Evaluate the Uses and Technology for Truck-Mounted Attenuators

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Prepared for:
The Ohio Department of Transportation,
Office of Statewide Planning & Research

Project ID Number 107305 / State Job Number 135767

December 2020

Final Report

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
FHWA/OH-2020-19		
4. Title and Subtitle		5. Report Date
Evaluate the Uses and Technology for Truck-Mounted Attenuators		**December 2020**
		6. Performing Organization Code
7. Author(s)		8. Performing Organization Report No.
Melisa D. Finley, Leonard Ruback, and Fan Ye		
9. Performing Organization Name and Address		10. Work Unit No. (TRAIS)
Texas A&M Transportation Institute The Texas A&M University System College Station, Texas 77843-3135		
		11. Contract or Grant No.
		PID: 107305
12. Sponsoring Agency Name and Address		13. Type of Report and Period Covered
Ohio Department of Transportation 1980 West Broad Street Columbus, Ohio 43223		**Final Report**
		14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract

Mobile maintenance operations on multi-lane highways, such as pothole patching and sweeping, present unique safety challenges due to the highly variable conditions encountered. While the Ohio Department of Transportation and Ohio Turnpike currently have procedures for temporary traffic control for mobile maintenance operations, both agencies wanted to review these procedures and identify new strategies and technologies that could be used to improve the safety of these operations, especially those for shadow vehicles with impact attenuators (truck or trailer mounted). The research tasks included a review of the state of the practice, identification of potential safety improvements, field evaluation of select safety improvements, and development of a roll-ahead distance alarm.

17. Keywords	18. Distribution Statement
Work zone, mobile operations, maintenance operations, light-emitting diode sign, changeable message sign, real-time notification	**No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161**

19. Security Classification (of this report)	20. Security Classification (of this page)	21. No. of Pages	22. Price
Unclassified	**Unclassified**	**96**	

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

Credits and Acknowledgments Page

Prepared in cooperation with the Ohio Department of Transportation (ODOT) and the U.S. Department of Transportation, Federal Highway Administration.

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The time, support, and assistance of the following members of the Technical Advisory Committee (TAC) is gratefully acknowledged: Jacqueline Martindale (ODOT), Ronzell Clayton (ODOT), James Cook (ODOT), Nick Hegemier (ODOT), Chris Matta (Ohio Turnpike), and Dennis Oneil (ODOT). The authors also wish to acknowledge the contributions of George Holloway (ODOT), Joe Phillips (ODOT), and the many ODOT District 12 and Ohio Turnpike maintenance staff who helped with field data collection. In addition, the authors wish to acknowledge LuAnn Theiss (Texas A&M Transportation Institute [TTI]), Geza Pesti (TTI), Gerald Ullman (TTI), Kevin Magee (TTI), Sara Florian (Ohio Northern University [ONU]), and Deana Flanagan (ONU), who assisted with this research.

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PROBLEM STATEMENT

Mobile maintenance operations on multi-lane highways, such as pothole patching and sweeping, present unique safety challenges due to the highly variable conditions encountered (e.g., traffic volume, operating speed, time of day, and weather). While the Ohio Department of Transportation (ODOT) and Ohio Turnpike currently have procedures for temporary traffic control for mobile maintenance operations, both agencies wanted to review these procedures and identify new strategies and technologies that could be used to improve the safety of these operations, especially those for shadow vehicles with impact attenuators (truck or trailer mounted).

RESEARCH BACKGROUND

This section contains the research goal, objectives, and a brief description of the tasks accomplished. This section also includes an overview of the state of the practice.

RESEARCH GOAL AND OBJECTIVES

The goal of this research was to provide safe, efficient, and cost-effective temporary traffic control methods to conduct mobile maintenance operations on multi-lane highways. The research was divided into two phases. The objectives of Phase 1 were to:

- Evaluate current ODOT and Ohio Turnpike procedures.
- Identify and conduct a preliminary assessment of potential temporary traffic control treatments.
- Recommend temporary traffic control alternatives for further evaluation.

The objectives of Phase 2 were to:

- Evaluate the use of the following to better inform approaching drivers of mobile sweeping operations:
    - A portable, ground-mounted, static warning sign with flashing lights around the border of the sign.
    - A full-matrix, truck-mounted changeable message sign (CMS) on the advance warning vehicle.
    - Real-time work zone location technology.
- Develop a prototype roll-ahead distance alarm (i.e., a device that alerts the shadow vehicle driver when he/she is too close to the work space).
- Recommend safe, efficient, and cost-effective alternatives for implementation.

To accomplish these objectives, the research team completed the following tasks:

- Review and evaluate ODOT and Ohio Turnpike procedures.
- Develop a matrix of current procedures.
- Review the literature and identify the state of the practice.
- Develop a matrix of safety enhancements.

- Evaluate select safety enhancements.
- Design, build, and test a prototype roll-ahead distance alarm.

STATE-OF-THE-PRACTICE OVERVIEW

According to ODOT records, shadow vehicles with impact attenuators were involved in 20 crashes from 2016 to 2018. All the crashes occurred on divided multi-lane highways, and 60 percent occurred at night. In order to retrieve more detailed information about the crashes, the research team matched 19 out of the 20 crashes with the Ohio Department of Public Safety (ODPS) police-recorded crash reports. Detailed information on the crash characteristics and estimated cost to ODOT is in Appendix A.

The research team also reviewed current ODOT and Ohio Turnpike procedures for mobile maintenance operations on multi-lane highways. To accomplish this, the research team reviewed applicable ODOT traffic manuals and standards. The research team then interviewed select ODOT and Ohio Turnpike personnel in District 12 to identify the types of mobile maintenance operations conducted on multi-lane highways and discuss the conditions surrounding these types of operations that cause maintenance workers the most concern. In addition, the research team reviewed findings from previous observations of mobile maintenance operations on multi-lane highways in Franklin County (*1*). Based on these findings, the research team developed a matrix of the current procedures used by ODOT and the Ohio Turnpike for the mobile maintenance operations on multi-lane highways. Appendix B contains this matrix and additional information on these activities.

In early 2019, the research team performed an extensive literature review to identify the state of the practice regarding mobile maintenance operations on multi-lane highways and gather information on practices and innovative devices that could potentially improve the safety of ODOT operations. The research team also searched state department of transportation (DOT) websites in order to identify state traffic control standards for mobile maintenance operations on multi-lane highways and review the recommended spacing of work convoy vehicles. Based on these findings, the research team developed a matrix of potential safety improvements (methods and devices) for mobile maintenance operations on multi-lane highways that includes possible benefits and disadvantages. The following methods and devices, as well as the matrix of potential safety improvements, are discussed in Appendix C:

- Shadow vehicles:
  - Impact attenuators.
  - Autonomous impact protection vehicle.
  - Distance between shadow vehicle and work space.
  - Multiple shadow vehicles.
- Advance warning vehicle.
- Lead vehicle downstream of work space.
- Law enforcement.
- Warning lights:
  - Light color and color combinations.

  - Light intensity.
  - Flash patterns and/or sequences.
  - Number of lights.
  - Types of lights.
- Arrow boards.
- Truck-mounted static signs.
- Truck-mounted CMSs.
- Truck-mounted speed feedback signs.
- Intrusion alarms.
- Real-time work zone location technology.

RESEARCH APPROACH

The typical ODOT and Ohio Turnpike temporary traffic control for mobile sweeping operations were used as the base conditions. The typical ODOT setup consisted of:

- A ROAD SWEEPING NEXT 5 MI static warning sign placed on the right shoulder at the beginning of the work area.
- An advance warning vehicle equipped with high-intensity amber warning lights and a truck-mounted CMS that displayed WORKERS IN ROAD / LEFT LN CLOSED located on the right shoulder downstream of the static warning sign.
- A shadow vehicle with high-intensity flashing green, white, and amber warning lights and a towable trailer-mounted attenuator (TTMA) located in the left lane downstream of the advance warning vehicle. The TTMA had an arrow board that displayed a right arrow.
- A sweeper with high-intensity amber warning lights located in the left shoulder/lane downstream of the shadow vehicle.

The typical Ohio Turnpike setup consisted of:

- A shadow vehicle with high-intensity amber warning lights, an arrow board displaying the caution bar, and a truck-mounted attenuator.
- A sweeper with high-intensity amber warning lights.

Both vehicles traveled on the 14-ft-wide left shoulder and did not encroach into the left travel lane.

Based on the information collected in Phase 1 (see Appendices A–C), ODOT, the Ohio Turnpike, and the research team decided to evaluate the following equipment-related safety improvements in Phase 2 of the research:

- The addition of a second portable, ground-mounted, static warning sign with flashing lights around the border of the sign. The sign legend was LEFT LANE CLOSED NEXT 5 MI. The flashing lights around the border of the sign were used to draw drivers' attention to the sign, and the sign legend provided drivers information about which lane was closed ahead.
- The use of a larger, full-matrix, truck-mounted CMS on a different advance warning vehicle to increase the message size and remove the need to abbreviate "lane" (i.e., WORKERS IN ROAD / LEFT LANE CLOSED) in order to

provide a larger and clearer message that could be more easily read and understood at high speeds.
- Real-time work zone location technology to alert approaching drivers about the work operation and encourage them to exit the closed lane.

In addition, ODOT asked the research team to evaluate the impact of the presence of the advance warning vehicle on the right shoulder and the mounting location (i.e., right or left shoulder) of the portable, ground-mounted, static warning signs. Unfortunately, the impact of placing the static warning signs on the left shoulder (instead of the right shoulder) could not be evaluated due to a limited sample size and pandemic travel restrictions. Overall, the research team evaluated the following treatments on high-speed, multi-lane, divided highways:

- ODOT mobile sweeping operation in the left lane/shoulder:
  - Typical ODOT setup.
  - Addition of a static warning sign (LEFT LANE CLOSED NEXT 5 MI) with flashing lights around the border of the sign (referred to as a light-emitting diode [LED] sign) on the right shoulder.
  - Addition of the LED sign on the right shoulder but no advance warning vehicle.
  - Use of a full-matrix, truck-mounted CMS on the advance warning vehicle (FMTMCMS).
  - Use of real-time work zone location technology on the shadow vehicle.
- Ohio Turnpike mobile sweeping operation on the left shoulder:
  - Typical Ohio Turnpike setup.
  - Use of real-time work zone location technology on the shadow vehicle.

All ODOT sweeping operations were conducted at night, and all Ohio Turnpike sweeping operations were conducted during the day.

The research team conducted the field studies in cooperation with ODOT and Ohio Turnpike maintenance personnel over a five-week period. The research team used video cameras with internal global positioning systems (GPS), standardized data collection forms, a laptop, stand-alone GPS equipment and associated software, cell phones, and other data collection equipment/programs to observe and document driver behavior around the mobile sweeping operations. Appendix D contains additional details about the field study research approach.

In Phase 2, the research team was also asked to develop a prototype roll-ahead distance alarm that would alert the shadow vehicle driver when he/she is too close to the work space. During mobile operations on multi-lane highways, shadow vehicles with impact attenuators provide protection for workers and work vehicles. The *Field Guide for the Use and Placement of Shadow Vehicles in Work Zones* (*2*) provides guidance on the spacing of shadow vehicles based on speed limit, weight of the shadow vehicle, and whether the operation is stationary or moving (see Table 1). Similar guidance can also be found in the American Association of State Highway and Transportation Officials (AASHTO) *Roadside Design Guide* (*3*) and the ODOT *Construction and Material Specifications* (*4*). According to Table 1, on roadways with posted speed limits greater than 55 mph, mobile shadow vehicles should be at least 172 ft upstream of the work space. It is important that adequate distance is provided to allow for post-collision roll ahead of the shadow vehicle.

Table 1. Guidelines for Spacing of Shadow Vehicles (*2*).

Operating Speed[a]	Recommended Spacing for Vehicles Weighing 9,900 to 22,000 lb (ft)[b]		Recommended Spacing for Vehicles Weighing over 22,000 lb (ft)[b]	
	Stationary	Moving[c]	Stationary	Moving[c]
Greater than 55 mph	172	222	150	172
45 to 55 mph	123	172	100	150
Less than 45 mph	100	100	74	100

[a] Should use operating speed if higher than posted speed limit.
[b] Recommended spacing is distance between front of shadow vehicle and beginning of work space, that is, the first worker/operations/vehicle to be protected.
[c] Distances are appropriate for shadow vehicle speeds up to 15.5 mph.

Typically, shadow vehicle drivers judge their distance from the work space by visually counting lane line pavement markings (i.e., 10-ft line and 30-ft space). However, as discussed in Appendix A, sometimes the shadow vehicle is positioned too close to the work equipment (80 to 160 ft) to allow for post-collision roll ahead of the shadow vehicle. Limited visibility, high traffic volumes, and a lack of training could contribute to use of shorter distances between a shadow vehicle and the work space. Thus, the research team designed, built, and tested a prototype roll-ahead distance alarm that would alert the shadow vehicle driver when he/she is too close to the work space.

The roll-ahead distance alarm is comprised of two vehicle units (one for the work vehicle and one for the shadow vehicle). Each vehicle unit contains the following:

- 3-mm DC bulkhead power jack installed in the case as the main power input.
- 12-vDC to 5-vDC power converter with two output connectors.
- TP-Link travel router.
- Generic GPS module.
- SubMiniature version A (SMA) bulkhead connector and coax cable to connect to the GPS module to an external antenna.
- Magnetic-mount external GPS antenna.
- ESP8266 microcontroller development board.

The external GPS antenna on each vehicle measures the vehicle's location. The external GPS antenna should be placed on the vehicle roof but can also be located on the dashboard. The GPS module provides the latitude, longitude, time, and a location accuracy indication to the microcontroller. Each unit uses a small microcontroller to manage the system components (i.e., GPS unit and wireless network), calculate the distance between the two units, and generate the user output. The wireless network is provided by small travel WiFi routers, one in each vehicle's unit. Although this network uses the technology of the internet, the system is not connected to the internet. Instead, it simply provides a network to communicate among the two vehicle units and the shadow vehicle operator display using common robust protocols and proven equipment.

A small wirelessly connected tablet, mounted in the shadow vehicle, displays the distance information, time, and any alerts pertaining to loss of accuracy. The target distance is configurable within reasonable distance limits via the display screen on the browser. When the calculated distance is equal to or larger than the target distance (e.g., 172 ft), the display background is green (indicating the shadow vehicle is an adequate distance from the work vehicle to account for the roll-ahead distance). If the calculated distance is less than the target distance, the display background is red (indicating the shadow vehicle is too close to the work vehicle to account for the roll-ahead distance). When the GPS accuracy is too low (not enough satellites in view) for precise location measurements, the display background is yellow, and asterisks are located before and after the distance. The asterisks and yellow background will go away when the accuracy is sufficient for high-accuracy distance measurement. The display updates frequently to ensure accuracy and requires no user actions other than initially accessing the webpage located on the system microcontroller.

The components for each vehicle unit reside in a very durable resealable plastic case. The shadow vehicle unit case is outfitted with an external 5-vDC USB charging connector to provide power to the tablet while in operation. Each vehicle unit is powered from a standard 12-volt automobile auxiliary power outlet in a vehicle. Appendix E contains additional details about the roll-ahead distance alarm.

The research team tested the roll-ahead distance alarm system in two stages. Initial testing was conducted to establish whether the GPS unit selected would operate successfully and without spurious inaccurate location measurements in a mobile vehicle environment. Researchers frequently power-cycled the vehicle units to ensure the system's robustness and that the units could remain on a wireless network as environmental conditions change without user interaction. The second testing stage simulated a work vehicle and shadow vehicle operation. This testing established the accuracy of the GPS measurements and the resulting separation distance calculation. The separation distance was compared to the same distance measured using a laser range finder. The mobile network was also tested to ensure each unit could remain on the network and the network would be maintained between the vehicles.

RESEARCH FINDINGS AND CONCLUSIONS

Overall, neither the addition of a second warning sign nor the presence of the advance warning vehicle (with or without the FMTMCMS) considerably impacted the lane distribution 100 ft upstream of the advance warning vehicle or shadow vehicle. However, none of these treatments appeared to negatively impact the lane distribution either. These results are not surprising considering the limited comparison samples and potential changes in the baseline lane distributions before and after the pandemic. In addition, all the treatments involved the addition or modification of information provided to drivers. Even though drivers may have noticed the LED sign and its message more because of its conspicuity or read a message sooner because of a larger font and unabbreviated text, the acquisition of information does not always result in driver behavior changes. It could also be that the impact on lane distribution occurred further upstream of both vehicles (i.e., outside of the view of the video cameras). Anecdotal observations and discussions with the work crew support this hypothesis.

The initial configurations of the real-time work zone location technology produced fewer notifications in Waze, a GPS navigation software app, about the mobile sweeping operations than anticipated based on initial discussions with the manufacturers. However, changes to the GPS location refresh rate or the vehicle status increased the number of notifications in Waze.

For the roll-ahead distance alarm system, the research team verified that the GPS unit selected would operate successfully in a mobile vehicle environment. The GPS units provided sufficient accuracy to reliably compute the separation distance. Tests also showed the mobile network remained available for the expected distances between the two vehicles. The prototype roll-ahead distance alarm was given to District 12 maintenance personnel in August 2020.

RECOMMENDATIONS FOR IMPLEMENTATION

Even though the field study findings did not reveal practical impacts to the lane distribution immediately upstream of the advance warning and shadow vehicles, the research team still recommends the use of the LED sign, advance warning vehicle, and FMTMCMS. All of these temporary traffic control devices provide critical information to drivers about the closed lane and mobile operation. However, it is important to consider the possible impacts of the Move Over Law to the safety of mobile operations when the left lane is closed and an advance warning vehicle is used. When an advance warning vehicle is located on the right shoulder upstream of the shadow vehicle, according to the Move Over Law, drivers should move over one lane. Thus, drivers most likely move from the right lane to the middle lane upstream of the advance warning vehicle (assuming a three-lane road). However, as drivers approach the shadow vehicle (in the left lane), they need to move from the middle lane to the right lane to comply with the Move Over Law. The distance maintained between the advance warning and shadow vehicles should provide ample time for drivers to safely make these weaving maneuvers.

The research team recommends the continued use of real-time work zone location technology to inform drivers of mobile operations. Agencies should work with device manufacturers and third-party information providers to improve the message content, such as including which lane is closed or where the hazard is located, in order to provide more detailed information to drivers so they are better informed about real-time work zone conditions.

APPENDIX A: CHARACTERISTICS OF WORK ZONE CRASHES INVOLVING SHADOW VEHICLES

According to ODOT records, shadow vehicles with impact attenuators (truck or trailer mounted) were involved in 20 crashes from 2016 to 2018. Figure 1 shows that the crashes involving ODOT shadow vehicles with impact attenuators increased in 2018.

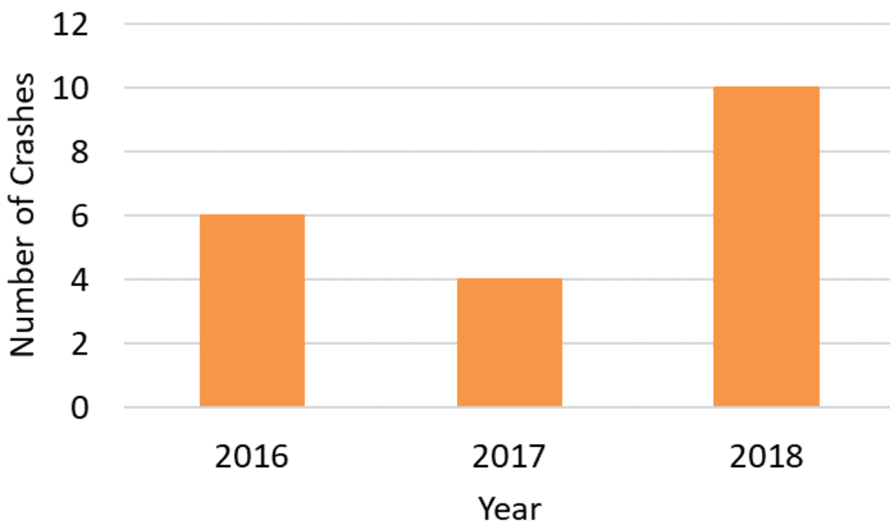


Figure 1. Three-Year Trend for Crashes Involving ODOT Shadow Vehicles with Impact Attenuators (2016–2018).

All 20 crashes occurred on divided multi-lane highways (19 on interstates and one on a state route). Most of the crashes occurred at night (12 out of 20), and about three-quarters of the nighttime crashes happened between midnight and 6:00 a.m. Figure 2 shows the spatial distribution of the crashes. The most crashes (six each) occurred in Cuyahoga and Franklin Counties (District 12 and District 6, respectively). Two crashes happened in Montgomery and Hamilton Counties. One crash occurred in Lucas, Medina, Ashtabula, and Clinton Counties.

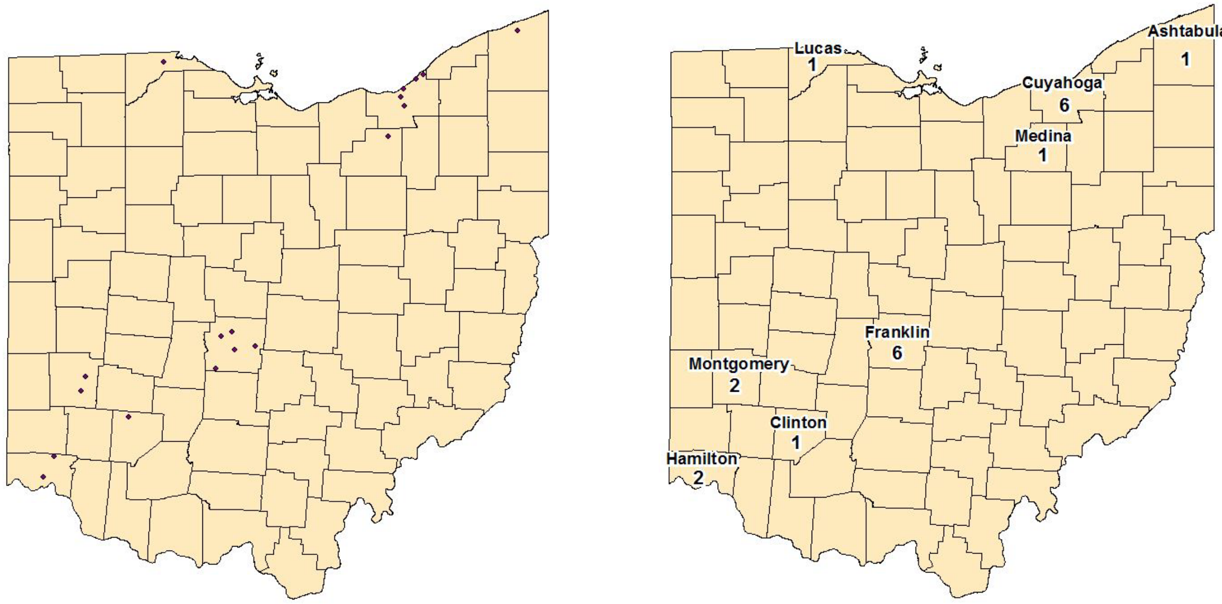


Figure 2. Spatial Distribution of Crashes Involving ODOT Shadow Vehicles with Impact Attenuators (2016–2018).

In order to retrieve more detailed information about the crashes, ODOT crash data were linked and matched with the ODPS police-recorded crash reports. Nineteen out of the 20 crashes were matched and identified. Based on information contained in police reports and obtained from ODOT, researchers concluded that 13 out of 19 crashes (68 percent) occurred during mobile maintenance operations, including activities such as pothole patching and sweeping. Four crashes were assumed to be related to stationary maintenance operations due to the type of work (i.e., guardrail repair) or incident description. Researchers could not determine the type of operation for the remaining two crashes. In 16 out of 19 crashes (84 percent), two vehicles were involved. The remaining three crashes involved three vehicles. For all 19 crashes, a non-work vehicle was at fault and hit the impact attenuator in the rear. Seventeen of the at-fault vehicles were passenger cars, and two were semi-tractor trailers.

Half of the crashes (10 out of 20) resulted in an injury. In five of the crashes, the driver and/or occupant(s) in the at-fault vehicle were the only persons injured. In four other crashes, the driver and/or occupant(s) in the at-fault vehicle and shadow vehicle driver were injured. In one crash, the shadow vehicle driver was injured, but injuries to other drivers/occupants were unknown. The 18 injuries involved in all 20 crashes were either possible or non-incapacitating, except for a driver and a passenger in a vehicle hitting the impact attenuator who both suffered from incapacitating injuries.

