$14,400 ($60/month/device)
MnDOT maintenance staff time to be present or coordinate during device maintenance performed by vendor	1 hour/device	$1,200
Routine maintenance of arrow board functions in IRIS	8 hours/year	$480
Routine maintenance of arrow board functions in the condition acquisition and reporting system (CARS)	8 hours/year	$480
Total	-	$16,560

Temporary Incident Detection System

Incident detection systems monitor the work zone using cameras or sensors to alert traffic management centers (TMCs) or emergency response systems when traffic incidents occur in the work zone (TxDOT, 2018). Incident detection systems are deployed to provide situational awareness, reduce incident response time, and reduce the probability of secondary incidents. When the detection system is in operation, data can also be shared with the TMC so that traffic control decisions are made to improve traffic conditions through the work zone (MnDOT, 1997, TxDOT, 2018). This information can be transmitted to drivers via the internet, or the TMC may choose to display information through the on-site VMS.

Benefits

The New Mexico State Highway and Transportation Department (NMSHTD) reported the performance of an incident detection system that was deployed on a two-year interchange project in Albuquerque. The system was deployed to provide traffic management capabilities and traveler information on traffic routing, detours, and significant incidents; and minimize capacity restrictions due to incidents by more quickly identifying incidents and determining an appropriate and effective response to clear the roadway. NMSHTD reported the following seven benefits: (1) reduction of 15% in traffic; (2) reduction of 32% in crashes during the first three months of the work zone compared to the previous year; (3) fewer expected crashes within work zone compared to historical estimates; (4) incident response and clearance time was reduced from the historical average of 45 minutes to 25 minutes in the work zone; (5) reduction in the frequency of secondary crashes caused by distracted drivers observing incidents due to faster incident response and clearance time; (6) more efficient and appropriate emergency response to incidents by identifying the required number of emergency services and motorist assistance vehicles that are needed for each incident based on live incident and traffic images; and (7) identifying areas where drivers have difficulty navigating the work zone that can be reconfigured to improve traffic flow (FHWA, 2004a).

Work Zone Application

A recent study reported that long-term and complex work zones benefit the most from temporary incident detection system due to their increased likelihood of experiencing incidents. The study also reported temporary incident detection system should be considered in work zones with: (1) long-term project durations in urban areas; (2) presence of a permanent intelligent transportation system (ITS) deployment, a TMC, or both; (3) high public exposure or traffic delay; (4) multiple construction stages or phasing; (5) frequent lane or ramp closures; (6) frequent crash history within the work zone corridor; and (7) work-zone corridor at or near capacity (NASEM, 2020).

Technical Requirements

Incident detection systems require on-site sensors/detectors, reliable communication with the TMC, communication with emergency responders, and the ability to communicate available information to the public (typically performed by the Transportation Management Center). The technical requirements of incident detection systems were reported to include (1) placing multiple closed-circuit television (CCTV) video cameras at strategic locations in the work zone to provide real-time information on traffic flow to system operators; (2) placing CCTVs in areas of high risk, such as the approach to a taper or crossover, or locations where the designer anticipates motorists taking evasive or aggressive action; (3) utilizing cameras that have pan, tilt, and zoom capabilities to enable comprehensive coverage of the work zone and approaches; (4) requiring continuous 24/7 operations; (5) providing live alerts to various agencies or a TMC; (6) integrating error detection and correction mechanisms; (7) placing speed radars on work zone towers for speed data collection; (8) providing data such as traffic volume, speed, incident detection and vehicle intrusion into the work zone; and (9) utilizing automatic message selection system that can change messages based on detected vehicle speeds (MnDOT, 1997; NASEM, 2020).

Cost

The cost of incident detection systems varies based on the required level of surveillance in a work zone. TxDOT recently reported the monthly and total incident detection systems costs that include equipment leasing, installation, operation, maintenance, and removal costs. These monthly and total costs were reported for three projects as follows: (1) approximately $32,000/month for 76 months for a total of $2,395,816 (1% of total construction cost) that includes 8 PCMS, 14 radars, 8 cameras, and 8 trailers deployed; (2) approximately $34,000/month for 46 months for a total of $1,574,058 (1% of total construction cost) that includes 9 PCMS, 8 radars, 9 cameras, and 9 trailers deployed; and (3) approximately $15,000/month for 20 months for a total of $306,616.75 (2% of total construction cost) that includes 3 trailers, 9 radars, 3 cameras, and 4 PCMS (TxDOT, 2018).

An IDOT official reported that typical cellular service for PTZ CCTV is about $150/camera/month. The cost of the trailers themselves range from $17,000-$20,000 and rented may be $1,500-$2,000 /unit/month. Many agencies also require a content delivery network and video walls for all their camera which adds additional costs to the system.

Construction Truck Alert Systems

Construction truck alert systems automatically detect when slow-moving construction vehicles exit work zones and provide advance warning to motorist through variable message signs (VMS) or flasher signs. This advance warning allows drivers to slow down and helps avoid collisions with construction vehicles exiting the work zone. These systems may also prevent vehicles from accidentally following construction vehicles into work zones (MassDOT, 2016; ADOT, 2019; NASEM, 2020).

Benefits

The benefits of construction truck alert systems were reported to include alerting motorists of slow construction vehicles entering/exiting the work zone, reducing frequency of motorists following construction vehicles into the work zone, reducing rear-end crashes caused by abrupt slowdowns, and allowing drivers to adjust speeds to react appropriately to merging construction trucks (NASEM, 2020; MnDOT, 2020, WisDOT, 2022).

Work Zone Application

MnDOT and WisDOT recently reported that construction truck alert systems should be considered in work zones that have: (1) construction vehicles using live traffic lanes to either decelerate or accelerate because a deceleration or acceleration lane cannot be provided; (2) extended construction durations; (3) minimal and infrequent changes; (4) crossing truck traffic moving much slower than anticipated by oncoming traffic; (5) sight restrictions that obstructs drivers from viewing trucks entering the traffic lane; and (6) high ADT that prohibits truck drivers from easily merging with traffic without causing traffic to suddenly adjust speed or change lanes (MnDOT, 2020; WisDOT, 2022). Additionally, MassDOT recommended the implementation of a construction vehicle warning system in work zones that are expected to have five or more construction truck maneuvers per hour including merging, entering, exiting, or crossing (MassDOT, 2016).

Technical Requirements

The technical requirements of construction truck alert systems were reported by TxDOT to include: (1) a minimum of one sensor and one warning device; (2) minimizing false positive detections by ensuring that the system is triggered only when vehicles enter the traffic stream; (3) utilizing short range transponder or Bluetooth based detection devices if other construction equipment is likely to be in close proximity to the vehicles leaving the work area, making it difficult for a detector such as radar to discriminate between vehicles; (4) communication between the construction vehicle detector and the message board must be point to point wireless because the transmission time must occur in milliseconds; (5) specifications for battery recharge rates on solar powered systems; (6) system will typically be a stand-alone system with no connectivity to a TMC (although this may not be this way anymore); (7) system operation hours - typically 24/7; (8) error detection and correction mechanisms; (9) removal/relocation of the system if/when the access roadway is eliminated or relocated; and (10) clearly define if there will be concurrent deployment of systems during the project (TxDOT 2018).

Cost

A recent study reported the cost for a construction truck alert system including VMS and detection equipment as $1000 per week (NASEM, 2020). TxDOT reported equipment leasing, installation, operation, maintenance, and removal costs for $44,000 that included 6 PCMSs, 6 sensors, and 16 advance flashers deployed over 6 months (TxDOT, 2018).

APPENDIX A2: FEDERAL AND STATE GUIDELINES FOR SMART WORK ZONE SYSTEMS

This chapter presents the findings of the conducted literature review on Federal and state guidelines for the design and deployment of smart work zone (SWZ) systems. These design guidelines often provide recommended locations of SWZ systems, distances between work zone and SWZ devices, minimum sight distances, and layouts of each system. The following sections provide a concise description of the analyzed Federal and state guidelines for each of the aforementioned 10 smart work zone systems.

Variable Message Signs

Several state DOTs have developed guidelines for the deployment of VMS in smart work zones, as shown in Table 62. These guidelines provide standards on the size of the letters, readability of the message, allowed abbreviations, message types, and number of signs (FHWA, 2013; Iowa DOT, 2005; Dudek and Ullman, 2016; INDOT, 2012; CTDOT, 2014; MDOT, 2011; IDOT, 2016; NTSDOT, 2018; King and McCrea, 2018; VDOT, 2020; and ADOT, 2019). For example, TxDOT guidelines provide recommendations on the displayed messages including: (1) engineer/inspector shall approve all messages used on PCMS; (2) messages on PCMS should contain no more than 8 words; (3) bottom of a stationary PCMS message panel should be a minimum 7-feet above the roadway, where possible; (4) do not "flash" messages or words, messages should be steady burn or continuous while displayed; (5) PCMS character height should be at least 18 inches for trailer mounted units, should be visible from at least ½ mile, and legible from at least 600 ft at night and 800 ft in daylight; (6) truck mounted PCMS must have a character height of 10 inches and must be legible from at least 400 feet; and (7) each line of text should be centered on the message board rather than left or right justified (TxDOT, 2021).

Table 62. State DOT Guidelines for VMS

Agency	Title	Year of publication	Reference
ADOT	TTC Design Guidelines	2019	ADOT, 2019a
Caltrans	CMS Guidelines	2021	Caltrans, 2021
CTDOT	PVMS Operations Guide	2014	CTDOT, 2014
FDOT	Design Manual: PCMS	2022	FDOT, 2022
GDOT	ITS Design Guidelines: Chapter 5	2020	GDOT, 2020
IDOT	Traffic Control Field Manual	2016	IDOT, 2016
INDOT	Guidelines for PCMS	2012	INDOT, 2012
Iowa DOT	Guidelines for PCMS	2016	Iowa DOT, 2005
Maine DOT	SOP for The Use of CMS	2007	Maine DOT, 2007
MDOT	Work zone safety and mobility manual	2021	MDOT, 2011
MnDOT	Minnesota MUTCD, 2L	2022	MnDOT, 2022b
MoDOT	Missouri MUTCD, 6F	2021	MoDOT, 2021
NYSDOT	VMS Guidelines	2018	NYSDOT, 2018
NDDOT	NDDOT DMS Guidelines	2008	NDDOT, 2008
ODOT	PCMS Handbook	2018	King and McCrea, 2018
PennDOT	CMS Operating Standards	2021	PennDOT, 2021
TxDOT	Traffic Standards: BC-21	2021	TxDOT, 2021
VDOT	Virginia Work Area Protection Manual	2020	VDOT, 2020
WSDOT	TS management and operations	2019	WSDOT, 2019
WisDOT	Development of Best Practices for PCMS in Work Zones	2015	Paulus, 2015
WYDOT	TC for Roadway Work Operations	2011	WyDOT, 2011

State DOT guidelines provide varying requirements for the placement of VMS in work zones including minimum sight distance, minimum legible distance, offset from road edge, spacing between consecutive signs, distance until decision point, height, and angle towards oncoming traffic, as shown in Figure 65. A comparison of these placement requirements among state DOTs is summarized in Table 63 to Table 69 . For example, the OrDOT PCMS Handbook provides detailed installation guidelines for PCMS as shown in Figure 66 (King and McCrea, 2018).

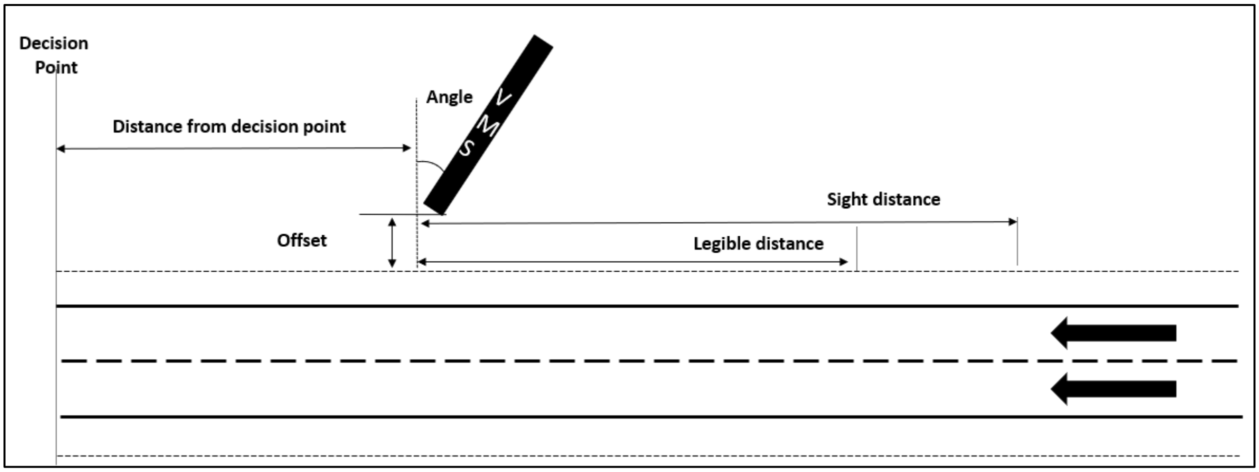


Figure 65. Diagram. Example work zone layout with variable message signs.

Table 63. Comparison of Minimum Sight Distance VMS State DOT Guidelines

Requirement	DOT
800 ft	ADOT, NDDOT
850 ft	WisDOT
900 ft	FDOT
1300 ft	IDOT
1500 ft	Caltrans
2640 ft	CTDOT, GDOT, Iowa DOT, NYSDOT, OrDOT

Table 64. Comparison of Minimum Legible Distance VMS State DOT Guidelines

Requirement	DOT
750 ft	Caltrans, MnDOT, IDOT
600-800 ft	GDOT, NYSDOT, OrDOT, TxDOT
650 ft	Iowa DOT

Table 65. Comparison of Offset from Road Edge VMS State DOT Guidelines

Requirement	DOT
Min. 8ft	ADOT
Max. 15 ft	Caltrans
6-12 ft	INDOT
15ft - 30ft	NYSDOT

Table 66. Comparison of Spacing Between Consecutive Signs VMS State DOT Guidelines

Requirement	DOT
Min. 1000 ft	Caltrans, CTDOT, NYSDOT, OrDOT, INDOT, MDOT, MnDOT
Min. 800 ft	GDOT

Table 67. Comparison of Distance from Decision Point VMS State DOT Guidelines

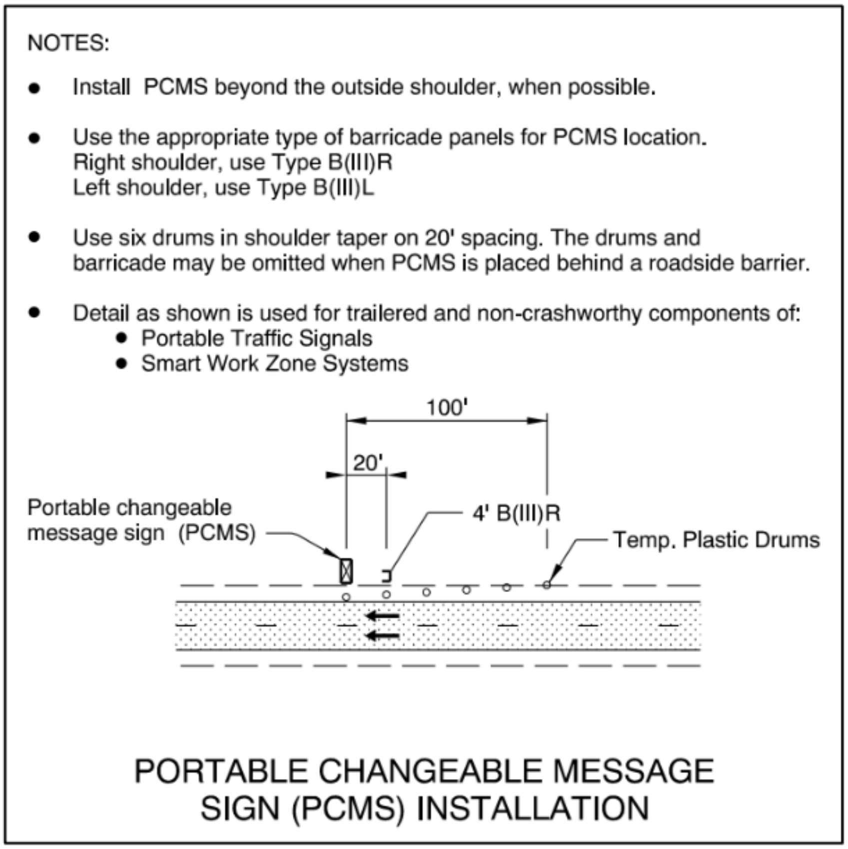
Requirement	DOT
Max. 1 mile	CTDOT
1445 ft	GDOT
1000 ft – 5280 ft	INDOT
500 ft - 1000 ft	WisDOT

Table 68. Comparison of Height (Ground to bottom of sign) VMS State DOT Guidelines

Requirement	DOT
5 ft - 7 ft	Caltrans, CTDOT, IDOT, Iowa DOT, MnDOT, NYSDOT, OrDOT

Table 69. Comparison of Angle Towards Oncoming Traffic VMS State DOT Guidelines

Requirement	DOT
5-10 degrees	CTDOT, OrDOT, IDOT
3 degrees	Iowa DOT



NOTES:

- Install PCMS beyond the outside shoulder, when possible.
- Use the appropriate type of barricade panels for PCMS location.
  Right shoulder, use Type B(III)R
  Left shoulder, use Type B(III)L
- Use six drums in shoulder taper on 20' spacing. The drums and barricade may be omitted when PCMS is placed behind a roadside barrier.
- Detail as shown is used for trailered and non-crashworthy components of:
  - Portable Traffic Signals
  - Smart Work Zone Systems

PORTABLE CHANGEABLE MESSAGE SIGN (PCMS) INSTALLATION

Figure 66. Photo. OrDOT’s PCMS installation details (King and McCrea, 2018).

Queue Warning Systems

Over the past six years, several state DOTs such as Massachusetts, Connecticut, Minnesota, Texas, and Arizona, have developed guidelines for the deployment of QWS in smart work zones. These guidelines however are general recommendations and do not provide specifics on the number of QWS equipment and/or their positioning and spacing in and around different types of work zones. This is likely because each work zone may have different geometric characteristics and tailored temporary traffic control plans need to be developed for each work zone separately.

For example, the Massachusetts Department of Transportation (MassDOT) provides layout guidelines for the deployment of QWS equipment by identifying their key locations within smart work zones based on project impact level. Project impact level in these guidelines is grouped into three categories: (i) levels 1 and 2 that represents worksite only; (ii) level 3 that represents work site and vicinity, and; (iii) level 4 and significant projects that represents work site, vicinity, and surrounding approaches (MassDOT, 2016). These guidelines recommend the positioning of QWS equipment in the following eight key points in and around the work zone as shown in Table 70 and Figure 67:

a) Start of the work zone.

b) End of the work zone.

c) The location of merge/lane drop for closure.

d) All approaches within 0.5 miles of the work activity.

e) The upstream decision points nearest to the work activity (i.e., the closest viable locations where drivers could exit the highway and take a suitable alternate route before reaching the work zone).

f) For Level 4 or Significant projects located on major highways or interstates, also identify any upstream intersections/interchanges with other major highways that could offer alternate routes.

g) One point upstream of the bottleneck where traffic should be stable during most operating hours.

h) One point downstream of the bottleneck where traffic should be stable during most operating hours.

It should be noted that the recommended positioning of QWS equipment at the aforementioned eight points (a – h) within a smart work zone depends on the project impact level, as shown in Table 70.

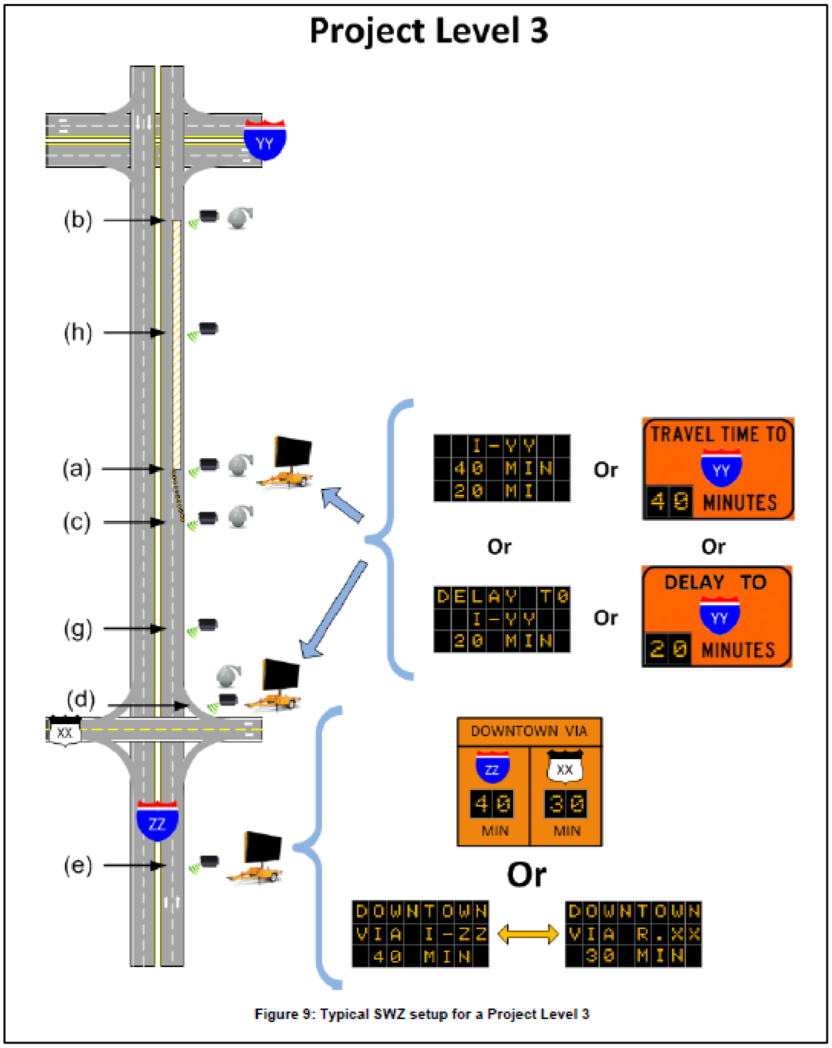


Figure 67. Photo. Example smart work zone layout for a project level 3 (MassDOT, 2016).

