AMR Leader-Follower System TMA Evaluation

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16. Abstract

To reduce worker injuries in truck mounted attenuator (TMA) crashes, the Missouri Department of Transportation (MoDOT) is piloting a Leader-Follower TMA system, which allows the worker to be removed from the follower vehicle, in two districts. The objectives of this research study are to evaluate MoDOT's pilot program for Leader-Follower TMAs in two districts, to synthesize practices of other state Departments of Transportation (DOTs) regarding Leader-Follower TMAs, and to identify obstacles to implementation faced by other state DOTs. The research methodology to meet this objective includes a literature review, DOT survey and interviews, field study, interviews with MoDOT personnel, and economic analysis. Results from field evaluations conducted in this research study and other prior research studies generally show that the system performs as expected, with some challenges related to GPS-denied environment, tight turns, and path deviations. Based on the survey results, four agencies have implemented Leader-Follower TMA systems, 19 agencies are exploring or have previously explored them, and 20 agencies are not exploring their potential use. Overall, the study findings indicate that the Leader-Follower TMA has the potential to be an effective tool in improving safety for workers in mobile work zones. A benefit-cost-ratio (BCR) of 0.83 was calculated in this research study. There is potential for the BCR to increase in the future as costs will likely decrease due to economies of scale. Challenges to implementation are both technical (e.g., GPS signal loss, need for situational awareness of hills and curves, need for performance data, and need for procedures to reset the system when there is no driver in follower vehicle) and non-technical (e.g., legislation, procurement, competing priorities, and lack of awareness of the system and its capabilities). Potential enhancements to help address some of the technical challenges include a supplementary guidance system for loss of GPS signal, a remote reset feature, additional cameras, and a remote alarm trigger.

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ABSTRACT

To reduce worker injuries in truck mounted attenuator (TMA) crashes, the Missouri Department of Transportation (MoDOT) is piloting a Leader-Follower TMA system, which allows the worker to be removed from the follower vehicle, in two districts. The objectives of this research study are to evaluate MoDOT's pilot program for Leader-Follower TMAs in two districts, to synthesize practices of other state Departments of Transportation (DOTs) regarding Leader-Follower TMAs, and to identify obstacles to implementation faced by other state DOTs. The research methodology to meet this objective includes a literature review, DOT survey and interviews, field study, interviews with MoDOT personnel, and economic analysis. Results from field evaluations conducted in this research study and other prior research studies generally show that the system performs as expected, with some challenges related to GPS-denied environment, tight turns, and path deviations. Based on the survey results, four agencies have implemented Leader-Follower TMA systems, 19 agencies are exploring or have previously explored them, and 20 agencies are not exploring their potential use. Overall, the study findings indicate that the Leader-Follower TMA has the potential to be an effective tool in improving safety for workers in mobile work zones. A benefit-cost-ratio (BCR) of 0.83 was calculated in this research study. There is potential for the BCR to increase in the future as costs will likely decrease due to economies of scale. Challenges to implementation are both technical (e.g., GPS signal loss, need for situational awareness of hills and curves, need for performance data, and need for procedures to reset the system when there is no driver in follower vehicle) and non-technical (e.g., legislation, procurement, competing priorities, and lack of awareness of the system and its capabilities). Potential enhancements to help address some of the technical challenges include a supplementary guidance system for loss of GPS signal, a remote reset feature, additional cameras, and a remote alarm trigger.

EXECUTIVE SUMMARY

Improving work zone safety is a priority for state and local transportation agencies. Mobile and slow-moving operations, such as lane striping, sweeping, bridge flushing, and pothole repair, experience another threat in the form of vehicles crashing into the truck mounted attenuator (TMA) that protects the workers. To reduce worker (i.e., operator) injuries in TMA crashes, the Missouri Department of Transportation (MoDOT) is piloting a Leader-Follower TMA system in the Kansas City and Southwest Districts. With this system, the worker can be removed from the follower vehicle, and connected and automated vehicle technology is used to guide the follower vehicle to follow the path of the leader vehicle. The objectives of this research study are to evaluate MoDOT's pilot program for Leader-Follower TMAs in the Kansas City and Southwest Districts, to synthesize practices of other state DOTs regarding Leader-Follower TMAs, and to identify obstacles to implementation faced by state DOTs. The research methodology to meet this objective includes a literature review, DOT survey and interviews, field study, interviews with MoDOT personnel, and economic analysis.

The Leader-Follower TMA system consists of a leader TMA and a follower TMA. Both the leader and follower TMA vehicles were converted from regular TMA trucks by installing retrofit autonomous kits provided by the system vendor. During operations, the leader-follower TMA system uses electronic breadcrumbs (E-Crumbs) to guide the follower TMA to follow the path of the leader vehicle while maintaining a user-defined, safe distance. The leader-follower TMA system will initialize an Automatic Stop (A-Stop) if there is an obstacle in the path of the follower TMA. If Global Positioning System (GPS) satellite signal is lost, the system will switch into dead reckoning (DR) mode. If GPS signals are not re-established in less than 45 seconds after entering DR mode, an A-Stop will be triggered.

Evaluation or feasibility studies for Leader-Follower TMA systems have been conducted by six state DOTs. Results generally show that the system performed as expected, with some challenges related to GPS-denied environment, tight turns, and path deviations. A Leader-Follower TMA system developed by a Virginia consortium was found to operate successfully for the following conditions: speeds of 15 mph or less, reliable GPS signal present, following distances between 50 feet and 400 feet, lateral offsets of plus or minus 12 feet, clear weather, and night and day conditions (White et al. 2021). Economic evaluations have found benefit-cost ratios (BCRs) of 0.76 (Agarwal et al. 2021) and 1.01 (Mandokhot et al. 2022). Other research studies have investigated topics such as operational parameters and design domain (Tang et al. 2022, Tang et al. 2021), human factors (Miller and Pourfalatoun 2021), and a table-top exercise for incident response (Morehead and Peterson 2021).

Agency practices for leader-follower TMAs were assessed through an online survey and follow-up interviews. The survey was sent to the DOTs from all 50 states and the District of Columbia and Turnpike Authorities (TAs) from Ohio and Pennsylvania. Responses were received from 43

agencies for a response rate of 81 percent. Follow-up interviews were conducted with six DOTs to learn more about their implementation or exploration of Leader-Follower TMA systems.

Among the 43 agencies that completed the survey, the breakdown of implementation or exploration status is as follows: four agencies (Colorado DOT, Missouri DOT, North Dakota DOT, and Rhode Island DOT) have implemented Leader-Follower TMA systems, 19 agencies are exploring or have previously explored Leader-Follower TMA systems, and 20 agencies are not exploring the potential use of Leader-Follower TMA systems. Agencies are currently using Leader-Follower TMA systems for pothole patching, lane striping, and sweeping on various types of facilities, including freeways, multi-lane highways, and rural two-lane highways. Longitudinal accuracy, worker injuries, and worker perception of the system are the most frequently used performance measures for assessing implementation of Leader-Follower TMA systems. Most agencies that have implemented the system are generally satisfied with the system. There are some concerns regarding reliability of the system, especially with regard to losing GPS signal. Among the four DOTs that have implemented Leader-Follower TMA systems, the highest ranked challenges to implementation in the survey include lack of agency buy-in, maintenance cost of the system, and technology cost. Other non-technical challenges, such as procurement, operations, legislation, were also noted.