For the five injured shadow vehicle drivers, the medical expenses paid by ODOT ranged from $782 to $11,985, with the average medical cost of $3,719 per person and the total medical claims of $18,597. In addition, three of the shadow vehicle drivers experienced lost working time ranging from 41 to 153 days off (one driver was still unable to work as of February 14, 2019), with the total lost time of 253 days. As

ODOT employees, the shadow vehicle drivers are entitled to salary continuation for the time off due to a workers' compensation injury. While specific figures were unavailable, using the standard hourly salary for highway technicians ($19.96 excluding benefits) and assuming an eight-hour work day, their salary continuation totaled $40,399 for the 253 days of lost time. The amount of damage to a shadow vehicle with an impact attenuator varied from no damage to $32,797, with the average damage costing $20,350 and the total damage costing $345,947 over the previous three years. Considering the medical expenses paid, salary continuation produced by the shadow vehicle drivers' lost working time, and damage to the shadow vehicle, the overall financial impact to ODOT totaled $404,943 for the time period studied.

APPENDIX B: PROCEDURES FOR MOBILE MAINTENANCE OPERATIONS ON MULTI-LANE HIGHWAYS

In Phase 1, the research team reviewed current ODOT and Ohio Turnpike procedures for mobile maintenance operations on multi-lane highways. To accomplish this, the research team reviewed applicable ODOT traffic manuals and standards. The research team then interviewed select ODOT and Ohio Turnpike personnel in District 12 to identify the types of mobile maintenance operations conducted on multi-lane highways and discuss the conditions surrounding these types of operations that cause maintenance workers the most concern. In addition, the research team reviewed findings from previous observations of mobile maintenance operations on multi-lane highways in Franklin County (*1*). Based on these findings, the research team developed a matrix of the current procedures used by ODOT and the Ohio Turnpike for the mobile maintenance operations on multi-lane highways.

ODOT MANUALS AND STANDARDS

The *Ohio Manual on Uniform Traffic Control Devices* (OMUTCD) (*5*) defines the minimum temporary traffic control requirements on streets and highways in Ohio. This document contains typical applications that depict common uses of temporary traffic control devices since defining details that would be adequate to cover all applications is not practical. Ultimately, the temporary traffic control selected for each situation depends on many variables, including but not limited to the type of roadway, type of work, duration of operation, and location of work with respect to road users.

A major factor in determining the traffic control devices to be used is work duration. The duration is defined relative to the length of time a work operation occupies a spot location. The five categories of work duration are (*5*):

- Mobile—work that moves intermittently or continuously.
- Short duration—work that occupies a location up to one hour.
- Short-term stationary—daytime work that occupies a location for more than one hour within a single daylight period.
- Intermediate-term stationary—work that occupies a location more than one daylight period up to three days, or nighttime work lasting more than one hour.
- Long-term stationary—work that occupies a location more than three days.

Mobile operations include work activities during which workers and equipment move continuously along the roadway at slow speeds. However, mobile operations often involve frequent short stops for activities such as litter cleanup and pothole patching. Thus, mobile operations are inherently different from stationary operations.

According to OMUTCD Section 6G.02, the temporary traffic control for mobile operations is generally portable and consists of relatively few devices due to the mobile nature of the work space. Even so, the safety of mobile operations should not be compromised. Appropriately marked vehicles with high-intensity lights may be used in place of signs and channelizing devices. Warning signs, arrow boards, and/or CMSs may be mounted on or towed by work vehicles in the mobile operation. The OMUTCD states that the SLOW TRAFFIC AHEAD (W23-1) sign may be mounted on the rear of a shadow vehicle along with other appropriate signs to warn of slow-moving work vehicles. A ROAD WORK (W20-1) sign may also be used with the SLOW TRAFFIC AHEAD sign. A shadow vehicle with an arrow board and impact attenuator should follow the work vehicle, especially on roadways with high traffic speeds or volumes. Shadow vehicles act as a barrier between workers and the traveling public. Shadow vehicles with impact attenuators are designed to be hit, absorbing the colliding vehicle's kinetic energy and redirecting errant vehicles that would otherwise enter the work space. On high-volume roadways, agencies should also consider conducting mobile operations during off-peak hours.

The OMUTCD typical application in Figure 3 should be used for mobile operations on the shoulder. Stationary warning signs may be omitted for mobile operations if the work vehicle displays high-intensity rotating, flashing, oscillating, or strobe lights. If an arrow board is used, the caution mode shall be used. Vehicle-mounted signs must be mounted such that they are not obscured. The legend of vehicle-mounted signs must be covered or turned from view when work is not in progress.

The OMUTCD typical application in Figure 4 should be used for mobile operations on multi-lane roadways. This typical application applies to work in a travel lane of a non-access-controlled highway, freeway, or expressway. At a minimum, arrow boards must be Type B and at least 60 by 30 inches in size. Arrow boards must be in use when a freeway lane is closed, and separate arrow boards must be used for each lane closed. As with mobile operations on the shoulder, vehicle-mounted signs must be mounted such that they are not obscured. The legend of vehicle-mounted signs must be covered or turned from view when work is not in progress. All vehicles must display high-intensity rotating, flashing, oscillating, or strobe lights. Shadow vehicle 1 should have an arrow board and impact attenuator. Shadow vehicle 2 should have an arrow board and appropriate lane closure signs. While the OMUTCD states that shadow vehicle 2 may also have an impact attenuator, the ODOT *Traffic Engineering Manual* (*6*) requires shadow vehicle 2 to be equipped with a truck-mounted or trailer attenuator. In addition, for mobile operations on multi-lane highways with speed limits 45 mph and above, the ODOT *Traffic Engineering Manual* requires impact attenuators be used on shadow vehicles. According to both manuals, the shadow vehicle should be positioned a sufficient distance in advance of workers or equipment being protected but not so much that errant vehicles can cut into the work convoy or work space.

According to the OMUTCD typical application in Figure 4, when the work occupies an interior lane and there is a right-hand shoulder at least 10 ft wide, shadow vehicle 2 should drive on the right-hand shoulder with a sign indicating the work is occurring in an interior lane. A third shadow vehicle can be used on high-speed roadways. In this setup, shadow vehicle 1 would drive in the closed lane, shadow vehicle 2 would straddle the edge line, and shadow vehicle 3 would drive on the shoulder. If an adequate shoulder is not available, shadow vehicle 3 would also straddle the edge line.

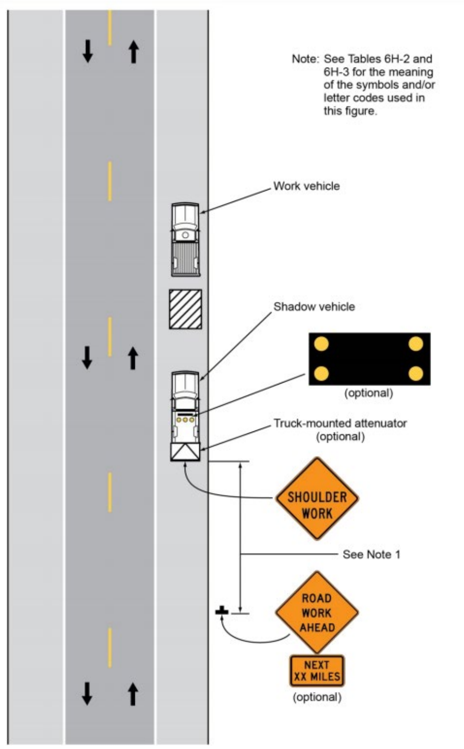


Figure 3. OMUTCD Figure 6H-4 Short-Duration or Mobile Operations on a Shoulder (TA-4) (*5*).

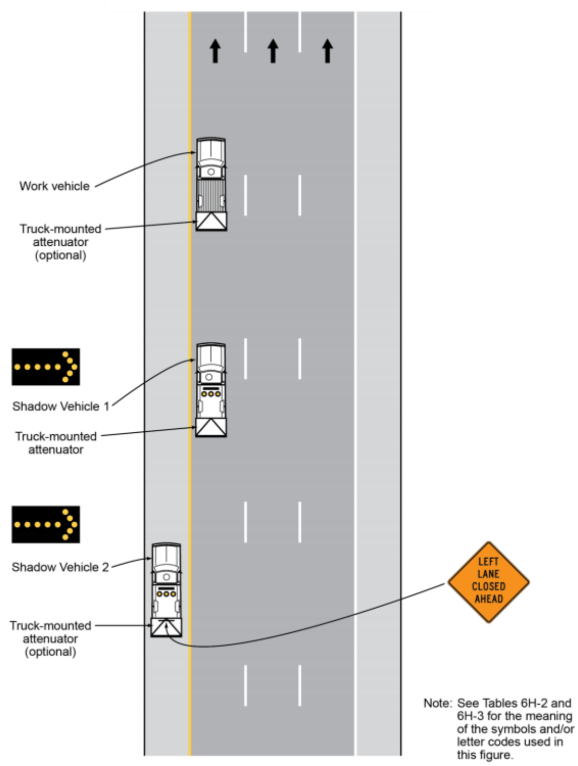


Figure 4. OMUTCD Figure 6H-35 Mobile Operation on a Multi-lane Road (TA-35) (*5*).

The research team also reviewed two other ODOT documents that address temporary traffic control. The *Temporary Traffic Control Manual* (*7*) is simply a reprint of portions of the OMUTCD that deal with temporary traffic control (Parts 1, 5, and 6). The *Guidelines for Traffic Control in Work Zones (Pocket Guide)* (*8*) summarizes the guidelines established in the OMUTCD regrading temporary traffic control in work zones. The pocket guide is intended to provide the principles of proper temporary traffic control but is not a standard. The audience for the pocket guide includes state and local governments' road and street departments, utilities, companies performing construction by permit, and any other entity providing maintenance or construction on a public roadway.

INTERVIEWS

In December 2018 and January 2019, the research team interviewed select ODOT and Ohio Turnpike personnel in District 12. The objectives of these interviews were to identify the types of mobile maintenance operations conducted on multi-lane highways and discuss the conditions surrounding these types of operations that cause maintenance workers the most concern. Researchers also asked if these employees had any suggestions on how to improve the safety of mobile maintenance operations on multi-lane highways.

Types of Mobile Maintenance Operations on Multi-lane Highways

Table 2 lists the types of mobile maintenance operations conducted by ODOT and the Ohio Turnpike on multi-lane highways. Both agencies routinely use mobile operations for pothole patching and sweeping. Other mobile maintenance operations include herbicide application, bridge spall repair, mowing, drain cleaning, clearing of debris, and delineator repair.

Table 2. Types of Mobile Maintenance Operations on Multi-lane Highways.

ODOT District 12	Ohio Turnpike
Pothole patching	Pothole patching
Sweeping	Sweeping
Bridge spall repair	Herbicide application
Mowing	Drain cleaning
Herbicide application	Right-of-way cleanup (clearing of debris)
	Delineator repair

ODOT District 12

ODOT District 12 conducts most of its mobile operations on multi-lane highways at night. The district uses the OMUTCD typical application in Figure 4 for all mobile operations on multi-lane highways. In ODOT District 12, the advance warning vehicle (AWV) is referred to as the road cruiser truck. This vehicle has flashing amber warning lights and a truck-mounted CMS (58 inches by 28 inches) that displays messages about the mobile operation and the desired driver action (e.g., LEFT LN

CLOSED/WORKERS IN ROAD). The road cruiser truck is positioned between 1500 and 2000 ft upstream of the mobile operation but can be located further upstream as needed to provide advance warning. The road cruiser truck is typically located on the right shoulder since most roadways do not have adequate left shoulder width.

In ODOT District 12, all shadow vehicles have arrow boards and flashing green, white, and amber warning lights. Shadow vehicles in the closed lanes, and sometimes on the shoulder, use TTMAs since the shadow vehicles are used for snowplowing during the winter.

The pothole patching operation typically involves a 1-ton dump truck carrying the cold mix (i.e., work vehicle), a shadow vehicle with a TTMA behind the work vehicle, and the road cruiser truck on the right shoulder upstream of the mobile operation. Workers are located in the work vehicle and get in and out as needed to fill potholes. If the distance between potholes is short, workers may walk to the next pothole. If pothole patching is conducted in the middle lane, a second shadow vehicle with a TTMA is added to the mobile operation.

The sweeping operation typically involves a truck that travels in front of the sweeper to pick up large debris, the sweeper, a shadow vehicle with a TTMA behind the sweeper in the closed lane, and a shadow vehicle with a TTMA on the shoulder (if needed). A static ROAD SWEEPING NEXT 5 MI sign is generally placed on the right shoulder upstream of the mobile sweeping operation.

Bridge spall repair is conducted as a mobile operation since a stationary temporary traffic control operation takes too long to set up compared to the work duration at each bridge (i.e., less than 30 minutes) and the bridges are spaced far apart. The bridge spall repair operation generally involves the road cruiser truck and two shadow vehicles with TTMAs (one in each closed lane).

The mobile mowing operation involves a trim mower on the shoulder and one shadow vehicle with a TTMA. When a roadway has a narrow shoulder, one shadow vehicle with a TTMA is used with herbicide operations.

Ohio Turnpike

The Ohio Turnpike mainly conducts mobile maintenance operations on multi-lane highways during the day. Night work is generally limited to operations involving multi-lane closures. The Ohio Turnpike has two or three shadow vehicles with impact attenuators in each district (24 total). All impact attenuators are truck mounted, except for one that is a TTMA. Ohio Turnpike shadow vehicles have arrow boards, most of which are full-matrix CMSs with 42 standard messages. The warning lights on all work vehicles are amber (no green and white lights like ODOT).

For pothole patching operations, the Ohio Turnpike uses the standard drawing in Figure 5. The work vehicle typically contains three workers (i.e., two workers to complete the work and one worker to act as a spotter/flagger). The shadow vehicle directly behind the work vehicle is in the closed lane and includes an arrow board, static sign, and impact attenuator. The second shadow vehicle straddles the edge line and contains an arrow board and impact attenuator. The advance warning vehicle, with an arrow board and static sign mounted on it, is on the shoulder. Although the arrow boards are full-matrix CMSs, they only display flashing arrows. If available, a trailer-mounted CMS can be positioned upstream of the mobile operation to provide additional information to drivers. Occasionally, law enforcement vehicles are also positioned on the shoulder upstream of the mobile operation.

For the Ohio Turnpike, sweeping, herbicide, and drain-cleaning operations are mainly mobile operations on the shoulder. A contractor operates the sweeper, but the Ohio Turnpike provides the shadow vehicle with an impact attenuator that follows the sweeper. The driver of the shadow vehicle is typically the inspector. The shadow vehicle displays a two-phase message on the full-matrix CMS (e.g., caution mode/WORK ON RIGHT SHOULDER). Similarly, for herbicide and drain-cleaning operations, a contractor drives the work vehicle followed by an Ohio Turnpike shadow vehicle with an impact attenuator. If spraying herbicide around guardrails on a roadway with multiple lanes in each direction and a grass median, the Ohio Turnpike uses the standard drawing in Figure 5.

For the right-of-way cleanup (clearing of debris) and delineator repair, the Ohio Turnpike just uses a shadow vehicle with an impact attenuator and full-matrix CMS. The workers are in the shadow vehicle (no separate work vehicle). One of the 42 standard messages is displayed on the truck-mounted CMS.

Concerning Conditions and Hazards

As expected, high-volume and high-speed conditions concerned ODOT and Ohio Turnpike personnel. High-volume roadways are the main reason why ODOT District 12 conducts a majority of maintenance work at night. However, at night, visibility is reduced. Union contracts limit the amount of night work the Ohio Turnpike can conduct. Meanwhile, both agencies follow permitted lane closure schedules that were developed to restrict lane closures during peak traffic periods. Neither agency reduces the speed limit for mobile maintenance operations.

For ODOT District 12 personnel, one of the main conditions affecting the safety of mobile maintenance operations on multi-lane highways is the lack of left shoulders. When there is a narrow or no left shoulder, the road cruiser (i.e., AWV) must be positioned on the right shoulder even though the mobile operation is in the left lane(s). Dependent upon the number of lanes, traffic volume, visibility, and other site conditions, drivers may not notice the road cruiser or be able to adequately read and comprehend the message displayed. In addition, Ohio’s Move Over Law may push traffic away from the AWV on the right shoulder and into the left lane(s). The Ohio Turnpike personnel noted that they only have a few locations with limited left shoulder width.

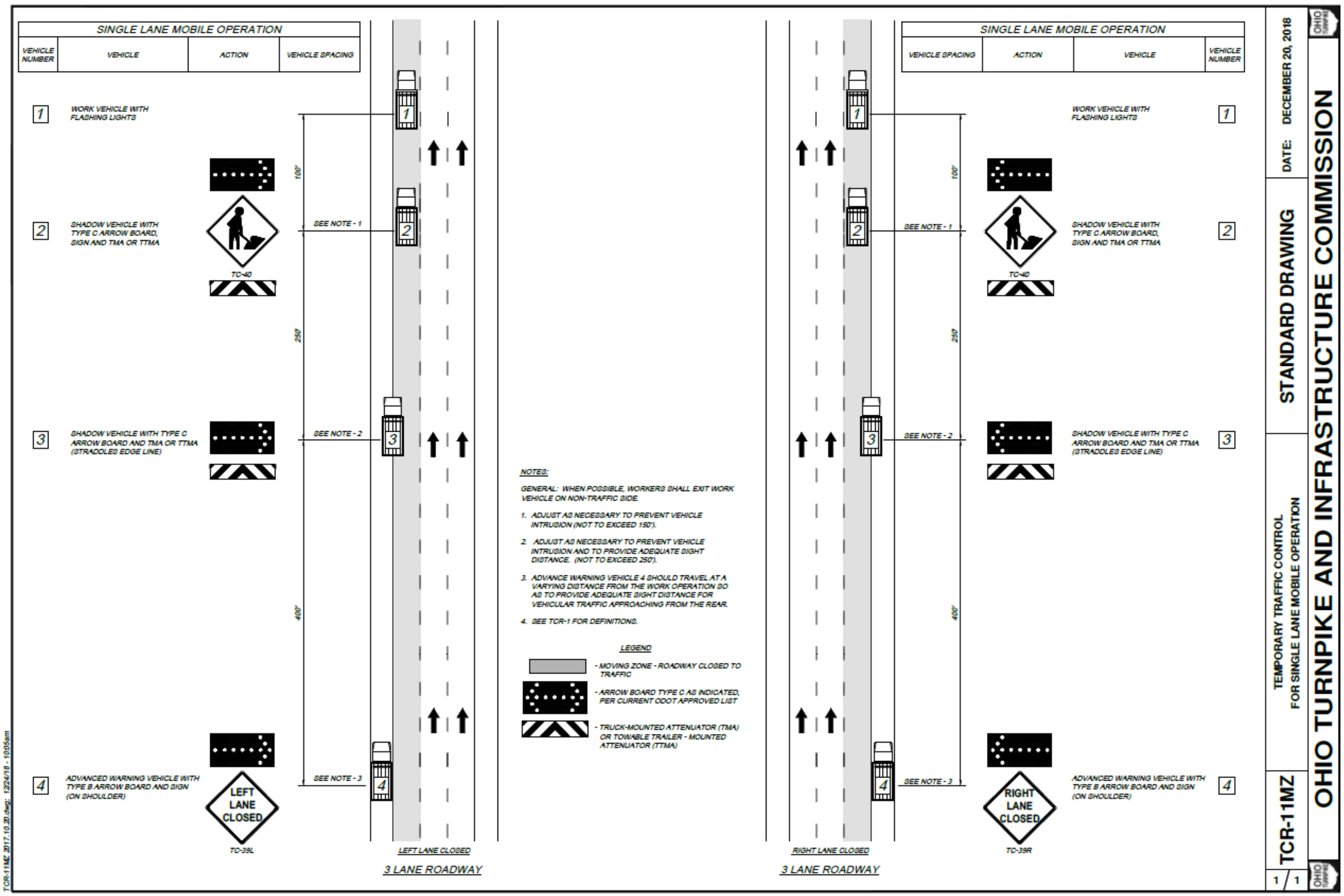


Figure 5. Ohio Turnpike Standard Drawing for Single-Lane Mobile Operation (TCR-11MZ).

ODOT District 12 personnel also mentioned the difficulty with maintaining adequate buffer space between the shadow vehicle and work vehicle. Personnel from both agencies felt that shadow vehicle drivers do a good job of dropping back to ensure adequate sight distance, especially at horizontal and vertical curves. In addition, neither agency noted issues with drivers cutting into the work convoy, which typically occurs when the distance between the shadow vehicle and the work vehicle is too large. However, both agencies stated that many times it is hard to maintain the minimum distance that allows for post-collision roll ahead of the shadow vehicle.

The ODOT night crew in District 12 typically consists of workers with less experience and seniority. In addition, the night crew has a higher turnover rate (when available workers move to other crews). Worker complacency, especially for personnel that have been working on the roads for a long period of time, was also mentioned. ODOT District 12 personnel conduct tailgate talks daily and uses spotters to help address this issue. The main hazards encountered dealt with the following road user behaviors: inattentive or distracted drivers, drivers following too close to shadow vehicles, and drivers moving out of the closed lane at the last minute.

Potential Safety Enhancements

ODOT District 12 and Ohio Turnpike personnel suggested the following devices and strategies that could be used to improve the safety of mobile maintenance operations on multi-lane highways:

- An alarm to alert shadow vehicle drivers when they are too close to work space.
- Autonomous truck-mounted attenuator trucks.
- LED border-illuminated construction warning signs.
- Advisory speed limits.
- Truck-mounted speed feedback signs.
- Law enforcement.
- Blue lights on work vehicles.
- Clear, understandable, consistent messages on truck- and trailer-mounted CMSs.
- Messages on overhead CMSs, where available.
- Technology that communicates lane closure location to drivers.

Both agencies also acknowledged that the Move Over Law has helped but needs to be advertised more.

PREVIOUS RESEARCH OBSERVATIONS

In 2015, members of the research team observed ODOT staff conducting eight mobile maintenance operations on multi-lane highways in Franklin County in District 6 (see Table 3) (*1*). The work activities included pothole patching, retroreflectivity measurements, sweeping, and arm mowing. Six of the mobile operations closed a single lane, one closed two lanes, and one involved work on the shoulder.

Table 3. Matrix of Mobile Maintenance Operations Observed in 2015 (*1*).

Site	Date	Day or Night	Roadway and Direction	Roadway Type	From	To	Speed Limit (mph)	Type of Work Operation	Type of Temporary Traffic Control	Lane(s) Closed	OMUTCD Typical Application
3	9.10.15	Night	I-270 WB	Freeway	US 315	Sawmill Rd.	65	Pothole patching	Mobile	2 left	TA-35
6	9.15.15	Night	I-70 EB	Freeway	Brice Rd.	Exit 112A	65	Pothole patching	Mobile	1 right	TA-35
8	9.17.15	Day	US 33 EB	Freeway	Gender Rd.	Rager Rd.	60	Pothole patching	Mobile	1 left	TA-35
9	9.18.15	Day	I-270 SB	Freeway	Tuttle Crossing Blvd.	Cemetery Rd.	65	Pothole patching	Mobile	1 left	TA-35
10a[1]	10.5.15	Day	US 23 SB	4 lane divided	OH 665	OH 665	55	Retroreflectivity measurements	Mobile	1 right	TA-35
10b	10.5.16	Day	US 23 NB	4 lane divided	OH 665	OH 665	55	Retroreflectivity measurements	Mobile	1 right	TA-35
10c	10.5.17	Day	US 23 SB	4 lane divided	OH 665	OH 665	55	Retroreflectivity measurements	Mobile	1 left	TA-35
10d	10.5.18	Day	US 23 NB	4 lane divided	OH 665	OH 665	55	Retroreflectivity measurements	Mobile	1 left	TA-35
11	10.5.15	Day	I-70 NB	Freeway	Exit 101B	Exit 101B	55	Retroreflectivity measurements	Mobile	1 right	TA-35
12	10.5.15	Night	I-71 NB	Freeway	1-70 merge	I-670 split	55	Sweeping	Mobile	1 left	TA-35
15	10.7.15	Night	I-270 NB	Freeway	US 33	US 33	65	Arm mowing	Mobile	Shoulder	TA-4

SB = southbound; NB = northbound; WB = westbound; EB = eastbound

[1] Multiple entries are shown for Site 10 because the work changed location (direction and which lane was closed).