Table 70. QWS Equipment Location Based on Project Impact Level (MassDOT, 2016)

Equipment	Level 1 & 2	Level 3	Level 4 & Significant Project Status
Traffic detectors	(c)*	(c) (g) (h)	(c) (d) (g) (h)
Short-range receivers for travel time measurement	(a)* (b)*	(a) (b) (d) (e)	(a) (b) (d) (e) (f)
Cameras	(c)*	(a) (b) (c) (d)*	(a) (b) (c) (d)* (e)* (f)
Special Detectors (e.g., hazardous conditions, intrusion warning)	Project specific	Project specific	Project specific
PVMS/HMS	(a)* (d)*	(a) (d) (e) (g)	(a) (d) (e) (f) (g)

***Optional**

Connecticut Department of Transportation (CTDOT) released a SWZ design guide in 2017 that recommends the deployment of QWS when there are frequent planned lane closures or when emergency shoulders are closed through the work zone. The design guide provides a general layout of the QWS equipment that was adapted from NHDOT (2011), as shown in Figure 68. The CTDOT guide divides the work zone area into advance warning, transition, activity, and termination areas. The guide however does not specify the length of these work zone areas or the spacing between QWS equipment. The designer and contractor are responsible for designing a project-specific layout to ensure all MUTCD (FHWA, 2009) standards are met (Venugoal et al., 2017).

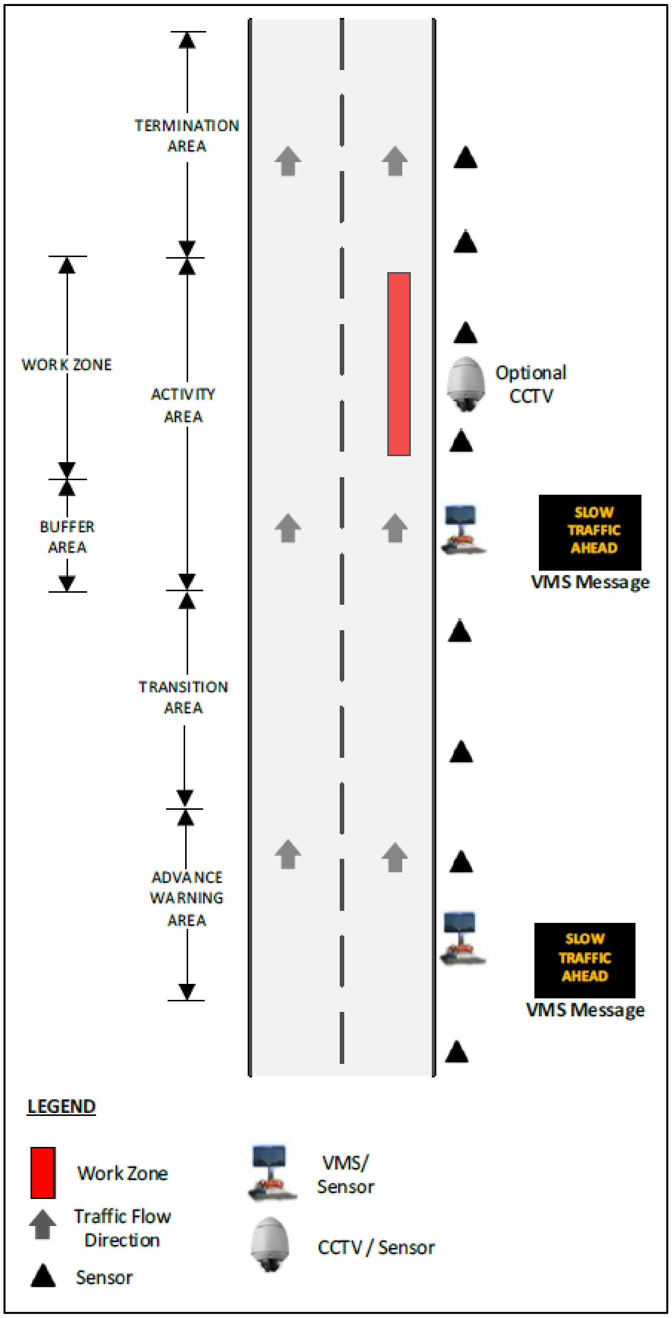


Figure 68. Photo. Example work zone layout with queue warning system (Venugoal, 2017).

The Arizona Department of Transportation (ADOT) developed recommendations and conceptual layouts as part of their SWZ Technical Concept Study. ADOT recommendations specifies that the distance between the work zone and the first VMS can vary based on project characteristics, however subsequent VMS equipment need to be placed in 1-mile increments, as shown in Figure 69. The ADOT recommendations also specify that the first data collection point should be approximately 0.25 miles upstream from the first work zone cone lane taper, and one data collection point should be located between each pair of VMS equipment on one side of the road upstream of the work zone (see Figure 69). Additionally, ADOT recommends that VMS should be deployed at both sides of the road if there are three or more travel lanes for the same direction of traffic, or when the work zone is on routes with truck volumes exceeding 15% of the traffic. For project specific layout, ADOT also developed an Excel tool which provides the VMS spacing as a function of the project characteristics and agency needs (as discussed later in Chapter 4) (ADOT, 2019).

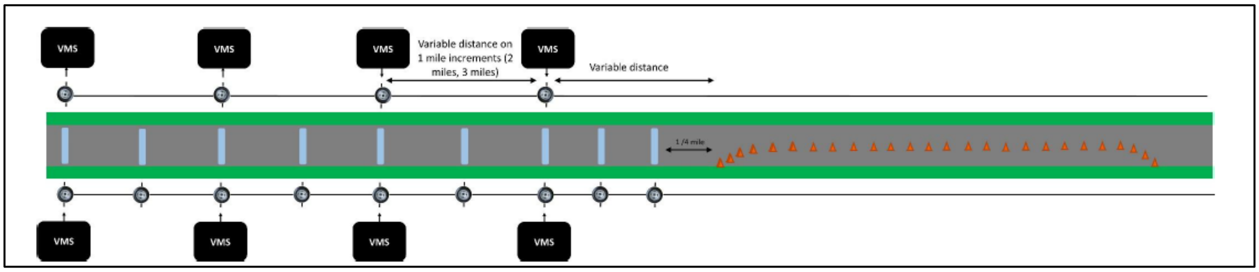
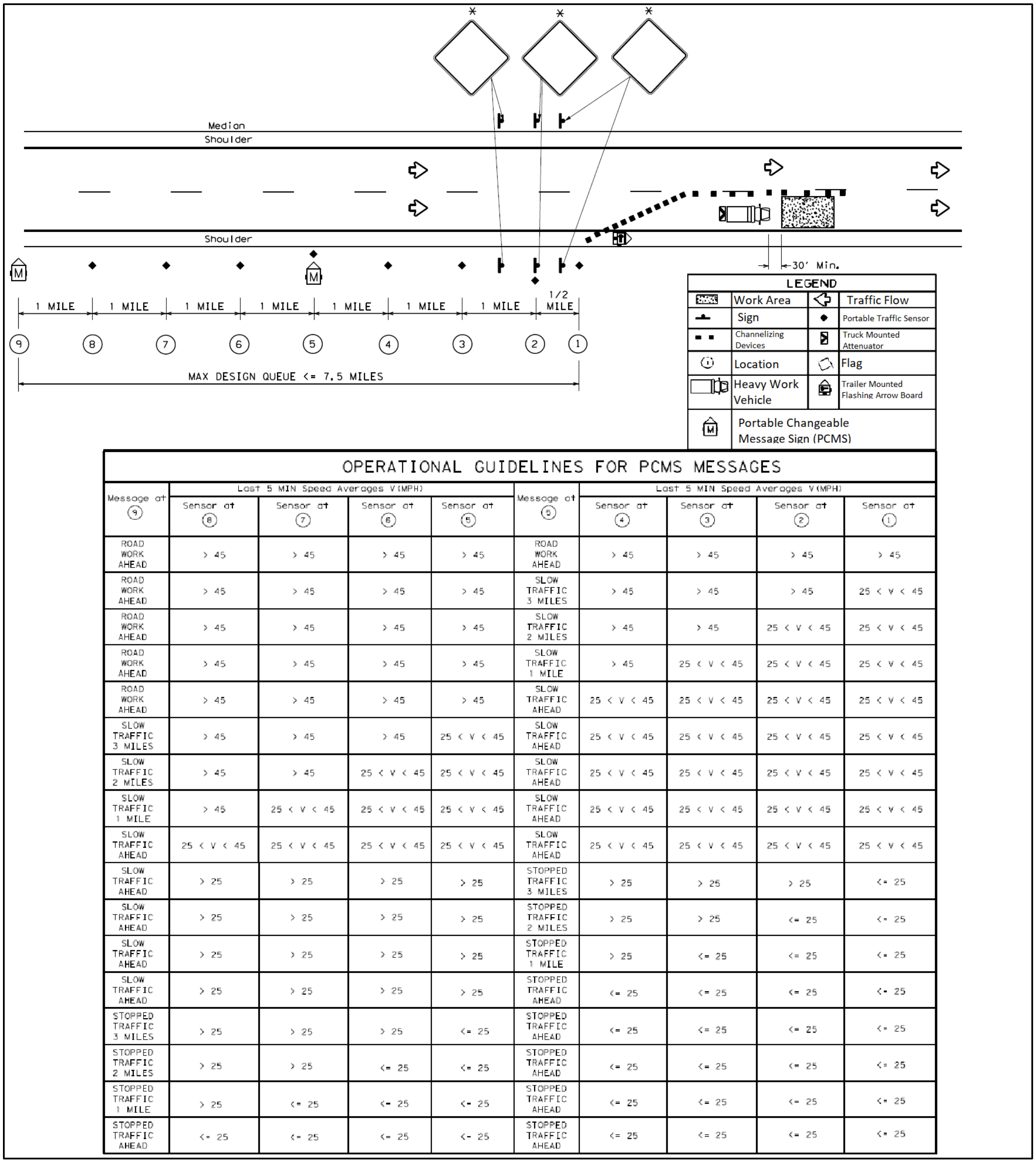


Figure 69. Photo. Example ADOT work zone layout with queue warning system (ADOT, 2019).

The Minnesota Department of Transportation (MnDOT) developed the *IWZ Toolbox* (MnDOT, 2020) that provides general guidelines for deploying queue warning systems but does not provide specific distances between sensors. The following guidelines provide a starting point for MnDOT officials and should be adjusted based on the project specific characteristics:

- Primary detector should be located 0 to 600 feet in advance of lane closures with additional detector spacing at 0.5 to 1.25 mile.
- Speed/volume sensors should be placed within work zones that are greater than 1500 feet in length.
- Sensors within a work zone should be spaced at 0.5 to 1 mile intervals and should collect data from both directions of travel when possible.
- Queue detection sensors also act as monitoring sensors.
- PVMS placement should be placed at locations where sight distance is limited. Preference should also be given for locations 0.5 to 1.5 miles in advance of exits to provide drivers with the option to select alternative routes.
- VMS should be programmed for queue detection when possible.

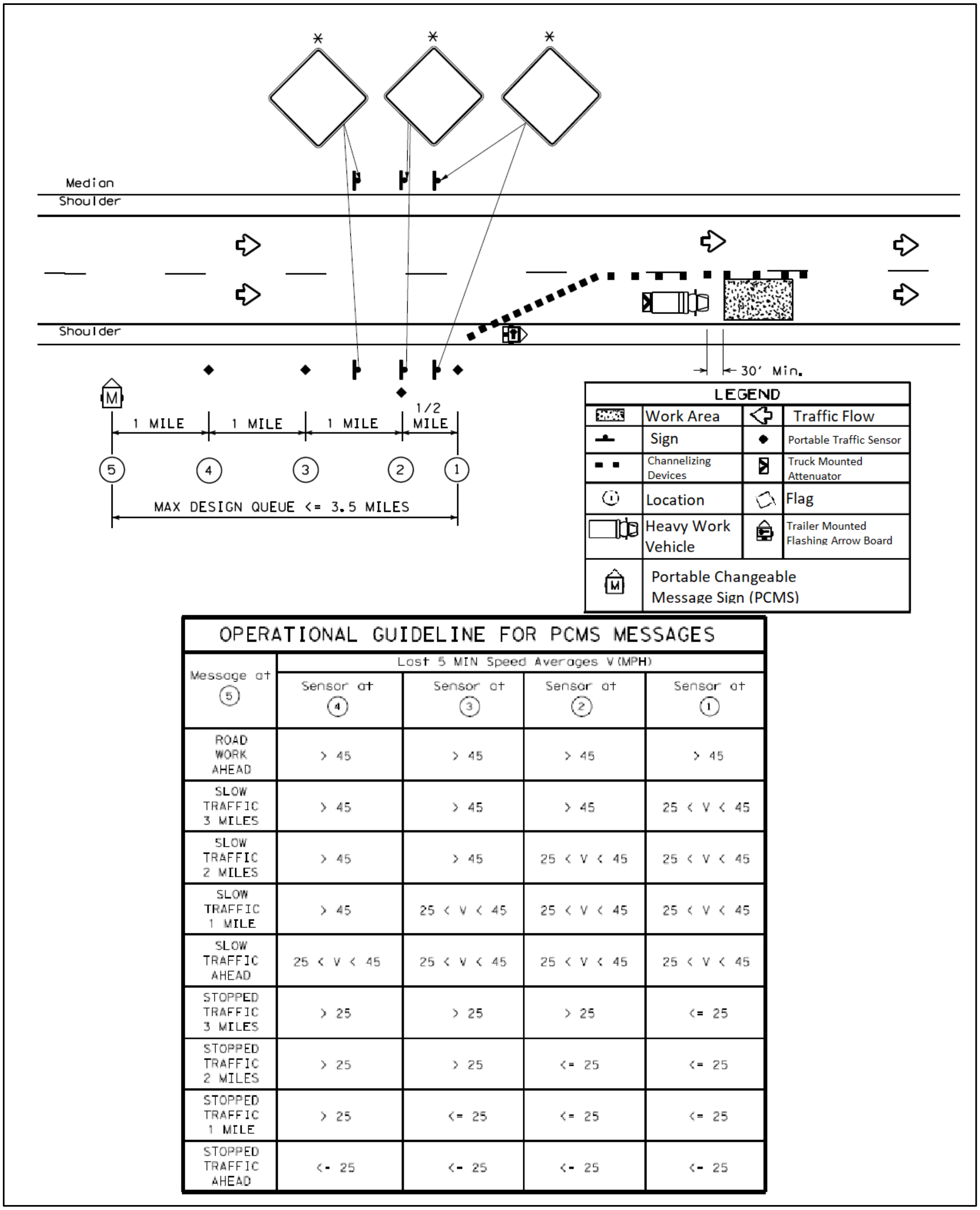
The Texas Department of Transportation (TxDOT) developed the *Design Guidelines for Deployment of Work Zone Intelligent Transportation* that includes standard sheets for the deployment of QWS. The guidelines divide the QWS deployment into (i) type 1 with a maximum design queue length less than 7.5 miles, and (ii) type 2 with a maximum design queue less than 3.5 miles. Figure 70 and Figure 71 illustrate the standard operational guidelines for the deployment of QWS for type 1 and type 2 systems, respectively (TxDOT, 2018; TxDOT, 2022). Other state DOTs such as Pennsylvania (PennDOT) have developed similar QWS deployment plans (PennDOT, n.d.).



OPERATIONAL GUIDELINES FOR PCMS MESSAGES

Message at ⑨	Last 5 MIN Speed Averages V(MPH)				Message at ⑤	Last 5 MIN Speed Averages V(MPH)			
	Sensor at ⑧	Sensor at ⑦	Sensor at ⑥	Sensor at ⑤		Sensor at ④	Sensor at ③	Sensor at ②	Sensor at ①
ROAD WORK AHEAD	> 45	> 45	> 45	> 45	ROAD WORK AHEAD	> 45	> 45	> 45	> 45
ROAD WORK AHEAD	> 45	> 45	> 45	> 45	SLOW TRAFFIC 3 MILES	> 45	> 45	> 45	25 < V < 45
ROAD WORK AHEAD	> 45	> 45	> 45	> 45	SLOW TRAFFIC 2 MILES	> 45	> 45	25 < V < 45	25 < V < 45
ROAD WORK AHEAD	> 45	> 45	> 45	> 45	SLOW TRAFFIC 1 MILE	> 45	25 < V < 45	25 < V < 45	25 < V < 45
ROAD WORK AHEAD	> 45	> 45	> 45	> 45	SLOW TRAFFIC AHEAD	25 < V < 45	25 < V < 45	25 < V < 45	25 < V < 45
SLOW TRAFFIC 3 MILES	> 45	> 45	> 45	25 < V < 45	SLOW TRAFFIC AHEAD	25 < V < 45	25 < V < 45	25 < V < 45	25 < V < 45
SLOW TRAFFIC 2 MILES	> 45	> 45	25 < V < 45	25 < V < 45	SLOW TRAFFIC AHEAD	25 < V < 45	25 < V < 45	25 < V < 45	25 < V < 45
SLOW TRAFFIC 1 MILE	> 45	25 < V < 45	25 < V < 45	25 < V < 45	SLOW TRAFFIC AHEAD	25 < V < 45	25 < V < 45	25 < V < 45	25 < V < 45
SLOW TRAFFIC AHEAD	25 < V < 45	25 < V < 45	25 < V < 45	25 < V < 45	SLOW TRAFFIC AHEAD	25 < V < 45	25 < V < 45	25 < V < 45	25 < V < 45
SLOW TRAFFIC AHEAD	> 25	> 25	> 25	> 25	STOPPED TRAFFIC 3 MILES	> 25	> 25	> 25	<= 25
SLOW TRAFFIC AHEAD	> 25	> 25	> 25	> 25	STOPPED TRAFFIC 2 MILES	> 25	> 25	<= 25	<= 25
SLOW TRAFFIC AHEAD	> 25	> 25	> 25	> 25	STOPPED TRAFFIC 1 MILE	> 25	<= 25	<= 25	<= 25
SLOW TRAFFIC AHEAD	> 25	> 25	> 25	> 25	STOPPED TRAFFIC AHEAD	<= 25	<= 25	<= 25	<= 25
STOPPED TRAFFIC 3 MILES	> 25	> 25	> 25	<= 25	STOPPED TRAFFIC AHEAD	<= 25	<= 25	<= 25	<= 25
STOPPED TRAFFIC 2 MILES	> 25	> 25	<= 25	<= 25	STOPPED TRAFFIC AHEAD	<= 25	<= 25	<= 25	<= 25
STOPPED TRAFFIC 1 MILE	> 25	<= 25	<= 25	<= 25	STOPPED TRAFFIC AHEAD	<= 25	<= 25	<= 25	<= 25
STOPPED TRAFFIC AHEAD	<= 25	<= 25	<= 25	<= 25	STOPPED TRAFFIC AHEAD	<= 25	<= 25	<= 25	<= 25

Figure 70. Photo. TxDOT guidelines for type 1 QWS deployment (TxDOT, 2022).



OPERATIONAL GUIDELINE FOR PCMS MESSAGES

Message at ⑤	Last 5 MIN Speed Averages V (MPH)			
	Sensor at ④	Sensor at ③	Sensor at ②	Sensor at ①
ROAD WORK AHEAD	> 45	> 45	> 45	> 45
SLOW TRAFFIC 3 MILES	> 45	> 45	> 45	25 < V < 45
SLOW TRAFFIC 2 MILES	> 45	> 45	25 < V < 45	25 < V < 45
SLOW TRAFFIC 1 MILE	> 45	25 < V < 45	25 < V < 45	25 < V < 45
SLOW TRAFFIC AHEAD	25 < V < 45	25 < V < 45	25 < V < 45	25 < V < 45
STOPPED TRAFFIC 3 MILES	> 25	> 25	> 25	<= 25
STOPPED TRAFFIC 2 MILES	> 25	> 25	<= 25	<= 25
STOPPED TRAFFIC 1 MILE	> 25	<= 25	<= 25	<= 25
STOPPED TRAFFIC AHEAD	<- 25	<- 25	<- 25	<- 25

Figure 71. Photo. TxDOT guidelines for type 2 QWS deployment (TxDOT, 2022).