The survey collected information from agencies that have not deployed Leader-Follower TMA systems. Approximately half of the 19 agencies exploring the potential use of Leader-Follower TMA systems are in the process of gathering information. These agencies are most interested in reviewing performance data for loss of communications, loss of GPS signal, and obstacle detection and avoidance. In addition, these agencies ranked an inability to obtain the desired performance, funding constraints, and the need for data on performance as the highest challenges to implementation.

The 20 agencies that are not exploring the use of Leader-Follower TMA systems identified lack of data on system performance and other initiatives being a higher priority as the most frequently cited reasons for not exploring the use of Leader-Follower TMA systems. In addition, some agencies indicated a lack of awareness of the technology. In some states, a change in legislation is needed to allow the follower vehicle to operate without a safety driver or operator in the vehicle.

The field study included the collection and analysis of video data using four video cameras and processing of log data obtained from the system vendor. The research team accompanied lane striping crews during system operations during nighttime in the Southwest District and during daytime in the Kansas City District. The following MOEs were processed from the log data: automatic stops (A-stops), instances of dead reckoning (DR) when the system loses GPS signal, gap distance between the leader and follower vehicles, and speed. Video data and Google Earth were used to identify potential causes of DRs. The data were processed separately for the Southwest and Kansas City Districts because the Southwest District typically sets the desired gap between the leader and follower vehicle at 700 feet while the Kansas City District sets the desired gap at 175 feet to 200 feet. The system used allows up to 1,500 feet based on interviews with system operators. In addition, log data from two days for the Kansas City District were processed to assess possible effects of a software update that was provided by the vendor to the Kansas City District in August 2022. Overall, approximately 12 hours of log data were analyzed.

Results indicated that the system experienced some A-stops and DRs. The average number of A-stops per hour ranged from 0.32 (Kansas City District after software update) to 1.15 (Southwest District). These A-stops were typically caused by loss of GPS signal for 45 seconds or more after the system entered DR mode. The average disconnected time for the A-stops was less than 1 minute 30 seconds. The average number of DRs per hour ranged from 6.06 (Kansas City District after software update) to 13.61 (Southwest District). DRs were most commonly associated with bridges, followed by sign trusses. Based on these results, the use of a shorter desired gap distance and the software update may help to reduce the number of instances of GPS signal loss.

Based on the analysis of log data, the Leader-Follower TMA system seemed effective at maintaining gap distance and speed. The average difference between the actual gap and desired gap ranged from -3.21 feet (Kansas City District after software update) to 15.38 feet (Southwest District), while the average difference between the average speed and actual speed ranged from -0.006 mph (Kansas City District before software update) to -0.39 mph (Southwest District). The results indicate that the use of a shorter desired gap distance and the software update may help to reduce the gap difference.

From the Southwest District night shift video data, one instance of unusual follower TMA behavior was observed. After entering DR mode due to the loss of GPS signal, the follower TMA drifted slightly to the left and traveled over the fresh paint. No other unusual driving behavior in traffic, close calls, or ATMA-related crashes were recorded.

The research team conducted interviews with four MoDOT employees from the Southwest District and three MoDOT employees from the Kansas City District to learn about their perceptions of the Leader-Follower TMA system. The interviews were conducted individually and covered various topics regarding the system, such as level of experience, training, performance, and suggested improvements. The MoDOT employees generally had a positive perception of the system and believed that it could potentially help to improve work zone safety. The primary areas of concern regarding the system were loss of GPS signal and logistical considerations for the follower vehicle (e.g., stopping at the top of a hill and alerting vehicles in close proximity). Solutions suggested by the MoDOT employees to address these concerns include a supplementary lane assist system, additional cameras on the follower vehicle, and a remote alarm for alerting traffic.

The research team conducted an economic analysis to quantify the benefits and costs of the Leader-Follower TMA deployments. The costs incorporated into the analysis include the system integration cost for existing equipment, training costs, and annual maintenance and support costs. The primary benefit of the Leader-Follower TMA system is to eliminate the costs of worker injuries (i.e., staff time, lost wages, and medical bills) caused by TMA hits. The benefit was estimated based on the data for TMA hits, average crash costs, and the follower TMA hit rate. The results of the economic analysis indicated a BCR of 0.83. A user-friendly spreadsheet developed in this project can be used to adjust the input values to calculate BCRs for different situations. The cost of the system has been declining as more systems have been deployed, so there is potential that further cost reductions could increase the BCR to 1.0 or greater.

Overall, the study findings indicate that the Leader-Follower TMA has the potential to be an effective tool in improving safety for workers in mobile work zones. With the system, the driver can be removed from the follower vehicle, thus reducing exposure to risk. If the driver is still in the follower vehicle, the system allows the driver to focus more on traffic. Challenges to implementation are both technical (e.g., GPS signal loss, need for situational awareness of hills and curves, need for performance data, and need for procedures to reset the system when there is no driver in follower vehicle) and non-technical (e.g., legislation, procurement, competing priorities, and lack of awareness of the system and its capabilities). The vendor has been able to resolve some of the technical issues faced by other states. Potential enhancements to help address some of the remaining technical challenges include a supplementary guidance system for loss of GPS signal, a remote reset feature, additional cameras, and a remote alarm trigger. Bringing together a multidisciplinary team has been found to be beneficial in helping to address some of the non-technical challenges to implementation of the system.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

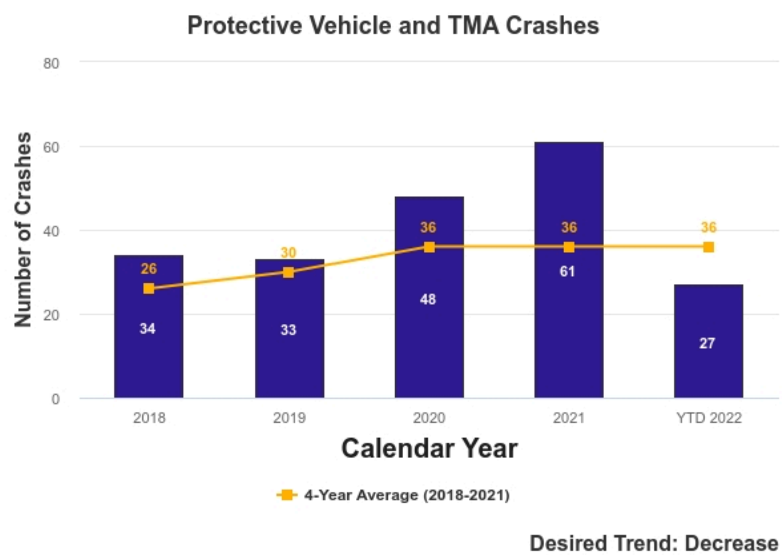
LIST OF ABBREVIATIONS

AASHTO	American Association of State Highway and Transportation Officials
ADT	Average daily traffic
AID	Accelerated Innovation Deployment
AFAD	Automated Flagger Assistance Device
AMR	Accelerated Market Readiness
AMT	Autonomous Maintenance Technology
A-Stop	Automatic Stop
BCR	Benefit-Cost Ratio
Caltrans	California Department of Transportation
CDOT	Colorado Department of Transportation
CPI	Consumer Price Index
DR	Dead reckoning
E-Crumbs	Electronic Breadcrumbs
E-Stop	Emergency Stop
FHWA	Federal Highway Administration
FOV	Field of view
GPS	Global Positioning System
HMI	Human-machine interface
LiDAR	Light Detection and Ranging
MnDOT	Minnesota Department of Transportation
MoDOT	Missouri Department of Missouri
MOE	Measure of effectiveness
NDDOT	North Dakota Department of Transportation
OCU	Operator Control Unit
ODOT	Ohio Department of Transportation
RFI	Request for Information
TA	Turnpike Authority
TAC	Technical Advisory Committee
TMA	Truck Mounted Attenuator
URL	Uniform Resource Locator
V2V	Vehicle-to-Vehicle
VDOT	Virginia Department of Transportation
vpd	Vehicles per day
VTTI	Virginia Tech Transportation Institute
WACCIC	Weighted Average Comprehensive Crash Injury Cost