All the single-lane closure mobile operations used an AWV and a shadow vehicle plus work vehicle(s)/equipment. The AWV was typically a pickup truck with an arrow board displaying the appropriate flashing arrow, static RIGHT (LEFT) LANE CLOSED AHEAD sign (mounted below the arrow board), and flashing amber warning lights. The AWV normally did not have an impact attenuator. The shadow vehicle was in the closed lane. It had an impact attenuator, arrow board displaying the appropriate flashing arrow, static ROAD WORK AHEAD sign (mounted below the arrow board), and flashing green, white, and amber warning lights. The work vehicles had flashing amber warning lights.

The two-lane mobile operation involved two work vehicles, an AWV, and two shadow vehicles. The AWV was located on the left (inside) shoulder. This vehicle displayed a static LEFT 2 LANES CLOSED AHEAD sign and a flashing right arrow on a trailer-mounted arrow board. Each closed lane contained a shadow vehicle, staggered to form a taper. Both of the shadow vehicles had impact attenuators and displayed a static ROAD WORK AHEAD sign and flashing right arrow on a truck-mounted arrow board. The shadow vehicles in the closed lanes and one of the work vehicles had flashing green, white, and amber warning lights. The other work vehicle and AWV had flashing amber warning lights.

The mobile operation on the shoulder of a multi-lane highway included four vehicles: an AWV, a shadow vehicle, a work vehicle with a trailer-mounted light tower, and a mower. The AWV was located upstream of the work activity on the right shoulder. It had flashing amber warning lights and was towing a trailer-mounted arrow board displaying the horizontal line flashing caution mode (see Figure 6). A SHOULDER WORK AHEAD sign was mounted under the arrow board. The shadow vehicle was also on the shoulder but closer to the work activity. The shadow vehicle had an impact attenuator, an arrow board displaying the horizontal line flashing caution, a static ROAD WORK AHEAD sign (mounted below the arrow board), and flashing green, white, and amber warning lights. The two work vehicles had flashing amber warning lights. While the horizontal line flashing caution mode is acceptable under the OMUTCD (5), concerns exist that some drivers interpret this display to be a malfunctioning flashing arrow and thus may make unnecessary lane changes. Researchers recommended that other acceptable caution modes (i.e., four-corner flashing caution and alternating diamond caution) be used instead.

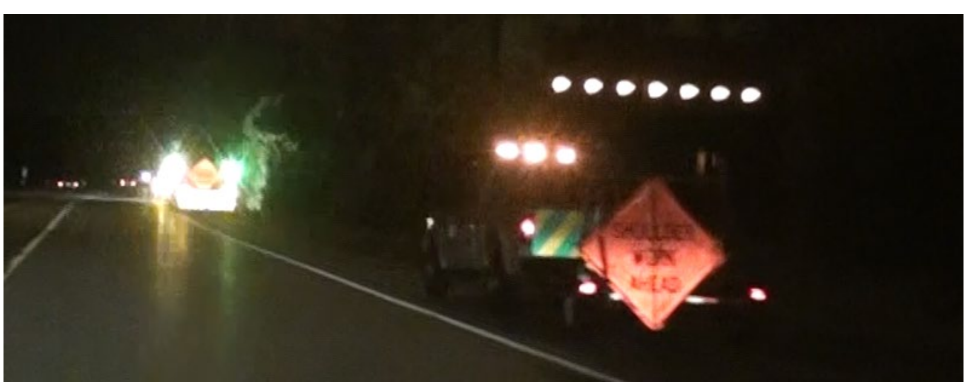


Figure 6. AWV with Horizontal Line Flashing Caution Mode.

Researchers conducting the observations noted the following potential safety concerns:

- Distance between the shadow vehicle and work vehicle/equipment.
- Arrow board and vehicle light intensity.
- Early deployment of the warning sign.
- Queuing and hard braking.

During three of the mobile maintenance operations (sites 3, 8, and 9 in Table 3), the shadow vehicle was positioned too close to the work equipment (80 to 160 ft). The *Field Guide for the Use and Placement of Shadow Vehicles in Work Zones* (2) provides guidance on the spacing of shadow vehicles based on speed limit, weight of the shadow vehicle, and whether the operation is stationary or moving (see Table 1). Similar guidance can also be found in the AASHTO *Roadside Design Guide* (*3*) and the ODOT *Construction and Material Specifications* (*4*). According to Table 1, on roadways with posted speed limits greater than 55 mph, mobile shadow vehicles should be at least 172 ft upstream of the work space. It is important that adequate distance is provided to allow for post-collision roll ahead of the shadow vehicle, especially on high-speed roadways serving a significant proportion of large trucks.

While the minimum roll-ahead spacing requirements were met at Site 10 (see Table 3), sometimes the distance measured between shadow and work vehicles was twice as much as the recommended spacing. Occasionally, the shadow vehicle driver increased the spacing to position the shadow vehicle before a horizontal curve or at the apex of a vertical curve in order to ensure that adequate decision sight distance was provided to approaching drivers. While this is a good practice, leaving a large gap between the shadow and work vehicles can encourage drivers to cut into the work convoy.

Researchers noted that the intensity of the arrow board displays and other vehicle lights made the static truck-mounted warning signs difficult, if not impossible, to read at two locations (Sites 3 and 12 in Table 3). Researchers recommended ODOT staff check the automatic dimming function on all arrow panels.

On the way to Site 10, which was located approximately 6 miles from the garage, the work crew did not cover the RIGHT LANE CLOSED sign on the arrow board trailer pulled by one of the shadow vehicles. The OMUTCD requires that temporary traffic control devices that are not appropriate for conditions be removed or covered (*5*). Thus, advance warning signs should not be displayed while traveling to the site because this may confuse drivers following the work vehicles. In addition, ODOT credibility may be reduced when drivers realize that the information displayed is inaccurate.

At Site 8, the mobile maintenance operation caused traffic to slow to a stop (periodically) upstream of the work. However, researchers did not observe any hard braking by drivers. At Site 9, traffic volumes were greater than anticipated due to several special events occurring on the weekend (e.g., a concert and a football game). The backups occurred quickly and created hard braking, so the work was postponed to another day.

MATRIX OF CURRENT PROCEDURES

Based on the review of ODOT manuals and standards, interviews with ODOT and Ohio Turnpike personnel in District 12, and previous research, the research team developed a matrix of the current processes used for mobile maintenance operations on multi-lane highways (see Table 4).

Table 4. Matrix of Current Procedures Used for Mobile Maintenance Operations on Multi-lane Highways.

Type of Work	Description of Temporary Traffic Control (Non-work Vehicles)	
	ODOT	**Ohio Turnpike**
Pothole patching	**District 6**—AWV with flashing amber warning lights, arrow board, and static warning sign. At least one shadow vehicle with impact attenuator, arrow board, static warning sign, and flashing green, white, and amber warning lights. **District 12**—AWV with flashing amber warning lights and truck-mounted CMS. At least one shadow vehicle with impact attenuator, arrow board, and flashing green, white, and amber warning lights. Static warning signs were also mounted on some shadow vehicles.	AWV with flashing amber warning lights, arrow board, and static sign. One shadow vehicle with flashing amber warning lights, impact attenuator, and arrow board. Second shadow vehicle with flashing amber warning lights, impact attenuator, arrow board, and static warning sign.
Sweeping	**District 6**—AWV with flashing amber warning lights, arrow board, and static warning sign. One shadow vehicle with impact attenuator, arrow board, static warning sign, and flashing green, white, and amber warning lights. **District 12**—At least one shadow vehicle with impact attenuator, arrow board, and flashing green, white, and amber warning lights. Static warning signs may be placed on the shoulder upstream of the operation.	Shadow vehicle with flashing amber warning lights, impact attenuator, and truck-mounted, full-matrix CMS.
Mowing	**District 6**—One shadow vehicle with impact attenuator, arrow board, static warning sign, and flashing green, white, and amber warning lights. **District 12**—AWV with flashing amber warning lights, arrow board, and static warning sign. One shadow vehicle with impact attenuator, arrow board, static warning sign, and flashing green, white, and amber warning lights.	
Bridge spall repair	**District 12**—AWV with flashing amber warning lights and truck-mounted CMS. Two shadow vehicles with impact attenuators, arrow boards, static warning signs, and flashing green, white, and amber warning lights.	
Retro-reflectivity measurement	**District 6**—AWV with flashing amber warning lights, arrow board, and static warning sign. One shadow vehicle with impact attenuator, arrow board, static warning sign, and flashing green, white, and amber warning lights.	

Table 4. Matrix of Current Procedures Used for Mobile Maintenance Operations on Multi-lane Highways (Continued).

Type of Work	Description of Temporary Traffic Control (Non-work Vehicles)	
	ODOT	**Ohio Turnpike**
Striping		Three vehicles with arrow board in caution mode and static WET PAINT/KEEP RIGHT(LEFT) sign. Two shadow vehicles with impact attenuators and arrow boards. Law enforcement located in the middle of the mobile operation.
Herbicide application		Shadow vehicle with flashing amber warning lights, impact attenuator, and truck-mounted, full-matrix CMS.
Drain cleaning		Shadow vehicle with flashing amber warning lights, impact attenuator, and truck-mounted, full-matrix CMS.
Right-of-way cleanup		Shadow vehicle with flashing amber warning lights, impact attenuator, and truck-mounted, full-matrix CMS.
Delineator repair		Shadow vehicle with flashing amber warning lights, impact attenuator, and truck-mounted, full-matrix CMS.
Pretreatment for snow and/or ice		Shadow vehicle with flashing amber warning lights, impact attenuator, and truck-mounted, full-matrix CMS.

APPENDIX C:
POTENTIAL SAFETY IMPROVEMENTS

In the first quarter of 2019, the research team performed an extensive literature review to identify the state of the practice regarding mobile maintenance operations on multi-lane highways and gather information on practices and innovative devices that could potentially improve the safety of ODOT operations. The research team also searched state DOT websites to identify state traffic control standards for mobile maintenance operations on multi-lane highways and review the recommended spacing of work convoy vehicles. For 14 states, the research team could not find traffic control standards for mobile maintenance operations on multi-lane highways online. Out of the 36 remaining states, only 22 state DOTs had standards online that specifically addressed the requirements for work convoy vehicle spacing for mobile maintenance operations on multi-lane highways. Among those 22 state DOTs, 18 standards covered general mobile operations, eight addressed striping operations (i.e., pavement markings and/or markers), and one addressed rumble strip operations. The research team focused on the 18 standards that covered general mobile operations. This appendix discusses the following methods and devices:

- Shadow vehicles.
- Advance warning vehicles.
- Lead vehicles downstream of the work space.
- Law enforcement.
- Warning lights.
- Arrow boards.
- Truck-mounted static signs.
- Truck-mounted CMSs.
- Truck-mounted speed feedback signs.
- Intrusion alarms.
- Real-time work zone location technology.

SHADOW VEHICLES

Impact Attenuators

The *Field Guide for the Use and Placement of Shadow Vehicles in Work Zones* (2) addresses the use and placement of shadow vehicles in work zones. The guide recommends the use of a shadow vehicle with an impact attenuator for mobile operations on freeways when workers are on foot in an active travel lane or on the shoulder. Even when workers are inside work vehicles (i.e., not on foot), a shadow vehicle with an impact attenuator may still be justified. *A Guide to Short-Term, Short-Duration, and Mobile Work Zone Temporary Traffic Control* (*9*) recommends the use of impact attenuators on all shadow vehicles.

In 2013, Theiss and Bligh (*10*) completed research that compared the level of protection provided to workers by truck-mounted attenuators (TMAs) and TTMAs. These researchers found that many TMAs and TTMAs require some type of modification to the rear bumper of vehicles to mount or tow the impact attenuator. Generally, TMAs tend to provide more height challenges for workers in terms of maneuverability, and TTMAs may be more difficult to turn around. However, these utility challenges do not appear to be any greater for one type of device over the other. Theiss and Bligh also found no evidence that occupant impact velocities and ride-down accelerations were different between TMAs and TTMAs. Based on their findings, Theiss and Bligh recommended that the Texas Department of Transportation (TxDOT) develop a specification for the purchase of TTMAs. These researchers also recommended that TxDOT continue to require 20,000±1000-lb shadow vehicles for impact attenuators, regardless of attenuator type. Heavier shadow vehicles reduce roll-ahead distance, occupant impact velocity, and ride-down acceleration for workers in the shadow vehicle.

Autonomous Impact Protection Vehicle

Recently, agencies have been examining the use of an autonomous impact protection vehicle (AIPV) (also known as an autonomous truck-mounted attenuator). AIPVs employ a suite of technologies to enable a leader/follower capability, allowing the AIPV (follower) to be completely unmanned (i.e., no driver required). The manned leader vehicle transmits position, heading, and speed information to the unmanned AIPV in packets of data called *e-crumbs*. The AIPV uses those data to follow the path and speed of the leader vehicle (see Figure 7). Both vehicles are equipped with multiple safety and redundant systems. An advanced user interface that enables easy monitoring and adjustment of the system to suit specific operations is also included. Potential advantages of AIPVs include:

- Reduced injuries and fatalities by removing the shadow vehicle driver (it also reduces the potential for the shadow vehicle driver to flinch and turn off the roadway if he/she notices an impending rear-end collision about to occur, which would reduce the effectiveness of the impact attenuator during the crash and possibly expose workers on foot).
- Increased productivity (the shadow vehicle driver can perform other work duties).
- Reduced operational costs (smaller maintenance crews).
- More consistent distance between the AIPV and work space (ensures adequate roll-ahead distance).

The Royal Truck and Equipment AIPV was first demonstrated in August 2015 in a parking lot in Bethlehem, Pennsylvania, for the Pennsylvania Department of Transportation (*11*). The first major consumer was Colas UK, one of the largest highway construction companies in the United Kingdom. Colas UK began the process of adding AIPVs to its fleet to test the effectiveness of the AIPV shadowing a cone-setting truck.

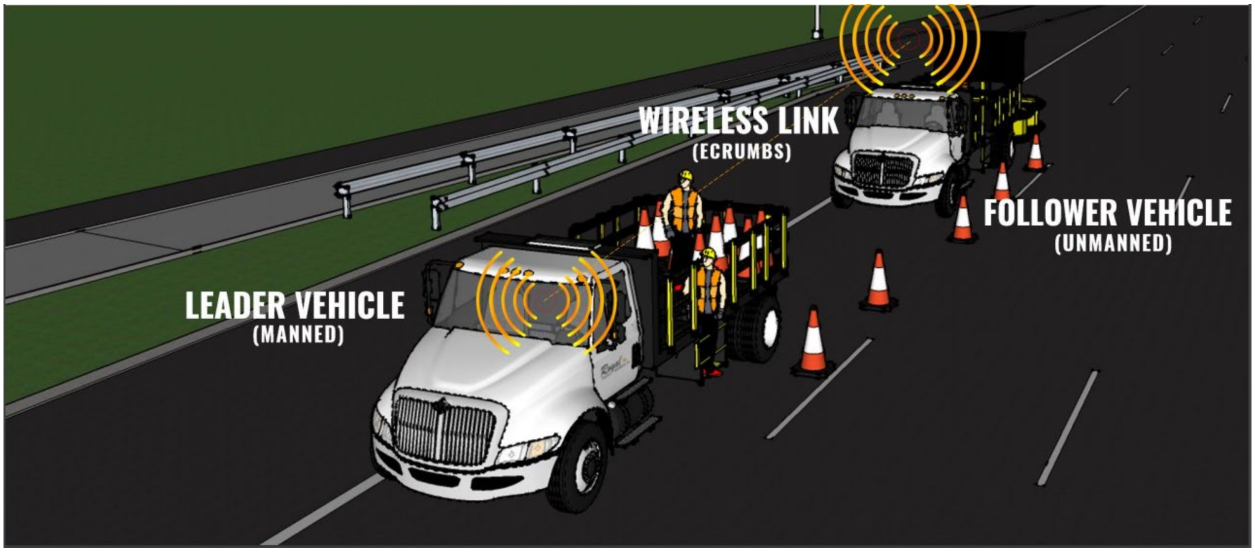


Figure 7. Example of a Leader/Follower AIPV System.

In 2017, the Colorado Department of Transportation (CDOT), through its RoadX program, launched an AIPV pilot project (*12*). Through this program, CDOT purchased a Royal Truck and Equipment AIPV, further developed and tested the AIPV on a test track, and then executed a successful use of the AIPV in an actual work zone in Fort Collins, Colorado, in August 2017 (*13*). At that time, the AIPV cost was approximately $330,000 (about $180,000 for the technology and $150,000 for the chassis), and the leader truck technology cost was approximately $63,000.

In September 2017, Battelle and the Federal Highway Administration (FHWA) conducted a two-day workshop with CDOT to demonstrate the use of the AIPV truck (*14*). Representatives from 17 state DOTs, including ODOT, attended the workshop. The workshop included presentations by the CDOT implementation team and field demonstrations with a striping operation traveling at approximately 7 mph, both on a test track and on an actual roadway. The operational capacities of the system at that time allowed the AIPV to follow the leader vehicle with high accuracy, provide quick and safe emergency stops, and provide protection within certain conditions (i.e., no GPS-denied environments and no complex maneuvering). Some of the issues identified through CDOT's testing included the need for software and hardware changes to:

- Dynamically adjust the distance between the leader and follower vehicles.
- Temporarily pause the operation of the system.
- Change system parameters during the operation.
- Improve the user interface.
- Address GPS-denied environments.
- Improve the follower vehicle's ability to track accurately around sharp curves.

Other institutional and procedural issues identified by CDOT included:

- Procedures for moving the system to/from the work site and/or deploying the system from a staging area.
- Training requirements.

- System security.
- Fail-safe systems (e.g., signal interference, loss of power, and product/software issues).
- Policy and regulatory considerations for permitting autonomous vehicles on actual roads.
- Insurance implications.

CDOT developed standard operating procedures for the AIPV in October 2017 (*15*), continued additional testing in 2018, and certified the AIPV for autonomous use on actual roadways in May 2018. According to the CDOT standard operating procedures, when the AIPV is in autonomous mode, a safety observer (located in the leader vehicle) is the formal operator of the AIPV and must maintain visual contact with the AIPV. The safety observer must be a CDOT employee with a Class B commercial driver license with air brake endorsements and trained on the AIPV operation. The AIPV is only authorized for use in one maintenance section and only for mobile striping operations. Other autonomous operations can only be conducted as authorized by the director of highway maintenance. Each AIPV field use must be approved by the Region 4 traffic operations engineer or his/her designee. When used in autonomous mode, operations may only be conducted within the following parameters:

- Mobile traffic control operations per CDOT standard plan S-630-1 (*16*):
    - Case 34 mobile pavement marking zone, mobile shoulder closure on two-lane undivided highway.
    - Case 35 mobile pavement marking zone, centerline striping on two-lane undivided highway.
    - Case 39 mobile operation of lane closure on multi-lane highway.
- Operation speed less than 10 mph.
- Generally linear operation.
- Few to no overhead or anticipated GPS obstructions or interference from bridges, tunnels, overhead sign gantries, canyons, valleys, or heavy timber within 100 ft of the roadway.
- Visual contact that can be maintained between the leader vehicle and AIPV.
- Safety driver present in the leader vehicle and able to operate an emergency stop, if needed.
- Few to no traffic signals.
- Rural arterial or collector highways (may be divided and multiple lanes in each direction).

For autonomous operation, CDOT employees must comply with the following procedure:

- Conduct a job hazard analysis to determine if the operation is consistent with standard operating procedures.
- Get approval of the job hazard analysis from the traffic operations engineer before conducting the striping operation.
- Complete a pre-trip inspection and document it using a checklist.
- Turn on autonomous systems and leave in IDLE for transit to the site.
- Transport the AIPV to the work location in non-autonomous mode.
- Place the AIPV into operation per the checklist.

- Complete the striping operation.
- Transport the AIPV back to the office in non-autonomous mode.
- Conduct a post-trip inspection and document it in the AIPV operation log.

The CDOT standard operating procedures also address emergency stop conditions and crashes/incidents involving the AIPV. In June 2018, CDOT received a two-day hands-on training from Kratos Defense and Security Systems. CDOT also certified one employee as a train-the-trainer so CDOT could train additional employees in-house. Between July 2018 and January 2019, CDOT logged about 100 miles in autonomous mode and approximately 17,000 miles in non-autonomous mode. Lessons learned include the need for:

- Internal leadership support.
- Development of standard operating procedures and training.
- Installation of autonomous technologies on newer trucks (leader and follower vehicles).
- Identification of an off-road testing area where personnel can use the autonomous system, which allows:
  - Personnel to familiarize themselves with technology before deploying on an actual roadway.
  - Testing of technology.
  - Identification of potential issues.

Building on the original AIPV and input from early adopters, Royal Truck and Equipment developed the NextGen system, which includes the following system enhancements:

- Seamless/continuous operation in GPS-denied environments enabled by a backup, non-GPS-based, inertial navigation system.
- Increased safety with redundant frontal collision avoidance and side-view obstacle detection.
- Protection against radio frequency interference and malicious hacking with a robust encrypted vehicle-to-vehicle communication system.
- Remote operator controls (via a touchscreen tablet computer mounted in the leader vehicle) with a status display of key parameters provided through additional robust controls to the user interface.

The AIPV NextGen system user interface enables the operator to remotely set the gap (follow) distance between the leader and follower vehicles using a slider-bar touchscreen control (see Figure 8). The following distance (measured from the rear of the leader vehicle to the front of the AIPV) can be any of the following discrete values: 25 ft, 100 ft, 165 ft, 200 ft, 300 ft, 400 ft, and 500 ft. A speed/gap algorithm controls the following distance accuracy within ±15 ft of the set distance during typical driving conditions. The user interface also includes a pause feature that enables the operator to initiate a command that automatically brings the AIPV to a temporary stop. When initiated, the pause feature automatically shifts the AIPV transmission to neutral, releases the throttle, and applies the brakes. When the pause feature is disengaged, the AIPV shifts into drive, the brakes release, and the throttle engages. The AIPV will drive at speeds up to 20 mph to the specified gap distance following the path of the leader vehicle. The AIPV NextGen system is also able to record up to 24 hours of vehicle performance data that can be downloaded and analyzed using standard spreadsheet graphing, printing, and data reduction tools.

Figure 8. User Interface with Concept Software Layout.

In early 2019, CDOT was in the process of purchasing the AIPV NextGen system. The plan was to purchase a truck according to CDOT specifications and then have the manufacturer program and install the AIPV NextGen system. The programming of the AIPV NextGen system was dependent upon the type of truck. If the manufacturer has not programmed the AIPV NextGen system for the type of truck provided by an agency, there is a one-time charge of about $100,000 to complete the initial system programming. Due to the system enhancements discussed previously, the AIPV NextGen system technology for the follower vehicle costs approximately $240,000, and the leader vehicle technology costs approximately $95,000. Other costs include the impact attenuator, arrow board, transport to/from the manufacturer, and other desired upgrades (e.g., radar board, digital video recorder [DVR], and cameras). CDOT planned to purchase multiple leader kits so the follower vehicle can be used with several leader vehicles.

Other state agencies actively studying and testing AIPVs include Missouri and California. The Missouri Department of Transportation has invested in a two-year study that includes the installation of the AIPV system on two of its vehicles. Testing and evaluation will be completed in partnership with the Missouri University of Science and Technology and Kratos Defense and Security Systems.

CDOT also leads the Autonomous Maintenance Technology (AMT) pooled-fund study (TPF-5[380]) to support and promote collaborative research efforts of autonomous technologies in work zones (*17*). As of March 2019, the state DOTs in Alabama, California, Illinois, Kansas, Minnesota, Missouri, Ohio, Texas, Virginia, and Washington State are pooled-fund partners. The mission of the study is to develop and deploy AIPVs to protect highway workers' lives through interagency cooperative research and to facilitate communication among agencies implementing AIPVs (*18*). The goals and subsequent objectives are to (*18*):

- Drive enhancements in AIPVs to improve system performance.

- Foster collaboration in AIPV operations by identifying common research and deployment needs.
- Share research methods and results with agency members and the public.
- Improve safety of AIPV operations.