Dynamic Lane Merge Systems

FHWA developed *Guidance for use of Dynamic Lane Merging Strategies* that provides a number of situational work zone layouts. The most common layout is the two-to-one lane merge, as shown in

Figure 72. While the layout provides distances between signs, the FHWA recommends that exact distances should be modified according to the geometry of the road, expected queue lengths, and average expected speed of vehicles (FHWA, 2012).

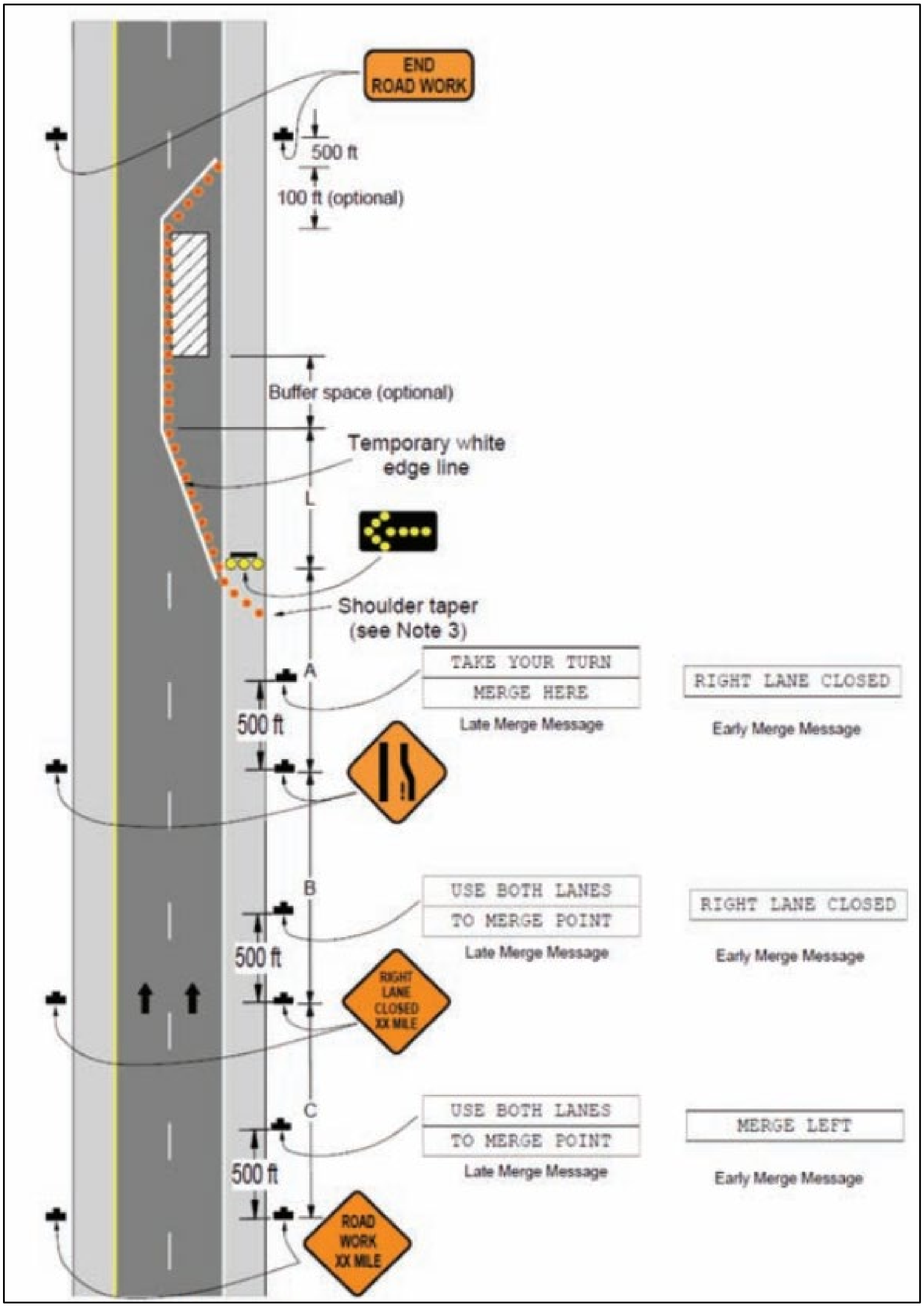
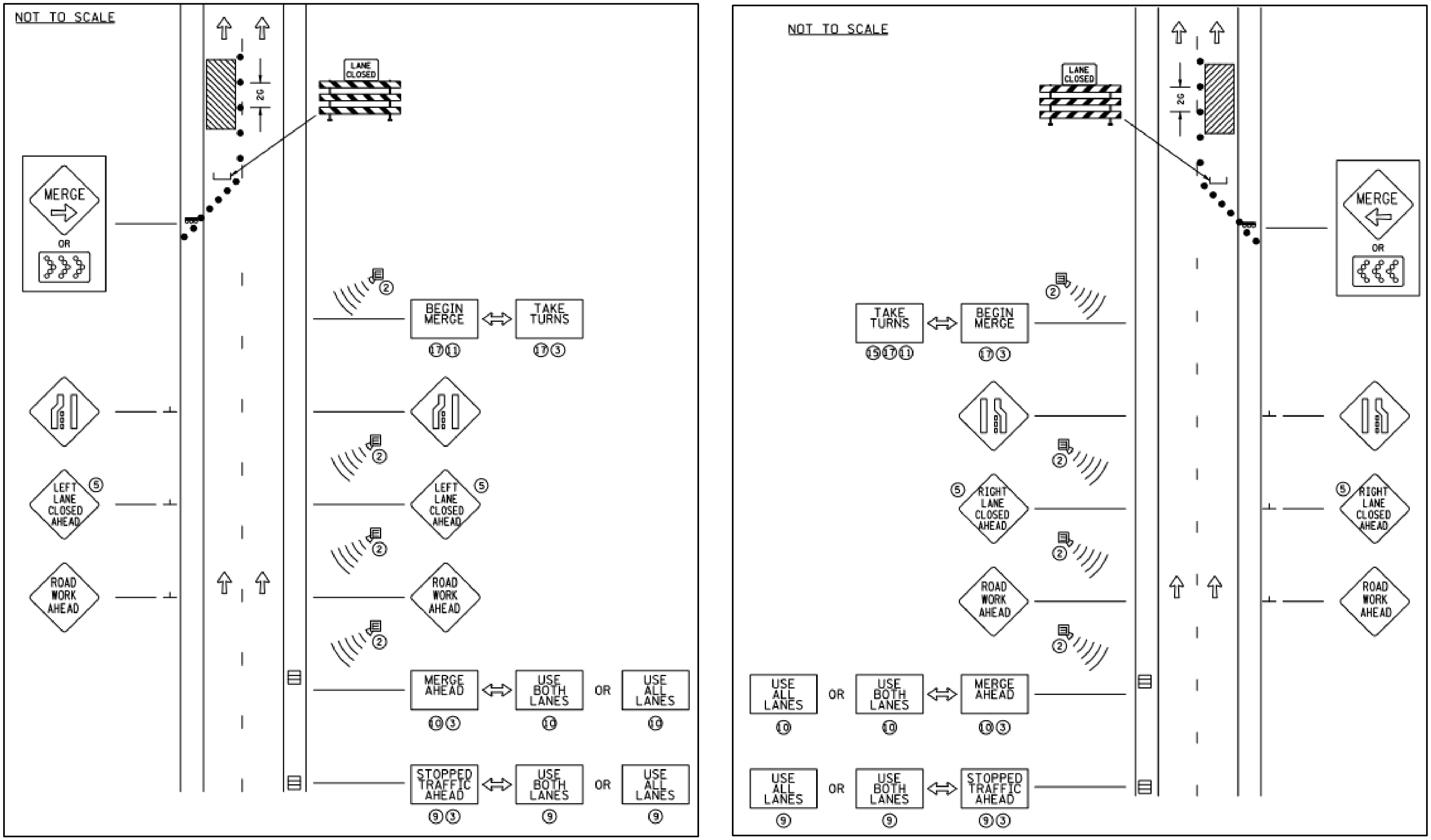


Figure 72. Photo. Example dynamic lane merge layout of two-to-one lane system (FHWA, 2012).

MnDOT also provided sample layouts of dynamic lane merge applications in their MnDOT IWZ Toolbox and on their website under Long Term Typical Applications of IWZ systems, as shown in the two layouts for both left and right lane closures with DLMS applications in Figure 73-A and Figure 73-B (MnDOT, 2020 & 2022a). Similar layouts can also be found in MassDOT and PennDOT guidelines (MassDOT, 2016; Beacher, 2005). Additionally, MnDOT (2022a) provides the following DLMS design guidelines:

- Non-intrusive detection devices should be placed along the route as needed.
- If 48’’x48’’ advance warning signs will not fit on the left side because of a narrow median (less than 6ft.) then reduce left side sign sizes or eliminate the left side signage.
- An additional set of “RIGHT LANE CLOSED AHEAD” signs may be added on high volume roads.
- Signs are activated in response to queued traffic when the queue is detected between signs.
- When no queue is detected, all the PCMS should be blank or used for another ITS.
- For label (9) in the figures: When PCMS devices are used, the two-part message should read: - - STOPPED/SLOW TRAFIC AHEAD - - USE BOTH LANES/USE ALL LANES - -.
- For label (10) in the figures: When PCMS devices are used, the two-part message should read: - - MERGE AHEAD - - USE BOTH LANES/USE ALL LANES - -
- For label (11) in figures: When PCMS devices are used, the two-part message should read: - - BEGIN MERGE - - TAKE TURNS - -
- As the queue extends beyond a CMS location, the sign should switch to the “BE PREPARED TO STOP” message.
- Estimated maximum queue length may be determined by the engineer analysis or previous experience, and should be reviewed and field adjusted to fit actual conditions such that the first warning device is upstream of the queue.
- Stopped or slow traffic ahead when flashing sign or the PCMS should activate and deactivate when the downstream detector senses traffic speeds meeting threshold values as set by the engineer.
- System may be combined with QWS, congestion advisory, and or TTIF.
- For label (17) in figures: Locate PCMS approximately 100 ft ahead of static merge sign.
- Analysis should be done ahead of time for signing placement and proper PCMS functioning.



A. Left-lane closure with DLMS

B. Right-lane closure with DLMS

Figure 73. Diagram. Example applications of MnDOT DLMS (MnDOT, 2022a).

ADOT developed layout recommendations with specific distances in their *SWZ Technical Concept Study*, as shown in Figure 74. Their conceptual layout provides guidance on the distance between VMS placed upstream of the work zone. Additionally, they provide the following guidance on activating the early, and late merge scenarios: (1) VMS at lane taper point will always be needed; (2) any VMS upstream of taper point can say "USE BOTH LANES" or "MERGE OVER" signage to support either late or early merge scenarios; (3) early merge scenarios: Low traffic volume and free flow average speed; (4) late merge scenarios: moderate to heavy traffic volume and lower than free flow average speed; (5) volume threshold to transition from early merge to late merge application when an average speed of vehicles is less than ¾ of the normal average speed; and (6) VMS should be deployed on both sides of the travel way when there are 3 or more travel lanes for the same direction (ADOT, 2019).

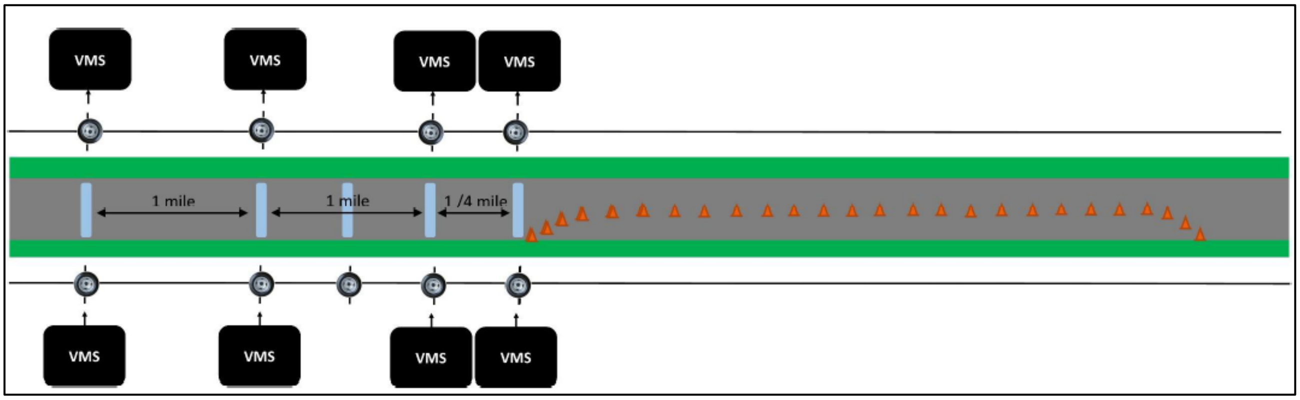
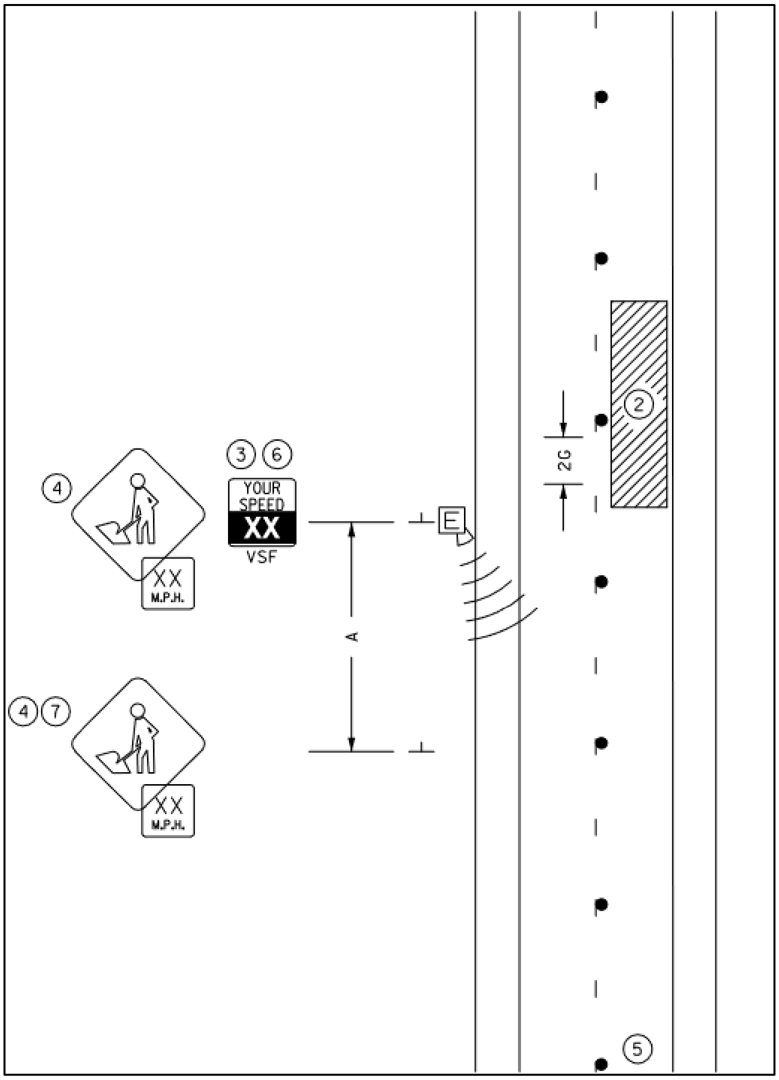


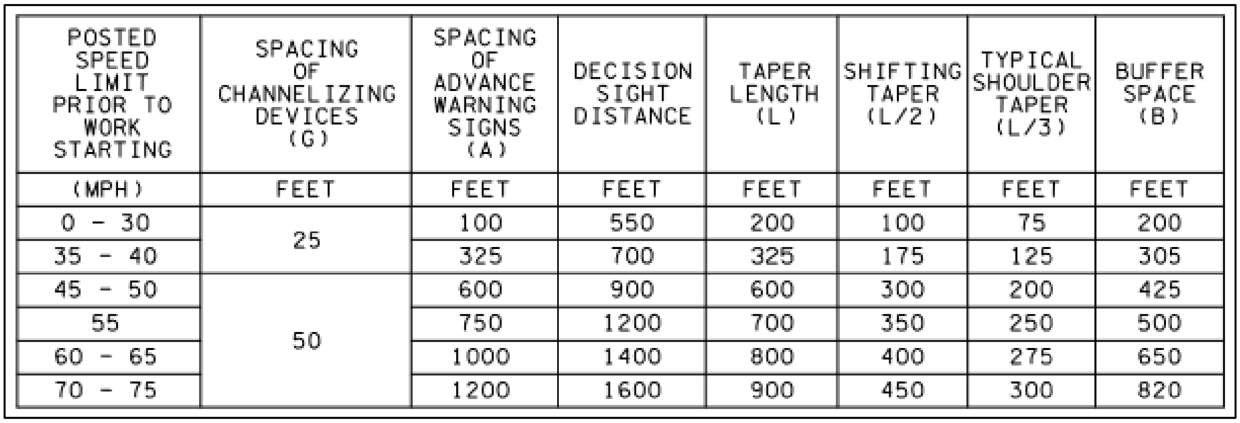
Figure 74. Photo. Example work zone layout of ADOT DLMS (ADOT, 2019).

Speed Feedback Signs

Both the speed feedback signs and VMS must comply with all related MUTCD requirements (e.g., sections 2A. 18, 2A19, and 2A20, for height, lateral offset, and orientation of mounted signs). Several DOTs provide sample layouts that illustrate the deployment of speed feedback signs in work zones. For example, a sample MnDOT work zone layout with speed feedback signs and their related work zone measurements is shown in Figure 75 (MnDOT, 2022a). Similarly, another sample layout from the DOT Smart Work Zone Guidelines is shown in Figure 76 (TxDOT, 2018). Additional sample layouts can be found in the MUTCD as the one presented in Figure 77 for mobile operations (FHWA, 2009; Gambatase and Jafarnejad, 2015).



A. Sample layout



POSTED SPEED LIMIT PRIOR TO WORK STARTING	SPACING OF CHANNELIZING DEVICES (G)	SPACING OF ADVANCE WARNING SIGNS (A)	DECISION SIGHT DISTANCE	TAPER LENGTH (L)	SHIFTING TAPER (L/2)	TYPICAL SHOULDER TAPER (L/3)	BUFFER SPACE (B)
(MPH)	FEET	FEET	FEET	FEET	FEET	FEET	FEET
0 - 30	25	100	550	200	100	75	200
35 - 40		325	700	325	175	125	305
45 - 50	50	600	900	600	300	200	425
55		750	1200	700	350	250	500
60 - 65		1000	1400	800	400	275	650
70 - 75		1200	1600	900	450	300	820

B. Work zone measurements from sample layout.

Figure 75. Photo. Example MnDOT work zone layout with speed feedback signs (MnDOT, 2022a).

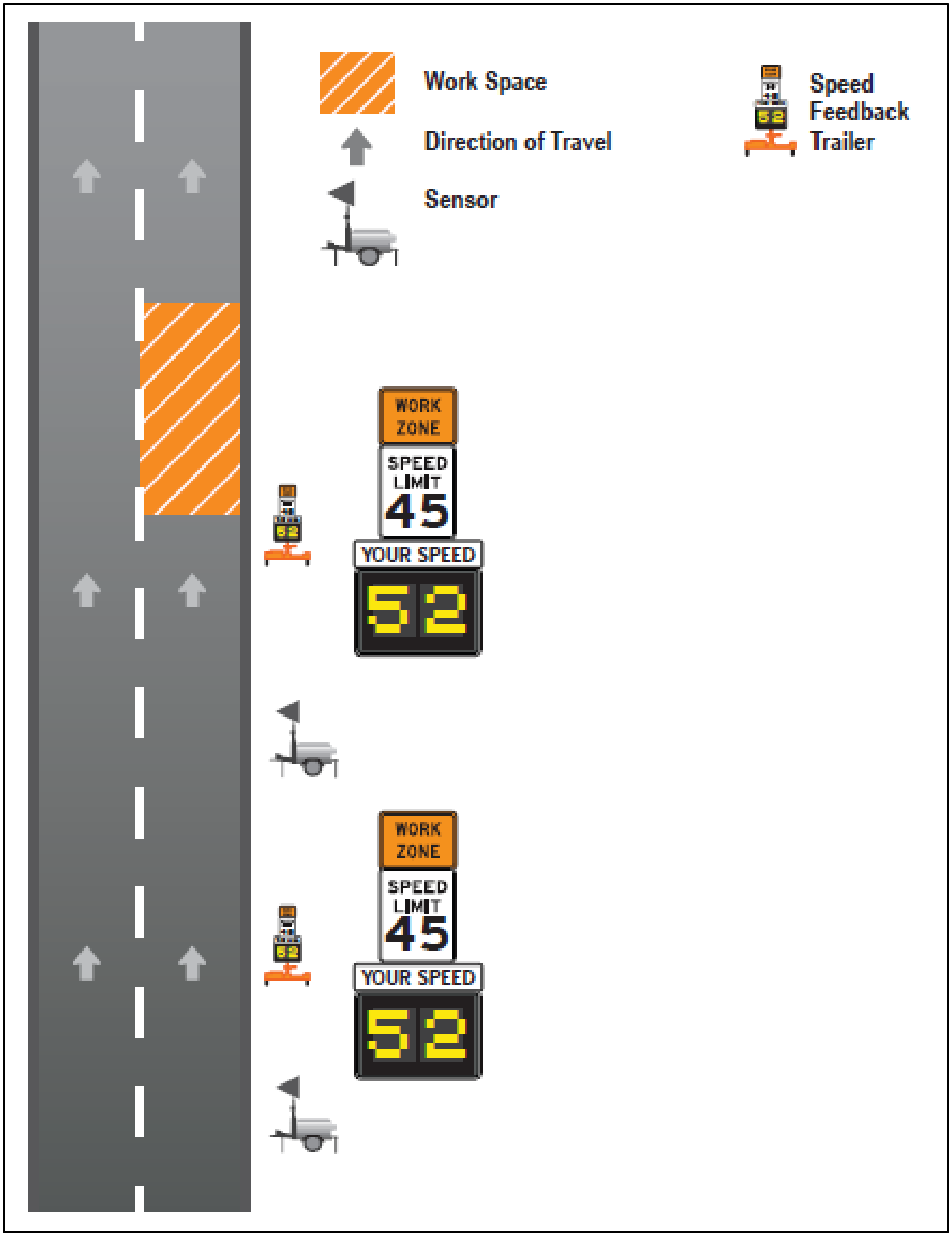


Figure 76. Photo. Example TxDOT work zone layout with speed feedback signs (TxDOT, 2018).