1. INTRODUCTION

Background and Motivation

Improving work zone safety is a major focus for engineering practitioners. One situation that involves an additional concern is mobile and slow-moving operations, such as lane striping, sweeping, bridge flushing, and pothole repair. Although workers are protected by a truck mounted attenuator (TMA), vehicle crashes with TMAs and worker injuries still occur. As shown in Figure 1-1, the number of TMA crashes in Missouri continues to increase (MoDOT 2022b).



(MoDOT 2022b)

Figure 1-1. MoDOT Tracker statistics for number of TMA crashes

To reduce worker injuries in TMA crashes, MoDOT is currently piloting a Leader-Follower TMA system similar to the one shown in Figure 1-2. With this system, the worker can be removed from the follower vehicle, and connected and automated vehicle technology is used to guide the follower vehicle to follow the path of the leader vehicle. MoDOT is piloting Leader-Follower TMA systems in the Kansas City and Southwest Districts, with funding for the Southwest District pilot provided by a Federal Highway Administration (FHWA) Accelerated Market Readiness (AMR) grant. As part of the AMR grant, MoDOT sponsored a third-party evaluation of the systems in both the Kansas City and Southwest Districts.

(MoDOT 2022a)

Figure 1-2. Leader-Follower TMA configuration for MoDOT

Study Objective and Methodology

The project objectives are to evaluate MoDOT's pilot program for Leader-Follower TMAs in the Kansas City and Southwest Districts, to synthesize practices of state DOTs regarding Leader-Follower TMAs, and to identify obstacles to implementation faced by state DOTs. The research methodology to meet this objective includes a literature review, DOT survey and interviews, field study, interviews with MoDOT personnel, and data analysis. Attainment of the project objectives will help MoDOT to assess the potential for continued implementation of the Leader-Follower system beyond the pilot study and facilitate identification of challenges to implementation.

Overview of Leader-Follower TMA System

The Leader-Follower TMA system consists of a leader TMA and a follower TMA. Both the leader and follower TMA vehicles were converted from regular TMA trucks by installing retrofit autonomous kits provided by the system vendor (Kratos). The autonomous kits enable both TMAs to receive GPS signals and maintain constant communication with each other over two redundant vehicle-to-vehicle (V2V) communication links.

Besides the GPS receiver and V2V communication units, the leader TMA is equipped with a battery breaker, a leader operator control unit (OCU), a rear-looking camera, an interactive console, and an independent emergency stop (E-Stop) control (Figure 1-3). The battery breaker controls the power supply to the system, which is mounted near the battery and not shown in Figure 1-3. The OCU displays the status of operations (i.e., ON/OFF/IDEL/GO) and allows the operator to change the status. The rear-looking camera monitors the traffic behind and the operation of the follower TMA. The image captured by the camera is displayed on the interactive console for the operator. The interactive console also allows the operator to pause and resume the follower TMA operation, change the gap between the leader and follower TMAs from 25 feet to 1500 feet, monitor the status of GPS and V2V communications, and clear an automatic stop (A-Stop) during operations. The independent E-Stop control allows the operator to stop the follower TMA and kill its engine for emergency stops.

Figure 1-3. Leader TMA system overview

The follower TMA is equipped with a battery breaker, a steering actuator, a follower OCU with an E-Stop button, an external E-Stop control, and an obstacle detection system (Figure 1-4). The steering actuator drives the steering wheel to make turns during operations. The OCU works the same as the leader OCU with an E-Stop button aside. An extra E-Stop controller was installed outside the cab to allow workers to stop the vehicle in emergencies. The obstacle detection system includes front view and side view subsystems. The front view detection uses radar, LiDAR, and ultrasonic sensors to detect objects in front of the follower TMA and can initialize an A-Stop before hitting them. The side view obstacle detection uses four ultrasonic sensors to detect and warn the operator if an object is on the side, but it does not stop the follower TMA.

Figure 1-4 Follower TMA system overview

During operations, the leader-follower TMA system uses electronic breadcrumbs (E-Crumbs) to guide the follower TMA to follow the path of the leader vehicle while maintaining a user-defined, safe distance. The leader-follower TMA system will initialize an A-Stop if there is an obstacle in the path of the follower TMA. The operator can clear an A-Stop using the interactive console if the obstacle is removed or is too small to affect the operations (e.g., debris on the road). If GPS satellite signals are blocked due to obstructions (e.g., bridges and trusses), the system will switch into dead reckoning (DR) mode. Figure 1-5 shows the console of the leader vehicle in DR mode. If GPS signals are not re-established in less than 45 seconds, an A-Stop will be triggered. This event is also known as an E-crumb error. After each A-Stop, the leader-follower TMA system needs to conduct the vehicle alignment and rollout process to resume autonomous operations.

Figure 1-5. Screenshot of leader console in DR mode

Report Organization

The following chapters of this report are organized as follows:

- Chapter 2 provides information regarding a review of existing literature regarding Leader-Follower TMA systems, including evaluation studies.
- Chapter 3 provides a synthesis of practices of other agencies based on a practitioner survey and interviews with state DOTs.
- Chapter 4 describes the methodology and results for the field study of Leader-Follower TMA systems.
- Chapter 5 discusses feedback from MoDOT personnel on the system based on interviews with MoDOT employees.
- Chapter 6 presents an economic analysis of the costs and benefits of Leader-Follower TMA systems.
- Chapter 7 provides the conclusions from the research.

Table 1-1 lists the supplemental information for the report included in the appendices.