Specific areas of interest include (18):

- Documenting the evolution of AIPVs.
- System developments:
  - Improvements to adjustable gap distance.
  - System-level challenges.
  - Human-machine interfaces.
  - Regulatory guidance.
- Technology improvements:
  - Low-GPS environments.
  - Electronic pre- and post-trip logs.
  - Peer support.
  - Control system checks.
  - Pause and turn mode.
  - Radar verification.
  - Application to more types of work operations.
  - Training.
  - Career development.

Distance between Shadow Vehicle and Work Space

The *Field Guide for the Use and Placement of Shadow Vehicles in Work Zones* (*2*) provides guidance on the minimum spacing of shadow vehicles based on speed limit, weight of the shadow vehicle, and whether the operation is stationary or moving (see Table 1). The guide recommends using both the heaviest shadow vehicle to optimize protection and engineering judgment to increase distances by considering traffic conditions, vehicle mix, sight distance, and other site conditions. Both ODOT and the Ohio Turnpike primarily perform maintenance on high-speed roadways (i.e., greater than 55 mph) and use shadow vehicles that weigh over 22,000 lb. Based on Table 1, the shadow vehicle should be 172 ft upstream of the work space for moving operations (up to 15.5 mph).

Nationally, discussions are also occurring about whether additional guidance should be provided regarding shadow vehicle size and spacing when performing work operations on high-speed facilities, which serve a significant proportion of large trucks. In the event of a rear-end collision by a fully loaded (80,000-lb) semi-tractor trailer unit, the roll/skid-ahead distances of a shadow vehicle of the sizes in Table 1 will likely far exceed the current spacing guidelines, pushing the shadow vehicle into the work space and workers. For example, an engineering analysis of kinetic energy dissipation requirements suggested that a fully loaded semi-tractor trailer unit traveling at 55 mph would push a stationary 10,000-lb shadow vehicle with a Test Level 3 rated TMA nearly 500 ft before coming to rest, and a 25,000-lb shadow vehicle/TMA combination more than 300 ft. If the semi-tractor trailer unit impacts a 25,000-lb shadow vehicle/TMA combination in a 15.5-mph moving operation, the roll/skid-ahead distance could reach 450 ft or more. Using larger and heavier shadow vehicles, such as dump trucks loaded with sand, to bring vehicle weights up toward 50,000 lb would bring these roll/skid-ahead distances down closer to the recommended values in Table 1. ODOT would need to ensure that the impact attenuators used are designed to provide acceptable crash test performance for smaller vehicles if mounted on heavier shadow vehicles. An analysis by Steele and Vavrik (*19*) resulted in similar findings.

Two of the ODOT crashes reviewed involved a semi-tractor trailer hitting a shadow vehicle (see Appendix A). Both crashes resulted in damages to the shadow vehicle ($39,892), injuries to the shadow vehicle driver ($12,426), and injuries to the driver and passenger of the at-fault vehicle.

The OMUTCD typical applications do not include spacing requirements (see Figure 3 and Figure 4). Based on conversations with ODOT District 12 personnel, for mobile maintenance operations on multi-lane highways, the shadow vehicle is typically located 100 ft to 120 ft upstream of the work vehicle(s). Similarly, the Ohio Turnpike standard drawing for single-lane mobile operations (see Figure 5) shows 100 ft between the work vehicle and shadow vehicle along with a note to adjust as necessary up to 150 ft. These distances are less than the recommended roll-ahead distance of 172 ft.

Table 5 summarizes the findings from the state DOT standards for the spacing between the shadow and work vehicles for single-lane closure mobile operations with one shadow vehicle. Focusing on high-speed roadways (i.e., greater than 55 mph), most of the standards contain a spacing between the shadow and work vehicles greater than 172 ft (when a single shadow vehicle is used). Exceptions included North Dakota and South Carolina. Overall, the spacing between the shadow and work vehicles was quite varied, ranging from 100 to 1000 ft. Most of the standards included a specific value, instead of a range, for the spacing.

Multiple Shadow Vehicles

Both the *Field Guide for the Use and Placement of Shadow Vehicles in Work Zones* (*2*) and *A Guide to Short-Term, Short-Duration, and Mobile Work Zone Temporary Traffic Control* (*9*) discuss the balance between providing adequate space for post-collision roll ahead of shadow vehicles and creating too much space, which encourages vehicles to enter the area between the shadow and work vehicles. When post-collision roll-ahead distances require longer spacings than preferred, a buffer vehicle can be used to reduce the likelihood of drivers cutting back into the convoy. Steele and Vavrik (*20*) recommended buffer vehicles be used to double the distance between the shadow vehicle and the workers. Inserting a buffer vehicle between the shadow vehicle and workers keeps the shadow vehicle from being pushed into workers (although it could hit the buffer truck) and deters lateral intrusions. Steele and Vavrik (*20*) recommended the buffer vehicle be located 100 to 150 ft downstream of the shadow vehicle and 100 to 150 ft upstream of the work space.

Table 5. Spacing between Shadow Vehicle and Work Vehicle for Single-Lane Closure Mobile Operations from State DOT Standards (One Shadow Vehicle).

<table>
<tr><th>State</th><th>Number of Shadow Vehicles</th><th colspan="2">Condition</th><th colspan="2">Spacing between Shadow Vehicle and Work Vehicle (ft)</th></tr>
<tr><td>North Dakota</td><td>1</td><td colspan="2"></td><td colspan="2">150</td></tr>
<tr><td>Virginia</td><td>1</td><td colspan="2"></td><td colspan="2">240</td></tr>
<tr><td rowspan="2">Florida</td><td rowspan="2">1</td><td colspan="2">Rural</td><td colspan="2">500-800</td></tr>
<tr><td colspan="2">Urban</td><td colspan="2">300-500</td></tr>
<tr><td rowspan="2">Illinois</td><td rowspan="2">1</td><td colspan="2">Speed ≤45 mph</td><td colspan="2">120</td></tr>
<tr><td colspan="2">Speed 50-70 mph</td><td colspan="2">180</td></tr>
<tr><td rowspan="4">Indiana</td><td rowspan="4">1</td><td colspan="2">Speed ≤45 mph</td><td colspan="2">150</td></tr>
<tr><td colspan="2">Speed 50-55 mph</td><td colspan="2">200</td></tr>
<tr><td colspan="2">Speed 60-65 mph</td><td colspan="2">275</td></tr>
<tr><td colspan="2">Speed 70 mph</td><td colspan="2">325</td></tr>
<tr><td rowspan="4">Iowa</td><td rowspan="4">1</td><td colspan="2">Speed limit ≤35 mph</td><td colspan="2">300</td></tr>
<tr><td colspan="2">Speed limit 40-45 mph</td><td colspan="2">500</td></tr>
<tr><td colspan="2">Speed limit 50-55 mph</td><td colspan="2">500</td></tr>
<tr><td colspan="2">Speed limit ≥60 mph</td><td colspan="2">1000</td></tr>
<tr><td rowspan="3">Michigan</td><td rowspan="3">1</td><td colspan="2">Speed limit 45 mph</td><td colspan="2">100</td></tr>
<tr><td colspan="2">Speed limit 50-55 mph</td><td colspan="2">150</td></tr>
<tr><td colspan="2">Speed limit 60-70 mph</td><td colspan="2">175</td></tr>
<tr><td rowspan="4">South Carolina</td><td rowspan="4">1</td><td rowspan="3">Intermittent on routes with high volume and speed</td><td>Speed limit ≤35 mph</td><td colspan="2">50-250</td></tr>
<tr><td>Speed limit 40-50 mph</td><td colspan="2">75-500</td></tr>
<tr><td>Speed limit ≥55 mph</td><td colspan="2">100-750</td></tr>
<tr><td colspan="2">Continuous on primary and secondary routes</td><td colspan="2">150-300</td></tr>
<tr><td rowspan="7">Tennessee</td><td rowspan="7">1</td><td colspan="2">Speed limit (mph)</td><td>Flashing arrow board on work vehicle</td><td>No flashing arrow board on work vehicle</td></tr>
<tr><td colspan="2">0-30</td><td>125-275</td><td>100</td></tr>
<tr><td colspan="2">35-40</td><td>163-350</td><td>100</td></tr>
<tr><td colspan="2">45-50</td><td>300-450</td><td>175</td></tr>
<tr><td colspan="2">55</td><td>375-600</td><td>175</td></tr>
<tr><td colspan="2">60-65</td><td>500-700</td><td>225</td></tr>
<tr><td colspan="2">70-75</td><td>600-800</td><td>225</td></tr>
<tr><td rowspan="4">Washington</td><td rowspan="4">1</td><td colspan="2">Speed limit (mph)</td><td>Shadow vehicle weight 9,900-22,000 lb</td><td>Shadow vehicle weight >22,000 lb</td></tr>
<tr><td colspan="2"><45</td><td>100</td><td>100</td></tr>
<tr><td colspan="2">45-55</td><td>172</td><td>150</td></tr>
<tr><td colspan="2">>55</td><td>222</td><td>172</td></tr>
</table>

Table 6 summarizes the findings from the state DOT standards for the spacing between the shadow and work vehicles for single-lane closure mobile operations with more than one shadow vehicle. Again, the spacing between the shadow and work vehicles is quite varied. When more than one shadow vehicle is used, some states allow for spacings less than 172 ft. However, other states maintain a spacing equal to or greater than 172 ft even with the addition of another shadow vehicle. Overall, the spacing between the shadow and work vehicles when more than one shadow vehicle is used ranged from 50 to 800 ft. About half of the standards include a specific value, while the other half provide a range of values.

Table 6. Spacing between Shadow Vehicle and Work Vehicle for Single-Lane Closure Mobile Operations from State DOT Standards (More than One Shadow Vehicle).

<table>
<tr><th>State</th><th>Number of Shadow Vehicles</th><th>Condition</th><th colspan="2">Spacing between Shadow Vehicle and Work Vehicle (ft)</th></tr>
<tr><td>New York</td><td>2</td><td></td><td colspan="2">160</td></tr>
<tr><td>Texas</td><td>2</td><td></td><td colspan="2">120–200</td></tr>
<tr><td rowspan="2">Florida</td><td rowspan="2">2</td><td>Rural</td><td colspan="2">100-500</td></tr>
<tr><td>Urban</td><td colspan="2">50–300</td></tr>
<tr><td rowspan="7">Tennessee</td><td rowspan="7">2</td><td>Speed limit (mph)</td><td colspan="2">Late merge</td></tr>
<tr><td>0–30</td><td colspan="2">100</td></tr>
<tr><td>35-40</td><td colspan="2">100</td></tr>
<tr><td>45-50</td><td colspan="2">175</td></tr>
<tr><td>55</td><td colspan="2">175</td></tr>
<tr><td>60-65</td><td colspan="2">225</td></tr>
<tr><td>70–75</td><td colspan="2">225</td></tr>
<tr><td>Maine</td><td>2 or 3</td><td></td><td colspan="2">≥120</td></tr>
<tr><td>Pennsylvania</td><td>2 or 3</td><td></td><td colspan="2">125-200</td></tr>
<tr><td>South Carolina</td><td>3</td><td>Intermittent with pedestrian workers</td><td colspan="2">100</td></tr>
<tr><td>Connecticut</td><td>3</td><td></td><td colspan="2">150</td></tr>
<tr><td rowspan="7">Minnesota</td><td rowspan="7">2</td><td>Speed limit (mph)</td><td>Shadow vehicle weight 9,900–22,000 lb</td><td>Shadow vehicle weight >22,000 lb</td></tr>
<tr><td>0–30</td><td>100</td><td>100</td></tr>
<tr><td>35-40</td><td>100</td><td>100</td></tr>
<tr><td>45-50</td><td>175</td><td>150</td></tr>
<tr><td>55</td><td>175</td><td>150</td></tr>
<tr><td>60-65</td><td>225</td><td>175</td></tr>
<tr><td>70–75</td><td>225</td><td>175</td></tr>
</table>

Steele and Vavrik (*19*) found that the number and spacing of shadow vehicles varied greatly across locations based on area type (i.e., urban versus rural), location of work (e.g., shoulder, right lane, or left lane), roadway geometry, and type of work. On rural freeways with lower traffic volumes, shadow vehicles were spaced 500 ft apart, forming a gradual 1500-ft taper. In contrast, on urban freeways (especially those with higher volumes), shadow vehicles tended to be spaced closer together (50 to 100 ft) to prevent vehicles from intruding into the work convoy. Based on field observations, discussions with industry professionals, and an analysis of national and Illinois standards, Steele and Vavrik (*20*) developed spacing recommendations based on conditions (see Table 7). Their recommended minimum and maximum spacings between shadow vehicles were 200 ft and 500 ft, respectively. Steel and Vavrik believed shadow vehicle spacing less than 200 ft did not provide adequate sight and reaction distance for drivers approaching at high speeds. Likewise, they thought shadow vehicle spacing up to 500 ft provided the perspective of a continuous transition for drivers. In the Ohio Turnpike standard drawings for single-lane mobile operations (see Figure 5), the distance between shadow vehicles is 250 ft, which is in alignment with the recommendations by Steele and Vavrik in Table 7.

Table 7. Guidelines for Shadow Vehicle and AWV Spacing (*20*).

Minimum Recommended Spacing	Decreases Spacing	Condition and Effect on Spacing ⟷	Increases Spacing	Maximum Recommended Spacing
Advance Warning = 1,000 ft Truck Spacing = 200 ft	Congested	**Traffic flow**	Free-flow	Advance Warning = 2,500 ft Truck Spacing = 500 ft
	Low	**Traffic speed**	High	
	Flat, straight	**Road geometry**	Curves	
	Aggressive	**Driver nature**	Passive	
	Urban	**Setting**	Rural	

Table 8 summarizes the findings from the state DOT standards for the spacing between multiple shadow vehicles for single-lane closure mobile operations. Some states provide single values for all conditions, while others provide a single value for certain conditions (e.g., type of roadway and speed limit). One state provided a distance range based on speed limit. As with the other state findings, the spacing between multiple shadow vehicles was quite varied, ranging from 100 to 1500 ft.

Table 8. Spacing between Shadow Vehicles for Single-Lane Closure Mobile Operations from State DOT Standards (More than One Shadow Vehicle).

State	Condition	Spacing between Shadow Vehicles (ft)	
South Carolina	Intermittent with pedestrian workers	100	
Texas		400	
Indiana		500	
New York		≤750	
Connecticut		800	
Illinois		200–1,500	
Pennsylvania	Urban ≤35 mph highways	100	
	Urban >35 mph highways	350	
	Rural highways	500	
	Freeways and expressways	1000	
Tennessee	Speed limit 0–30 mph	125-275	
	Speed limit 35–40 mph	163–350	
	Speed limit 45–50 mph	300–450	
	Speed limit 55 mph	375-600	
	Speed limit 60–65 mph	500–700	
	Speed limit 70–75 mph	600–800	
Minnesota	Speed limit (mph)	Shadow vehicle weight 9,900–22,000 lb	Shadow vehicle weight >22,000 lb
	0–30	100	100
	35–40	100	100
	45-50	175	150
	55	175	150
	60-65	225	175
	70-75	225	175

ADVANCE WARNING VEHICLES

AWVs are typically located upstream of the mobile work convoy to alert drivers to the maintenance operation. Table 7 contains Steele and Vavrik's (*20*) recommendations for AWV spacing. Their recommended minimum and maximum spacing between the AWV and first shadow vehicle encountered by drivers were 1000 ft and 2500 ft, respectively. Steele and Vavirk (*20*) thought distances in this range provided enough advance warning while still being relevant to the work convoy.

In the Ohio Turnpike standard drawing for single-lane mobile operations (see Figure 5), the distance between the AWV and first shadow vehicle encountered by drivers is 400 ft. A note on the drawing does acknowledge that the AWV should travel at a varying distance to provide adequate sight distance for approaching traffic. According to Steele and Vavrik's (*20*) recommendations, 400 ft may not provide enough advance warning, especially on high-speed roadways.

Table 9 summarizes the findings from the state DOT standards for the spacing between the shadow vehicle and AWV for single-lane closure mobile operations. Focusing on high-speed roadways (i.e., greater than 55 mph), most of the standards showed a spacing of 1000 ft or more between the shadow vehicle and AWV. Overall, the spacing between the shadow vehicle and AWV ranged from 100 to 2000 ft. About half of the standards included a specific value, while the other half provided a range of values.

Table 9. Spacing between Shadow Vehicle and Advance Warning Vehicle for Single-Lane Closure Mobile Operations from State DOT Standards.

<table>
<tr><th>State</th><th colspan="2">Condition</th><th>Spacing between Shadow Vehicle and Advance Warning Vehicle (ft)</th></tr>
<tr><td>Michigan</td><td colspan="2"></td><td>650</td></tr>
<tr><td>New York</td><td colspan="2"></td><td>750</td></tr>
<tr><td>Virginia</td><td colspan="2"></td><td>1,000</td></tr>
<tr><td>Connecticut</td><td colspan="2"></td><td>1,000</td></tr>
<tr><td>Texas</td><td colspan="2"></td><td>1,500</td></tr>
<tr><td>Illinois</td><td colspan="2"></td><td>200-1,500</td></tr>
<tr><td>Indiana</td><td colspan="2"></td><td>1000-2,000</td></tr>
<tr><td rowspan="2">Florida</td><td colspan="2">Rural</td><td>500-1,500</td></tr>
<tr><td colspan="2">Urban</td><td>300-500</td></tr>
<tr><td rowspan="4">Pennsylvania</td><td colspan="2">Urban ≤35 mph highways</td><td>100</td></tr>
<tr><td colspan="2">Urban >35 mph highways</td><td>350</td></tr>
<tr><td colspan="2">Rural highways</td><td>500</td></tr>
<tr><td colspan="2">Freeways and expressways</td><td>1,000</td></tr>
<tr><td rowspan="4">Iowa</td><td colspan="2">Speed limit ≤35 mph</td><td>300</td></tr>
<tr><td colspan="2">Speed limit 40-45 mph</td><td>500</td></tr>
<tr><td colspan="2">Speed limit 50-55 mph</td><td>1,000</td></tr>
<tr><td colspan="2">Speed limit ≥60 mph</td><td>2,000</td></tr>
<tr><td rowspan="6">Minnesota</td><td colspan="2">Speed limit 0-30 mph</td><td>100-550</td></tr>
<tr><td colspan="2">Speed limit 35-40 mph</td><td>325-700</td></tr>
<tr><td colspan="2">Speed limit 45-50 mph</td><td>600-900</td></tr>
<tr><td colspan="2">Speed limit 55 mph</td><td>750-1,200</td></tr>
<tr><td colspan="2">Speed limit 60-65 mph</td><td>1,000-1,400</td></tr>
<tr><td colspan="2">Speed limit 70-75 mph</td><td>1,200-1,600</td></tr>
<tr><td rowspan="6">Colorado</td><td colspan="2">Speed limit 0-30 mph</td><td>250-550</td></tr>
<tr><td colspan="2">Speed limit 35-40 mph</td><td>325-700</td></tr>
<tr><td colspan="2">Speed limit 45-50 mph</td><td>600-900</td></tr>
<tr><td colspan="2">Speed limit 55 mph</td><td>750-1,200</td></tr>
<tr><td colspan="2">Speed limit 60-65 mph</td><td>1000-1,400</td></tr>
<tr><td colspan="2">Speed limit 70-75 mph</td><td>1200-1,600</td></tr>
<tr><td rowspan="6">Tennessee</td><td colspan="2">Speed Limit 0-30 mph</td><td>250-550</td></tr>
<tr><td colspan="2">Speed Limit 35-40 mph</td><td>325-700</td></tr>
<tr><td colspan="2">Speed Limit 45-50 mph</td><td>600-900</td></tr>
<tr><td colspan="2">Speed Limit 55 mph</td><td>750-1,200</td></tr>
<tr><td colspan="2">Speed Limit 60-65 mph</td><td>1000-1,400</td></tr>
<tr><td colspan="2">Speed Limit 70-75 mph</td><td>1200-1,600</td></tr>
<tr><td rowspan="3">South Carolina</td><td colspan="2">Intermittent with pedestrian workers</td><td>2,000</td></tr>
<tr><td rowspan="2">Continuous on primary and secondary routes</td><td>Speed limit ≤45 mph</td><td>250-500</td></tr>
<tr><td>Speed limit ≥50 mph</td><td>500-1,000</td></tr>
</table>

When the AWV is positioned at a significant distance upstream from the first shadow vehicle, a second AWV can be added to fill the gap between the first AWV and the first shadow vehicle. Steele and Vavirk (*20*) recommended that the second AWV be placed 500 to 1000 ft upstream of the first shadow vehicle encountered by drivers. Steele and Vavrik (*19*) found that adding the second AWV increased the number of vehicles vacating the closed lane at a safe distance upstream of the first shadow vehicle from 82 to 96 percent.

When there is a narrow or no left shoulder, workers must drive the AWV on the right shoulder even though the mobile operation is located in the left lane(s). Dependent upon the number of lanes, traffic volume, visibility, and other site conditions, drivers in the left lane may not notice the AWV or be able to adequately read and comprehend the message displayed on the right shoulder. In addition, Ohio's Move Over Law may push traffic away from the AWV on the right shoulder and into the left lane(s).

It is important to provide short, clear, and specific messages to drivers so that they understand a left lane(s) is closed. This is challenging to achieve with arrow boards on the AWV because the board must be in caution mode when on the shoulder. It is also difficult to accomplish with static warning signs on the AWV because the vehicle-mounted arrow board display and high-intensity flashing lights may negatively affect the legibility of the static warning signs.

Full-matrix truck-mounted CMSs allow transportation agencies to provide a variety of information that can heighten drivers' attention and be useful in decision making as they approach the mobile operation. Full-matrix truck-mounted CMSs allow greater flexibility in messages (e.g., traditional arrow board symbols, text, and other symbols) and negate the need for the AWV to tow a trailer-mounted arrow board. However, these devices are limited to the amount of information that can be displayed. Therefore, proper design of messages on these types of signs is critical to ensure correct driver understanding and response. Poor message design can overload drivers and lead to confusion, incorrect decisions, and unsafe driving behaviors. Steele and Vavrik (*20*) also preferred truck-mounted CMSs over static warning signing.

LEAD VEHICLES DOWNSTREAM OF WORK SPACE

Steele and Vavrik (*19*) found that adding a lead vehicle downstream of the work space helped deter drivers from returning to the closed lane too soon. In urban areas, drivers typically returned to the closed lane 50 to 100 ft downstream of the work space. In rural areas, drivers tended to wait longer to return to the closed lane, with the majority returning 150 to 400 ft downstream of the work space. Steele and Vavrik (*20*) recommended a lead vehicle be positioned 50 to 100 ft downstream of the work space as a way to encourage drivers to wait another 50 to 100 ft before returning to the closed lane.

LAW ENFORCEMENT

Steele and Vavrik (*19*) found that police presence in mobile operations drastically decreased speed but also caused congestion and did not seem to affect the distance at which drivers vacated the closed lane. FHWA's *Safe and Effective Use of Law Enforcement Personnel in Work Zones* materials (*21*) remind law enforcement personnel that their job in mobile operations is presence and that they are not impact attenuators. The National Highway Institute developed an interactive web-based training based on the FHWA materials (*22*). The *Guidelines on Use of Law Enforcement in Work Zones* (*23*) recommends that law enforcement should generally be located on the shoulder or protected by a shadow vehicle with an impact attenuator. Figure 9 and Figure 10 provide examples of how law enforcement should be deployed. Law enforcement should not be placed on the right shoulder upstream of a mobile operation in the left lane(s) since the Move Over Law will likely result in traffic shifting into the left lane(s) about the same time they need to exit the left lane to avoid the work convoy.

WARNING LIGHTS

Vehicle- and equipment-mounted flashing warning lights are critical safety devices used to attract driver attention and improve the recognition of those vehicles/equipment as a hazard or unusual roadway condition. A fair amount of research has been devoted to the effectiveness of flashing warning lights through the years. However, the more recent use of LED technology with micro-processing capabilities has made it possible to create a wide range of flashing patterns and sequences, very few of which have received significant research attention to date.

Light Colors and Color Combinations

Most states regulate the colors that can be used for lights on motor vehicles and equipment operated on public roadways (*24*). Historically, amber lights have been used on construction and maintenance vehicles and equipment, and red and blue lights have been authorized for emergency and law enforcement vehicles. One international study (*25*) suggested that adding another color to amber flashing warning lights on vehicles increases the vehicles' conspicuity when viewed in an environment containing other flashing amber warning beacons.