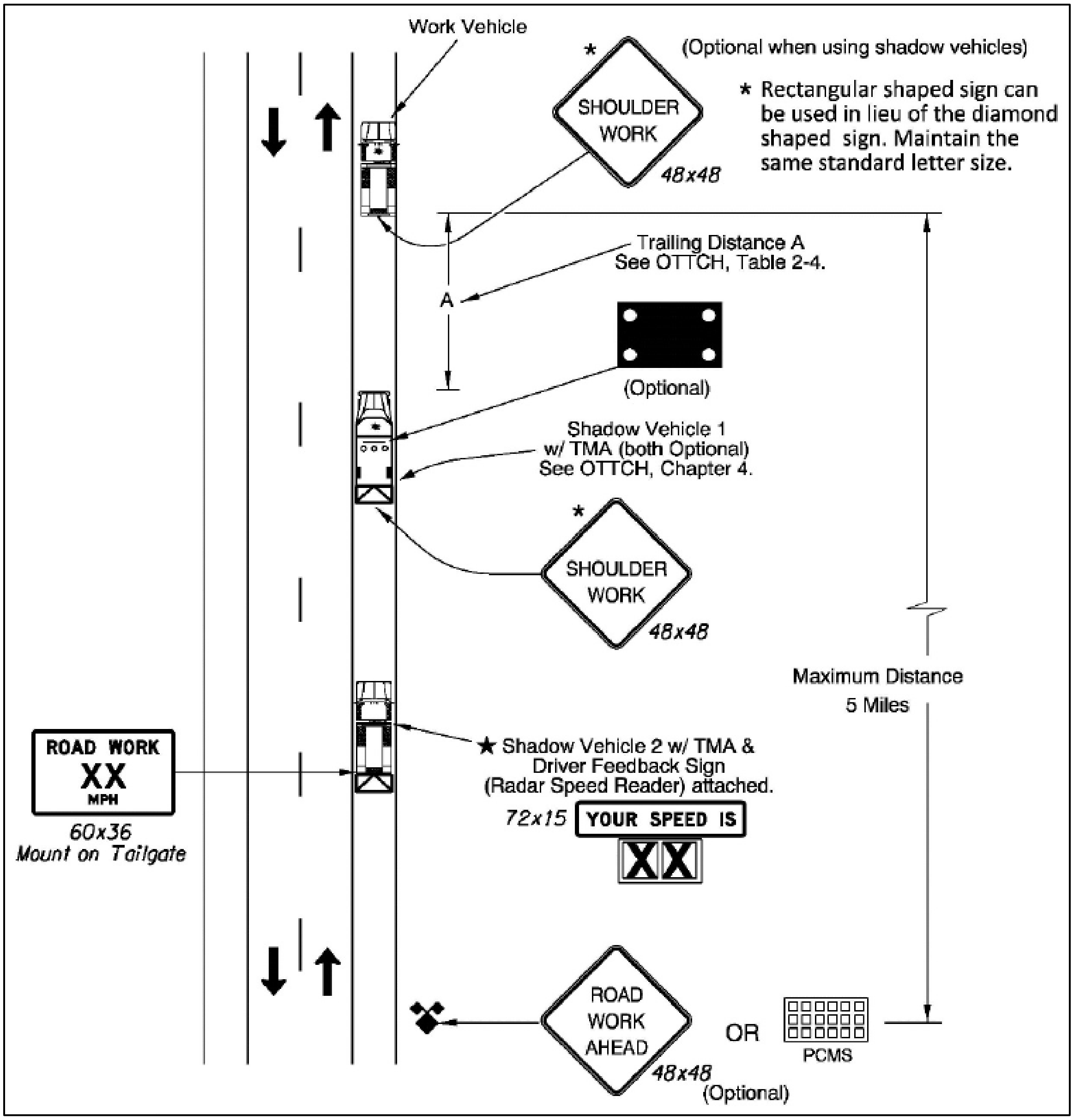


Figure 77. Photo. Example work zone layout for a non-freeway mobile operation shoulder closure with speed feedback signs (Gambatase and Jafarnejad, 2015).

Automated Speed Enforcement

Maryland State Highway Administration provides a typical layout for automated speed enforcement which includes protection for the ASE vehicle and display with proper sight distance, as shown in Figure 78 (MSHA, 2012).

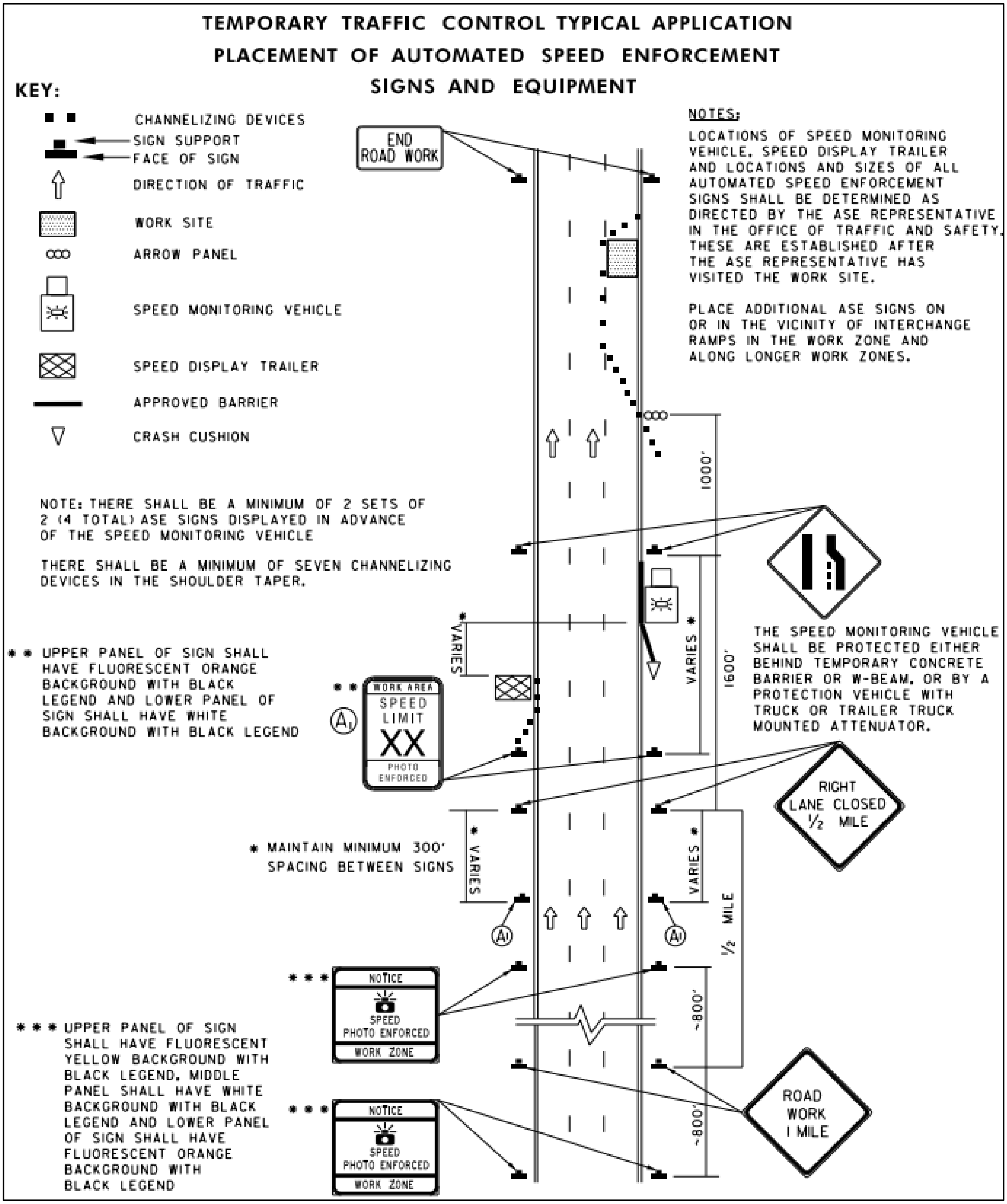


Figure 78. Photo. Example work zone layout with automated speed enforcement (MSHA, 2012).

Variable Speed Advisory Systems

MnDOT developed guidelines for the deployment of variable speed advisory systems in smart work zones, as shown in Figure 79 (MnDOT 2020). These guidelines recommend that VMS communicating speeds to drivers must be placed at least ½ mile to 1 mile before the slow traffic or queue, and longer work zones may require multiple VMS (MnDOT 2020).

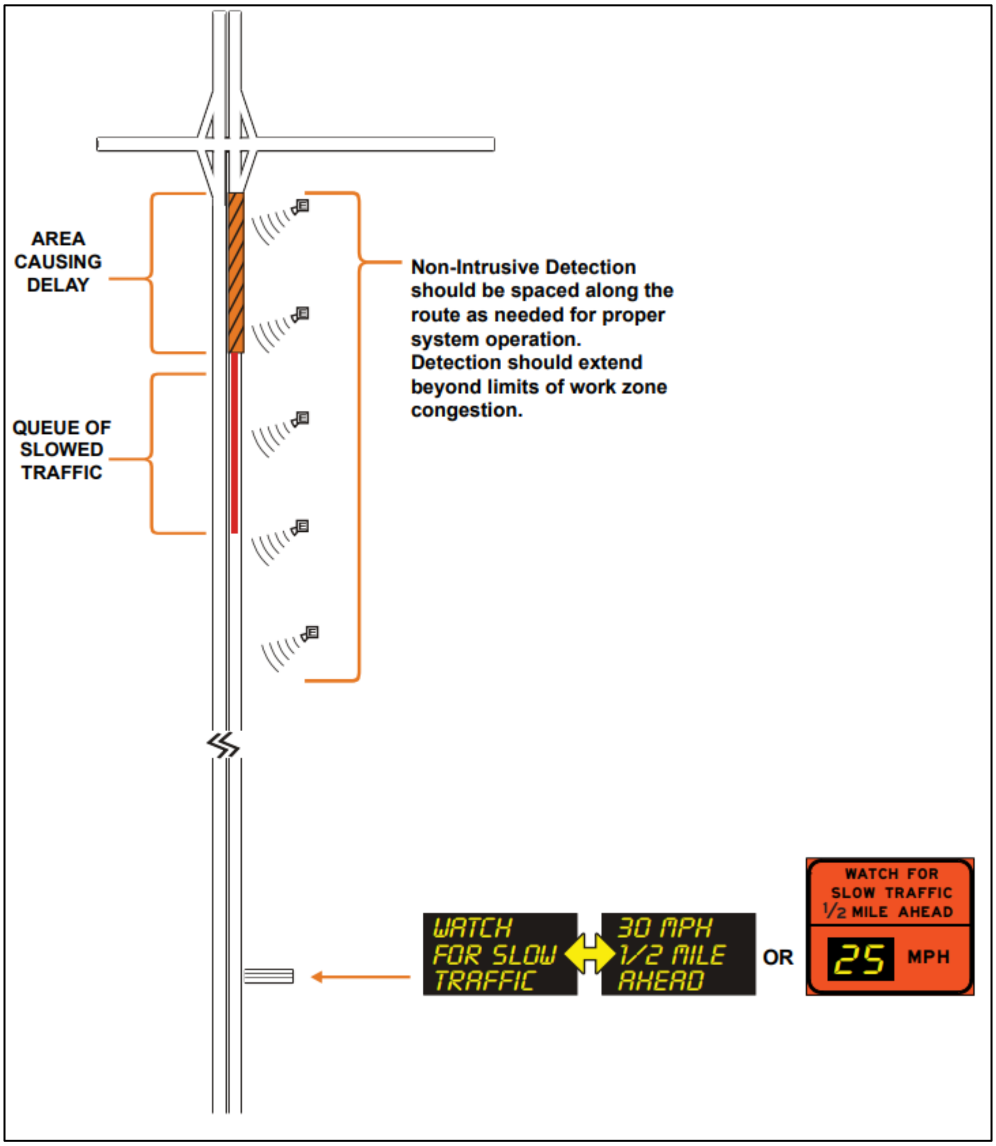


Figure 79. Photo. Example work zone layout with variable speed advisory system (MnDOT, 2020).

Travel Time Information System

Several state DOTs have developed guidelines for the deployment of travel time information systems in smart work zones (MnDOT 2022, TxDOT 2022, and MassDOT 2016). The deployment of TTIS equipment and their locations highly depend on the specific needs of the work zone and the available alternate routes. For example, the MassDOT guidelines for the deployment of TTIS in smart work zones utilizes a similar approach to the aforementioned QWS guidelines. The MassDOT guidelines specify the key locations of TTIS equipment in the following eight key points in and around the work zone, as shown in Figure 80-A and Figure 80-B:

a) Start of the work zone.

b) End of the work zone.

c) Location of merge/lane drop for closure.

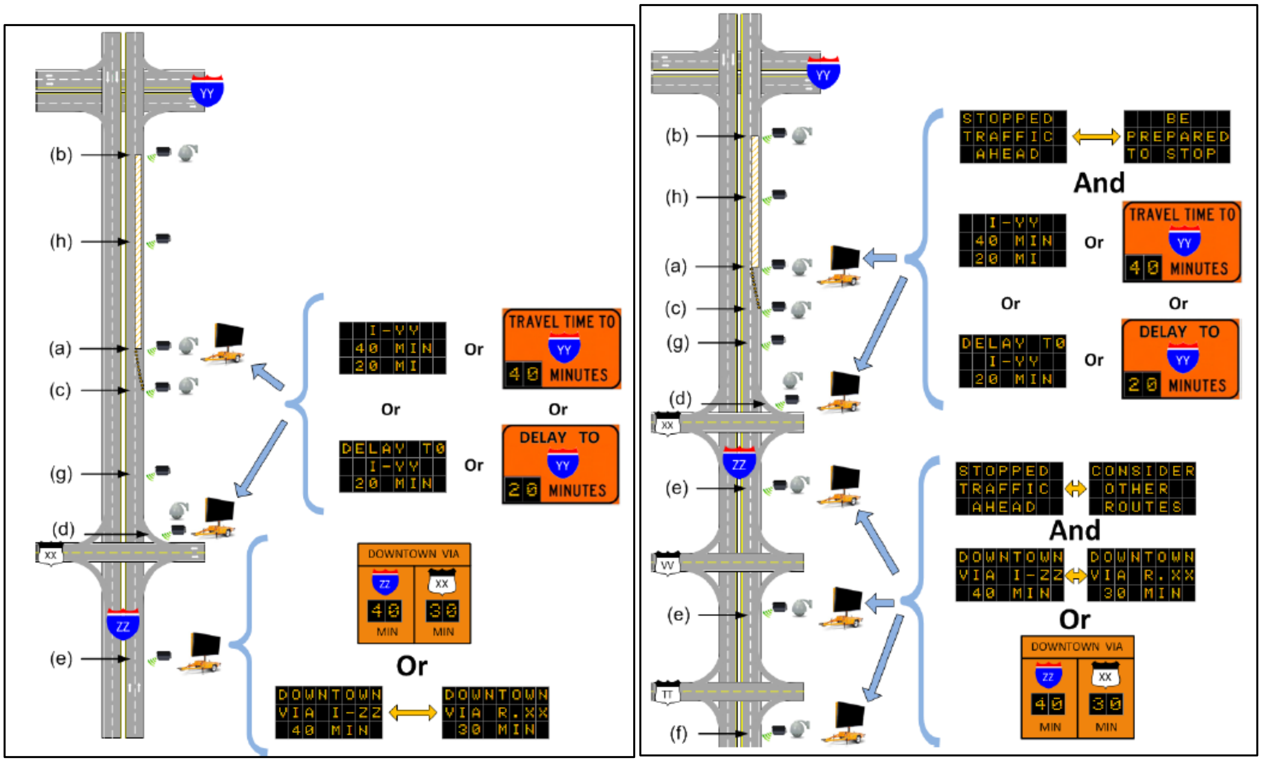
d) All approaches within 0.5 miles of the work activity.

e) Upstream decision points nearest to the work activity (i.e., the closest viable locations where drivers could exit the highway and take a suitable alternate route before reaching the work zone).

f) For Level 4 or Significant projects located on major highways or interstates, also identify any upstream intersections/interchanges with other major highways that could offer alternate routes.

g) One point upstream of the bottleneck where traffic should be stable during most operating hours.

h) One point downstream of the bottleneck where traffic should be stable during most operating hours.



A. Sample layout of "project level 3." B. Sample layout of "project level 4."

Figure 80. Photo. Sample work zone layouts with travel time information systems (MassDOT, 2016).

Smart Arrow Boards

The deployment of smart arrow boards can significantly vary from one work zone to another based on three main categories of design requirements: reporting system, deployment setting, and TMC system. For example, the arrow board reporting system category depends on the design specifications for device type, data processing capabilities, communication mechanism, and connected vehicle capabilities, as shown in Table 71. Similarly, the design specifications and available options for the two remaining categories of deployment setting and TMC system are summarized in Table 72 and Table 73 (Enterprise 2017).

Table 71. Options for Smart Arrow Board Design Specifications Based on Reporting System Variations (Enterprise, 2017)

Variation	Option 1	Option 2	Option 3
Device type	Truck-mounted	Trailer	-
Data processing capabilities	None	Present	-
Communication mechanism	To TMC	To 3rd-party server	To DOT staff
Connected vehicle capabilities	None	Present	-

Table 72. Options for Smart Arrow Board Design Specifications Based on Deployment Setting Variations (Enterprise, 2017)

Variation	Option 1	Option 2	Option 3
Area	Urban	Rural	-
Roadway type	Freeway	Arterial	-
Work zone type	Stationary	Mobile	-
Lanes closed	Single lane	Multiple lanes	-
Work zone duration	Short (hours)	Medium (days, weeks)	Long (months)

Table 73. Options for Smart Arrow Board Design Specifications Based on TMC System Variations (Enterprise, 2017)

Variation	Option 1	Option 2	Option 3
Integration with TMC systems	RCRS	ATMS	ATIS
Level of automation	Manually generated	Manually approved	Fully automated
Staff notification recipients	Field staff	Operator staff	-
Staff Notification mechanism	Text	E-mail	TMC interface
Staff Notification Events	Activation/De-activation	All display status changes	-
Achieved Database	Existing archived	New archived	-

Temporary Incident Detection System

Incident detection system highly depend on the desired level of surveillance and specific work zone characteristics. For example, TxDOT developed guidelines for the deployment of incident detection systems in smart work zones, as shown in Figure 81 (TxDOT 2018).

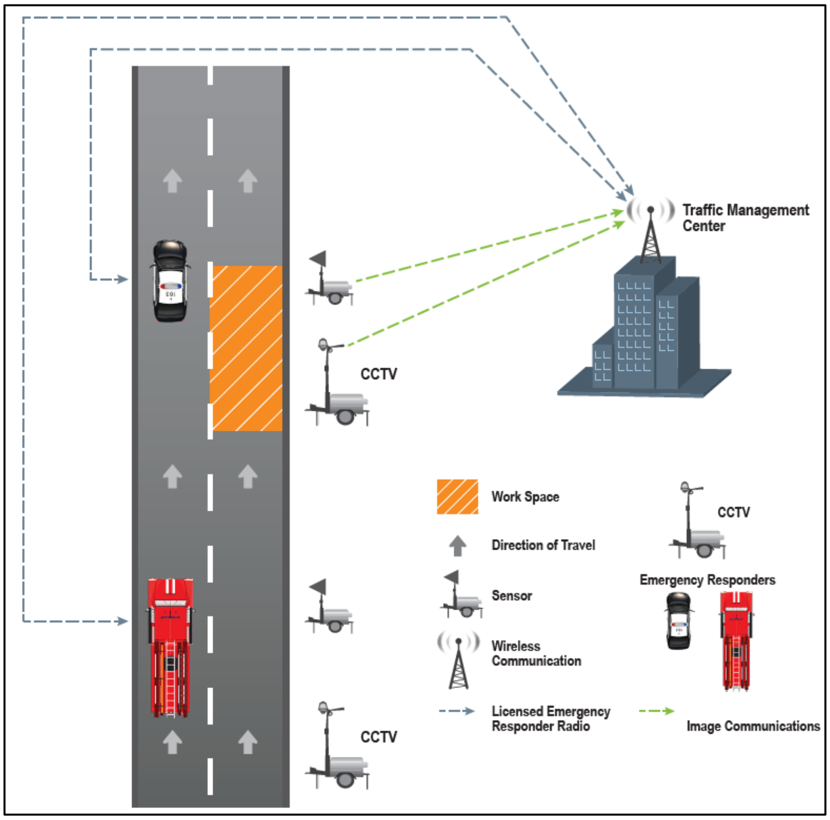


Figure 81. Photo. Example work zone layout with temporary incident detection system (TxDOT, 2018).