Table 1-1. Report Appendices

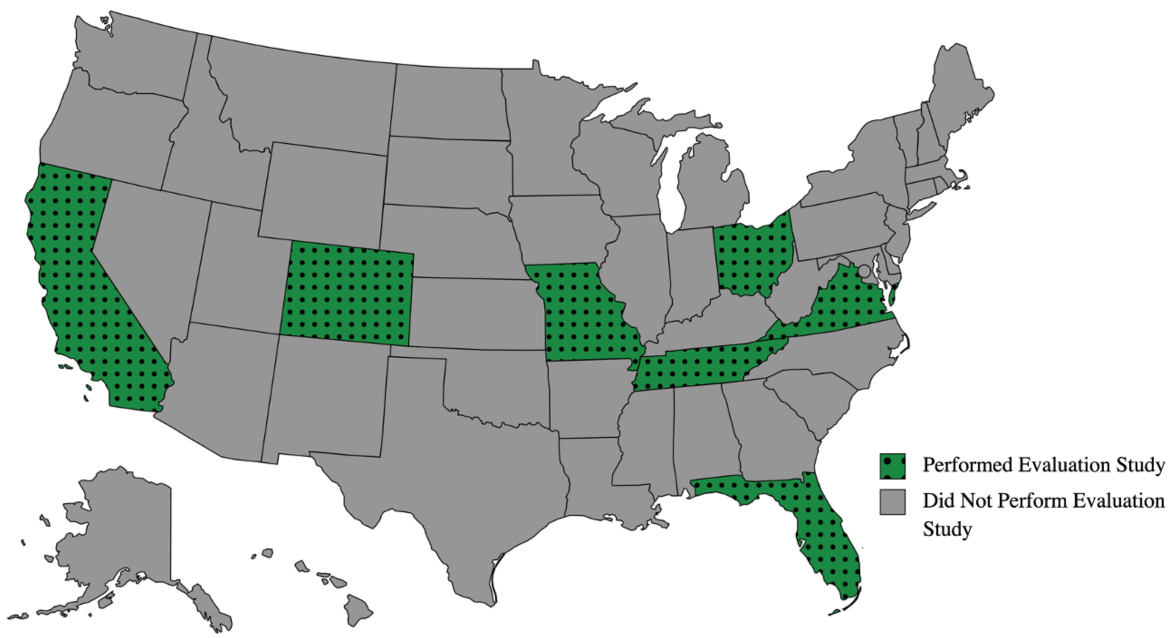
Appendix	Title
A	Summary of Existing Literature and Resources for Leader-Follower TMAs
B	Questions for Agency Survey
C	Survey Responses by Agency
D	Example Questions for DOT Interviews
E	Questions for MoDOT Employee Interviews

2. LITERATURE REVIEW

This chapter provides an overview of existing literature regarding Leader-Follower TMA systems, including evaluation studies, state legislation, research studies, and emerging research. A tabular summary of existing literature and DOT resources is provided in Appendix A.

Evaluation Studies

Evaluation studies for Leader-Follower TMA systems have been conducted by several states (Figure 2-1), as described in the following sections.



(Map created with mapchart.net ©)

Figure 2-1. Map showing states that have completed evaluation studies for Leader-Follower TMA systems

California

An evaluation study for the California Department of Transportation (Caltrans) included the development of a purchase specification, procurement, and closed course testing of the Kratos system (Bennett and Lasky 2021). The system was purchased by the Advanced Highway Maintenance and Construction Technology Research Center. The closed course testing included 26 scenarios in two categories: safety (e.g., A-Stop and E-Stop operation, communications loss, and obstacle detection mapping) and performance (e.g., straight-line guidance accuracy, E-Crumb errors and recovery operation, and driving under a highway overcrossing). The vehicle configuration included the use of a pickup truck as the leader vehicle as shown in Figure 2-2. Kratos made several system enhancements during the study, such as the installation of a more sensitive LiDAR sensor for obstacle detection and updated control software to address abrupt steering corrections at highway overpasses. The results indicated that all the safety and performance scenarios were completed successfully. The researchers suggested limiting initial implementation to sweeping operations. However, Caltrans needs authorization for highway driving with a Leader-Follower TMA.

(© Bennett and Lasky 2021)

Figure 2-2. Leader-Follower TMA configuration for Caltrans study

Colorado

Validation testing for Region 5 of the Colorado Department of Transportation (CDOT) included 15 scenarios in a test environment during a three-day period (Colorado DOT 2022b). These scenarios covered various aspects of Leader-Follower TMA operation, such as follow distance, collision avoidance, braking, lane changes, automatic and emergency stops, following accuracy on curves, and the offset feature. Data were collected from system log files and physical measurement. The results were tabulated for each scenario.

Florida

Florida DOT sponsored a research study to assess the Kratos Leader-Follower TMA system through training, an economic analysis, and testing on two closed courses and six work zones (Agarwal et al. 2021). The system was leased from Kratos. The training included both online and hands-on content, and operator feedback on the training was positive. In the economic analysis, a benefit-cost tool was developed, and a benefit-cost ratio (BCR) of 0.76 was calculated.

The closed course testing encompassed 26 scenarios in the following focus areas: safety, following accuracy, lateral accuracy, turning, obstacle, operational tests, and communication. During the testing, there was a safety operator in the follower vehicle. The system performance met expectations for 23 of the 26 scenarios, and there were three exceptions (minimum turn radius, roundabouts, and leader reverse) and two critical errors (not stopping for obstacle and suddenly deviating from path). The follower vehicle was able to navigate through a turning radius of 45 feet but not 25 feet. The roundabout scenario could not be verified due to the lack of a suitable roundabout location with an internal diameter of at least 130 feet, which is the minimum internal diameter that the system can negotiate. For another exception, the follower vehicle did not stop when the leader vehicle went in reverse. In one of eight runs, the follower vehicle did not automatically stop for an obstacle. Figure 2-3 shows an external camera view of obstacle testing. There was one instance in the closed course testing in which the follower vehicle veered off its path.

(Agarwal et al. 2021)

Figure 2-3. Obstacle testing from Florida study

Field testing was performed for falling weight deflectometer testing at six locations. System performance met expectations at three of the six locations, with exceptions at the other three locations. The exceptions were due to deviation from the vehicle path, a system misinterpretation of hard brake event as a collision, challenges with two-lane operations, and the inability of the follower vehicle to navigate through a roundabout with an internal diameter less than 130 feet.

Missouri

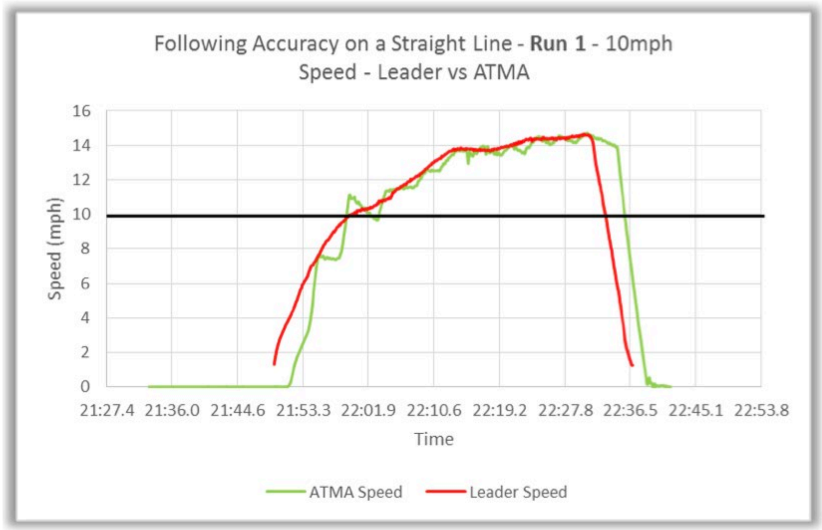
Tang et al. (2021a) developed an analysis methodology for Leader-Follower systems and performed field testing in Sedalia, Missouri. The field testing evaluated system performance with respect to following distance and accuracy, obstacle detection, and emergency situations. Overall, the results indicated that the system consistently performed as intended.