A 2008 National Cooperative Highway Research Program (NCHRP) research study (*26*) ultimately concluded that amber and white lights were best suited for roadway operations vehicles and equipment. This assessment was based on the detectability of those colors and their consistent association with roadway work operations rather than with emergency vehicle response or law enforcement. Survey data collected in Texas suggested that using blue and/or red warning lights in conjunction with amber warning lights increased the perceived degree of hazard by drivers as they approached a roadway operations vehicle (*24*). In addition, observational studies found increased brake light activations by drivers approaching work vehicles with multiple warning light colors displayed compared to those with only amber lights displayed (*24*). In another evaluation of blue and amber warning lights (*27*), researchers found that the blue and amber light combinations reduced speeds passing by a stationary work vehicle the most and yielded the highest percentage of vehicles moving one lane farther away from the work vehicle.

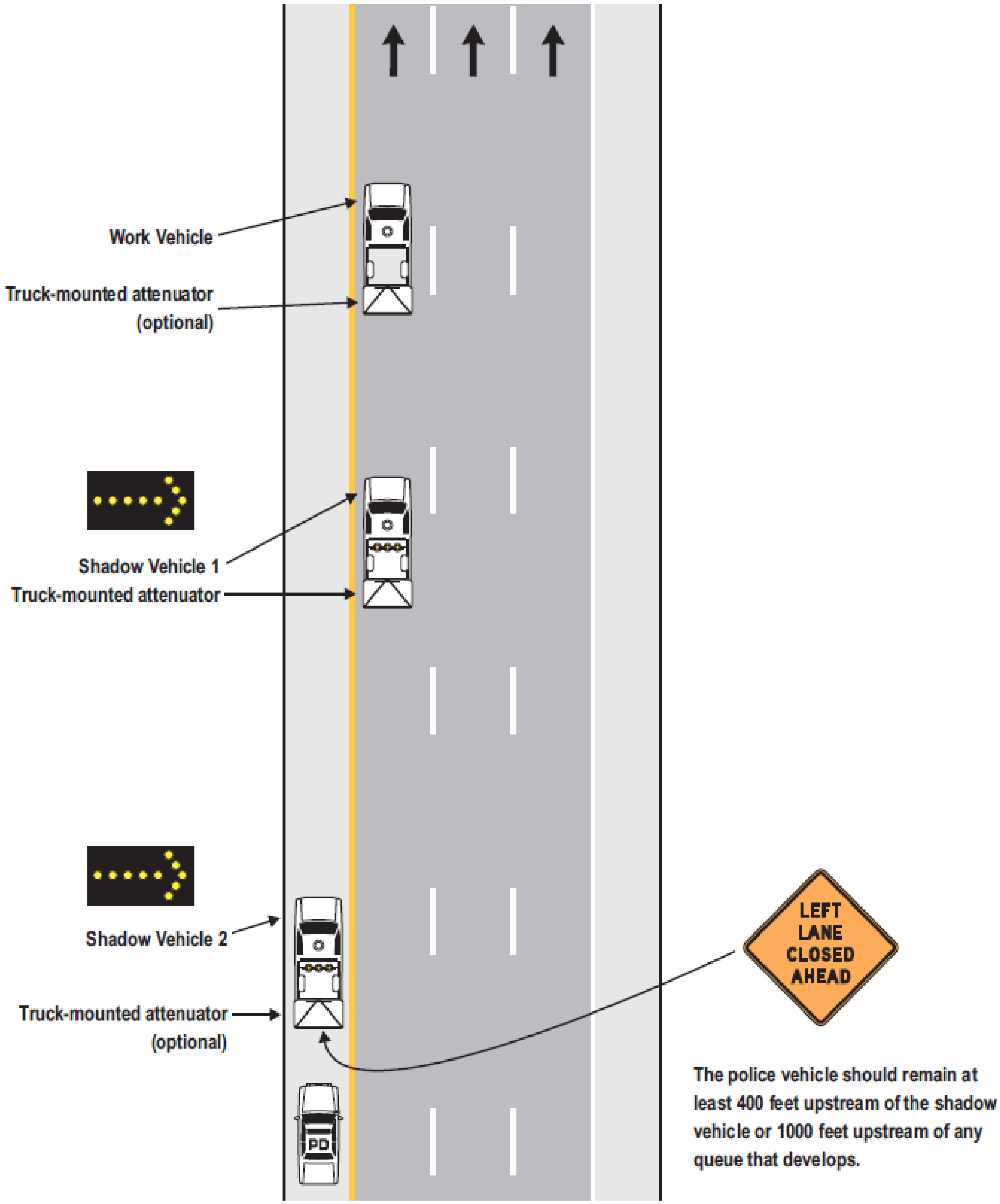


Figure 9. Recommended Enforcement Position for Mobile Operation When Continuous Shoulder Available (*23*).

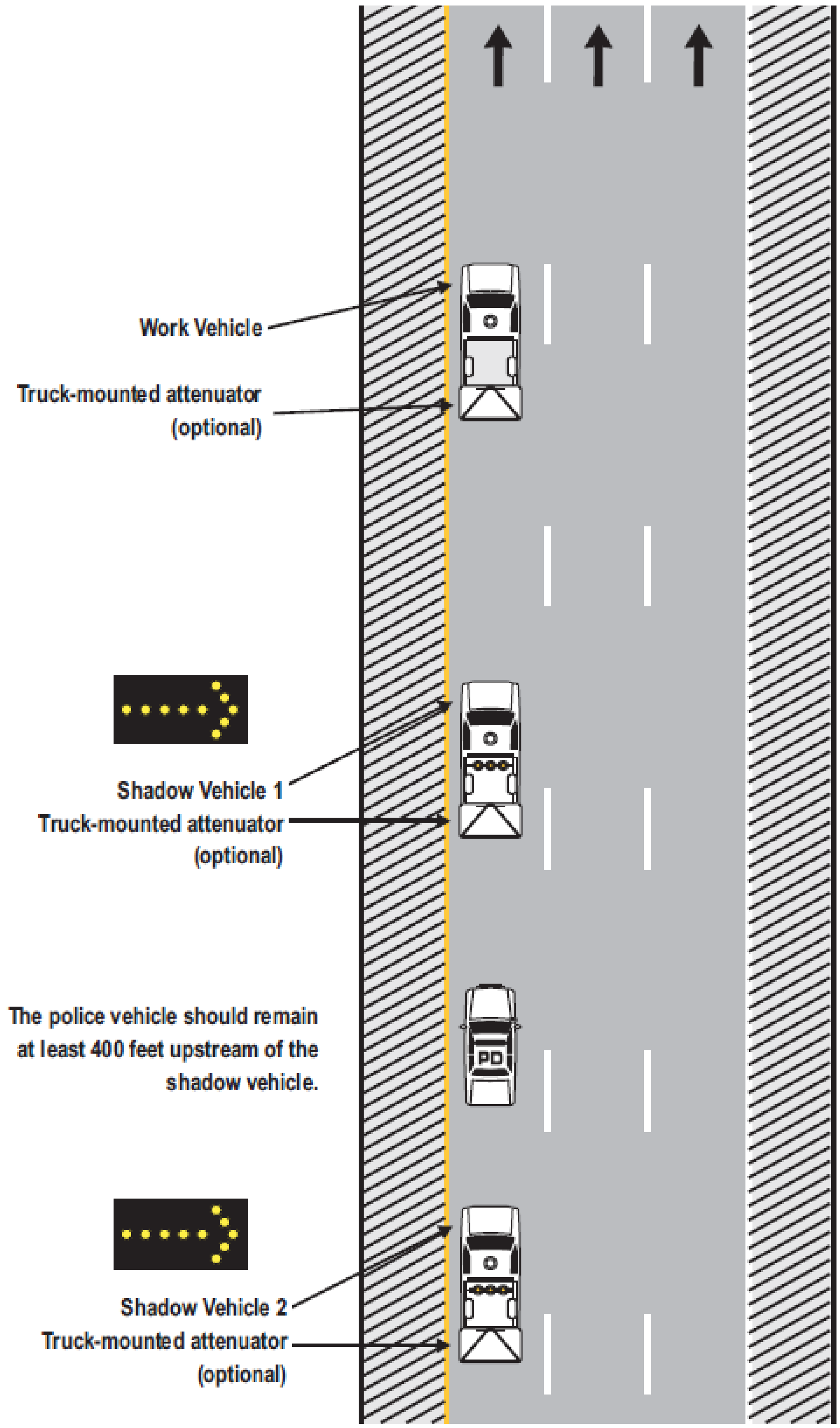


Figure 10. Recommended Enforcement Position for Mobile Operation When No Continuous Shoulder Available (*23*).

Because traffic laws in many states restrict roadway operation vehicles and equipment from displaying blue warning lights, a few agencies have investigated using green flashing lights in conjunction with amber and/or white lights on their snowplowing equipment and other work vehicles (*28,* 29). Simulator and field studies of a work crew with a TTMA found that a green/amber flashing light combination was most preferred by drivers. The green/amber flashing light combination also received fewer "too bright" ratings than amber/white or green/white light combinations, and was just as effective as the brighter amber/white light combination in making drivers aware of the work zone and work vehicles (*29*).

Light Intensity

Multiple studies have concluded that light intensity has a significant effect on attracting attention. The 2008 NCHRP study (*26*) found that higher intensities that create greater levels of contrast with the visual background were associated with greater attention-getting ratings and longer detection distances. However, as the light intensity increases, ratings of discomfort or disabling glare increase, especially at night. Higher-intensity lights have also been shown to adversely affect the ability of drivers to detect pedestrians and low-contrast objects at night (*30*). In the 2015 field observations of ODOT District 6 mobile maintenance operations (*1*), researchers noted that at night the flashing warning lights and arrow board display made it difficult to read the static warning signs that were mounted on the back of the AWV and shadow vehicle. It is important that vehicle-mounted warning lights do not mask or otherwise degrade a driver's ability to effectively process and respond to the information presented by truck-mounted static signing.

Flash Patterns and/or Sequences

It is generally accepted that flashing lights are better at attracting attention than steady-burn lights of the same peak light intensity, while creating less discomfort glare (*26*). However, flashing lights on vehicles have been shown to be less effective than steady-burn lights in assisting drivers in detecting and recognizing movement of vehicles or equipment, as well as accurately estimating the rate of closure to those vehicles (*31*). There are a myriad of ways in which light pulses can be created and combined into a particular flash pattern. In addition, the luminance intensity of LED lights can be dynamically adjusted throughout the duration of a flash cycle, making it possible to keep a light on continuously at a lower-level luminance, and add increased luminous intensities on top of that baseline luminance level. However, it is unclear whether the multitude of possible flash patterns and sequences has any real benefit to vehicle and equipment detection, recognition, or scene interpretation by drivers.

Number of Lights

The effect of the number of warning lights used on a roadway operation vehicle or piece of equipment also appears to be dependent upon individual study designs and the measures of effectiveness used. One study did find that too many lights on a vehicle flashing in a random, asynchronous manner were more confusing to drivers than warning lights that operated in a sequential and synchronized manner (*32*).

Types of Lights

A variety of light sources are used to create vehicle and equipment warning lights, including incandescent bulbs, strobes, halogen bulbs, and, most recently, LEDs. The 2008 NCHRP study (*26*) concluded that all four light types were acceptable for use on roadway operation vehicles and equipment if they met intensity and flash frequency requirements. However, many agencies are transitioning their fleets to LED technology, citing the advantages the technology provides in lower power consumption and the availability of many flash patterns.

ARROW BOARDS

ODOT and the Ohio Turnpike use multiple arrow boards mounted on vehicles to alert drivers to shoulder and/or lane closures during mobile operations. While this is consistent with the OMUTCD, previous research questioned whether drivers understood that in some mobile operations only a single lane is closed even though more than one arrow board display is used. Schrock et al. (*33*) assessed the effectiveness of different arrow board displays in short-term and mobile lane closures through focus groups. Participants' opinions and understanding of the following three scenarios were obtained:

- Individual arrow display mounted on a single vehicle.
- Multiple arrow displays mounted on several work vehicles.
- Individual caution displays mounted on a single vehicle.

The arrow board displays included a flashing arrow, sequential arrow, flashing chevron (not in the OMUTCD), sequential chevron, flashing four-corner caution, and flashing horizontal line caution.

Seventy-eight percent of participants thought the sequential displays were more effective in conveying information about a lane closure than the flashing displays. Almost none of the participants thought the flashing chevron was the most effective arrow display. Participants ultimately understood the caution displays, but there was less confidence in their responses.

When multiple arrow displays were used in the work convoy, 88 percent of participants understood that only one lane was closed. Participants agreed that the presence of more than one work vehicle was effective in communicating that they were approaching a more extensive work operation. In addition, participants generally preferred the staggering of work vehicles into the closed lane. However, participants were not in favor of mixing arrow displays within the same work convoy. Participants did like having additional information in the form of static signing on the back of the shadow vehicles although there was no agreement on the nature of that information.

TRUCK-MOUNTED STATIC SIGNS

ODOT and the Ohio Turnpike use truck-mounted static signs on the back of AWVs and shadow vehicles. In addition, previous research (*33*) has found that drivers like having the additional information provided by truck-mounted static signs. However, as discussed previously, other vehicle-mounted traffic control devices (i.e., warning lights and arrow boards) can mask or otherwise degrade a driver's ability to effectively process and respond to the information presented by truck-mounted static signing. In addition, the research team believes that full-matrix truck-mounted CMSs allow greater flexibility in messages, especially for the AWV.

Even so, the research team wanted to briefly discuss two methods for increasing the conspicuity of static signing. Fluorescent orange sign sheeting is in common use nationally and may increase driver detection of signs (*34*, *35*). Fluorescent sign sheeting reflects incoming visible wavelengths of light and transforms invisible ultraviolet rays into reflected visible light. During the day, fluorescent signs appear brighter, especially at dawn, at dusk, or in overcast conditions.

Some manufacturers also offer warning signs with flashing LEDs around the border of the sign. While these may be effective at drawing attention to ground-mounted signs (which have limited application in mobile operations), the additional lights on vehicles in the mobile work convoy may further degrade a driver's ability to read and respond to the information presented.

TRUCK-MOUNTED CHANGEABLE MESSAGE SIGNS

As discussed previously, full-matrix truck-mounted CMSs allow transportation agencies to provide a variety of information that can heighten drivers' attention and be useful in decision making as they approach the work zone. However, these devices are limited in the amount of information that can be displayed. Thus, proper design of messages on these types of signs is critical to ensure correct driver understanding and response. Poor message design can overload drivers and lead to confusion, incorrect decisions, and unsafe driving behaviors. Some guidelines on how to properly design messages for truck-mounted CMSs are available for striping operations (*36*); however, similar guidelines for other mobile operations are not readily available. If they are used, ODOT should develop a list of pre-approved truck-mounted CMS messages for various maintenance activities for field personnel to use. Any non-standard messages (or possible graphics indications) should be properly evaluated for correct driver comprehension and driving response prior to formal adoption by the agency. Use of non-standard graphics in actual field operations would also require permission to experiment from FHWA. Since field personnel are most often the ones responsible for programming the signs, these personnel should be trained on the design, selection, and application of truck-mounted CMS messages in order to minimize the misuse of these devices.

TRUCK-MOUNTED SPEED FEEDBACK SIGNS

In 2004, the Texas A&M Transportation Institute (TTI) completed a study for TxDOT in which researchers evaluated truck-mounted speed feedback signs to increase driver awareness of speeding and the speed differential between the work convoy and approaching vehicles (*37*). Motorist surveys found that truck-mounted speed feedback signs displaying the speed of approaching vehicles were well understood. However, truck-mounted speed feedback signs displaying only the speed of the shadow vehicle or both the speed of the shadow vehicle and the speed of approaching vehicles were not well understood.

Several other agencies have investigated the influence of truck-mounted speed feedback signs. In Oregon (*38, 39*), researchers found that vehicle speeds were typically lower and there was less variation among vehicle speeds when a truck-mounted speed feedback sign displaying the speed of approaching vehicles was activated. The types of maintenance work for which the Oregon Department of Transportation anticipated using the truck-mounted speed feedback signs primarily included sweeping and drainage-cleaning operations. Similar results were found in a Connecticut study (*40*).

INTRUSION ALARMS

Devices that detect and then notify workers of an errant vehicle that has entered or is about to enter the work space have been of significant interest to agencies and contractors. Several potential system designs have been developed through the years (*41*, *42*, *43*), but most have not been successful due to challenges in keeping the systems properly aligned and tuned, which in turn has resulted in high numbers of false alarms.

More recently, alarm systems are being designed to detect and track vehicles without the need for the vehicle to cross a line or strike a detection device in order to trigger an alarm. A new directional audible system (DAS) technology has been developed and tested in a mobile work zone field deployment (*44*). One study evaluated the accuracy of an alarm with DAS technology and found that the system performed poorly in horizontal curve situations (*45*).

In addition to these studies, a private-sector company has been working to develop an intelligent work zone intrusion alarm system, the Advance Warning and Risk Evasion (AWARE) system. Unlike previous intrusion alarm systems that rely on the detection of vehicles crossing a predetermined perimeter (typically identified with pneumatic tubes or infrared beams), this new system uses a target threat detection and tracking methodology to logically assess approaching vehicle speed, location, and possible trajectory. If the trajectory of the approaching vehicle is computed to intrude into the work space (or to be exceeding a reasonable speed approaching the work zone), the AWARE system is activated to alert the driver (flashing lights and audible alarm) and notify workers of the intrusion threat. Although the system is not currently commercially available, beta testing of the product is occurring across the country. In addition, the system has been successfully tested in a controlled environment (*46*, *47*). However, no field tests of its effectiveness in real work zones have yet occurred.

REAL-TIME WORK ZONE LOCATION TECHNOLOGY

Another method for alerting drivers to the presence of mobile maintenance operations includes using technology to identify the real-time location of a work convoy and then notifying road users through third-party traveler information providers (e.g., Waze, HERE, and Google). Several products that can be retrofitted to arrow boards, vehicle hazard lights, and/or vehicle warning lights are currently available (*48*, *49*, *50*).

MATRIX OF POTENTIAL SAFETY IMPROVEMENTS

Based on the review of previous literature, the research team developed a matrix of the previously discussed potential safety improvements (methods and devices) for mobile maintenance operations on multi-lane highways (see Table 10 and Table 11). The research team investigated each safety improvement to determine which, if any, would be suitable for further study in Phase 2 of the research. For each safety improvement, the research team determined the potential benefits and disadvantages. For the equipment-related safety improvements that are commercially available, the research team also estimated the following costs:

- AIPV and leader technology (vehicle and one-time programming costs not included) = $335,000.
- Full-matrix, truck-mounted CMS = $12,000 to $14,000.
- Truck-mounted speed feedback sign (second generation) and DVR/camera system = $26,500.
- Real-time mobile operation location technology = $1000.

Table 10. Matrix of Potential Procedural Safety Improvements.

Candidate Safety Improvement	Potential Benefit(s)	Potential Disadvantage(s)
Provide adequate space between shadow vehicle and work space for post-collision roll ahead of shadow vehicle	Reduces the potential for worker injuries and equipment damage due to roll/skid ahead when errant vehicle strikes shadow vehicle	Larger spacing may encourage vehicles to cut into convoy
Use buffer vehicle between shadow vehicle and work space when post-collision roll ahead requires a spacing greater than 150 ft	Reduces likelihood of vehicles cutting back into convoy	Requires additional worker and equipment; Could be hit by shadow vehicle
Space shadow vehicles 200 to 500 ft apart	Provides adequate sight and reaction distance; Provides continuous transition for drivers	May require additional workers and equipment
Position AWV 1000 to 2500 ft upstream of the work convoy	Provides advance warning to drivers	Locating on the right shoulder when left lane(s) closed
Use a second AWV if first AWV located a significant distance upstream of work convoy	Provides additional warning to drivers; Increases number of vehicles exiting closed lane(s)	Requires additional worker and equipment; Locating on the right shoulder when left lane(s) closed
Use lead vehicle 50 to 100 ft downstream of work space	Reduces likelihood of vehicles cutting back into work space	Requires additional worker and equipment
Use law enforcement	Alerts drivers; Decreases vehicle speeds	May cause congestion; Limited impact on distance at which drivers exit the closed lane; Locating on the right shoulder when left lane(s) closed

AWV = advance warning vehicle

Table 11. Matrix of Potential Equipment Safety Improvements.

Candidate Safety Improvement	Potential Benefit(s)	Potential Disadvantage(s)
Use AIPV	Reduces injuries and fatalities to workers; Increases productivity; Smaller maintenance crews; Distance between shadow vehicle and work space more consistent	Limited to striping operations less than 10 mph; Limited to generally linear operations; Limited to locations with few to no overhead or anticipated GPS obstructions or interferences from structures
Use full-matrix, truck-mounted CMSs	Heightens drivers' attention; Provides more specific information; Greater flexibility in messages	Requires the development of standard messages; Might limit use of vehicle
Use truck-mounted speed feedback signs	Decreases vehicle speeds; Reduces variation among speeds; Records data for later use	More information for drivers to process; More lighting on vehicles
Use truck-mounted intrusion alarms	Alerts workers to errant vehicles; Alerts approaching drivers	In development; Not commercially available
Use real-time work zone location technology	Alerts drivers to presence of work; Provides device status information	Latency; Has not been used with mobile operations

AIPV = autonomous impact protection vehicle; CMS = changeable message sign

APPENDIX D: FIELD EVALUATION OF SELECT SAFETY IMPROVEMENTS

Based on the information collected in Phase 1 (see Appendices A–C), ODOT, the Ohio Turnpike, and the research team decided to evaluate the following equipment-related safety improvements in the field in Phase 2 of the research:

- Portable, ground-mounted, static warning sign with flashing LED lights around the border of the sign (referred to as an LED sign).
- Full-matrix, truck-mounted CMS on the AWV.
- Real-time work zone location technology.

In addition, ODOT asked the research team to evaluate the impact of the presence of the AWV on the right shoulder and the mounting location (i.e., right or left shoulder) of the portable, ground-mounted, static warning signs. This appendix documents the treatments, experimental design, sites, data reduction and analysis, and results of the field studies.

TREATMENTS

The research team collected data for the following treatments with mobile sweeping operations in the left lane/shoulder:

- Typical ODOT setup (ODOTTypical).
- Typical Ohio Turnpike setup (OTTypical).
- Addition of the LED sign on the right shoulder (RLEDSign).
- Addition of the LED sign on the right shoulder but no AWV (RLEDSignNoAWV).
- Addition of the LED sign on the left shoulder (LLEDSign).
- Use of a full-matrix, truck-mounted CMS on the AWV (FMTMCMS).
- Use of real-time work zone location technology on the shadow vehicle (Beacon 1 and Beacon 2).

Typical ODOT and Ohio Turnpike Operations

Figure 11 shows the typical ODOT setup for mobile sweeping operations. A ROAD SWEEPING NEXT 5 MI static warning sign (6-inch letters) was placed on the right shoulder at the beginning of the work area. The AWV was located downstream of the static sign on the right shoulder. The AWV was equipped with high-intensity amber warning lights and a truck-mounted CMS that displayed WORKERS IN ROAD / LEFT LN CLOSED (message #57) (see Figure 12). The CMS automatically used a single-stroke font for WORKERS IN ROAD and a double-stroke font for LEFT LN CLOSED. The truck-mounted CMS was 58 inches by 28 inches with 11-inch letters and two lines of text. Thus, “lane” was abbreviated LN although researchers noted that with the double-stroke font drivers may have interpreted LN as LH. A shadow vehicle with high-intensity flashing green, white, and amber warning lights and a TTMA was located downstream of the AWV. The shadow vehicle blocked the left lane since the left shoulder was less than 10 ft wide. The TTMA had an arrow board that displayed a right arrow (see Figure 13). The sweeper was located downstream of the shadow vehicle. The sweeper had high-intensity amber warning lights.