Construction Truck Alert Systems

MnDOT developed guidelines for the deployment of construction truck alert systems in smart work zones, as shown in Figure 82 (MnDOT 2022a). These guidelines provide varying recommendations based on three possible construction truck merging systems that use (1) dedicated lane, (2) acceleration lane, or (3) no acceleration lane, as shown in Figure 82. In the dedicated lane merging system, MnDOT advises that there is no need for deployment of construction truck entering system (MnDOT, 2022a). For the acceleration lane or no acceleration lane merging systems, MnDOT provides recommendation on the use of construction truck entering system, as shown in Figure 82. Similarly, other states have developed guidelines for the deployment of construction truck alert systems (CTDOT, 2017; MassDOT, 2016; and TxDOT, 2018). For example, TxDOT guidelines recommend that a dedicated PCMS should be used exclusively for the construction truck alert system, and should not display any other messaging (TxDOT, 2018). Furthermore, the American Road and Transportation Builders Association (ARTBA) provides recommendations on the distance from warning sign to construction vehicle merge point based on operating speed on travel lanes, as shown in Figure 83 (ARTBA, 2019).

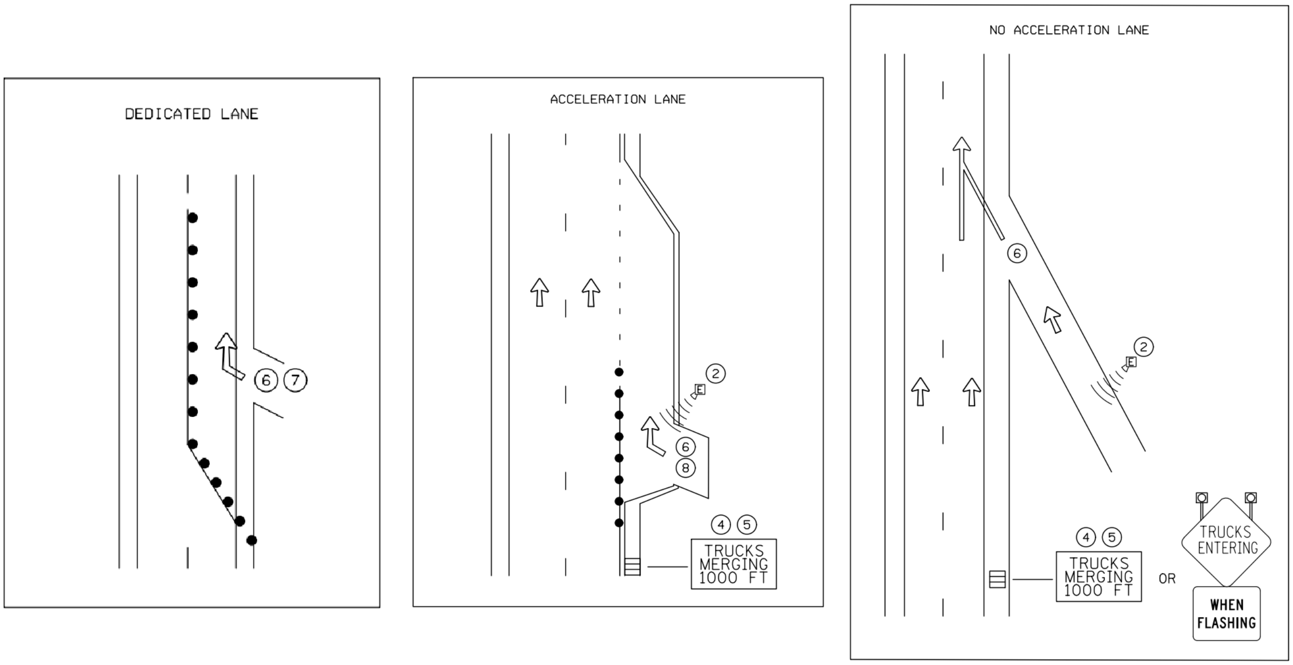


Figure 82. Photo. Example work zone layout with construction vehicle merging system (MnDOT, 2022a).

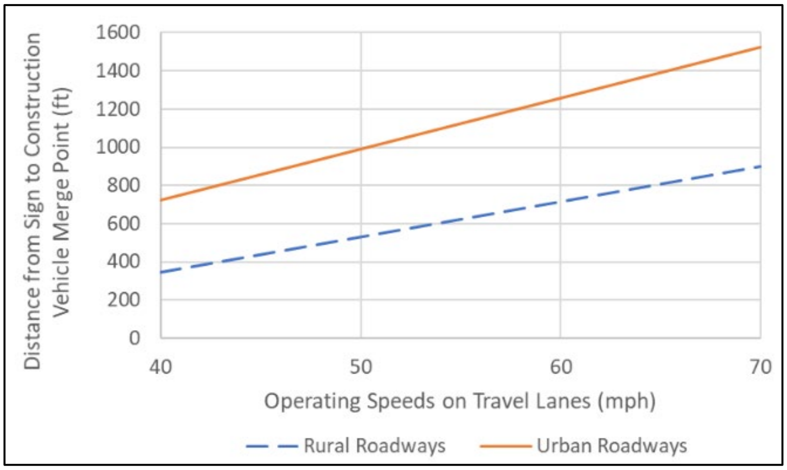


Figure 83. Graph. Recommended sign location for construction vehicle merge point (ARTBA, 2019).

APPENDIX A3: SMART WORK ZONE DECISION AND DESIGN TOOLS

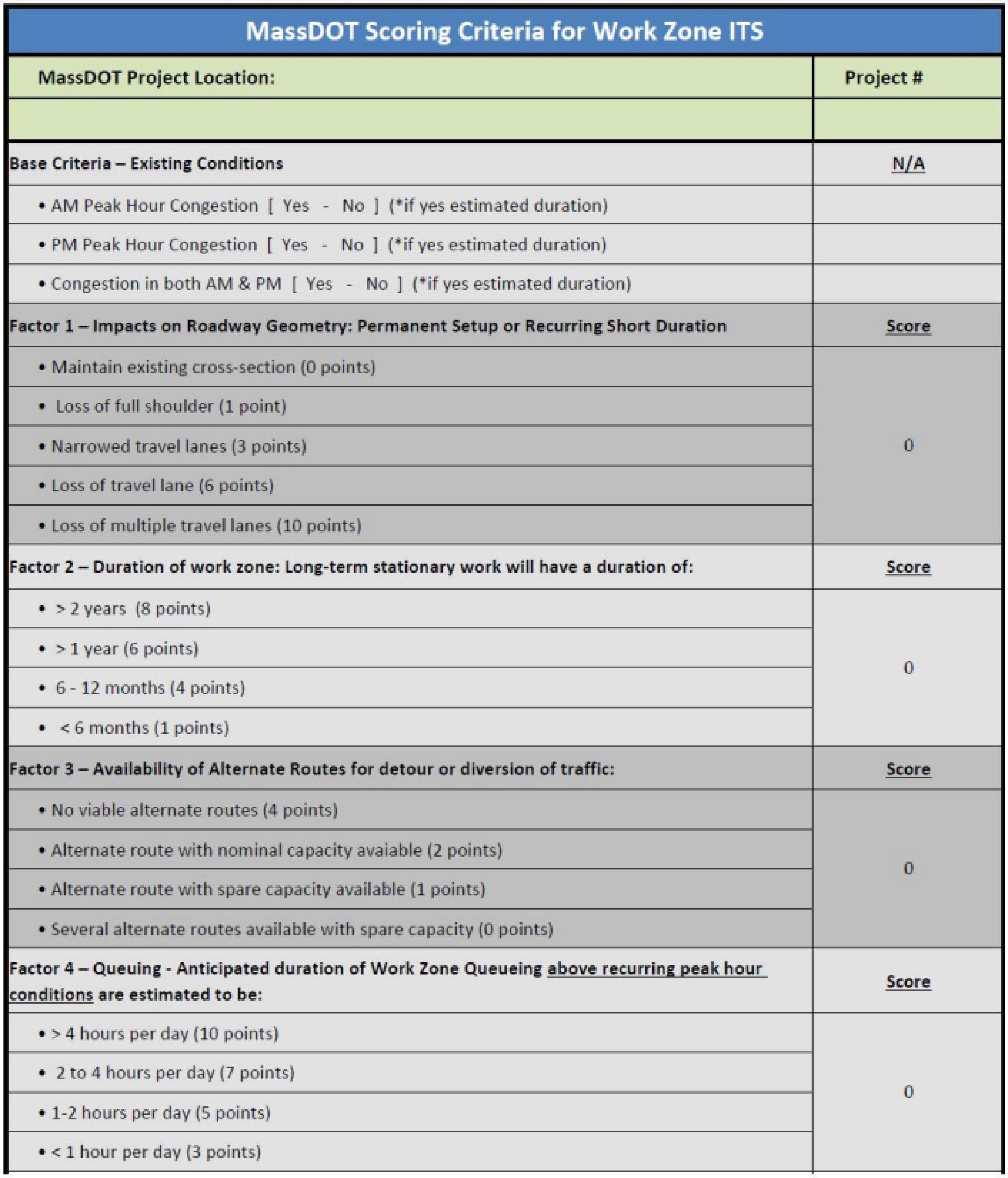
This chapter presents the findings of the conducted literature review on smart work zone decision and design tools developed by FHWA and other state DOTs to support their decision-makers in effectively selecting and deploying smart work zone systems. Four SWZ decision and design tools were analyzed in this literature review: (1) FHWA and State DOTs Feasibility Worksheet and Work Zone Design Tools; (2) TxDOT Go/No-Go Decision Tool; (3) ADOT Work Zone Design Tool; and (4) MnDOT Decision Tree to Identify Potential ITS/IWZ Scoping Needs and Best Practices for ITS/IWZ Deployment. These decision and design tools were developed using MS excel or decision flow charts and are discussed in the following sections.

FHWA and State DOTs Scoring Criteria for Work Zone ITS

In 2014, the FHWA developed the *Work Zone Intelligent Transportation Systems Implementation Guide* that includes scoring criteria that can be used by state DOTs to analyze the feasibility of deploying ITS in work zones. The developed FHWA scoring criteria are grouped into five main categories of factors: (1) duration of work zone; (2) impact to traffic, businesses, other destinations, or other users; (3) queuing and delay; (4) temporal aspects of traffic impacts; and (5) specific issues expected, as shown in Table 74 (FHWA 2014). For example, the duration of work zone factor can be used to assign a score of 10 points, 6 points, and 3 points if the work zone duration is greater than 1 construction season, 4-10 months, and less than 4 months, respectively (see Table 74). Similarly, the remaining scores can be assigned based on the specific conditions or characteristics of the work zone. These scores are then summed up to determine the feasibility of the work zone to deploy ITS. If the total score is greater or equal to 30, then an ITS is likely to provide significant benefits relative to procurement costs. If the score is between 10 and 30, ITS may provide some benefits and should be considered to mitigate impacts. Otherwise, if the score is lower than 10, then ITS may not provide enough benefit to justify the costs associated with the smart work zone systems. The FHWA recommended that state DOTs modify their feasibility tools based on their specific needs (FHWA, 2014). This FHWA scoring criteria was used as is by ADOT to develop its own SWZ feasibility tool that was implemented as an MS Excel spreadsheet, as shown in Table 74 (ADOT 2020). Similarly, MassDOT developed its own SWZ feasibility tool by expanding the FHWA scoring criteria to include additional factors such as impact on roadway geometry, and availability of alternate routes, as shown in Figure 84 and Figure 85 (MassDOT 2016). TxDOT expanded the FHWA scoring criteria to develop its own Go/No-Go Decision Tool in 2018 to determine if a specific smart work zone (SWZ) system is needed on a roadway project. This tool can be used to determine the need for six different types of SWZ systems: queue detection, speed monitoring, construction vehicle alerts, travel time systems, over-height warning system, and temporary incident-detection system and they are described in more detail in the next section (TxDOT 2018).

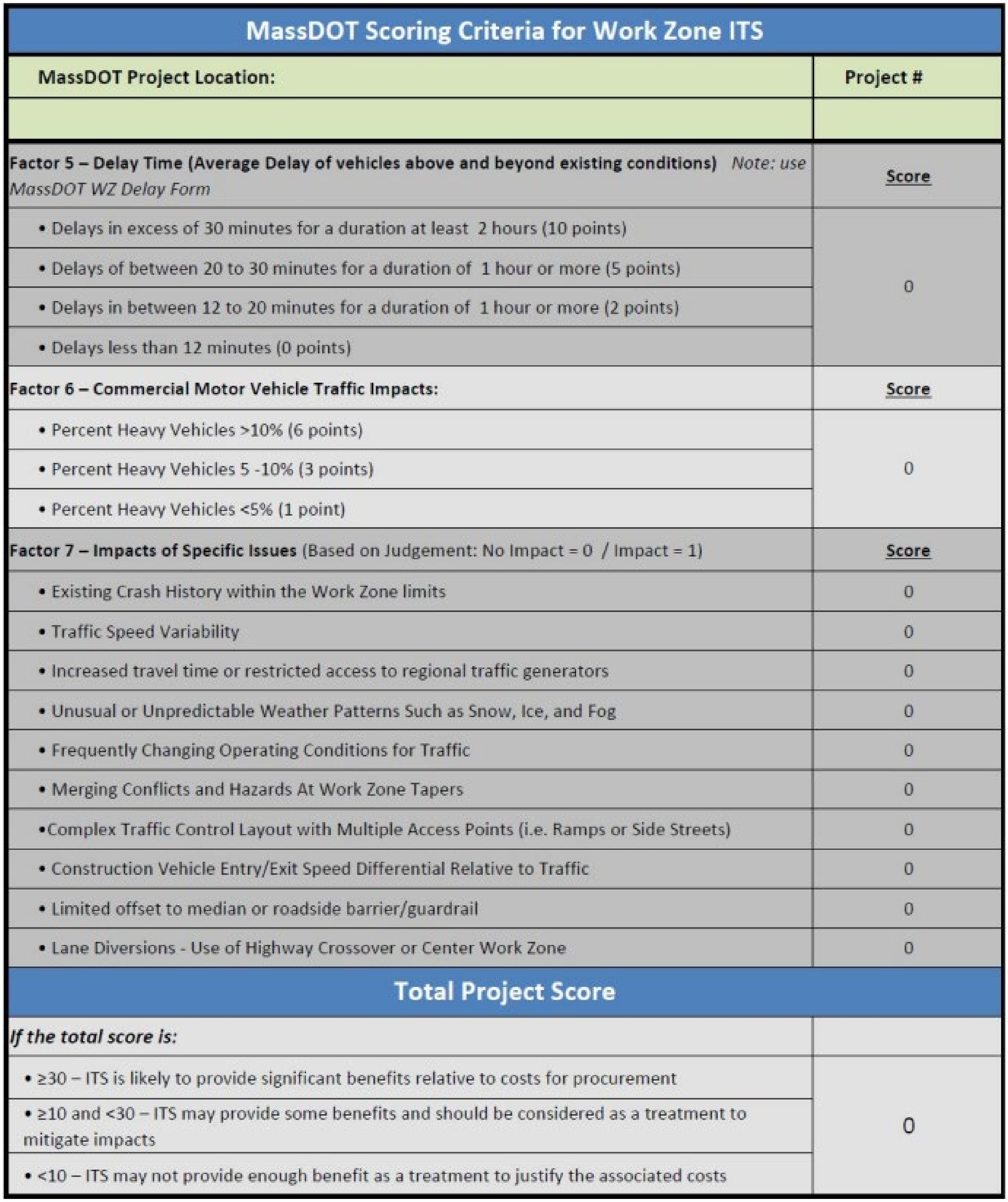
Table 74. FHWA/ADOT Smart Work Zone Feasibility Worksheet (FHWA, 2014; ADOT, 2020)

Criteria		Score
Factor 1 - Duration of Work Zone: Long-term stationary work will have a duration of:		
*	> 1 Construction Season (10 points)	
*	4-10 months (6 points)	
*	< 4 months; procurement & installation timeline is available prior to work starting (3 points)	
Factor 2 - Impact to traffic, businesses, other destinations or other users (e.g. extremely long delays, high risk of speed variability, access issues) for the duration of work is expected to be:		
*	Significant (10 points)	
*	Moderate (6 points)	
*	Minimal (3 points)	
Factor 3 - Queuing & Delay: Queue lengths are estimated to be:		
*	>/= 2 miles for periods >/= 2 hours per day (8 to 10 points)	
*	1-2 miles for periods of 1-2 hours per day (6 to 8 points)	
*	</= 1 mile (or queue length estimates are not available, but pre-construction, recurring congestion exists for periods < 1 hour per day (4 points)	
Factor 4 - Temporal Aspects of Traffic Impacts: Expected traffic impacts are:		
*	Unreasonable for a time period that covers more than just peak hours (10 points)	
*	Unreasonable during most of morning & afternoon peak hours in either direction (6 points)	
*	Unreasonable during most of a peak hour in either direction (3 points)	
*	Unpredictable; highly variable traffic volumes (1 point)	
Factor 5 - Specific Issues Expected (0 to 3 points each based on judgement)		
*	Traffic Speed Variability	
*	Back of Queue & Other Sight Distance Issues	
*	High Speeds/Chronic Speeding	
*	Work Zone Congestion	
*	Availability of Alternate Routes	
*	Merging Conflicts & Hazards at Work Zone Tapers	
*	Frequently Changing Operating Conditions for Traffic	
*	Variable Work Activities (that may benefit from Variable Speed Limits)	
*	Oversized Vehicles and/or Heavy Truck % > 10%	
*	Large Speed Differentials of Construction Vehicle Entering/Exiting Relative to Traffic	
*	Data Collection needs for Work Zone Performance Measures	
*	Unusual or Unpredictable Weather Patterns (Snow, Ice, Fog, Wind)	
TOTAL SCORE (If the total score is):		**0**



MassDOT Scoring Criteria for Work Zone ITS	
MassDOT Project Location:	**Project #**
Base Criteria – Existing Conditions	**N/A**
• AM Peak Hour Congestion [Yes - No] (*if yes estimated duration)	
• PM Peak Hour Congestion [Yes - No] (*if yes estimated duration)	
• Congestion in both AM & PM [Yes - No] (*if yes estimated duration)	
Factor 1 – Impacts on Roadway Geometry: Permanent Setup or Recurring Short Duration	**Score**
• Maintain existing cross-section (0 points)	0
• Loss of full shoulder (1 point)	
• Narrowed travel lanes (3 points)	
• Loss of travel lane (6 points)	
• Loss of multiple travel lanes (10 points)	
Factor 2 – Duration of work zone: Long-term stationary work will have a duration of:	**Score**
• > 2 years (8 points)	0
• > 1 year (6 points)	
• 6 - 12 months (4 points)	
• < 6 months (1 points)	
Factor 3 – Availability of Alternate Routes for detour or diversion of traffic:	**Score**
• No viable alternate routes (4 points)	0
• Alternate route with nominal capacity avaiable (2 points)	
• Alternate route with spare capacity available (1 points)	
• Several alternate routes available with spare capacity (0 points)	
Factor 4 – Queuing - Anticipated duration of Work Zone Queueing above recurring peak hour conditions are estimated to be:	**Score**
• > 4 hours per day (10 points)	0
• 2 to 4 hours per day (7 points)	
• 1-2 hours per day (5 points)	
• < 1 hour per day (3 points)	

Figure 84. Photo. MassDOT scoring criteria for work zone ITS (Factors 1 - 4) (MassDOT, 2016).