Ohio

A research study sponsored by Ohio DOT focused on work zone analysis (e.g., analysis of work zone crashes, economic analysis, and Ohio DOT needs assessment), market survey, and specification development (Mandokhot et al. 2022). Results from an economic analysis found that the system was feasible with a BCR of 1.01. The market survey included concepts for two types of systems: Upgraded Mobile Vehicle and Mobile Remote Platform. The Upgraded Mobile Vehicle includes a towable attenuator that would be driven to the work zone before operating in the work zone without a driver, while the Mobile Remote Platform includes an attached attenuator and would be driven or towed to the work zone before being operated remotely. The market review identified 25 vendors who could meet at least some of the specified system requirements. Functional specifications were developed for both concepts in the following categories: general requirements, guidance for traveling between the garage and work zone, operability, prevention of crashes, monitoring for potential crashes, protection from a crash, and requirements after a crash event.

Tennessee

The pilot evaluation study of the Kratos system sponsored by Tennessee DOT included 24 scenarios at two locations for one week (Kohls 2020). The scenarios were grouped into the following categories: safety (e.g., A-Stop and E-Stop), following accuracy (e.g., on straight line, on lane course), typical application (e.g., trash pick-up, herbicide application, pothole patching), detection (e.g., vehicle intrusion, cone detection), communication, and miscellaneous (e.g., tight turn radius, bump test). In general, the system performed as expected. Example results for following accuracy are shown in Figure 2-4. The results indicated that the Leader-Follower TMA was more suitable for continuous operations in the work zone. The system could function in a GPS-denied environment for only a limited time. The researcher concluded that the system had the potential to improve work zone safety, and further enhancements could help to address the issues encountered during the testing.

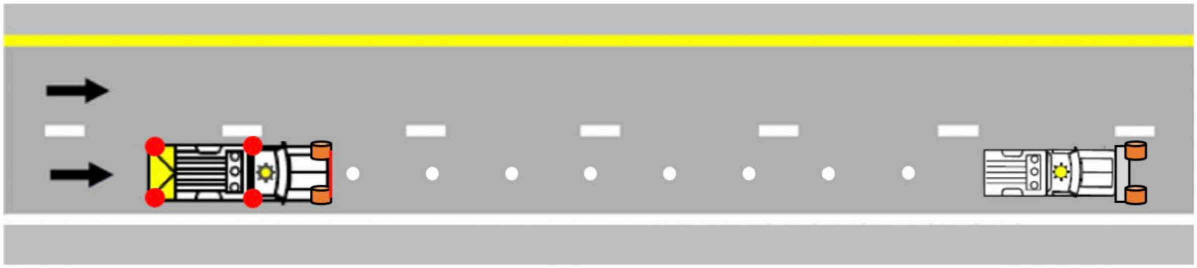


(Kohls 2020)

Figure 2-4. Example speed profile for test for following accuracy in Tennessee DOT study

Virginia

A consortium consisting of Virginia Tech Transportation Institute (VTTI), Virginia Department of Transportation (VDOT), dBi Services, and Transurban collaborated to design and build an automated Leader-Follower TMA system (White et al. 2021). System features, as shown in Figure 2-5, include LiDAR sensors for object detection, three computer systems, emergency stop functions, communications links, and a human-machine interface (HMI) tablet. The screen displays for the Hold state are shown in Figure 2-6. The system was tested on a 2.2-mile-long test track under different conditions. Performance measures included lateral and longitudinal accuracy for various speeds and grades. The study results demonstrated that they system operated successfully for the following conditions: speeds of 15 mph or less, reliable GPS signal present, following distances between 50 feet and 400 feet, lateral offsets of plus or minus 12 feet, clear weather, and night and day conditions.



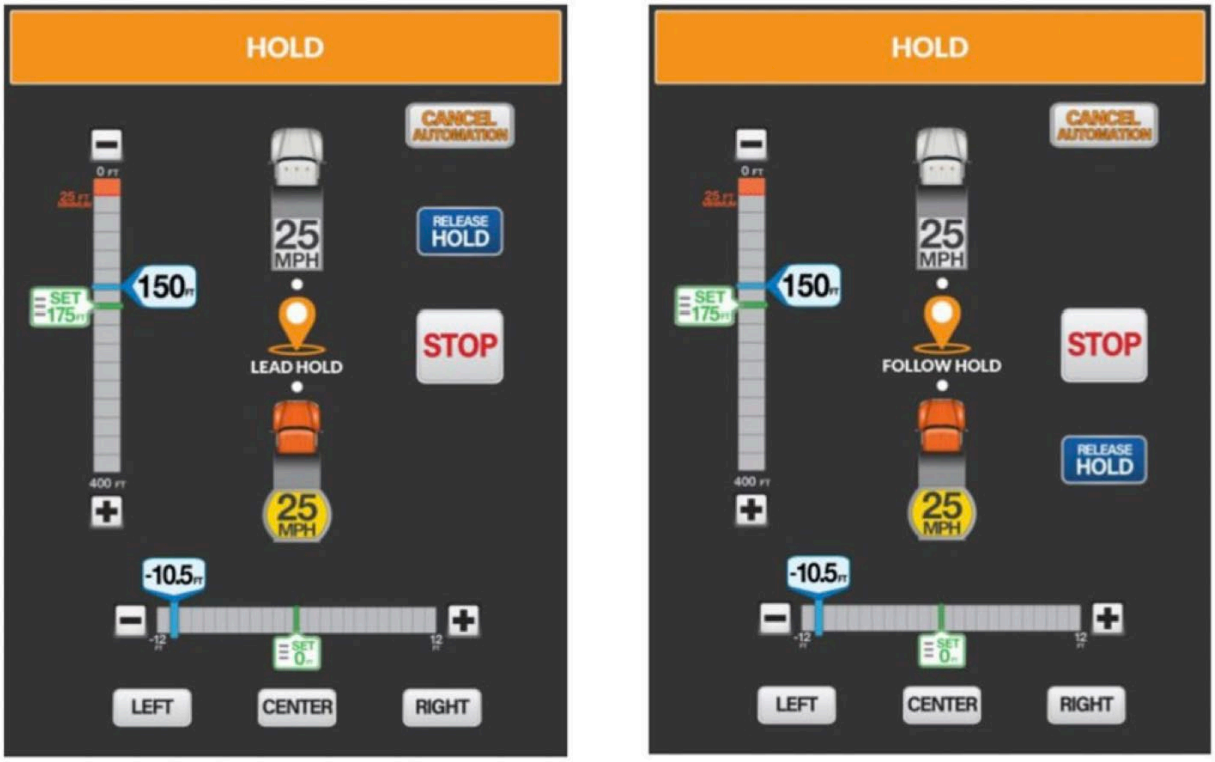
FV Features
- AVRP system
- HMI tablet
- V2V communications
- GPS with RTK
- IMU
- SLAM map interpreter
- LIDAR (2, orange)
- Forward camera
- 4 external e-stop plungers (red)
- Forward e-stop bar
- Internal revert to factory e-stop
- Remote wireless e-stop
- VTTI data acquisition system

V2V Transmission Content
- System and position status
- GPS path information
- SLAM map features
- Operation modes
- Commanded headway
- Waypoint management (hold/release)
- Object detection in safety zone

LV Features
- AVRP
- HMI tablet
- Tablet with forward video feed from FV
- V2V communications
- GPS with RTK
- IMU
- SLAM map builder
- LIDAR (2, orange)

(White et al. 2021)

Figure 2-5. Features for Leader-Follower TMA configuration developed in Virginia



(White et al. 2021)

Figure 2-6. HMI screens for hold state for Virginia Leader-Follower TMA system for lead vehicle (left) and follower vehicle (right)

An integration plan for the system was also developed. The integration plan provides recommendations for testing using a phased approach, performance metrics, and an overview of suggested training for management and system operators (VTTI 2021). The testing plan includes 25 scenarios to cover various aspects of Leader-Follower TMA operation, such as emergency stop, environmental factors, functional components, evaluation of the HMI, and system response to a vehicle intrusion.