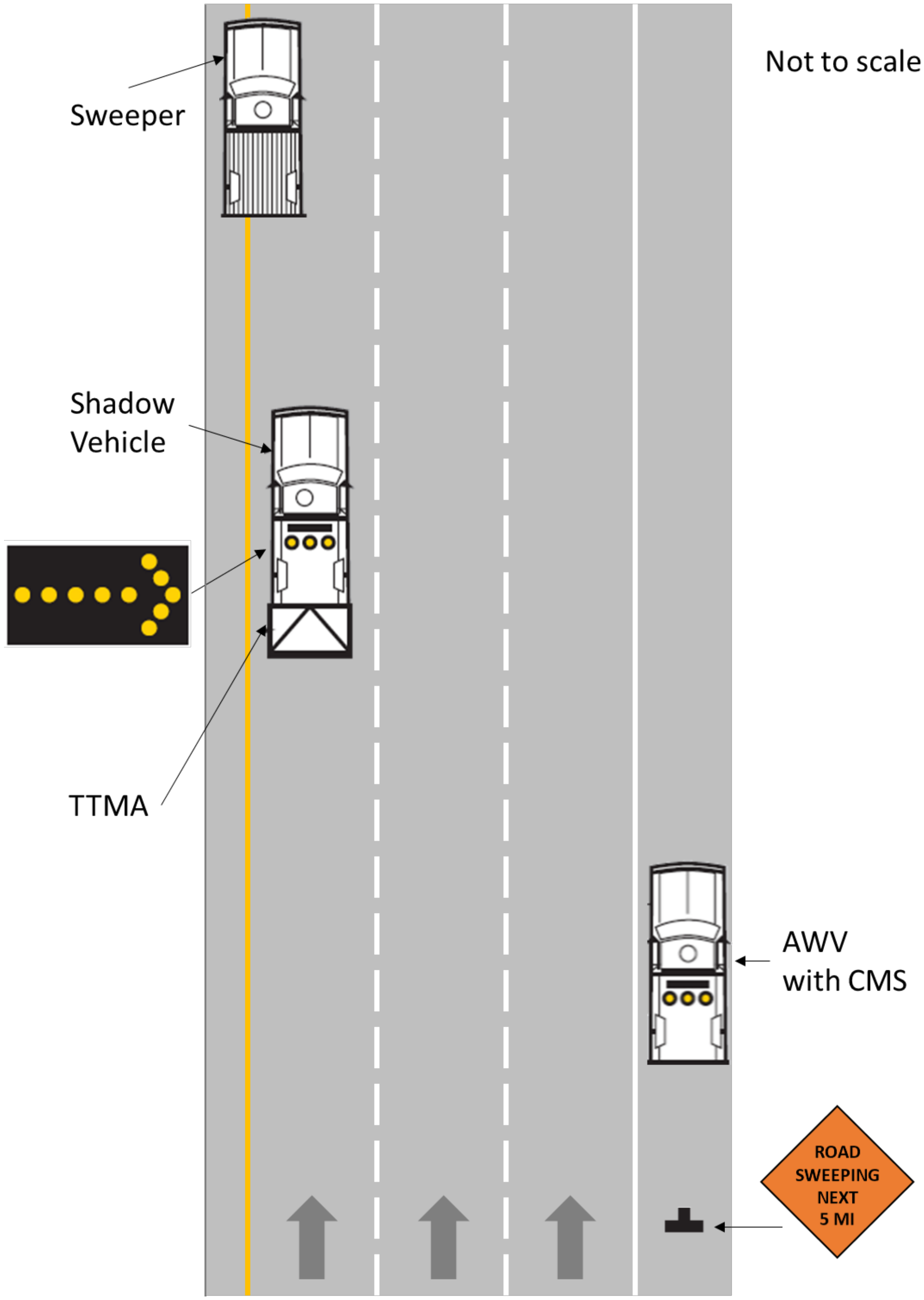


Figure 11. Typical ODOT Setup.

Figure 12. AWV with Truck-Mounted CMS.

Figure 13. Shadow Vehicle with TTMA.

The Ohio Turnpike typical setup for mobile sweeping operations only consisted of a shadow vehicle and a sweeper. The shadow vehicle had high-intensity amber warning lights, an arrow board displaying the caution bar, and a TMA (see Figure 14). The sweeper had high-intensity amber warning lights. Both vehicles traveled on the 14-ft-wide left shoulder and did not encroach into the left travel lane.

Figure 14. Ohio Turnpike Shadow Vehicle.

Alternative Treatments

LEDs around the border of signs are used to draw drivers' attention to the sign and its message. The LED static warning sign was only added to the typical ODOT setup. The LED sign legend was LEFT LANE CLOSED NEXT 5 MI (see Figure 15). The LED sign provided drivers information about which lane was closed ahead. Workers placed the LED sign upstream of the ROAD SWEEPING NEXT 5 MI sign; the LED sign was the first sign seen by drivers when used. Every night of the field study except one, the static signs used were located on the right shoulder. Most roadways do not have adequate shoulder width to place the static signs on the left shoulder. Thus, the signs are located on the right shoulder even though the work operation is in the left lane. However, one night both static signs were located on the left shoulder. One night when both static signs were located on the right shoulder, the AWV was not used.

On two nights, the work crew used a different AWV with the ODOT mobile sweeping operations. It had a full-matrix, truck-mounted CMS that was 98 inches by 48 inches with 12-inch letters and three lines of text. The WORKERS IN ROAD / LEFT LANE CLOSED message was displayed, but a single-stroke font was used for all text (see Figure 16). In addition, due to the larger size, "lane" was not abbreviated, resulting in a three-line message. The amber warning lights were also in a different location (under the CMS instead of to the side). The intention of this treatment was to provide a larger and clearer message (i.e., bigger font and no abbreviations that have to be interpreted by drivers) that could be more easily read at high speeds.

Figure 15. LED Sign.

Figure 16. Full-Matrix, Truck-Mounted CMS.

The research team also tested two technologies that identify the real-time location of a work vehicle and share the location with road users through third-party traveler information providers (e.g., Waze, HERE, and Google). It was hoped this technology would notify drivers of the work operation and encourage them to exit the closed lane. Beacon 1 was purchased from iCone® and retrofitted to an arrow board on an ODOT TTMA (*48*). In addition to transmitting the vehicle's location, Beacon 1 transmits the on/off status of the arrow board and the arrow board display. Beacon 2 was purchased from HAAS and retrofitted to the flashing warning lights on an Ohio Turnpike shadow vehicle (*50*). Beacon 2 transmits the vehicle's location and status (i.e., active responding, active on-scene, online, offline pending, and offline). When the flashing warning lights are activated (i.e., active responding and active on-scene), digital alerts are transmitted. Both systems have associated software that can be used to identify a vehicle's location and status in real time and provide statistics on the vehicle's operation. According to the manufacturers, both technologies had been primarily used with stationary work zone operations, safety service patrol vehicles, and emergency responders (i.e., fire, police, and ambulance).

EXPERIMENTAL DESIGN

For the treatment evaluations, the research team observed driver behavior around sweeping operations in the left lane/shoulder of high-speed, multi-lane, divided highways. The research team mounted video cameras with internal GPS to the back of the advance warning vehicle and shadow vehicle. The cameras were mounted such that they did not block any other devices or functions. The cameras faced backward to capture approaching traffic. The research team's vehicle had a video camera mounted inside the vehicle (facing forward), a GPS unit, a laptop, cell phones, and software needed to monitor equipment remotely. The types of data collected and used in the analyses include the following.

- Traffic volume by lane approaching the AWV and shadow vehicle (video cameras).
- Number of vehicles in each lane 100 ft upstream of the AWV and shadow vehicle (video cameras).
- Location of the AWV (GPS on the video camera), LED sign (GPS equipment in the research team's vehicle), and shadow vehicle (GPS on the video camera, Beacon 1, and Beacon 2, and Waze).
- Events in iCone® and HAAS Alert software systems.
- Events in Waze (XML data feed and cell phone app).
- Other data from iCone® and HAAS Alert software systems.

Researchers also documented the mobile work zone characteristics on a written standardized data collection form, with GPS equipment and associated software, in photographs, and with drive-through videos.

SITES

The research team conducted the field studies in cooperation with ODOT and Ohio Turnpike maintenance personnel over a five-week period. Table 12 contains an overview of the field study sites. The research team collected field data at all sites except Sites 11 through 14. Due to the pandemic, the research team could not travel to Ohio in April 2020. Therefore, the research team only collected event and other pertinent data from Ohio Turnpike staff in the field, the HAAS Alert software system, and Waze.

Table 12. Overview of Field Study Sites.

Site	Date	Time of Day	Agency	Roadway	Direction	Number of Lanes	Speed Limit (mph)	Treatment
1	8/25/19	Night	ODOT	I-71	SB	2, 3, 4	60	ODOTTypical
2	8/27/19	Night	ODOT	I-77	SB	2, 3	50, 60	RLEDSignNoAWV
3	8/28/19	Night	ODOT	I-90	EB, WB	4, 5	50, 60	RLEDSign
4	8/29/19	Night	ODOT	I-480	EB, WB	2	60	LLEDSign
5	9/9/19	Day	Ohio Turnpike	I-80	EB	3	70	OTTypical
6	9/10/19	Day	Ohio Turnpike	I-80	EB, WB	3	70	Beacon 2
7	9/11/19	Day	Ohio Turnpike	I-80	WB	3	70	Beacon 2
8	9/12/19	Day	Ohio Turnpike	I-80	WB, EB	3	70	OTTypical
9a	11/17/19	Night	ODOT	I-71	SB	3, 4	60	FMTMCMS
9b	11/17/19	Night	ODOT	I-71	SB	3	60	FMTMCMS with Beacon 1
10	11/18/19	Night	ODOT	I-71	NB	3	60	FMTMCMS
11[a]	4/6/20	Day	Ohio Turnpike	I-80	WB	3	70	Beacon 2
12[a]	4/7/20	Day	Ohio Turnpike	I-80	WB	3	70	Beacon 2
13[a]	4/8/20	Day	Ohio Turnpike	I-80	WB	3	70	Beacon 2
14[a]	4/9/20	Day	Ohio Turnpike	I-80	WB	3	70	Beacon 2
15	9/13/20	Night	ODOT	I-71	SB	3, 4	60	RLEDSign
16	9/14/20	Night	ODOT	I-71	NB	3	60	Beacon 1
17	9/15/20	Night	ODOT	I-77	SB	3	60	Beacon 1
18	9/16/20	Night	ODOT	I-77	NB	3	60	RLEDSign

[a] No on-site data were collected due to the pandemic. Event and other data were collected from Ohio Turnpike staff, the HAAS Alert software system, and Waze.

DATA REDUCTION AND ANALYSIS

The research team reduced the video data in five-minute intervals and computed the following (when applicable):

- Number of vehicles in each lane 100 ft upstream of the AWV.
- Number of vehicles in each lane 100 ft upstream of the shadow vehicle.
- Hourly flow rate (vehicles per hour).
- Average distance from the AWV to the first warning sign.
- Average distance from the shadow vehicle to the first warning sign.

The research team also reduced the event data provided by the iCone® software, the HAAS Alert software, and Waze.

Table 13 contains an overview of the raw vehicle count data by comparison type 100 ft upstream of the AWV. Similarly, Table 14 contains an overview of the raw vehicle count data by comparison type 100 ft upstream of the shadow vehicle. The research team only used field data from three-lane sections in the analyses. The four-lane and five-lane data shown in these tables were not included in the analyses due to insufficient data for comparison. Two-lane data are shown for completeness but were not included in the analyses because drivers are more limited in their response than in three-lane sections.

Table 13. Overview of Field Data by Comparison Type 100 ft Upstream of AWV.

Comparison	Site	Treatment	Number of Lanes	Sum of Total Lane Count
Impact of LED sign on right shoulder	Site 1	ODOTTypical	2	107
			3	596
			4	135
	Site 15	RLEDSign	3	12
	Site 18		3	21
Impact of FMTMCMS	Site 1	ODOTTypical	2	107
			3	596
			4	135
	Site 9a	FMTMCMS	3	36
			4	19
	Site 10		3	355

Unfortunately, the impact of placing the two static signs on the left shoulder (instead of the right shoulder) could not be evaluated since Site 4 (treatment) was a two-lane road and Site 3 (control) consisted of four- and five-lane sections. The research team had planned to collect additional data in April 2020, but the pandemic canceled that trip. While the research team was able to travel to Ohio in September 2020, the team focused on obtaining data for treatments listed in the Phase 2 work plan.

Table 14. Overview of Field Data by Comparison Type 100 ft Upstream of Shadow Vehicle.

Comparison	Site	Treatment	Number of Lanes	Sum of Total Lane Count
Impact of LED sign on right shoulder	Site 1	ODOTTypical	2	29
			3	726
			4	35
	Site 3	RLEDSign	4	1,165
			5	152
	Site 15		3	626
			4	289
	Site 18		3	1,578
Impact of AWV	Site 2	RLEDSignNoAWV	2	401
			3	643
	Site 3	RLEDSign	4	1,165
			5	152
	Site 15		3	626
			4	289
	Site 18		3	1,578
Impact of signs on left shoulder	Site 3	RLEDSign	4	1,165
			5	152
	Site 4	LLEDSign	2	1,264
Impact of FMTMCMS	Site 1	ODOTTypical	2	29
			3	726
			4	35
	Site 9a	FMTMCMS	3	72
			4	82
	Site 10		3	358
Impact of Beacon 2	Site 5	OTTypical	3	3,710
	Site 8			3,698
	Site 6	Beacon 2		3,382
	Site 7			1,556
Impact of Beacon 1	Site 1	ODOTTypical	2	29
			3	726
			4	35
	Site 16	Beacon 1	3	1,803
	Site 17			1,671

RESULTS

The following sections contain the analysis results for the treatments evaluated. A significance level of 0.05 was used in all analyses.

Impact of Adding LED Sign on Right Shoulder

The research team used data from three-lane sections of Sites 1, 15, and 18 to evaluate the impact of adding the LED sign (LEFT LANE CLOSED NEXT 5 MI) on the right shoulder upstream of the typical static sign (ROAD SWEEPING NEXT 5 MI). Site 15 (on I-71) and Site 18 (on I-77) had the LED sign on the right side of road as the treatment, and Site 1 (on I-71) was used as a control group without treatment.

First, the research team investigated the impact of the sign on the lane distribution 100 ft upstream of the AWV. Table 15 summarizes the basic statistics of the extracted data. As shown in the table, more vehicles were driving in Lane 2 than in Lanes 1 and 3 at all three sites.

Table 15. Basic Statistics 100 ft Upstream of AWV for LED Sign Treatment.

Statistic		Lane 1 (Inside/Closed)	Lane 2 (Adjacent)	Lane 3 (Outer)
Total lane count	Site 1 (no LED sign)	109	348	139
	Sites 15 and 18 (LED sign)	344	1,046	401
Hourly flow rate (vph)	Average	683.2	683.3	711.1
	Std. dev.	280.7	294.2	284.0

Since vehicles were in all three lanes, each vehicle had three lane options (i.e., Lane 1, 2, or 3). Therefore, a multinomial logit regression model was used for lane distribution. In the procedure of estimating the multinomial logit regression model, lane option (using Lane 1 as the reference) was set as the dependent variable, with treatment (i.e., LED sign), hourly flow rate, and average distance from the first warning sign tested for inclusion as independent variables. Table 16 shows the final model estimation result for using Lane 2 or 3 over Lane 1.

The treatment was statistically significant to the probability of using Lane 3 but insignificant to Lane 2 and relative to Lane 1. The negative value of estimated treatment parameter for Lane 3 implies that drivers are less likely to use Lane 3 100 ft upstream of the AWV with the LED sign. However, the limited sample from only one control and two treatment sites could be introducing other contributing factors that were not accounted for in the model. In addition, baseline lane distributions most likely varied between the control site (collected pre-pandemic) and the treatment sites (collected post-pandemic). Mover Over Law education efforts may have also impacted the number of vehicles in Lane 3 when LED sign treatment was evaluated.

The average sign distance from the first warning sign was also a significant contributing factor to lane distribution. The positive values of the estimated sign distance parameter for Lanes 2 and 3 indicate that an increase in distance between the mobile operation and the sign results in a higher probability of using Lane 2 or 3 over Lane 1. The significant relationships are further supported by plots of predicted probabilities of lane distribution by average sign distance and treatment (see Figure 17). Regardless of the variation of lane usage probabilities caused by changes in average sign distance and/or treatment, drivers were more likely to use Lane 2 (probability higher than 0.5) compared to Lane 1 or 3. Even though the probability of using Lane 3 decreases slightly and the probability of using Lane 1 increases slightly, practically speaking, the lane distribution impacts appear to be minimal.

Table 16. Model Estimation Result for AWV and LED Sign Treatment.

Parameter	Lane	DF	Estimate	Standard Error	Wald Chi-Square	Pr > ChiSq
Intercept	2	1	0.8802	0.1001	77.2894	<0.0001
Intercept	3	1	−0.3710	0.1259	8.6849	0.0032
sign_distance	2	1	0.000022	6.752E-6	10.3120	0.0013
sign_distance	3	1	0.000045	8.154E-6	31.1272	<0.0001
treatment	2	1	−0.0869	0.0660	1.7324	0.1881[a]
treatment	3	1	−0.1806	0.0781	5.3428	0.0208

[a] Treatment is not significant to Lane 2 usage at a significance level of 0.05 (p-value larger than 0.05).

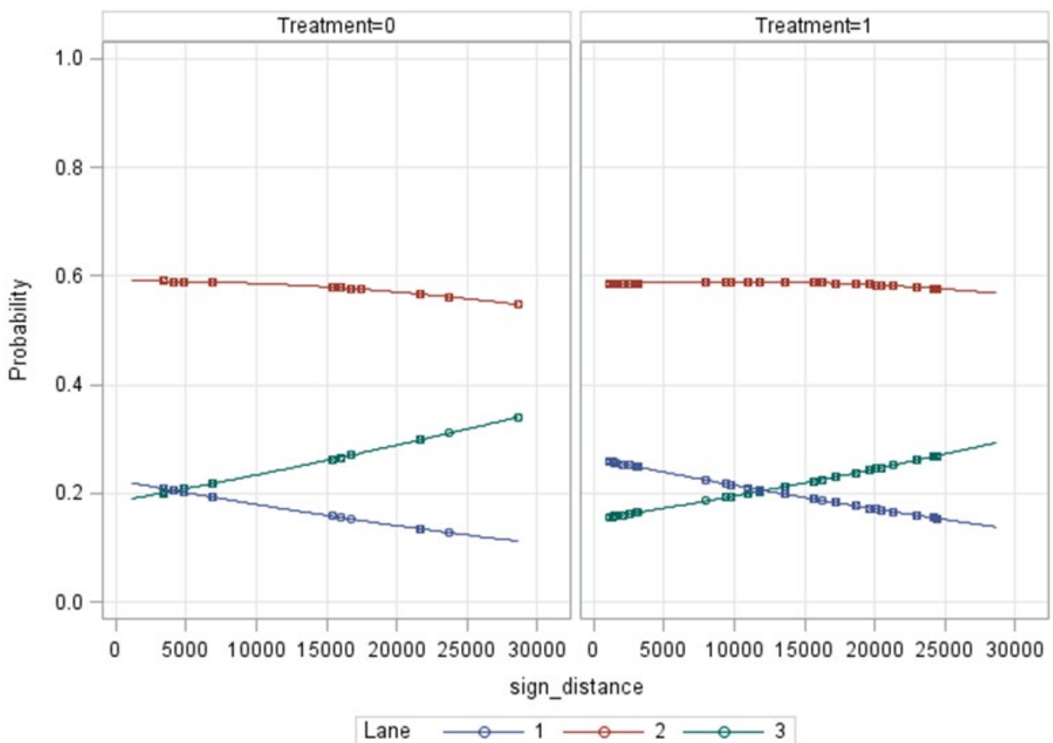


Figure 17. Predicted Probabilities of Lane Usage 100 ft Upstream of the AWV versus Average Sign Distance for the LED Sign Treatment.

Second, the research team investigated the impact of the LED sign on the lane distribution 100 ft upstream of the shadow vehicle. Table 17 summarizes the basic statistics of the extracted data. As shown in the table, no vehicles were observed driving in the inside closed lane (Lane 1) at Site 1, but a few vehicles were found driving in Lane 1 at Sites 15 and 18. Meanwhile, more vehicles were driving in the outer lane (Lane 3) than in the lane adjacent to the mobile operation (Lane 2) at all three sites.

Table 17. Basic Statistics 100 ft Upstream of Shadow Vehicle for LED Sign Treatment.

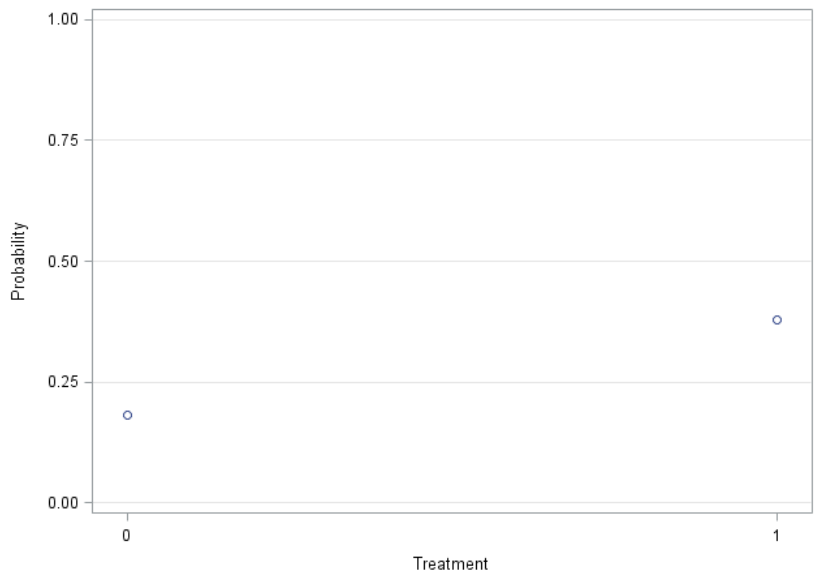
Statistic		Lane 1 (Inside/Closed)	Lane 2 (Adjacent)	Lane 3 (Outer)
Total lane count	Site 1 (no LED sign)	0	131	595
	Sites 15 and 18 (LED sign)	4	834	1,366
Hourly flow rate (vph)	Average	825.0	777.9	726.3
	Std. dev.	150.0	171.0	182.5

Because no vehicles were observed in Lane 1 at Site 1, there is no baseline for comparison for lane distribution related to Lane 1. Therefore, a binomial logit regression model was used for lane distribution between Lanes 2 and 3. In the procedure of estimating the binomial logit regression model, lane option (using Lane 2 as the reference) was set as the dependent variable, with treatment (i.e., LED sign), hourly flow rate, and average distance from the first warning sign tested for inclusion as independent variables. Table 18 shows the final model estimation result for using Lane 2.

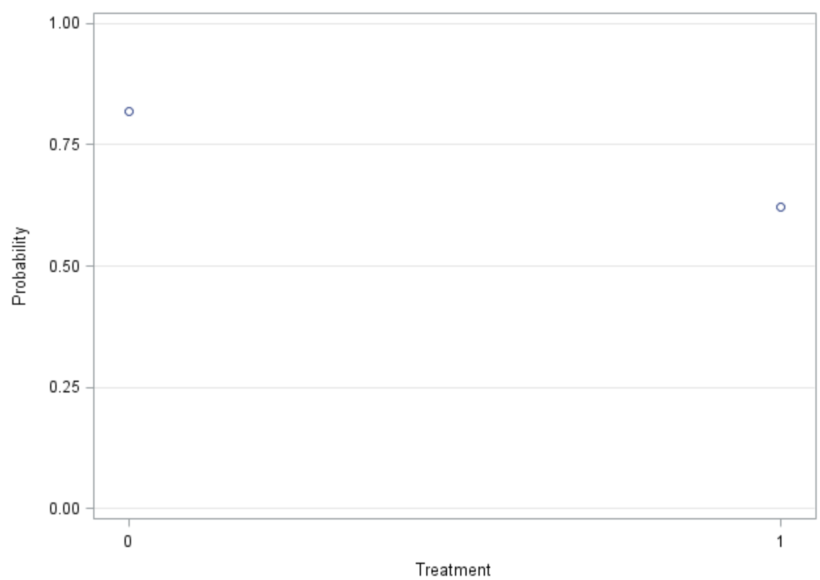
Table 18. Model Estimation Result for Shadow Vehicle and LED Sign Treatment.

Parameter	DF	Estimate	Standard Error	Wald Chi-Square	Pr > ChiSq
Intercept	1	−1.0034	0.0530	358.1139	<0.0001
treatment	1	0.5100	0.0530	92.5090	<0.0001

Treatment was the only contributing factor statistically significant to lane distribution between Lanes 2 and 3. The positive value of the estimated parameter implies that drivers are more likely to use Lane 2 with the LED sign. Figure 18 further supports the positive relationship between the probability of using Lane 2 and the treatment. Even though the probability of using Lane 2 increases from 0.2 to near 0.4 with the presence of the LED sign, it is still much smaller than the probability of using Lane 3 (about 0.8 without the LED sign and 0.6 with the LED sign). Thus, practically speaking, the lane distribution impacts again appear to be minimal (especially considering the limited sample and potential changes in the baseline lane distributions before and after the pandemic).



a) **Lane** 2.



b) Lane 3.