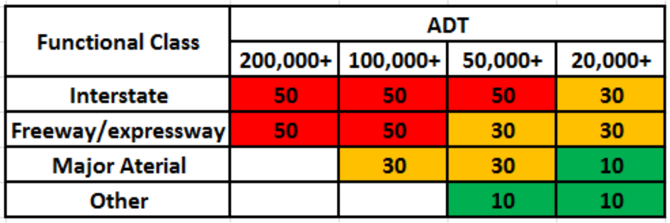
MassDOT Scoring Criteria for Work Zone ITS	
MassDOT Project Location:	**Project #**
Factor 5 – Delay Time (Average Delay of vehicles above and beyond existing conditions) *Note: use MassDOT WZ Delay Form*	**Score**
• Delays in excess of 30 minutes for a duration at least 2 hours (10 points)	0
• Delays of between 20 to 30 minutes for a duration of 1 hour or more (5 points)	
• Delays in between 12 to 20 minutes for a duration of 1 hour or more (2 points)	
• Delays less than 12 minutes (0 points)	
Factor 6 – Commercial Motor Vehicle Traffic Impacts:	**Score**
• Percent Heavy Vehicles >10% (6 points)	0
• Percent Heavy Vehicles 5 -10% (3 points)	
• Percent Heavy Vehicles <5% (1 point)	
Factor 7 – Impacts of Specific Issues (Based on Judgement: No Impact = 0 / Impact = 1)	**Score**
• Existing Crash History within the Work Zone limits	0
• Traffic Speed Variability	0
• Increased travel time or restricted access to regional traffic generators	0
• Unusual or Unpredictable Weather Patterns Such as Snow, Ice, and Fog	0
• Frequently Changing Operating Conditions for Traffic	0
• Merging Conflicts and Hazards At Work Zone Tapers	0
•Complex Traffic Control Layout with Multiple Access Points (i.e. Ramps or Side Streets)	0
• Construction Vehicle Entry/Exit Speed Differential Relative to Traffic	0
• Limited offset to median or roadside barrier/guardrail	0
• Lane Diversions - Use of Highway Crossover or Center Work Zone	0
Total Project Score	
If the total score is:	
• ≥30 – ITS is likely to provide significant benefits relative to costs for procurement	0
• ≥10 and <30 – ITS may provide some benefits and should be considered as a treatment to mitigate impacts	
• <10 – ITS may not provide enough benefit as a treatment to justify the associated costs	

Figure 85. Photo. MassDOT scoring criteria for work zone ITS (Factors 5 - 7) (MassDOT, 2016).

TXDOT Go/No-Go Decision Tool

Texas DOT (TxDOT) developed a “GO/No-GO Decision tool” in 2018 that can be used by decision-makers to determine if a specific smart work zone (SWZ) system is needed on a roadway project. The tool can be used to determine the need for six different types of SWZ systems: queue detection, speed monitoring, construction vehicle alerts, travel time systems, over-height warning system, and temporary incident-detection system. For each of these six SWZ systems, the tool utilizes a scoring table to evaluate the work zone needs based on a set of project-specific scoring factors and criteria. For example, the scoring factors used in the tool to determine the need for temporary travel time systems include duration of the work zone, highway function class and average daily traffic, impact from local traffic generators, estimated queue length, existing traffic issues, availability of alternate routes, adjacent/consecutive project, extreme weather condition, connected vehicle, existing its systems, and heavy vehicles, as shown in Table 75. For each of these scoring factors, the decision-maker needs to provide a project-specific score based on the scoring criteria listed in the table. For example, a score of 10 points should be assigned to the ‘duration of the work zone’ scoring factor if the project duration is greater than one year, as shown in Table 75. A total raw score is then calculated by summing up all the assigned scores for all scoring factors. The raw score is normalized using a scale that ranges from 0 to 100 to provide recommendations on the deployment of each SWZ system. If the normalized score is greater than 65, the SWZ system is “strongly recommended. If the score is between 33 and 65, the SWZ system should be “given consideration,” and if the score is below 33, the SWZ system is not recommended (TxDOT, 2018).

Table 75. Go/No-Go Decision Tree for Temporary Travel Time System (TxDOT, 2018)

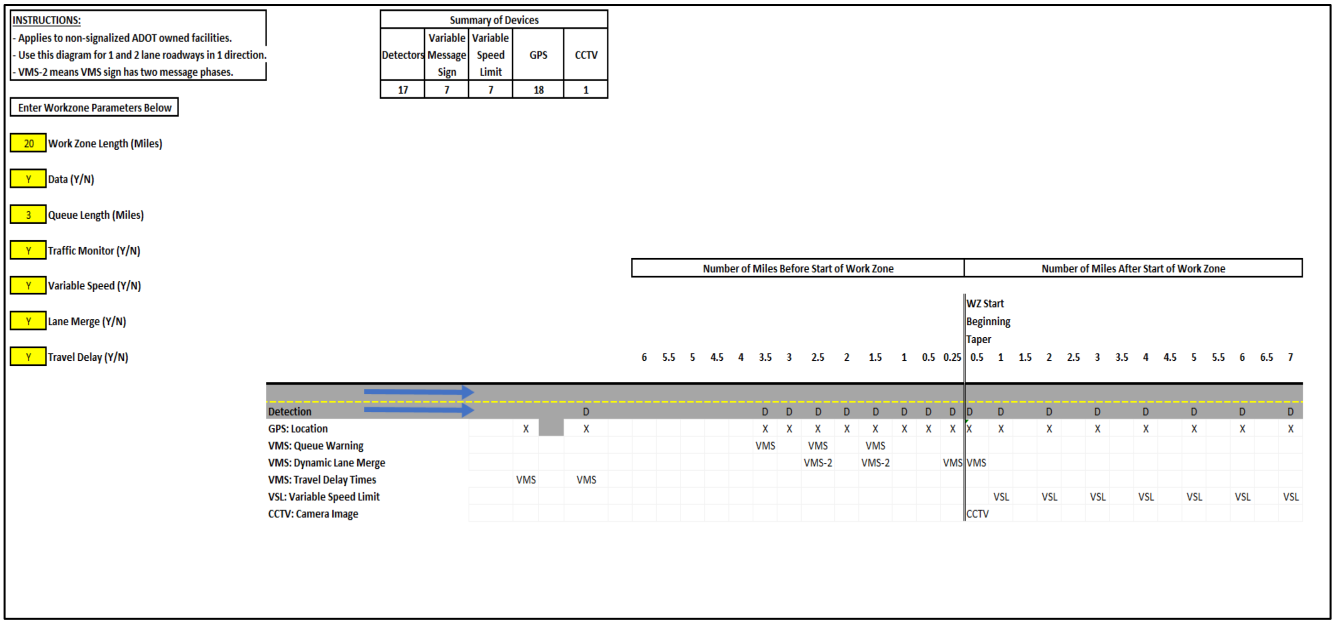
<table>
<tr><th>Scoring Factors</th><th>Scoring Range Criteria</th><th>Score</th></tr>
<tr><td>Duration of the Work Zone</td><td>For projects with multiple work zones (ex. bridge painting or patching), score the duration of the longest work zone only.
> 1 year (10 points)
1 - 10 months (5 points)
< 1 months (0 points)</td><td></td></tr>
<tr><td>Highway Function Class and ADT</td><td>
<table>
<tr><th rowspan="2">Functional Class</th><th colspan="4">ADT</th></tr>
<tr><th>200,000+</th><th>100,000+</th><th>50,000+</th><th>20,000+</th></tr>
<tr><td>Interstate</td><td>50</td><td>50</td><td>50</td><td>30</td></tr>
<tr><td>Freeway/expressway</td><td>50</td><td>50</td><td>30</td><td>30</td></tr>
<tr><td>Major Aterial</td><td></td><td>30</td><td>30</td><td>10</td></tr>
<tr><td>Other</td><td></td><td></td><td>10</td><td>10</td></tr>
</table></td><td></td></tr>
<tr><td>Impact from local traffic generators</td><td>Significant-local facilities are large enough to have official destination signs on the Interstate highway such as conference centers, sports arenas etc., so they produce large surges in traffic before/after large events (20 points)
Moderate-Local businesses or public facilities generate traffic volumes that routinely backup the on/off ramps such as morning and evening rush hours (10 points)
Minimal-Any circumstance that causes occasional backups on the on/off ramps such as congested local arterials or rail crossings (5 points)
None (0 points)</td><td></td></tr>
<tr><td>Estimated Queue Length (Calculated, or see Max Queue Length tab for rough estimate)</td><td>> 7 miles (80 points)
3.5 to 7 miles (70 points)
0 to 3.5 miles (60 points)
None (0 points)</td><td></td></tr>
<tr><td>Existing traffic issues</td><td>higher than normal crash rates, gridlock or frequent exit ramp backups (3 points)
Not applicable (0 points)</td><td></td></tr>
<tr><td>Availability of Alternate routes</td><td>Convenient alternate routes with capacity are available. (3 points)
No alternate routes available (0 points)</td><td></td></tr>
<tr><td>Adjacent/consecutive project</td><td>There are adjacent active projects effectively creating a mega-project that totals...
longer than 10 miles or longer than 2 years (3 points)
between 5 to 10 miles or between 1 and 2 years (2 points)
between 2 to 5 miles or between 6 months to 1 year (1 point)
less than 2 miles or less than 6 months (0 points)</td><td></td></tr>
<tr><td>Extreme weather condition</td><td>Work zone has a known history of sudden extreme weather condition, sandstorm, etc. Project duration covers several harsh weather season. (3 points)
Not applicable (0 points)</td><td></td></tr>
<tr><td>Connected vehicle</td><td>>5% (3 points)
<5% (0 points)</td><td></td></tr>
<tr><td>Existing ITS Systems</td><td>Project falls inside an existing Advanced Traffic Management System?
The TMC has the intent to incorporate the travel time and delay estimating system into the TMC operations?
The TMC can remotely control their existing advance traveler information systems?
(Each question worth 10 point)</td><td></td></tr>
<tr><td>Heavy vehicles</td><td>>12% (3 points)
>9% (2 points)
>6% (1 point)
<6% (0 points)</td><td></td></tr>
<tr><td>Raw Score</td><td>-</td><td>0</td></tr>
<tr><td>Normalized Score (0 to 100)</td><td>-</td><td>0</td></tr>
</table>

ADOT Work Zone Design Tool

In 2020, ADOT developed a SWZ design tool that can be used by designers to (1) analyze the feasibility of deploying smart work zone systems on roadway projects using the aforementioned FHWA scoring criteria, (2) identify SWZ subsystems that are needed in the work zone, and (3) determine the quantities and locations of SWZ devices in the work zone (ADOT 2020). First, ADOT developed SWZ feasibility tool (see Table 74) that can be used to determine the feasibility of deploying smart work zone systems using the aforementioned FHWA scoring criteria (ADOT 2020).

Second, ADOT developed a procedure to identify the need for all feasible SWZ subsystems in the work zone including queue warning, dynamic merge, travel delay, traffic monitoring, and variable speed limit. The need for these SWZ subsystems are analyzed based on five specific factors: congestion, lane restriction, delay information, surveillance capability, length of work zone and need for changing speeds when workers are present. For example, if the work zone is going to cause congestion or the volume to capacity ratio will exceed 1.0 then a queue warning system is needed in the work zone. Similarly, if the work zone is expected to restrict or close traffic lanes then a dynamic merge system is needed in the work zone. Additionally, if the work zone has an alternate route available within five miles upstream of the work zone, then a travel delay system is needed in the work zone. Furthermore, if there are no permanent camera or surveillance capability currently monitoring the work zone then a traffic monitoring camera system is needed in the work zone. Lastly, if the length of the work zone exceeds two miles and there is a desire to be able to lower the posted speed limits when workers are present then a variable speed limit system is needed in the work zone.

Third, ADOT developed a design tool using MS Excel to determine the quantities and locations of SWZ devices in the work zone based on seven types of work zone parameters: work zone length, data, queue length, traffic monitor, variable speed, lane merge, and travel delay, as shown in Figure 86 (ADOT 2020).



INSTRUCTIONS:
- Applies to non-signalized ADOT owned facilities.
- Use this diagram for 1 and 2 lane roadways in 1 direction.
- VMS-2 means VMS sign has two message phases.

Summary of Devices				
Detectors	Variable Message Sign	Variable Speed Limit	GPS	CCTV
17	7	7	18	1

Enter Workzone Parameters Below

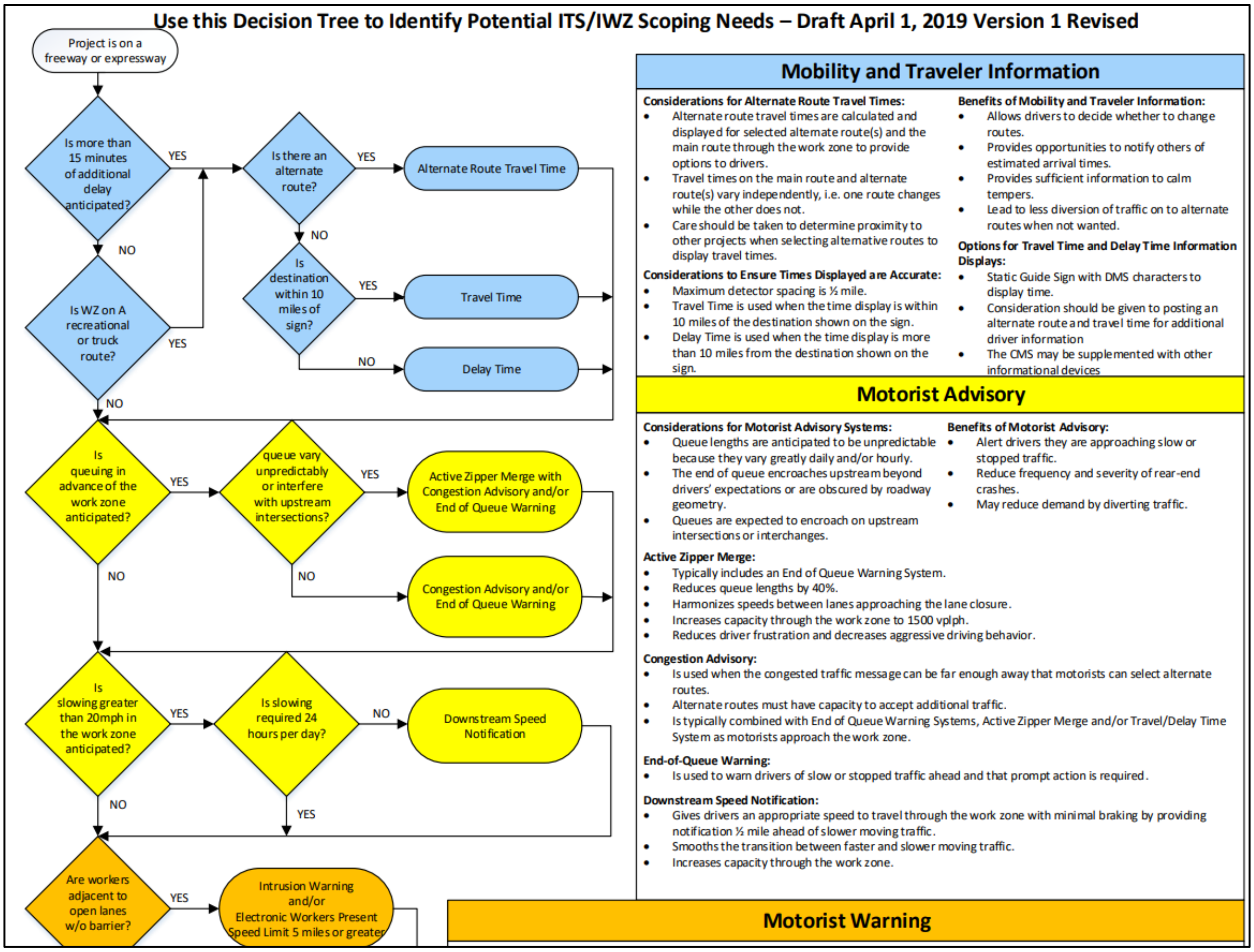
20	Work Zone Length (Miles)
Y	Data (Y/N)
3	Queue Length (Miles)
Y	Traffic Monitor (Y/N)
Y	Variable Speed (Y/N)
Y	Lane Merge (Y/N)
Y	Travel Delay (Y/N)

				Number of Miles Before Start of Work Zone													Number of Miles After Start of Work Zone													
																	WZ Start Beginning Taper													
				6	5.5	5	4.5	4	3.5	3	2.5	2	1.5	1	0.5	0.25	0.5	1	1.5	2	2.5	3	3.5	4	4.5	5	5.5	6	6.5	7
Detection			D						D	D	D	D	D	D	D	D	D	D		D		D		D		D		D		D
GPS: Location	X		X						X	X	X	X	X	X	X	X	X	X		X		X		X		X		X		X
VMS: Queue Warning									VMS		VMS		VMS																	
VMS: Dynamic Lane Merge											VMS-2		VMS-2			VMS	VMS													
VMS: Travel Delay Times	VMS		VMS																											
VSL: Variable Speed Limit																		VSL		VSL		VSL		VSL		VSL		VSL		VSL
CCTV: Camera Image																	CCTV													

Figure 86. Screenshot. ADOT work zone design tool layout example (ADOT, 2019).

MNDOT Decision Tree to Identify Potential ITS/IWZ Scoping Needs

In 2019, MnDOT developed *Decision Tree to Identify Potential ITS/IWZ Scoping Needs* to analyze the needs of work zones to deploy SWZ systems during the planning/scoping phase. For example, the need to deploy mobility and traveler information systems in the work zone is determined based on the length of delay and alternate routes, as shown in Figure 87. Similarly, the need to deploy motorist advisory systems, motorist warning systems, and route management systems are determined based on a detailed set of factors that are listed in the developed decision tree (MnDOT 2019).


Use this Decision Tree to Identify Potential ITS/IWZ Scoping Needs – Draft April 1, 2019 Version 1 Revised

Mobility and Traveler Information

Considerations for Alternate Route Travel Times:
- Alternate route travel times are calculated and displayed for selected alternate route(s) and the main route through the work zone to provide options to drivers.
- Travel times on the main route and alternate route(s) vary independently, i.e. one route changes while the other does not.
- Care should be taken to determine proximity to other projects when selecting alternative routes to display travel times.

Considerations to Ensure Times Displayed are Accurate:
- Maximum detector spacing is ½ mile.
- Travel Time is used when the time display is within 10 miles of the destination shown on the sign.
- Delay Time is used when the time display is more than 10 miles from the destination shown on the sign.

Benefits of Mobility and Traveler Information:
- Allows drivers to decide whether to change routes.
- Provides opportunities to notify others of estimated arrival times.
- Provides sufficient information to calm tempers.
- Lead to less diversion of traffic on to alternate routes when not wanted.

Options for Travel Time and Delay Time Information Displays:
- Static Guide Sign with DMS characters to display time.
- Consideration should be given to posting an alternate route and travel time for additional driver information
- The CMS may be supplemented with other informational devices

Motorist Advisory

Considerations for Motorist Advisory Systems:
- Queue lengths are anticipated to be unpredictable because they vary greatly daily and/or hourly.
- The end of queue encroaches upstream beyond drivers' expectations or are obscured by roadway geometry.
- Queues are expected to encroach on upstream intersections or interchanges.

Benefits of Motorist Advisory:
- Alert drivers they are approaching slow or stopped traffic.
- Reduce frequency and severity of rear-end crashes.
- May reduce demand by diverting traffic.

Active Zipper Merge:
- Typically includes an End of Queue Warning System.
- Reduces queue lengths by 40%.
- Harmonizes speeds between lanes approaching the lane closure.
- Increases capacity through the work zone to 1500 vplph.
- Reduces driver frustration and decreases aggressive driving behavior.

Congestion Advisory:
- Is used when the congested traffic message can be far enough away that motorists can select alternate routes.
- Alternate routes must have capacity to accept additional traffic.
- Is typically combined with End of Queue Warning Systems, Active Zipper Merge and/or Travel/Delay Time System as motorists approach the work zone.

End-of-Queue Warning:
- Is used to warn drivers of slow or stopped traffic ahead and that prompt action is required.

Downstream Speed Notification:
- Gives drivers an appropriate speed to travel through the work zone with minimal braking by providing notification ½ mile ahead of slower moving traffic.
- Smooths the transition between faster and slower moving traffic.
- Increases capacity through the work zone.

Motorist Warning

Figure 87. Diagram. Sample of MnDOT decision tree to identify potential ITS/IWZ scoping needs (MnDOT 2019)

APPENDIX B: STATE DOT SURVEY FORM

SMART WORK ZONE SYSTEMS APPLICATIONS AND BENEFITS

Introduction and Basic Information

The **Illinois Department of Transportation** is sponsoring an ongoing research project to study the **use of smart work zone (SWZ) systems to increase safety and mobility**. This online survey is designed to take less than 15 minutes to complete. Your valuable feedback will assist in evaluating the current use and effectiveness of SWZ systems. We would appreciate if you completed the survey by **September 30, 2022**.

The research team will be glad to share the findings of this survey with you upon completion. If you have any questions or comments, please contact the Principle Investigator (PI) of this research project:

Khaled El-Rayes, Professor

Department of Civil and Environmental Engineering

University of Illinois at Urbana-Champaign

E-mail: elrayes@illinois.edu

Thank you in advance for your time.