Summary of Evaluation Studies

This section summarizes the test results from the various states. The test scenarios may be grouped into six categories: communication, safety-stop, following accuracy, turning, detection, and operational tests.

- The communication testing involves assessing the system performance while in a GPS-denied environment, loss of radar and LiDAR sensor, and loss of communication between vehicles. The testing did not find any failures or wrong situations in the system. However, results from the Tennessee study indicated that the system could function in a GPS-denied environment for only a limited time (Kohls 2020).

- The Leader-Follower TMA system from Kratos has one automatic stop (A-Stop) button and three E-Stop buttons (two buttons in the leader vehicle and the other two buttons in the follower vehicle). All four buttons were executed properly, and the engine was stopped when the E-Stop buttons were activated. In addition, stopping distance and stopping time were recorded and did not show any unusual results.
- The following accuracy was tested on straight roads, curves, slalom curves, and during lane changes. Also, gap distance when the following distance is set by the user interface of the system was recorded to verify the performance. The Leader-Follower TMA system generally performed properly in all the courses, and the difference between the actual and desired gap distance was recorded from a few feet up to 150 feet. The Florida study noted some deviation from the vehicle path (Agarwal et al. 2021).
- In turning testing scenarios, tight turns, U-turns, and roundabouts were driven. From the Florida testing, one run out of four was not able to perform the tight turn with a radius of 45 feet (Agarwal et al. 2021). Also, while driving through the curve, lane accuracy was not maintained perfectly in two runs out of five, and the lateral deviation was shown as significantly different. The Tennessee report mentioned that the system encountered an A-Stop triggered by an E-Crumbs error for both trials in a tight turn testing scenario (Kohls 2020).
- Obstacle detection, vehicle intrusion, and object recognition were tested by several states. California, Colorado, and Tennessee tested hitting a bump (Bennett and Lasky 2021, Colorado DOT 2022b, Kohls 2020). Tennessee tested sensitivity to passing vehicles (Kohls 2020). The system generally performed as expected, although the follower vehicle did not automatically stop for an obstacle in one of eight runs in Florida (Agarwal et al. 2021).
- Operational testing scenarios have included speed tests, acceleration, and deceleration tests, braking tests, and testing to drop the follower vehicle. All of the testing showed proper operation. California also simulated rear impact to the follower vehicle, and the Leader-Follower TMA system continued to function. However, the magnitude of impact threshold required to stop the engine was set to 20 g by the vendor (Kratos). Due to the danger of simulating that magnitude of impact, the test was limited to a lower magnitude of impulse (Bennett and Lasky 2021).

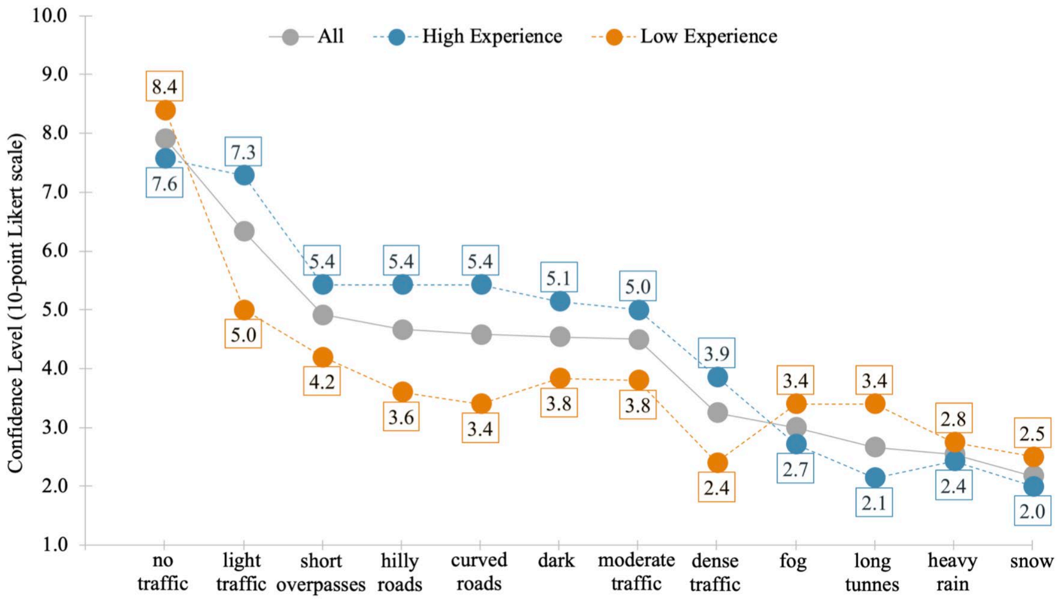
State Legislation

One potential implementation challenge to Leader-Follower TMAs involves the need for state legislation to authorize their use. An example of such legislation may be found in Pennsylvania, which passed a law that authorizes Pennsylvania DOT and the Pennsylvania Turnpike to operate a highly automated work zone vehicle, with the flexibility to require a driver in a work zone that is active (Pa C.S. 75 §8531).

Research Studies

Existing research on Leader-Follower TMAs has focused on operational parameters, employee perceptions, and incident response. Tang et al. (2022) developed guidelines for operators of Leader-Follower TMA systems. Based on a speed limit of 70 mph and operating speed for the Leader-Follower TMA of 10 mph, Tang et al. (2022) suggested the following minimum parameters: minimum car-following distances of 75 feet (leader) and 100 feet (follower), critical-lane changing gap of 912 feet, and minimum intersection clearance of 15 seconds. In addition, Tang et al. (2021b) investigated the traffic conditions for deployment of Leader-Follower TMA systems and recommended a maximum value of 40,000 vehicles per day (vpd) as the operating threshold.

Researchers have also investigated perceptions of the system by DOT personnel, including project managers, researchers, and operators. Tian et al. (2022) interviewed four project managers and two researchers from four state DOTs (Colorado, Minnesota, Missouri, and Virginia) to learn about their perspectives regarding implementation of Leader-Follower TMA technology. The study found that the major challenges to implementation are loss of GPS signal, the need for regular training, and regulatory concerns. A research study sponsored by CDOT investigated DOT workers' perceptions of using this technology through a survey of 13 workers from CDOT and Caltrans who worked with a Leader-Follower TMA system (Miller and Pourfalatoun 2021). The workers were divided into two groups based on their level of experience with the system. Overall, the results indicated that workers' opinions of the system were positive overall. However, some workers expressed concerns about operating the system in more complicated situations, as shown in Figure 2-7. The results also indicated that more training helped to improve workers' confidence in the system and in their abilities to operate the system.