Figure 18. Predicted Probabilities of Lane Usage 100 ft Upstream of the Shadow Vehicle for Control and LED Sign Treatment.

Impact of AWV

The research team used data from three-lane sections of Sites 2, 15, and 18 to evaluate the impact of using an AWV. Site 15 (on I-71) and Site 18 (on I-77) had the AWV on the right side of road as the treatment, and Site 2 (on I-77) was used as a control group without treatment. Table 19 summarizes the basic statistics of the extracted data. As shown in the table, no vehicles were observed driving in the inside closed lane (Lane 1) 100 ft upstream of the shadow vehicle at Site 2, but a few vehicles were found driving in Lane 1 at Sites 15 and 18. Meanwhile, more vehicles were driving in the outer lane (Lane 3) than in the lane adjacent to the mobile operation (Lane 2) at all three sites.

Table 19. Basic Statistics 100 ft Upstream of Shadow Vehicle for AWV Treatment.

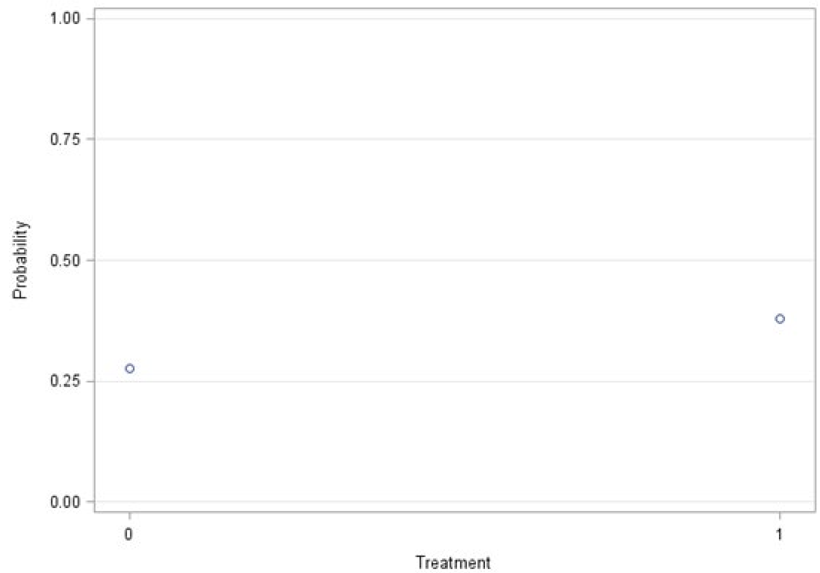
Statistic		Lane 1 (Inside/Closed)	Lane 2 (Adjacent)	Lane 3 (Outer)
Total lane count	Site 2 (no AWV)	0	178	465
	Sites 15 and 18 (AWV)	4	834	1,366
Hourly flow rate (vph)	Average	825.0	732.7	690.8
	Std. dev.	150.0	235.3	251.9

Because no vehicles were observed in Lane 1 at Site 2, there was no baseline for comparison for lane distribution related to Lane 1. Therefore, a binomial logit regression model was used for lane distribution between Lanes 2 and 3. In the procedure of estimating the binomial logit regression model, the lane option (using Lane 2 as the reference) was set as the dependent variable, with treatment (i.e., AWV), hourly flow rate, and average distance from the first warning sign tested for inclusion as independent variables. Table 20 shows the final model estimation result for using Lane 2.

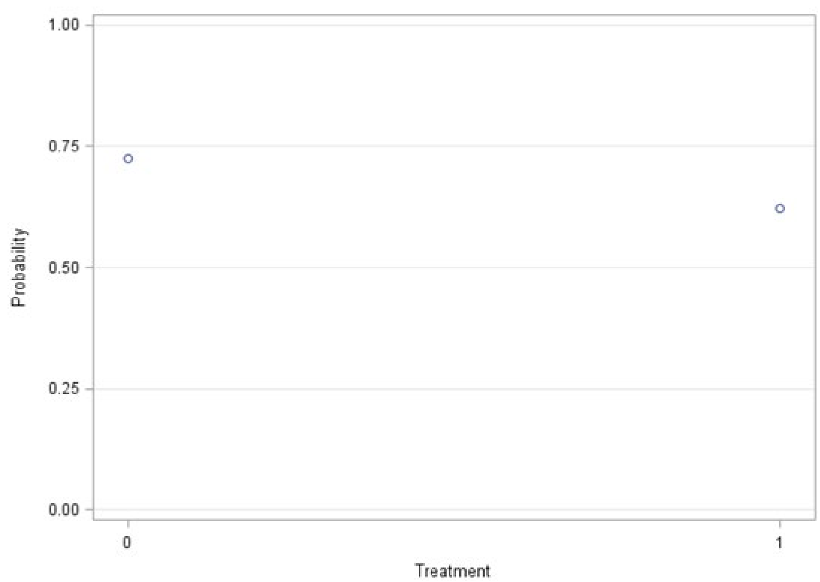
Table 20. Model Estimation Result for Shadow Vehicle and AWV Treatment.

Parameter	DF	Estimate	Standard Error	Wald Chi-Square	Pr > ChiSq
Intercept	1	−0.7268	0.0492	217.8335	<0.0001
treatment	1	0.2334	0.0492	22.4599	<0.0001

Treatment is the only significant contributing factor to lane distribution between Lanes 2 and 3. The positive value of the estimated parameter indicates that drivers are more likely to use Lane 2 over Lane 3 with the addition of AWV. Figure 19 further supports the positive relationship between the probability of using Lane 2 and the treatment. Even though the probability of using Lane 2 increases from 0.25 to about 0.4 with the presence of the AWV, it is much smaller than the probability of using Lane 3 (about 0.7 without AWV and 0.6 with AWV). Thus, practically speaking, the lane distribution impacts appear to be minimal. Yet, it is important to consider the possible impact of the Move Over Law on the findings. When an AWV is located on the right shoulder upstream of the shadow vehicle, according to the Move Over Law, drivers should move over one lane. Therefore, drivers most likely move from Lane 3 into Lane 2 upstream of the AWV. However, as drivers approach the shadow vehicle, they need to move from Lane 2 into Lane 3 to comply with the Move Over Law. The distance maintained between the AWV and shadow vehicle should provide ample time for drivers to safety make these weaving maneuvers.



a) Lane 2.



b) Lane 3.

Figure 19. Predicted Probabilities of Lane Usage 100 ft Upstream of the Shadow Vehicle for Control and AWV Treatment.

Impact of FMTMCMS on AWV

The research team used data from three-lane sections of Sites 1, 9a, and 10 to evaluate the impact of using an FMTMCMS on the AWV. Site 9a (on I-71) and Site 10 (on I-71) had the FMTMCMS on the AWV as the treatment, and Site 1 (on I-71) was used as a control group without treatment.

First, the research team investigated the impact of the sign on the lane distribution 100 ft upstream of the AWV. Table 21 summarizes the basic statistics of the extracted data. As shown in the table, more vehicles were driving in Lane 2 than Lanes 1 and 3 at all three sites.

Table 21. Basic Statistics 100 ft Upstream of AWV for FMTMCMS Treatment.

Statistic		Lane 1 (Inside/Closed)	Lane 2 (Adjacent)	Lane 3 (Outer)
Total lane count	Site 1 (no FMTMCMS)	109	348	139
	Sites 9a and 10 (FMTMCMS)	37	258	96
Hourly flow rate (vph)	Average	360.8	307.4	332.5
	Std. dev.	110.9	114.0	114.2

Because vehicles were in all three lanes, each vehicle had three lane options (i.e., Lane 1, 2 or 3). Therefore, a multinomial logit regression model was used for lane distribution. In the procedure of estimating the multinomial logit regression model, lane option (using Lane 1 as the reference) was set as the dependent variable, with treatment (i.e., FMTMCMS), hourly flow rate, and average distance from the first warning sign tested for inclusion as independent variables. Table 22 shows the final model estimation result for using Lane 2 or 3 over Lane 1.

Table 22. Model Estimation Result for AWV and FMTMCMS Treatment.

Parameter	Lane	DF	Estimate	Standard Error	Wald Chi-Square	Pr > ChiSq
Intercept	2	1	2.144	0.4614	21.5906	<0.0001
Intercept	3	1	0.1305	0.5408	0.0583	0.8093
sign_distance	2	1	6.561E-6	3.833E-6	2.9298	0.0870[a]
sign_distance	3	1	0.000011	4.34E-6	6.2944	0.0121
flow_rate	2	1	−0.00279	0.00107	6.8240	0.0090
flow_rate	3	1	0.000012	0.00124	0.0001	0.9926[b]

[a] Sign distance is not significant to Lane 2 usage at a significance level of 0.05 (p-value larger than 0.05).
[b] Flow rate is not significant to Lane 3 usage at a significance level of 0.05 (p-value larger than 0.05).

The treatment was not statistically significant for lane distribution. Thus, the FMTMCMS did not change the lane distribution 100 ft upstream of the AWV. This finding is not surprising since the message on the FMTMCMS—while larger (bigger font) and clearer (no abbreviations)—informs drivers about conditions downstream of the AWV. Drivers may read and understand the message yet not change their driving behavior in the test area.

Both average sign distance and hourly flow rate were significant contributing factors to lane distribution. However, average sign distance is only significant to Lane 3 usage over Lane 1, and hourly flow rate is only significant to Lane 2 usage.

The positive value of the estimated sign distance parameter for Lane 3 indicates that an increase in distance between the mobile operation and the first warning sign results in a higher probability of using Lane 3 than Lane 1. The negative value of estimated flow rate parameter for Lane 2 implies that drivers who drive in heavier traffic are less likely to use Lane 2 than Lane 1. These findings reflect the changing traffic conditions throughout the work duration. When the work operation initially begins around 9 p.m., it is close to the warning signs, and there are typically higher traffic volumes than when it ends in the early morning hours farther away from the warning signs. Overall, the probably of using Lane 2 100 ft upstream of the AWV is above 0.5, which was much higher than the probabilities of using Lane 1 or 3. This finding could again reflect impacts from the Move Over Law.

Second, the research team investigated the impact of the FMTMCMS on the lane distribution 100 ft upstream of the shadow vehicle. Table 23 summarizes the basic statistics of the extracted data. As shown in the table, no vehicles were observed driving in the inside closed lane (Lane 1) at any of the sites. More vehicles were driving in the outer lane (Lane 3) than in the lane adjacent to the mobile operation (Lane 2) at all three sites.

Table 23. Basic Statistics 100 ft Upstream of Shadow Vehicle for FMTMCMS Treatment.

Statistic		Lane 1 (Inside/Closed)	Lane 2 (Adjacent)	Lane 3 (Outer)
Total lane count	Site 1 (no FMTMCMS)	0	131	595
	Sites 9a and 10 (FMTMCMS)	0	81	349
Hourly flow rate (vph)	Average	0	431.6	446.3
	Std. dev.	0	116.6	132.2

Since no vehicles were observed in Lane 1, there is no baseline for comparison for lane distribution related to Lane 1. Therefore, a binomial logit regression model was used for lane distribution between Lanes 2 and 3. In the procedure of estimating the binomial logit regression model, lane option (using Lane 2 as the reference) was set as the dependent variable, with treatment (i.e., FMTMCMS), hourly flow rate, and average distance from the first warning sign tested for inclusion as independent variables. Table 24 shows the final model estimation result for using Lane 2.

Neither the treatment nor the hourly flow rate was statistically significant to lane distribution. Thus, the FMTMCMS did not change the lane distribution 100 ft upstream of the shadow vehicle. This does not mean that the FMTMCMS is not effective at providing information to drivers about the work operation. Drivers may have changed their driving behavior upstream of the test area.

Table 24. Model Estimation Result for Shadow Vehicle and FMTMCMS Treatment.

Parameter	DF	Estimate	Standard Error	Wald Chi-Square	Pr > ChiSq
Intercept	1	−1.0300	0.1574	42.8116	<0.0001
sign_distance	1	−0.000056	0.000017	10.3480	0.0013

Average sign distance was the only significant contributing factor to lane distribution. While the negative value of estimated sign distance parameter implies that as the mobile operation moved away from the first warning sign, the probability of using Lane 2 decreased, this finding did not result in a practical change in the probability of using Lane 2 or 3.

Impact of Real-Time Work Zone Location Technology on Shadow Vehicle

In the field, researchers did not have a method that could determine how many drivers passing the mobile sweeping operation had a device (e.g., cell phone or in-vehicle technology) that could receive notifications from third-party traveler information providers (e.g., Waze, HERE, and Google). Therefore, the research team was not confident that the results of lane distribution data analyses accurately reflected the impact of the real-time work zone location technology. Alternatively, the research team examined the content, accuracy, and timeliness of the information transmitted.

Beacon 1

The research team activated Beacon 1 on the TTMA connected to the shadow vehicle at Site 16 (on I-71) and Site 17 (on I-77). Table 25 contains data reduced from a data file provided by the manufacturer, real-time screen captures of the online Beacon 1 software, the Waze XML data feed, and real-time screen captures of the Waze app. Based on these data, the research team noted that the Beacon 1 software checks to see if the device is receiving information approximately every five minutes (see the second column of Table 25, "Beacon 1 Data Time"). However, the GPS location data were only updating approximately every 20 minutes or when the arrow board display changed (see the first column of Table 25, "Beacon 1 Location Time"). This resulted in eight Waze alerts from information received from Beacon 1 over about a two-hour period.

Discussions with the manufacturer the next day confirmed that the device software was set up to check the device every five minutes but only report the GPS location every 20 minutes or when the arrow board display changed (i.e., see the last row of Table 25). The manufacturer remotely updated the software to report the GPS location:

- Every 5 minutes if the device was moving and the difference between reporting locations was greater than 500 ft.
- Every 20 minutes if the device was not moving and there were no changes in the arrow board display change.

Additional testing at Site 17 verified the implementation of these software changes, which resulted in 18 Waze alerts over about a two-hour period (see Table 26).

Table 25. Site 16 Beacon 1 Data.

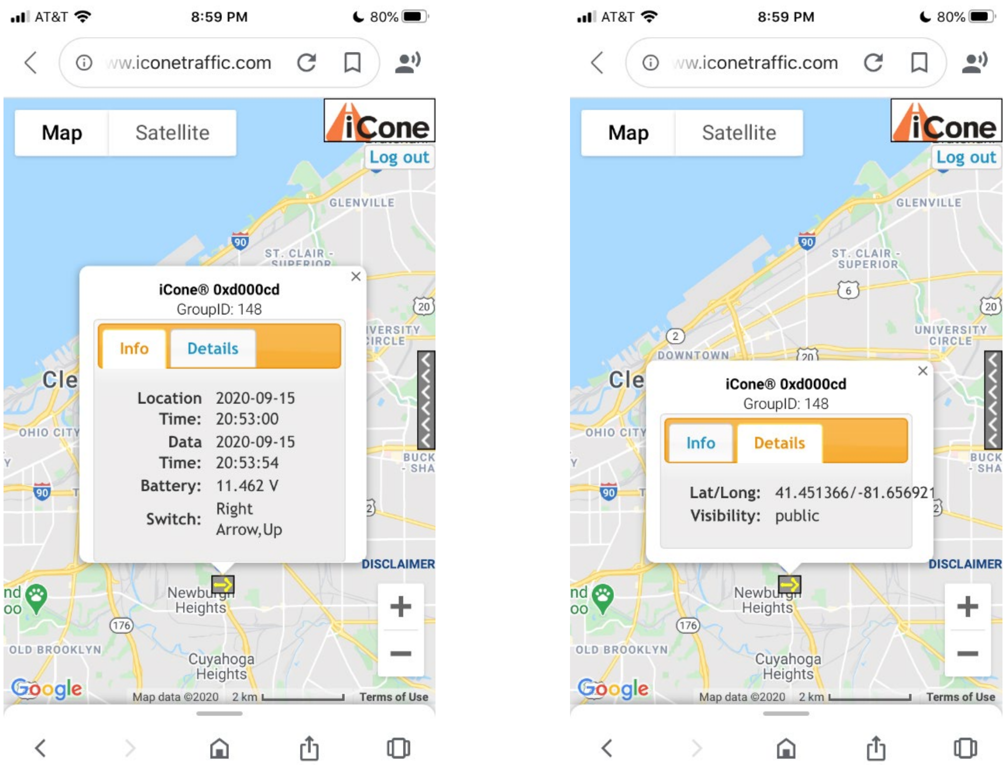
Beacon 1 Location Time	Beacon 1 Data Time	Arrow Board Display	Waze App Screen Capture	Waze App Message Time
20:52:00	20:52:00	Right arrow	8:53 p.m.	1 minute ago
20:52:00	20:57:00	Right arrow		
20:52:00	21:02:00	Right arrow		
20:52:00	21:07:00	Right arrow		
20:52:00	21:12:00	Right arrow		
21:17:00	21:17:00	Right arrow	9:32 p.m.	15 minutes ago
21:17:00	21:22:00	Right arrow		
21:17:00	21:27:00	Right arrow		
21:17:00	21:32:00	Right arrow		
21:39:00	21:39:00	Right arrow	9:41 p.m.	2 minutes ago
21:39:00	21:44:00	Right arrow		
21:39:00	21:49:00	Right arrow		
21:54:00	21:54:00	Right arrow	9:56 p.m.	2 minutes ago
21:54:00	21:59:00	Right arrow		
21:54:00	22:04:00	Right arrow		
21:54:00	22:09:00	Right arrow		
21:54:00	22:14:00	Right arrow		
22:17:00	22:17:00	Right arrow	10:23 p.m.	6 minutes ago
22:17:00	22:22:00	Right arrow		
22:17:00	22:27:00	Right arrow		
22:17:00	22:32:00	Right arrow		
22:39:00	22:39:00	Right arrow	10:41 p.m.	2 minutes ago
22:39:00	22:44:00	Right arrow		
22:39:00	22:49:00	Right arrow		
22:39:00	22:54:00	Right arrow		
23:02:00	23:02:00	Right arrow	11:03 p.m.	1 minute ago
23:02:00	23:23:00	Caution corners	11:25 p.m.	2 minutes ago

Table 26. Site 17 Beacon 1 Data.

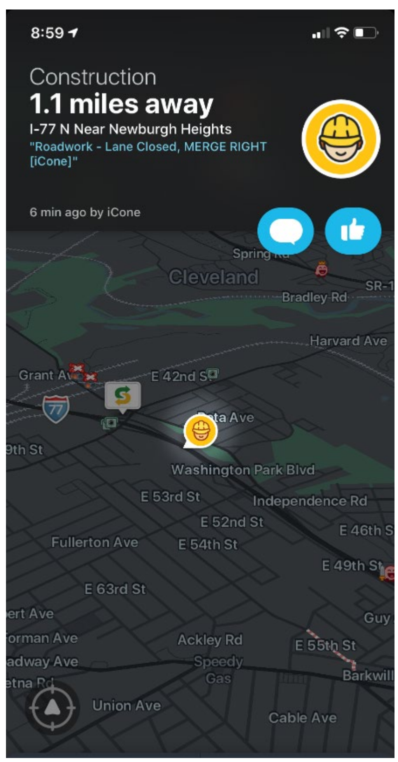
Beacon 1 Location Time	Beacon 1 Data Time	Arrow Board Display	Waze App Screen Capture or Data File Time	Waze App Message Time
20:53:00	20:53:00	Right arrow	8:59 p.m.	6 minutes ago
20:58:00	20:58:00	Right arrow	9:03 p.m.	5 minutes ago
21:04:00	21:04:00	Right arrow	9:08 p.m.	4 minutes ago
21:09:00	21:09:00	Right arrow	9:12 p.m.	3 minutes ago
21:14:00	21:14:00	Right arrow	9:16 p.m.	2 minutes ago
21:19:00	21:19:00	Right arrow	9:20 p.m.	1 minute ago
21:24:00	21:24:00	Right arrow	9:28 p.m.	3 minutes ago
21:24:00	21:29:00	Right arrow		
21:24:00	21:34:00	Right arrow		
21:35:00	21:35:00	Right arrow	21:35:00	NA
21:40:00	21:40:00	Right arrow	21:40:00	NA
21:45:00	21:45:00	Right arrow	21:45:00	NA
21:51:00	21:51:00	Right arrow	21:51:00	NA
21:51:00	21:56:00	Right arrow		
21:51:00	22:01:00	Right arrow		
22:06:00	22:06:00	Right arrow	22:06:00	NA
22:11:00	22:11:00	Right arrow	22:11:00	NA
22:16:00	22:16:00	Right arrow	22:16:00	NA
22:21:00	22:21:00	Right arrow	22:21:00	NA
22:26:00	22:26:00	Right arrow	22:26:00	NA
22:31:00	22:31:00	Right arrow	22:31:00	NA
22:37:00	22:37:00	Right arrow	22:37:00	NA

NA = not applicable.

Figure 20 contains screen captures from the Beacon 1 online software and Waze app. Based on the information provided by Beacon 1, the Waze app reported “Construction 1.1 miles away” at “ I-77 N Near Newburgh Heights.” The Waze message also warned drivers about “Roadwork – Lane Closed, MERGE RIGHT.” Waze users can see that the message was generated by the Beacon 1 manufacturer, as well as how long ago the message was reported (i.e., “6 min ago by iCone”). While the message warns approaching drivers of a lane closure and to merge right, the message does not tell drivers that the left lane is closed.



a) Beacon 1 Online Software.



b) Waze App.

Figure 20. Site 17 Screen Captures.

Beacon 2

The research team activated Beacon 2 on the shadow vehicle at Site 6 (on I-80) and Site 7 (on I-80). Researchers reviewed a data file provided by the manufacturer, real-time screen captures of the online Beacon 2 software, and real-time screen captures of the Waze app. Unfortunately, the Waze XML data feed was unavailable during data collection due to a change Waze made to the TTI account. Even so, the research team was able to deduce that when the shadow vehicle was responding (i.e., moving) (see Figure 21), Waze did not receive messages from Beacon 2. Only when the shadow vehicle had arrived (i.e., stationary) (see Figure 22) did Beacon 2 send a message to Waze (see Figure 23). At Site 6, this resulted in 30 Waze alerts from information received from Beacon 2 over about a five-hour period. The total duration of stationary events was approximately 1 hour and 12 minutes. Conversely, the total duration of moving events was approximately 3 hours and 52 minutes. At Site 7, this resulted in 43 Waze alerts from information received from Beacon 2 over about a 4.5-hour period. The total duration of stationary events was approximately 2 hours and 36 minutes. Conversely, the total duration of moving events was approximately 1 hour and 53 minutes.

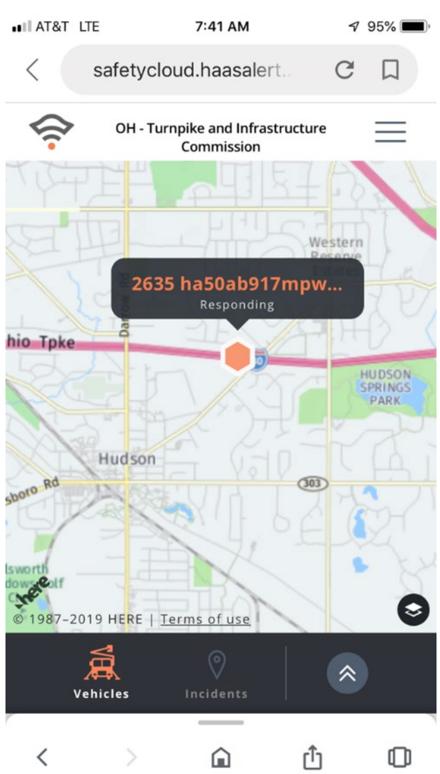


Figure 21. Site 6 Beacon 2 Software Screen Capture—Vehicle Responding.