1. What is your name? (Optional) ____________________
2. What state do you represent? (Required) ____________________
3. What is your current job title? (Optional) ____________________

Use of Smart Work Zone (SWZ) Systems

4. Which of the following SWZ systems have been used by your state DOT? (Select all that apply)

    [ ] Variable message signs (VMS), dynamic message signs (DMS), portable changeable message signs (PCMS), or dynamic message boards

    [ ] Queue warning systems (QWS) or end-of-queue warning systems (EQWS)

    [ ] Dynamic lane merge systems (DLMS)

    [ ] Speed feedback signs (SFS)

    [ ] Automated speed enforcement (ASE)

    [ ] Variable speed advisory (VSA) systems or speed notification systems (SNS)

    [ ] Travel time information systems (TTIS)

    [ ] Smart arrow boards

    [ ] Temporary incident detection and surveillance systems

    [ ] Construction truck entering and exiting systems

    [ ] Other – Please specify and provide a brief description ____________________

5. If your state does not currently utilize any of the following SWZ systems, does your state have plans to consider it in the future? (Select all that apply)

    [ ] No new technologies being considered

    [ ] Variable message signs (VMS), dynamic message signs (DMS), changeable message signs (CMS), or dynamic message boards

    [ ] Queue warning systems (QWS) or end-of-queue warning systems (EQWS)

    [ ] Dynamic lane merge systems (DLMS)

    [ ] Speed feedback signs (SFS)

    [ ] Automated speed enforcement (ASE)

    [ ] Variable speed advisory (VSA) systems or speed notification systems (SNS)

    [ ] Travel time information systems (TTIS)

    [ ] Smart arrow boards

[ ] Temporary incident detection and surveillance systems

[ ] Construction truck entering and exiting systems

[ ] Other – Please specify and provide a brief description ____________________

Effectiveness of Smart Work Zone (SWZ) Systems in Reducing Crashes

6. Please report the impact of each SWZ system in **<u>reducing the frequency and/or severity of vehicle crashes</u>** as Negative Impact, No Change, Slightly Positive Impact, Positive Impact, Very Positive Impact, or Inadequate Information.

SWZ Systems	Negative Impact	No Change	Slightly Positive Impact	Positive Impact	Very Positive Impact	Inadequate Information
Variable message signs						
Queue warning systems						
Dynamic lane merge systems						
Speed feedback signs						
Automated speed enforcement						
Variable speed advisory systems						
Travel time information systems						
Smart arrow boards						
Temporary incident detection and surveillance systems						
Construction truck entering and exiting systems						
Other – Please specify						

7. Has your state experienced a reduction in roadway crashes through utilizing SWZ systems?

[ ] Yes

[ ] No

8. If yes, please report experienced reduction in the frequency and/or severity of roadway crashes (%), or provide links to documented crash reduction if available

SWZ Systems	% Decrease in frequency and/or severity roadway crashes/Link to Report
Variable message signs	
Queue warning systems	
Dynamic lane merge systems	
Speed feedback signs	
Automated speed enforcement	
Variable speed advisory systems	
Travel time information systems	
Smart arrow boards	
Temporary incident detection and surveillance systems	
Construction truck entering and exiting systems	
Other – Please specify	

Effectiveness of Smart Work Zone (SWZ) Systems in Reducing Delay and Queue Length

9. Please report the impact of each SWZ system in **reducing delay and queue length** as Negative Impact, No Change, Slightly Positive Impact, Positive Impact, Very Positive Impact, or Inadequate Information.

SWZ Systems	Negative Impact	No Change	Slightly Positive Impact	Positive Impact	Very Positive Impact	Inadequate Information
Variable message signs						
Queue warning systems						
Dynamic lane merge systems						
Speed feedback signs						
Automated speed enforcement						
Variable speed advisory systems						
Travel time information systems						
Smart arrow boards						
Temporary incident detection and surveillance systems						
Construction truck entering and exiting systems						
Other – Please specify						

10. Has your state experienced a reduction in delay and/or queue length through utilizing SWZ systems?

[ ] Yes

[ ] No

11. If yes, please report experienced reduction in travel time delay or queue length (%), or provide links to documented travel time and queue length reduction if available

SWZ Systems	% Decrease in Travel Time Delay or Queue Length/Link to Report
Variable message signs	
Queue warning systems	
Dynamic lane merge systems	
Speed feedback signs	
Automated speed enforcement	
Variable speed advisory systems	
Travel time information systems	
Smart arrow boards	
Temporary incident detection and surveillance systems	
Construction truck entering and exiting systems	
Other – Please specify	

Project Conditions for Deploying Smart Work Zone (SWZ) Systems.

12. Please specify any project conditions that require the deployment of each of the following SWZ systems, or provide a link to your related DOT specifications. Examples of project conditions may include recurring queues, baseline crashes exceeded typical average in project location, or expected high truck volume.

SWZ Systems	Project conditions for deployment/related DOT specifications
Variable message signs	
Queue warning systems	
Dynamic lane merge systems	
Speed feedback signs	
Automated speed enforcement	
Variable speed advisory systems	
Travel time information systems	
Smart arrow boards	
Temporary incident detection and surveillance systems	
Construction truck entering and exiting systems	
Other – Please specify	

13. If your DOT use tools and/or design criteria to determine if a SWZ system is required on a project, please provide a link to this tool/design criteria.

____

Cost of Implementing Smart Work Zone (SWZ) Systems.

14. Please indicate if your state DOT owns, leases or rents SWZ equipment? (Select all that apply)

[ ] DOT owns equipment

[ ] DOT leases equipment

[ ] DOT rents equipment

15. Please provide the unit purchase cost of the following SWZ systems in $/unit, if they were purchased by your DOT.

SWZ Systems	Unit Cost in $/unit
Variable message signs	
Queue warning systems	
Dynamic lane merge systems	
Speed feedback signs	
Automated speed enforcement	
Variable speed advisory systems	
Travel time information systems	
Smart arrow boards	
Temporary incident detection and surveillance systems	
Construction truck entering and exiting systems	
Other – Please specify	

16. Please provide the cost of the following SWZ systems as a percentage of the total project cost, if they were purchased by your DOT.

SWZ Systems	Percentage of Total Cost
Variable message signs	
Queue warning systems	
Dynamic lane merge systems	
Speed feedback signs	
Automated speed enforcement	
Variable speed advisory systems	
Travel time information systems	
Smart arrow boards	
Temporary incident detection and surveillance systems	
Construction truck entering and exiting systems	
Other – Please specify	

17. Please provide the monthly rental costs of the following SWZ systems, if they were leased by your DOT.

SWZ Systems	Unit Rental Cost in $/unit
Variable message signs	
Queue warning systems	
Dynamic lane merge systems	
Speed feedback signs	
Automated speed enforcement	
Variable speed advisory systems	
Travel time information systems	
Smart arrow boards	
Temporary incident detection and surveillance systems	
Construction truck entering and exiting systems	
Other – Please specify	

Smart Work Zone (SWZ) Systems Problems and Challenges.

18. Please report the frequency of challenges encountered in operating and maintaining the following SWZ systems as None, Moderate, High, Very High or Inadequate Information and specify the type of challenges.

SWZ Systems	None	Moderate	High	Very High	Inadequate Information	Please Specify Encountered Challenges
Variable message signs						
Queue warning systems						
Dynamic lane merge systems						
Speed feedback signs						
Automated speed enforcement						
Variable speed advisory systems						
Travel time information systems						
Smart arrow boards						
Temporary incident detection and surveillance systems						
Construction truck entering and exiting systems						
Other – Please specify						

APPENDIX C: SWZ EQUIPMENT LOCATION

Table 76. DLMS Designed Equipment Location

State	System	Roadway Corridor Location	Activity Area Location
FHWA	VMS	• 1 or 2 miles from the start of activity area • End of queue	• Start of activity area
MassDOT	VMS	• Middle of queue • End of queue	• Start of activity area • Middle of activity area • End of activity area
MassDOT	Detectors	• Middle of queue • End of queue	• Start of activity area
MassDOT	CCTV	None	• Start of activity area • Middle of activity area
CTDOT	VMS	• End of queue	• Start of activity area
CTDOT	Detectors	• Full distance of the queue with spacing specified based on each project	None
ADOT	VMS	• 1.5 mile from the start of activity area • 2.5 mile from the start of activity area	• Start of activity area
ADOT	Detectors	• Every 0.5 mile until end of queue	• Start of activity area • Middle of activity area • End of activity area
ADOT	CCTV	None	• Start of activity area (optional)
MnDOT	VMS	• 0.5 or 1 mile before activity area • End of queue	• Start of activity area
MnDOT	Detectors	• Every 0.5 or 1 mile until end of queue	• Start of activity area
Recommended Designed Layout	VMS	• 1.5 mile from the start of activity area • End of queue	• Start of activity area
Recommended Designed Layout	Detectors	• Every 1 mile until end of queue	• Start of activity area

Table 77. VSA Designed Equipment Location

State	System	Roadway Corridor Location	Activity Area Location
MassDOT	VMS	• Middle of queue	• Start of activity area
MassDOT	Detectors	• Middle of queue	None
MassDOT	CCTV	None	• Start of activity area (optional) • Middle of activity area (optional)
CTDOT	VMS	• End of queue	• Start of activity area
CTDOT	Detectors	• Full distance of the queue with spacing specified based on each project	• Full distance of the activity area with spacing specified based on each project
ADOT	VMS	None	• Start of activity area
ADOT	Detectors	• Every 0.5 mile until end of queue	• Start of activity area • Middle of activity area • End of activity area • Every 1 mile within activity area
ADOT	CCTV	None	• Start of activity area (optional)
MnDOT	VMS	• 0.5 to 1 mile after end of queue	• Start of activity area
MnDOT	Detectors	• Full distance of the queue with spacing specified based on each project	• Full distance of the activity area with spacing specified based on each project
TxDOT	VMS	• End of queue	• Start of activity area
TxDOT	Detectors	• Full distance of the queue with spacing specified based on each project	None
Recommended Designed Layout	VMS	• End of queue	• Start of activity area
Recommended Designed Layout	Detectors	• Every 1 mile until end of queue	• Start of activity area • Middle of activity area • End of activity area
Recommended Designed Layout	CCTV	None	• Start of activity area (optional)

Table 78. TTIS Designed Equipment Location

State	System	Roadway Corridor Location	Activity Area Location
MassDOT	VMS	- Before alternative route exit	- Start of activity area
MassDOT	Detectors	- Middle of queue - End of queue - Before alternative route exit	- Start of activity area - Middle of activity area - End of activity area
MassDOT	CCTV	None	- Start of activity area (optional) - Middle of activity area (optional)
CTDOT	VMS	- End of queue	- Start of activity area
CTDOT	Detectors	- Full distance of queue with spacing specified based on each project	- Full distance of activity area with spacing specified based on each project
CTDOT	CCTV	None	- Start of activity area (optional)
ADOT	VMS	- Before and after alternative route exit	None
ADOT	Detectors	- Every 0.5 mile until end of queue	- Start of activity area - Middle of activity area - End of activity area
ADOT	CCTV	None	- Start of activity area (optional)
MnDOT	VMS	- End of queue - Before alternative route exit	None
MnDOT	Detectors	- Full distance of queue with spacing specified based on each project	- Full distance of activity area with spacing specified based on each project
TxDOT	VMS	- End of queue	- Start of activity area
TxDOT	Detectors	- Middle of queue - End of queue	- Middle of activity area - End of activity area
TxDOT	CCTV	- End of queue	None
Recommended Designed Layout	VMS	- End of queue - Before alternative route exit	- Start of activity area
Recommended Designed Layout	Detectors	- Every 1 mile until end of queue	- Start of activity area - Middle of activity area - End of activity area
Recommended Designed Layout	CCTV	None	- Start of activity area (optional)

Table 79. TIDS Designed Equipment Location

State	System	Roadway Corridor Location	Activity Area Location
MassDOT	VMS	• Before alternative route exit	• Start of activity area
MassDOT	Detectors	None	• Start of activity area • Middle of activity area • End of activity area
MassDOT	CCTV	None	• Start of activity area • Middle of activity area
MnDOT	VMS	• Before alternative route exit	• Start of activity area
MnDOT	Detectors	• Full distance of queue with spacing specified based on each project	• Full distance of activity area with spacing specified based on each project
TxDOT	Detectors	• Middle of queue • End of queue	• Start of activity area • End of activity area
TxDOT	CCTV	• End of queue	• Start of activity area
Recommended Designed Layout	VMS	• Before alternative route exit	• Start of activity area
Recommended Designed Layout	Detectors	• Middle of queue • End of queue	• Start of activity area • Middle of activity area • End of activity area
Recommended Designed Layout	CCTV	None	• Start of activity area

Table 80. CTEDS Designed Equipment Location

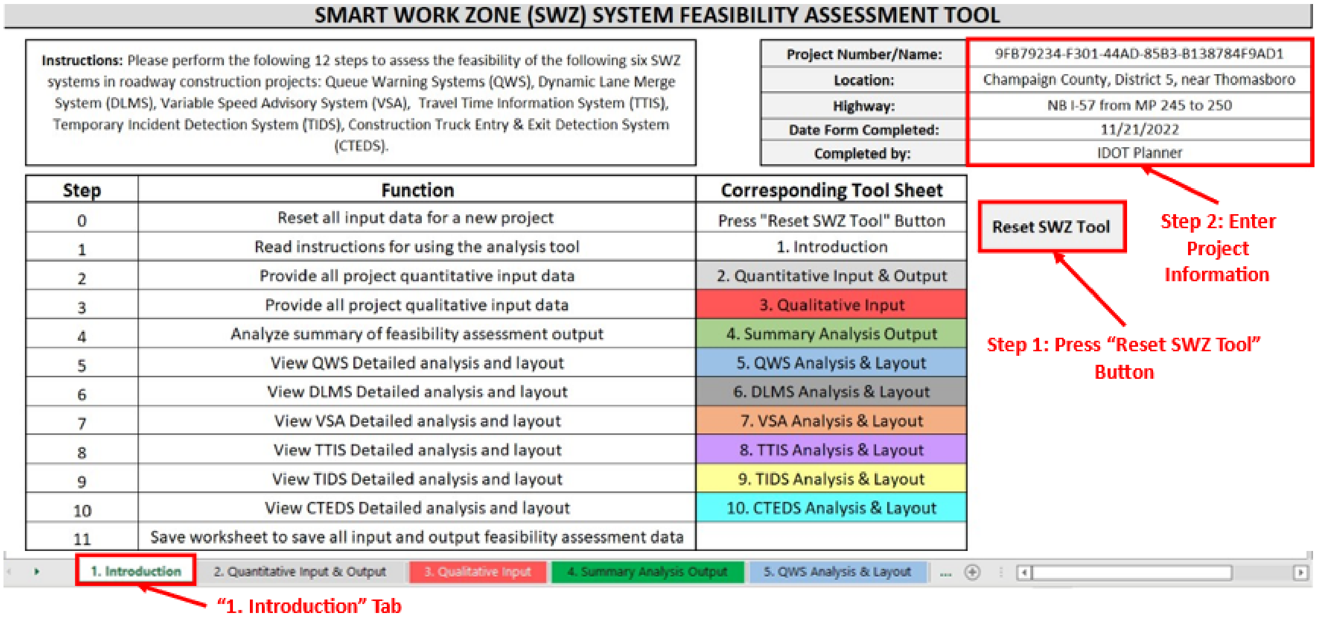
State	System	Roadway Corridor Location	Activity Area Location
MassDOT	VMS	None	• Start of activity area
MassDOT	Detectors	None	• Start of activity area • Middle of activity area • End of activity area
MassDOT	CCTV	None	• Start of activity area (optional) • Middle of activity area (optional)
CTDOT	VMS	• End of queue	None
MnDOT	VMS	None	• Start of activity area
MnDOT	Detectors	• Area after where the truck merges with spacing specified based on each project	• Area after where the truck merges with spacing specified based on each project
TxDOT	VMS	• End of queue	• Start of activity area
TxDOT	Detectors	None	• Start of activity area • Middle of activity area
Recommended Designed Layout	VMS	• End of queue	• Start of activity area
Recommended Designed Layout	Detectors	None	• Start of activity area • Middle of activity area • End of activity area

APPENDIX D: SWZ FEASIBILITY ASSESSMENT TOOL USER-FRIENDLY INTERFACE AND CASE STUDY

This section analyzes a case study to illustrate the user-friendly interface of the developed SWZ feasibility assessment tool and demonstrate its novel capabilities in predicting mobility and safety work zone factors to determine the need for deploying SWZ systems for different types of projects. The case study was obtained from the lane closure databases (OPER 2410) on the Illinois DOT Geographic Information System (IDOT GIS) available online and the designated project ID of the case study was '9FB79234-F301-44AD-85B3-B138784F9AD1' (IDOT, 2017). This roadway construction project is currently ongoing on I-57 northbound in Champaign County from mile post 245 to 250. This case study was analyzed by the developed tool using the following eight steps.

1. Reset any previously stored project data and start a new project by pressing the "Reset SWZ Tool" button in the spreadsheet tab named "1. Introduction," as shown in Figure 88.

2. Enter general project information in the same spreadsheet tab including project number/name, location, highway, date form completed, and completed by, as shown in Figure 88.



SMART WORK ZONE (SWZ) SYSTEM FEASIBILITY ASSESSMENT TOOL

Instructions: Please perform the folowing 12 steps to assess the feasibility of the following six SWZ systems in roadway construction projects: Queue Warning Systems (QWS), Dynamic Lane Merge System (DLMS), Variable Speed Advisory System (VSA), Travel Time Information System (TTIS), Temporary Incident Detection System (TIDS), Construction Truck Entry & Exit Detection System (CTEDS).

Project Number/Name:	9FB79234-F301-44AD-85B3-B138784F9AD1
Location:	Champaign County, District 5, near Thomasboro
Highway:	NB I-57 from MP 245 to 250
Date Form Completed:	11/21/2022
Completed by:	IDOT Planner

Step	Function	Corresponding Tool Sheet
0	Reset all input data for a new project	Press "Reset SWZ Tool" Button
1	Read instructions for using the analysis tool	1. Introduction
2	Provide all project quantitative input data	2. Quantitative Input & Output
3	Provide all project qualitative input data	3. Qualitative Input
4	Analyze summary of feasibility assessment output	4. Summary Analysis Output
5	View QWS Detailed analysis and layout	5. QWS Analysis & Layout
6	View DLMS Detailed analysis and layout	6. DLMS Analysis & Layout
7	View VSA Detailed analysis and layout	7. VSA Analysis & Layout
8	View TTIS Detailed analysis and layout	8. TTIS Analysis & Layout
9	View TIDS Detailed analysis and layout	9. TIDS Analysis & Layout
10	View CTEDS Detailed analysis and layout	10. CTEDS Analysis & Layout
11	Save worksheet to save all input and output feasibility assessment data	

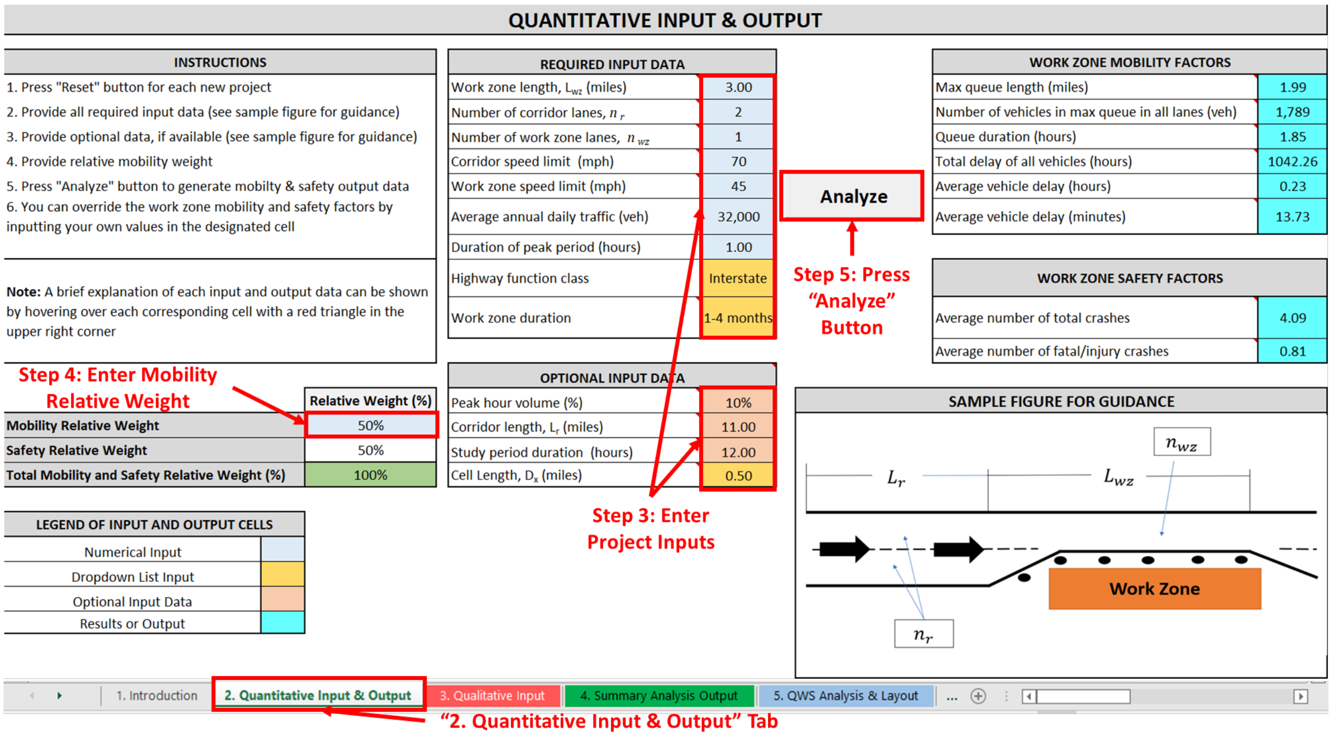
Figure 88. Screenshot. Introduction worksheet tab.