(Miller and Pourfalatoun 2021)

Figure 2-7. Worker confidence in automation reliability under different conditions (Miller and Pourfalatoun 2021)

A tabletop exercise in Colorado was conducted in 2021 to assess the immediate and long-term response to an incident in which a motorist strikes the Leader-Follower TMA during striping (Morehead and Peterson 2021). The exercise included four modules: initial actions at the crash scene, arrival of response partners at the crash scene, start of the collision investigation, and the continuing investigation. Suggestions for the After-Action Report/Improvement plan included development of a checklist for contacts to be notified, provision of accident packets, and developing procedures for documentation and data collection. A supplemental document to the tabletop exercise provided recommendations for data and security, such as improving data attribution, developing clear data download procedures, development of a tool to analyze log files, and adding the capability for data logging after an E-Stop (Daily et al. 2022).

Emerging Research

There are several research projects in progress related to Leader-Follower TMAs. Ongoing research for the Autonomous Maintenance Technology (AMT) pooled fund includes projects on development of deployment guidelines, documentation for promotion and deployment, cost-benefit analysis, literature review of current and potential applications, and system effects of a crash impact (Colorado DOT 2022c). The AMT pooled fund is also working on development of a toolkit with information and resources from several DOTs in various stages of implementation (Colorado DOT 2022d). An active research project sponsored by Indiana DOT is working towards creating implementation recommendations for Leader-Follower TMAs for Indiana DOT

(Purdue University 2022). A follow-up study to further development of Leader-Follower TMAs is underway in Virginia (VTTI 2022).

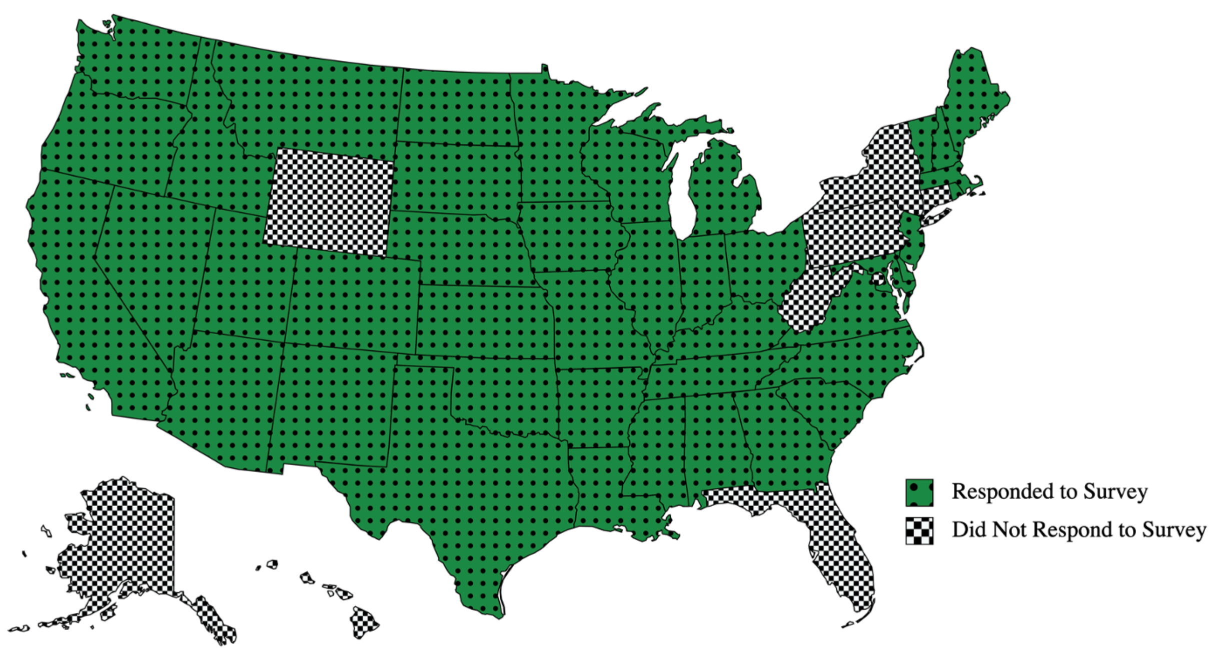
3. AGENCY PRACTICES

Agency practices for Leader-Follower TMAs were assessed through an online survey and follow-up interviews. The methodology and results for the survey and interviews are described in the following sections.

Agency Survey

Methodology for Agency Survey

An online survey on Leader-Follower TMAs was developed and administered by the researchers. The survey was reviewed by the project Technical Advisory Committee (TAC) before being sent to the DOTs from all 50 states and the District of Columbia and Turnpike Authorities (TAs) from Ohio and Pennsylvania via Qualtrics Survey Software (Qualtrics 2022). The survey was sent to one respondent from each agency using a contact list that was developed based on information obtained from various sources, including FHWA and agency contacts from prior projects. Each agency respondent received a unique survey link that could be shared internally for collaboration purposes, with responses limited to one per agency. As shown in Figure 3-1, responses were received from 43 agencies for a response rate of 81 percent. Pennsylvania DOT and Pennsylvania TA did not respond to the survey but provided information by email.



(Ohio DOT and Ohio TA responded to the survey)
(Pennsylvania DOT and Pennsylvania TA did not respond to survey)
(Map created with mapchart.net ©)

Figure 3-1. Map showing DOTs that responded to the survey on Leader-Follower TMAs

The survey consisted of 21 questions and used skip logic to display pertinent questions based on each agency's level of experience with Leader-Follower TMAs. The survey was divided into five sections as follows:

- Initial screening for all respondents (Questions 1 through 4)
- Agencies that have implemented Leader-Follower TMA systems (Questions 5 through 14)
- Agencies that are exploring or have previously explored the potential use of Leader-Follower TMA systems (Questions 15 through 19)
- Agencies that are not exploring the potential use of Leader-Follower TMA systems (Question 20)
- General comments for all respondents (Question 21).

The survey covered various topics, such as the use of technologies to improve work zone safety, performance measures, implementation practices, and challenges to implementation. A copy of the full survey is provided in Appendix B, and the survey responses for each agency, including comments, are given in Appendix C.

Results for Agency Survey

The survey results are presented in the following paragraphs, organized by survey section.

<u>General Information</u>

The first section of the survey sought general information from agencies regarding their practices for worker safety. The first question asked agencies if worker safety was a significant concern at their agency. As shown in Table 3-1, all responding agencies indicated worker safety is a significant concern at their agency.

Table 3-1. Survey results for worker safety as a significant concern (Question 1)

Answer Choice	Response
Yes	100%
No	0%
No Response	0%

Number of respondents who viewed question = 43

In response to Question 2, 70 percent of the respondents indicated that they have data on worker-related work zone concerns or incidents (Table 3-2). Survey comments indicated that the amount of information available varies between agencies, from formally tracking work zone crashes and worker presence to anecdotal information.

Table 3-2. Survey results for availability of data on worker-related work zone concerns or incidents (Question 2)

Answer Choice	Response
Yes	70%
No	25%
No response	5%

Number of respondents who viewed question = 43

Question 3 sought information from respondents regarding the use or consideration of different types of devices and technologies to help improve worker safety. As shown in Table 3-3, the most commonly used or considered devices and technologies are radar speed display feedback signs, temporary rumble strips, end of queue warning systems, and automated flagger assistance devices (AFADs). The least frequently used or considered technologies are wearable technologies and work zone intrusion alarms. Other countermeasures mentioned include smart work zone technologies, work zone speed limit reductions, flashing lights on the back of the attenuator that are activated by the operator, law enforcement, standard TMAs, and temporary pavement marking improvements.