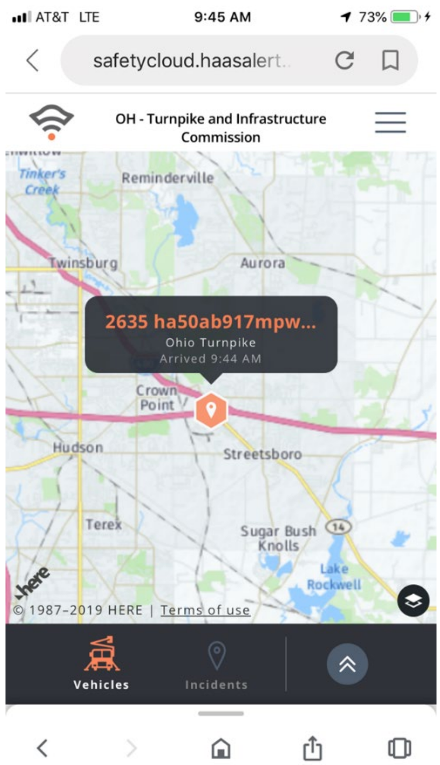


Figure 22. Site 6 Beacon 2 Software Screen Capture—Vehicle Arrived.

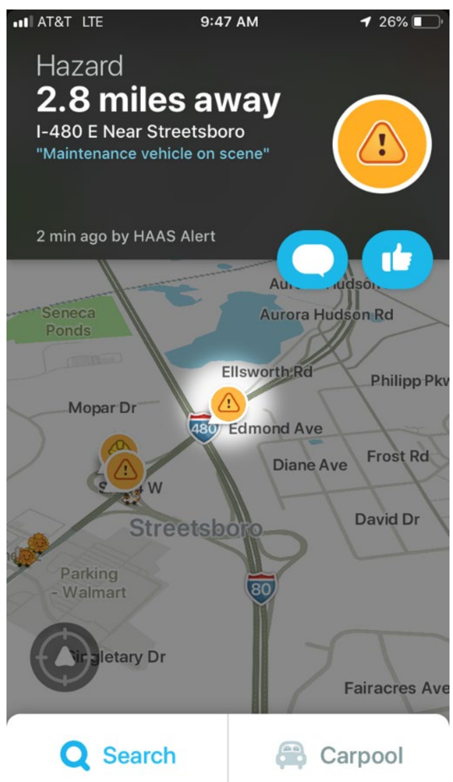


Figure 23. Site 6 Waze App Screen Capture.

Discussions with the manufacturer revealed that the shadow vehicle was classified as a "Maintenance Vehicle" in the Beacon 2 software. For this type of vehicle, the system does not report information to Waze when the vehicle is moving. In March 2020, the manufacturer changed the shadow vehicle classification to a "Moving Operation," so Waze would receive messages from Beacon 2 while the shadow vehicle was moving. Additional remote data collection in April and June 2020 verified the implementation of this software change.

Figure 24 shows a Waze app screen capture when the shadow vehicle was moving. The message notes a "Hazard 0.2 miles away" at "I-80 W Near North Royalton." The message also includes "DOT maintenance nearby" and that the message was generated by the Beacon 2 manufacturer (i.e., "4 sec ago by HAAS Alert"). Figure 25 shows a Waze app screen capture when the shadow vehicle was stationary. The message notes a "Car stopped 200 feet away" at "I-80 W Near North Royalton." The message also includes "DOT maintenance vehicle on scene." While both messages warn approaching drivers of a hazard, neither message tells drivers that the hazard is on the left shoulder.

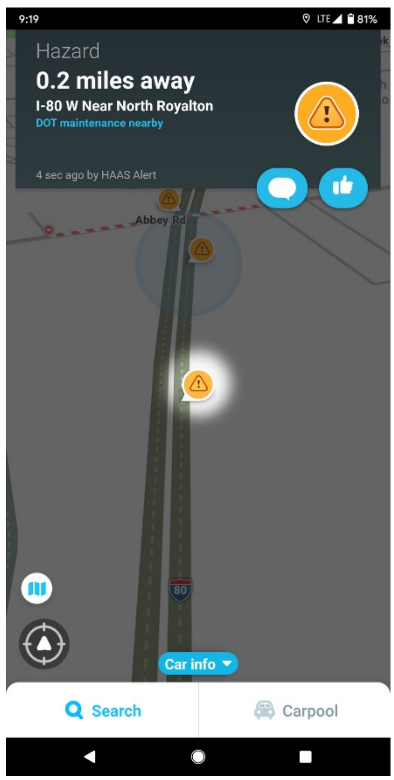


Figure 24. Beacon 2 Waze App Screen Capture—Vehicle Responding.

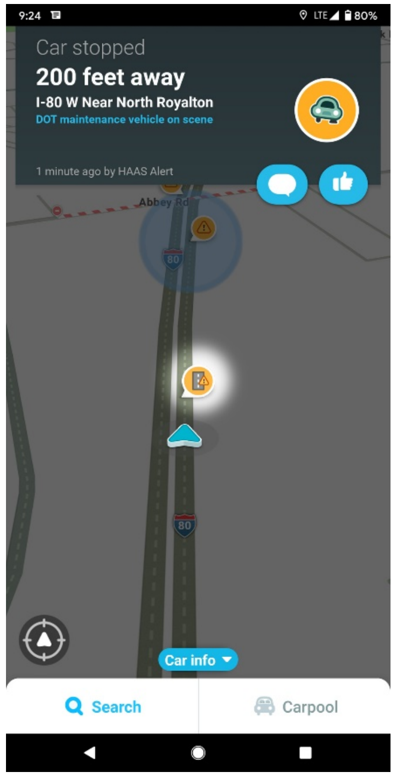


Figure 25. Beacon 2 Waze App Screen Capture—Vehicle Arrived.

CONCLUSIONS

Overall, neither the addition of a second warning sign nor the presence of the AWV (with or without the FMTMCMS) considerably impacted the lane distribution 100 ft upstream of the advance warning vehicle or shadow vehicle. However, none of these treatments appeared to negatively impact the lane distribution either. These results are not surprising considering the limited comparison samples and potential changes in the baseline lane distributions before and after the pandemic. In addition, all the treatments involved the addition or modification of information provided to drivers. Even though drivers may have noticed the LED sign and its message more because of its conspicuity or read a message sooner because of a larger font and unabbreviated text, the acquisition of information does not always result in driver behavior changes. It also could be that the impact on lane distribution occurred further upstream of both vehicles (i.e., outside the view of the video cameras). Anecdotal observations and discussions with the work crew support this hypothesis. Therefore, even though the analyses did not reveal practical impacts to the lane distribution immediately upstream of the advance warning and shadow vehicles, the research team still recommends the use of the LED sign, AWV, and FMTMCMS.

The initial configurations of the real-time work zone location technology produced fewer notifications in Waze about the mobile sweeping operations than anticipated based on initial discussions with the manufacturers. However, changes to the GPS location refresh rate or the vehicle status increased the number of notifications in Waze. The research team recommends the continued use of real-time work zone location technology to inform drivers of mobile operations. Agencies should work with device manufacturers and third-party information providers to improve the message content, such as including which lane is closed or where the hazard is located, in order to provide more detailed information to drivers so they are better informed about real-time work zone conditions.

APPENDIX E:
PROTOTYPE ROLL-AHEAD DISTANCE ALARM

During mobile operations on multi-lane highways, shadow vehicles with impact attenuators provide protection for workers and work vehicles. According to the OMUTCD (*5*) and ODOT *Traffic Engineering Manual* (*6*), a shadow vehicle should be positioned a sufficient distance in advance of workers or equipment being protected, but not so much that errant vehicles can cut into the work convoy or work space. The *Field Guide for the Use and Placement of Shadow Vehicles in Work Zones* (*2*) provides guidance on the spacing of shadow vehicles based on speed limit, weight of the shadow vehicle, and whether the operation is stationary or moving (see Table 1). Similar guidance can also be found in the AASHTO *Roadside Design Guide* (*3*) and the ODOT *Construction and Material Specifications* (*4*). According to Table 1, on roadways with posted speed limits greater than 55 mph, mobile shadow vehicles should be at least 172 ft upstream of the work space. It is important that adequate distance is provided to allow for post-collision roll ahead of the shadow vehicle, especially on high-speed roadways serving a significant proportion of large trucks.

Typically, shadow vehicle drivers judge their distance from the work space by visually counting lane line pavement markings (i.e., 10-ft line and 30-ft space). However, as discussed in Appendix A, sometimes the shadow vehicle is positioned too close to the work equipment (80 to 160 ft). Limited visibility, high traffic volumes, and a lack of training could be contributing to use of shorter distances between a shadow vehicle and the work space. The research team was tasked with designing, building, and testing a prototype roll-ahead distance alarm that would alert the shadow vehicle driver when he/she is too close to the work space.

OVERVIEW OF SYSTEM CONCEPT

The research team wanted to design a system with low-cost components easily found in the electronics marketplace. In addition, the research team wanted the design to be more like an original equipment manufacturer system rather than an integration of standalone off-the-shelf electronics. This allowed the research team to use equipment that met the design needs without using parts that were overly powerful, feature rich, and expensive.

Since the work activities take place outdoors in mostly open areas along roadways, the conditions were ideal for using GPS. The cost and size of basic GPS receivers have become extremely attractive for many applications needing high-quality location measurement. Figure 26 provides an overview of the system concept. The work vehicle is outfitted with a small GPS unit that measures its location. The shadow vehicle is also outfitted with a small GPS unit that measures its location. The two systems share their location via a low-power wireless radio network.

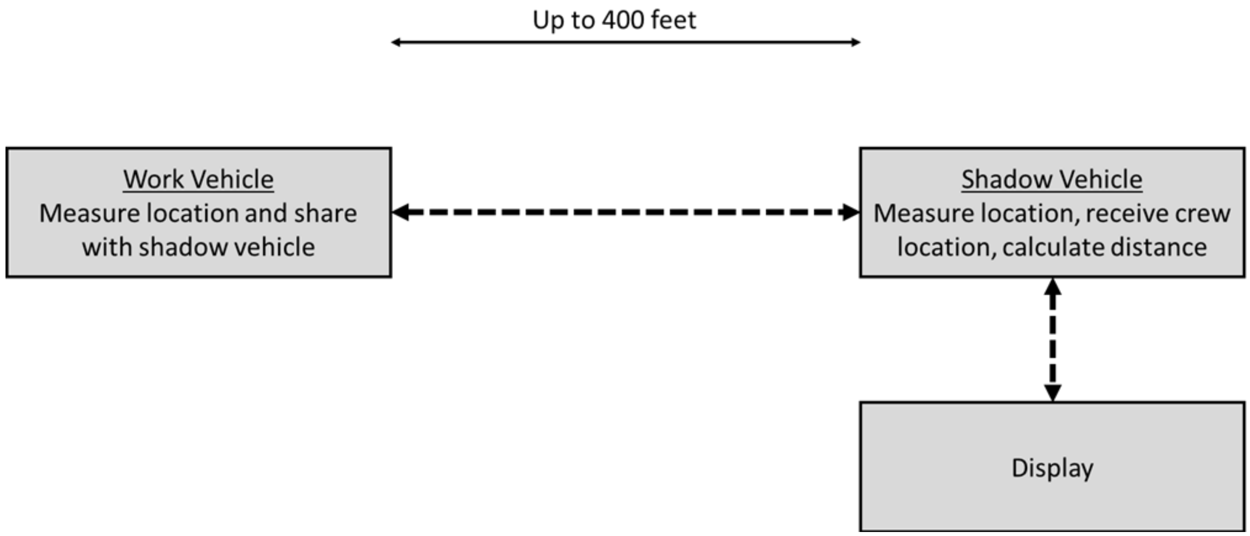


Figure 26. Roll-Ahead Distance Alarm System Concept.

Each unit would use a small microcontroller to manage the system components (i.e., GPS unit and wireless network), calculate the distance between the two units, and generate the user output. A small screen in the shadow vehicle would display the distance between the units and any associated information for use by the shadow vehicle operator. The system is referred to as the roll-ahead distance alarm system.

SYSTEM DESIGN

The heart of the design is a low-cost but highly functional microcontroller that provides processing and communication functions between individual sensors. The location sensor is a stand-alone GPS module that communicates serially (RS-232) with the microcontroller. The GPS module will provide latitude, longitude, time, and a location accuracy indication to the microcontroller. The microcontroller has an onboard IEEE 802.11 WiFi radio for local area wireless communication. While this radio could be used for unit-to-unit communication, the distances between vehicles could be close to the microcontroller's range limit depending on conditions. Thus, the research team constructed a secondary wireless network that reaches both the shadow and work vehicles. This network is provided by small travel WiFi routers, one in each vehicle's unit. Although this network uses the technology of the internet, the system is not connected to the internet. Instead, it simply provides a network to communicate among the two vehicle units and the shadow vehicle operator display using common robust protocols and proven equipment. Figure 27 shows the block diagram of each vehicle unit.

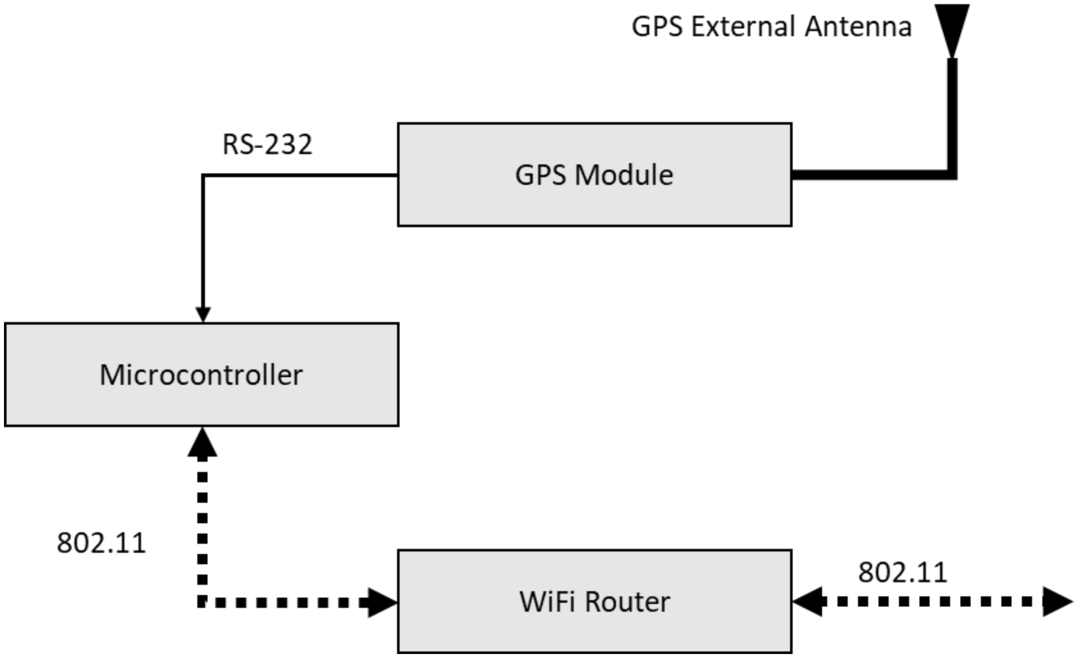


Figure 27. Vehicle Unit Block Diagram.

Each vehicle unit sends its local location information and receives the partner unit's remote location information. The remote data are then compared to the local unit's location and time stamp information, and a separation distance is calculated. A small wirelessly connected tablet computer, mounted in the shadow vehicle, displays the distance information, time, and any alerts pertaining to loss of accuracy. A consumer market Android tablet was chosen for value, flexibility, and availability. The display updates frequently to ensure accuracy and requires no user actions other than initially accessing the webpage located on the system microcontroller.

The calculated distance is highly accurate (within a few feet) when a full complement of GPS satellites is in view. An accuracy number is generated based on the number of satellites in view. Satellites may not be easily found in conditions with overhead obstacles (bridges or overpasses) and very tall adjacent buildings (metropolitan downtown).

In summary, each vehicle unit is comprised of the following:

- Hard plastic case.
- 3-mm DC bulkhead power jack installed in the case as the main power input.
- 12-vDC to 5-vDC power converter with two output connectors.
- TP Link Travel Router (model TL-WR902AC-US).
- Generic GPS module (U-Blox knockoff).
- SMA bulkhead connector and coax cable to connect the GPS module to an external antenna.
- Magnetic-mount external GPS antenna.
- ESP8266 microcontroller development board (requires a three-wire link to the GPS module to communicate and get location measurement data).

The components for each vehicle unit reside in a very durable resealable plastic case (Figure 28). The shadow vehicle unit case is also outfitted with an external 5-vDC USB charging connector to provide power to the tablet while in operation. Each vehicle unit is powered from a standard 12-volt automobile auxiliary power outlet in a vehicle. Each vehicle unit requires very little energy to run and therefore should have no impact on the power consumption of equipment in the vehicle.

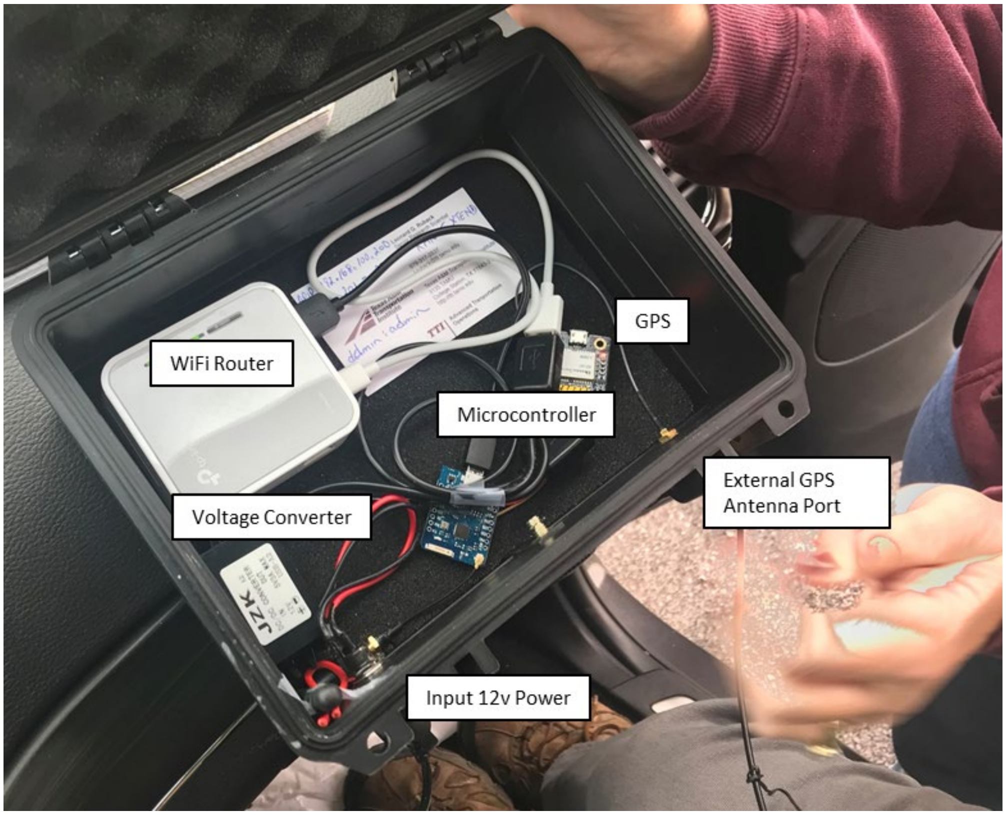


Figure 28. Vehicle Unit Components.

SYSTEM OPERATION

The system requires very little attention for operation. The GPS module needs an external antenna with a good view of the open sky. The antenna should be placed on the vehicle roof (preferred) but can also be located on the dashboard. The system does not require configuration. The vehicle units power up when plugged into the 12-volt automobile auxiliary power outlet. Upon applying power, each unit boots up and builds the wireless network between the two units.

The shadow vehicle unit has an additional external jack to provide 5-vDC power to the tablet to power it for the long term. For short periods, the tablet can simply run from its internal battery. The user powers up the tablet and lets it complete the boot-up sequence. The tablet will automatically establish a network connection with the WiFi router located in the vehicle unit. The user then simply clicks on the desktop link to the Distancer webpage and begins using the system.

The GPS modules require some initial time to discover and lock on as many satellites as possible after they start. This creates a period immediately after startup where the system does not have enough accuracy. As the number of locked-in satellites increases, the accuracy of the location increases. Once the satellites are found, the accuracy should remain within the expected limits. Brief cycling of power will not require the longer startup since the GPS unit remembers the satellites it had recently seen.

During the GPS warm-up period, the tablet displays distances. However, the distance has asterisks around it, and the screen background is yellow (see Figure 29). The asterisks and yellow background indicate that the system is indeed operating but the GPS accuracy is too low for precise location measurements (i.e., not enough satellites in view). Thus, distances are inaccurate and should not be used for safe distancing. The asterisks and yellow background go away when the accuracy is sufficient for high-accuracy distance measurement.

Figure 29. Low GPS Accuracy Screen.

During operation, the tablet continuously displays the calculated distance between the two vehicles. The shadow vehicle unit maintains a target distance in its memory. This distance is configurable within reasonable distance limits via the display screen on the browser. Based on the typical weight of ODOT shadow vehicles, the target distance should be 172 ft for mobile operations on roadways with posted speed limits greater than 55 mph (see Table 1). When the calculated distance is equal to or larger than target distance, the display background is green (see Figure 30). If the calculated distance is less than the target distance, the display background is red (see Figure 31).

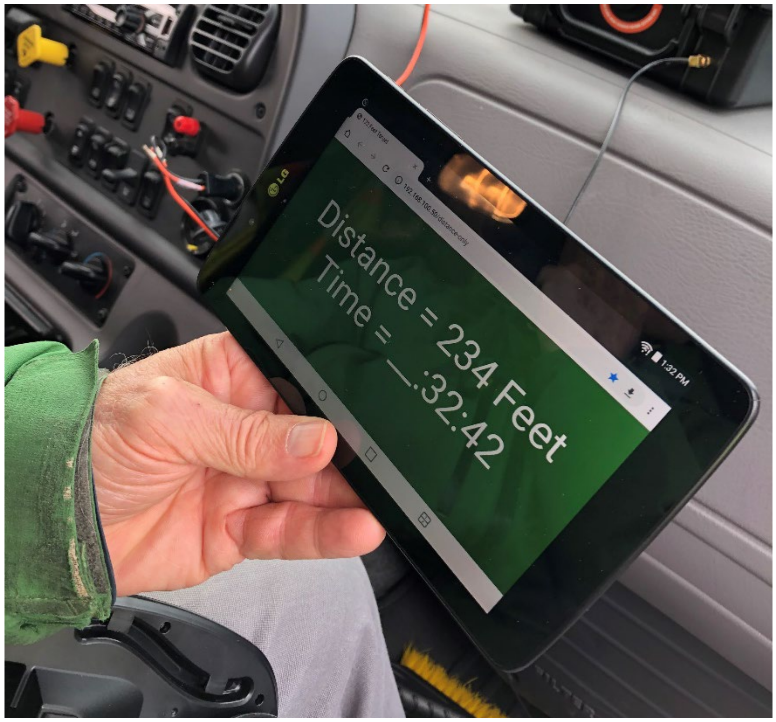


Figure 30. Following Distance ≥ Target Distance (172 ft) Screen.

Figure 31. Following Distance < Target Distance (172 ft) Screen.

The GPS modules provide a highly accurate time and timing functions. New location samples are captured and relayed every second on the second. This ensures both ends are using the location from the same point in time. The time is shown on the tablet to ensure the information coming from the GPS is updating. The hour component of the time was not shown so the time would not be inaccurate due to time zones and daylight savings time during development.

SYSTEM TESTING

The research team tested the roll-ahead distance alarm system in two stages. Initial testing was conducted using a single vehicle carrying both vehicle units. The purpose of the testing was to establish whether the GPS unit selected would operate successfully and without spurious inaccurate location measurements in a mobile vehicle environment. Researchers frequently power-cycled the vehicle units to ensure the system's robustness and that the units could remain on a wireless network since environmental conditions change without user interaction.

The second-stage testing simulated a work vehicle and shadow vehicle operation. The research team used two vehicles, each outfitted with a vehicle unit. The vehicles followed each other around in a parking lot environment. The testing established the accuracy of the GPS measurements and the resulting separation distance calculation. The separation distance was compared to the same distance measured using a laser range finder. The GPS units proved to provide sufficient accuracy. The mobile network was also tested to ensure each unit could remain on the network and the network would be maintained between the vehicles. Tests showed the network remained available for the expected distances between the two vehicles. Finally, the research team conducted tests to exercise the different color display screens presented to the shadow vehicle operator.

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