3. Enter project-specific input data in the spreadsheet tab named "2. Quantitative Input & Output," as shown in Figure 89. The project-specific input data are grouped into two sets: required and optional inputs. The required input data include 7 numerical input fields—work zone length, number of roadway lanes, number of work zone lanes, corridor speed limit, work zone speed limit, AADT, and peak period duration—and two dropdown list input—highway function class and work zone duration. Similarly, the optional input data includes two

numerical input fields—corridor length and study period duration—and two dropdown list input—peak hour volume and cell length. Note that the developed tool provides a sample figure for guidance as well as a brief description of input data cell, which can be displayed when the user hovers the mouse pointer over a cell with a red triangle in the corner, as shown in Figure 89.

4. Enter the mobility relative weight in the same spreadsheet tab "2. Quantitative Input & Output Data." The tool is designed to use this input to automatically calculate the safety relative weight and to verify that it sums up to 100%, as shown in Figure 89.

5. Calculate all quantitative work zone mobility and safety factors by pressing the "Analyze" button in the same spreadsheet tab. For example, the maximum queue length, average delay in minutes, and average number of total crashes were calculated and displayed by the developed tool as 4.77 miles, 22.66 minutes, and 4.02 crashes, respectively (see Figure 89). Similarly, the remaining mobility and safety performance factors were also calculated and displayed in the same spreadsheet, as shown in Figure 89.



QUANTITATIVE INPUT & OUTPUT

INSTRUCTIONS
1. Press "Reset" button for each new project
2. Provide all required input data (see sample figure for guidance)
3. Provide optional data, if available (see sample figure for guidance)
4. Provide relative mobility weight
5. Press "Analyze" button to generate mobilty & safety output data
6. You can override the work zone mobility and safety factors by inputting your own values in the designated cell
Note: A brief explanation of each input and output data can be shown by hovering over each corresponding cell with a red triangle in the upper right corner

REQUIRED INPUT DATA	
Work zone length, L_{wz} (miles)	3.00
Number of corridor lanes, n_r	2
Number of work zone lanes, n_{wz}	1
Corridor speed limit (mph)	70
Work zone speed limit (mph)	45
Average annual daily traffic (veh)	32,000
Duration of peak period (hours)	1.00
Highway function class	Interstate
Work zone duration	1-4 months

OPTIONAL INPUT DATA	
Peak hour volume (%)	10%
Corridor length, L_r (miles)	11.00
Study period duration (hours)	12.00
Cell Length, D_x (miles)	0.50

Step 3: Enter Project Inputs

Step 4: Enter Mobility Relative Weight

	Relative Weight (%)
Mobility Relative Weight	50%
Safety Relative Weight	50%
Total Mobility and Safety Relative Weight (%)	100%

LEGEND OF INPUT AND OUTPUT CELLS	
Numerical Input	▨
Dropdown List Input	▨
Optional Input Data	▨
Results or Output	▨

Step 5: Press "Analyze" Button

WORK ZONE MOBILITY FACTORS	
Max queue length (miles)	1.99
Number of vehicles in max queue in all lanes (veh)	1,789
Queue duration (hours)	1.85
Total delay of all vehicles (hours)	1042.26
Average vehicle delay (hours)	0.23
Average vehicle delay (minutes)	13.73

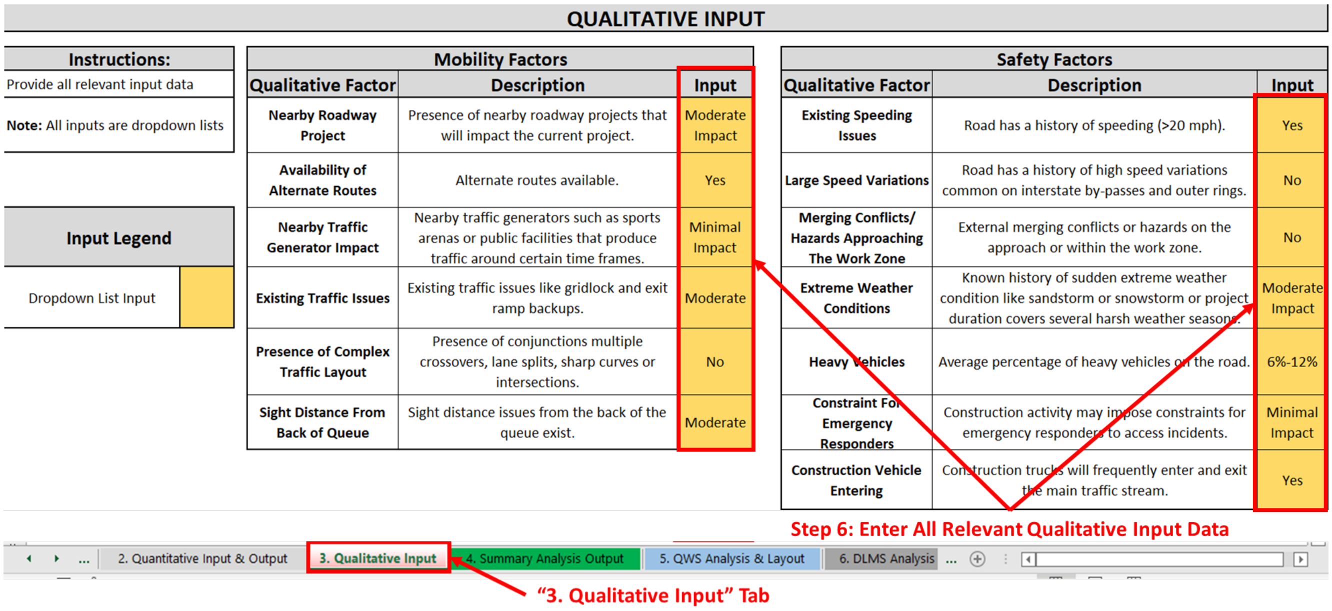
WORK ZONE SAFETY FACTORS	
Average number of total crashes	4.09
Average number of fatal/injury crashes	0.81

SAMPLE FIGURE FOR GUIDANCE

"2. Quantitative Input & Output" Tab

Figure 89. Screenshot. Quantitative input and output data worksheet tab.

6. Enter all relevant mobility and safety qualitative input data in the spreadsheet tab named "3. Qualitative Input." These qualitative categorical input data include 15 fields that are all dropdown lists to allow the user to choose the most relevant input according to their project conditions, as shown in Figure 90.



QUALITATIVE INPUT

Instructions:
Provide all relevant input data
Note: All inputs are dropdown lists

Input Legend	
Dropdown List Input	🟨

Mobility Factors		
Qualitative Factor	**Description**	**Input**
Nearby Roadway Project	Presence of nearby roadway projects that will impact the current project.	Moderate Impact
Availability of Alternate Routes	Alternate routes available.	Yes
Nearby Traffic Generator Impact	Nearby traffic generators such as sports arenas or public facilities that produce traffic around certain time frames.	Minimal Impact
Existing Traffic Issues	Existing traffic issues like gridlock and exit ramp backups.	Moderate
Presence of Complex Traffic Layout	Presence of conjunctions multiple crossovers, lane splits, sharp curves or intersections.	No
Sight Distance From Back of Queue	Sight distance issues from the back of the queue exist.	Moderate

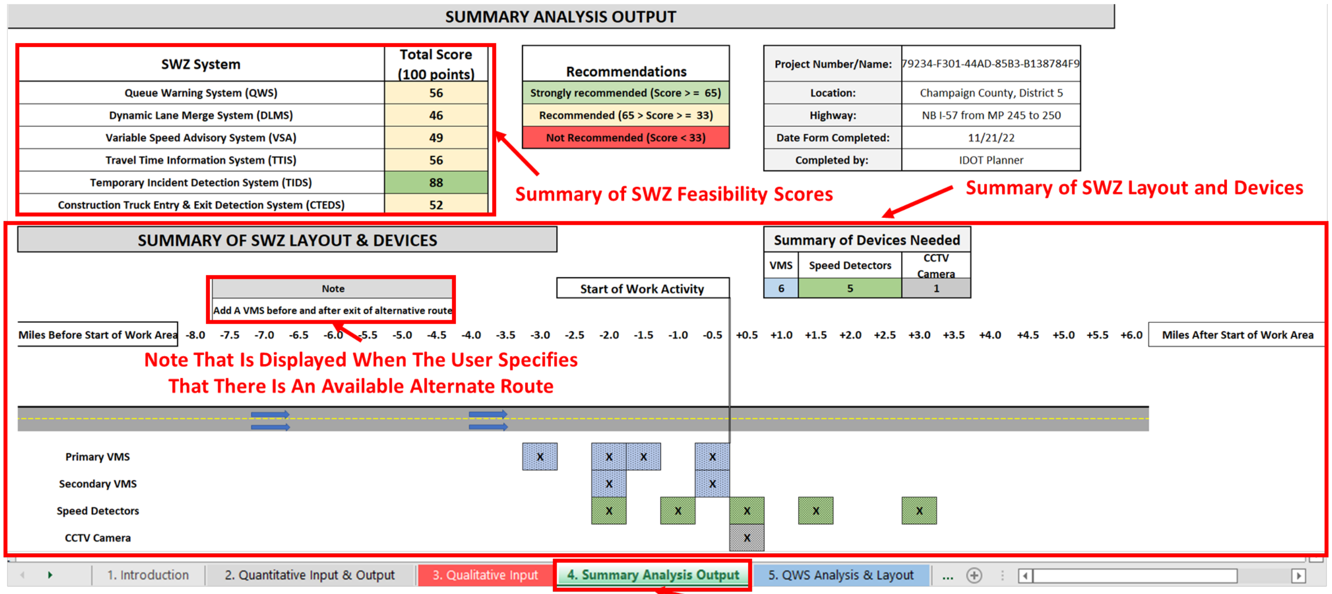
Safety Factors		
Qualitative Factor	**Description**	**Input**
Existing Speeding Issues	Road has a history of speeding (>20 mph).	Yes
Large Speed Variations	Road has a history of high speed variations common on interstate by-passes and outer rings.	No
Merging Conflicts/ Hazards Approaching The Work Zone	External merging conflicts or hazards on the approach or within the work zone.	No
Extreme Weather Conditions	Known history of sudden extreme weather condition like sandstorm or snowstorm or project duration covers several harsh weather seasons.	Moderate Impact
Heavy Vehicles	Average percentage of heavy vehicles on the road.	6%-12%
Constraint For Emergency Responders	Construction activity may impose constraints for emergency responders to access incidents.	Minimal Impact
Construction Vehicle Entering	Construction trucks will frequently enter and exit the main traffic stream.	Yes

Step 6: Enter All Relevant Qualitative Input Data

“3. Qualitative Input” Tab

Figure 90. Screenshot. Qualitative input worksheet tab.

7. Display feasibility scores of all six SWZ systems, which were automatically calculated by the developed tool in the spreadsheet tab named “4. Summary Analysis Output,” as shown in Figure 91. These feasibility scores are summarized in a table and are highlighted with the color associated with their recommendation. For example, the QWS feasibility score in the illustrated case study was calculated as 65, which indicates that it is strongly recommended for deployment and highlighted in green, as shown in Figure 91. Similarly, the DLMS and VSA feasibility scores were calculated as 49 and 44, respectively, and therefore they were recommended by the tool, as indicated by yellow highlighting (see Figure 91). Furthermore, the tool can also be used to display a designed layout for all recommended SWZ systems for the analyzed work zone case study, as shown in Figure 91. This designed layout illustrates the location and number of all recommended SWZ components. For example, the total number of VMS needed in the illustrated case study was determined to be 7, as shown in Figure 91. Note that when the user specifies that there is an available alternate route, the tool automatically displays a note to add an extra VMS before and after the alternate route exit, as shown in Figure 91.



SUMMARY ANALYSIS OUTPUT

SWZ System	Total Score (100 points)
Queue Warning System (QWS)	56
Dynamic Lane Merge System (DLMS)	46
Variable Speed Advisory System (VSA)	49
Travel Time Information System (TTIS)	56
Temporary Incident Detection System (TIDS)	88
Construction Truck Entry & Exit Detection System (CTEDS)	52

Recommendations
Strongly recommended (Score > = 65)
Recommended (65 > Score > = 33)
Not Recommended (Score < 33)

Project Number/Name:	79234-F301-44AD-85B3-B138784F9
Location:	Champaign County, District 5
Highway:	NB I-57 from MP 245 to 250
Date Form Completed:	11/21/22
Completed by:	IDOT Planner

Summary of SWZ Feasibility Scores

Summary of SWZ Layout and Devices

SUMMARY OF SWZ LAYOUT & DEVICES

Summary of Devices Needed		
VMS	Speed Detectors	CCTV Camera
6	5	1

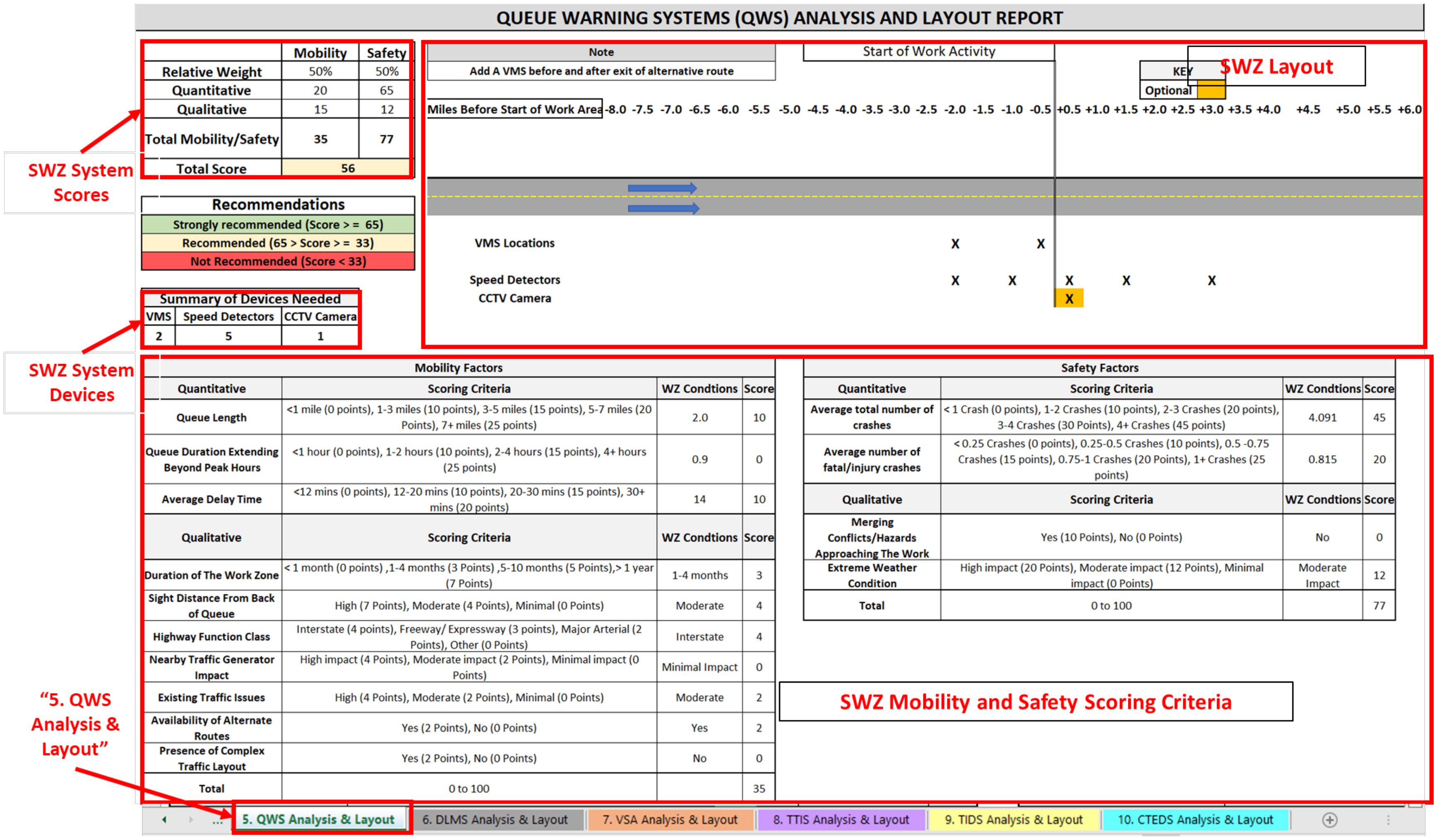
Note
Add A VMS before and after exit of alternative route

Note That Is Displayed When The User Specifies That There Is An Available Alternate Route

"4. Summary Analysis Output" Tab

Figure 91. Screenshot. Summary analysis output worksheet tab.

8. Generate a detailed analysis and layout design for each SWZ system in a separate worksheet tab. For each SWZ system, the tool displays their mobility and safety scores, which are automatically calculated by using the earlier described scoring criteria. For example, the overall QWS feasibility score was calculated as 65 based on its calculated mobility and safety scores of 62 and 67, respectively, as shown in worksheet tab "5. QWS Analysis & Layout" (see Figure 92). Similarly, the layout design for each SWZ system is automatically generated and displayed by the tool using the methodology described in the SWZ Layout Design section. For example, the QWS layout illustrated in worksheet tab "5. QWS Analysis & Layout" was designed to have two VMS, 11 traffic sensors, and one CCTV camera, as shown in Figure 92. A similar detailed analysis was performed, and a layout design was generated by the tool for each of the remaining SWZ systems—DLMS, VSA, TTIS, TIDS, and CTEDS—that can be displayed by selecting its corresponding worksheet tab, as shown in Figure 92.



QUEUE WARNING SYSTEMS (QWS) ANALYSIS AND LAYOUT REPORT

	Mobility	Safety
Relative Weight	50%	50%
Quantitative	20	65
Qualitative	15	12
Total Mobility/Safety	35	77
Total Score	56	

Recommendations
Strongly recommended (Score > = 65)
Recommended (65 > Score > = 33)
Not Recommended (Score < 33)

Summary of Devices Needed		
VMS	Speed Detectors	CCTV Camera
2	5	1

Note
Add A VMS before and after exit of alternative route

Start of Work Activity

KEY	
Optional	🟨

Miles Before Start of Work Area	-8.0	-7.5	-7.0	-6.5	-6.0	-5.5	-5.0	-4.5	-4.0	-3.5	-3.0	-2.5	-2.0	-1.5	-1.0	-0.5	+0.5	+1.0	+1.5	+2.0	+2.5	+3.0	+3.5	+4.0	+4.5	+5.0	+5.5	+6.0
VMS Locations													X			X												
Speed Detectors													X		X		X		X			X						
CCTV Camera																	X											

Mobility Factors			
Quantitative	Scoring Criteria	WZ Condtions	Score
Queue Length	<1 mile (0 points), 1-3 miles (10 points), 3-5 miles (15 points), 5-7 miles (20 Points), 7+ miles (25 points)	2.0	10
Queue Duration Extending Beyond Peak Hours	<1 hour (0 points), 1-2 hours (10 points), 2-4 hours (15 points), 4+ hours (25 points)	0.9	0
Average Delay Time	<12 mins (0 points), 12-20 mins (10 points), 20-30 mins (15 points), 30+ mins (20 points)	14	10
Qualitative	Scoring Criteria	WZ Condtions	Score
Duration of The Work Zone	< 1 month (0 points) ,1-4 months (3 Points) ,5-10 months (5 Points),> 1 year (7 Points)	1-4 months	3
Sight Distance From Back of Queue	High (7 Points), Moderate (4 Points), Minimal (0 Points)	Moderate	4
Highway Function Class	Interstate (4 points), Freeway/ Expressway (3 points), Major Arterial (2 Points), Other (0 Points)	Interstate	4
Nearby Traffic Generator Impact	High impact (4 Points), Moderate impact (2 Points), Minimal impact (0 Points)	Minimal Impact	0
Existing Traffic Issues	High (4 Points), Moderate (2 Points), Minimal (0 Points)	Moderate	2
Availability of Alternate Routes	Yes (2 Points), No (0 Points)	Yes	2
Presence of Complex Traffic Layout	Yes (2 Points), No (0 Points)	No	0
Total	0 to 100		35

Safety Factors			
Quantitative	Scoring Criteria	WZ Condtions	Score
Average total number of crashes	< 1 Crash (0 points), 1-2 Crashes (10 points), 2-3 Crashes (20 points), 3-4 Crashes (30 Points), 4+ Crashes (45 points)	4.091	45
Average number of fatal/injury crashes	< 0.25 Crashes (0 points), 0.25-0.5 Crashes (10 points), 0.5 -0.75 Crashes (15 points), 0.75-1 Crashes (20 Points), 1+ Crashes (25 points)	0.815	20
Qualitative	Scoring Criteria	WZ Condtions	Score
Merging Conflicts/Hazards Approaching The Work	Yes (10 Points), No (0 Points)	No	0
Extreme Weather Condition	High impact (20 Points), Moderate impact (12 Points), Minimal impact (0 Points)	Moderate Impact	12
Total	0 to 100		77

Figure 92. Screenshot. QWS detailed analysis and layout worksheet tab.

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