Table 3-3. Survey results for use or consideration of devices and technologies to help improve worker safety (Question 3)

Device or Technology	Response
Automated Flagger Assistance Device (AFAD)	72%
Automated Work Zone Speed Enforcement	26%
End of Queue Warning System	77%
Leader-Follower TMA System	28%
Notification of Construction Equipment Entering/Existing System	33%
Radar Speed Display Feedback Signs	84%
Temporary Rumble Strips	81%
Wearable Technologies	23%
Work Zone Intrusion Alarm	21%
Other (please describe)	19%
No Response	0%

Number of respondents who viewed question = 43

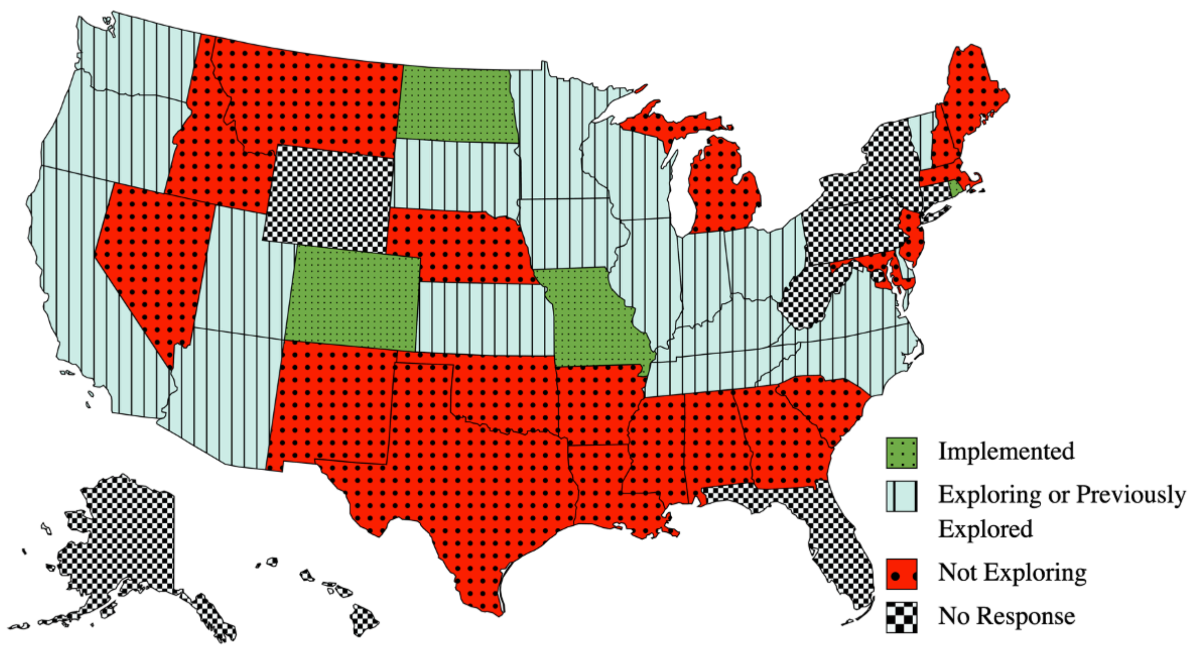
Question 4 asked about agencies' level of experience with Leader-Follower systems, and the results are shown in Table 3-4. Only 9 percent of respondents (4 agencies) indicated that they have implemented Leader-Follower TMA systems, while 44 percent of agencies (19 agencies) are exploring or have previously explored the use of Leader-Follower TMA systems. The remaining 47 percent (20 agencies) are not currently exploring the potential use of Leader-Follower TMA systems. A map showing the responses to this question by state is shown in

Figure 3-2. The results from this question were used to implement skip logic to ask pertinent questions to each of the three groups.

Table 3-4. Survey results for level of experience with Leader-Follower TMA systems (Question 4)

Level of experience	Response
My agency has implemented Leader-Follower TMA systems	9%
My agency is currently exploring or has previously explored the potential use of Leader-Follower TMA systems	44%
My agency is not currently exploring the potential use of Leader-Follower TMA systems	47%

Number of respondents who viewed question = 43

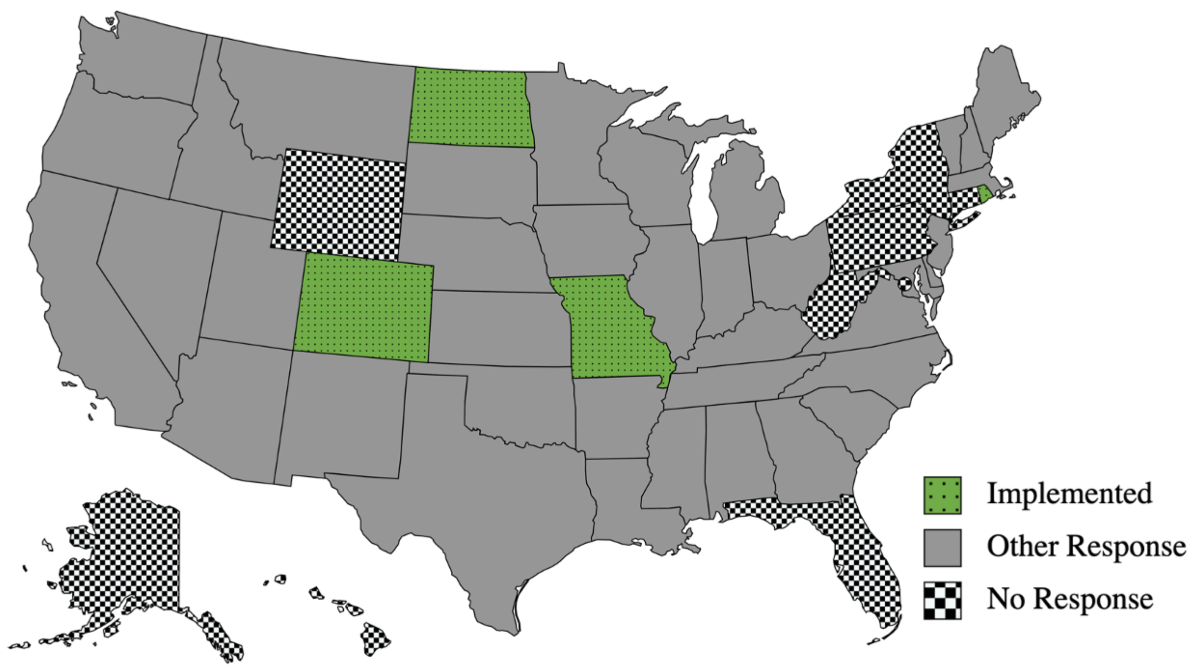


(Ohio TA = Not Exploring, Pennsylvania TA = No Response)
(Map created with mapchart.net ©)

Figure 3-2. Map showing status of implementation or exploration of Leader-Follower TMA systems by agency

<u>Agencies Implementing Leader-Follower TMA Systems</u>

Questions 5 through 14 of the survey were shown to the four agencies who responded that they have implemented Leader-Follower TMA systems. A map of these agencies is shown in Figure 3-3. These questions covered various topics related to implementation, such as types of operations and facilities, development of resources, performance, and implementation challenges.



(Map created with mapchart.net ©)

Figure 3-3. Map showing agencies that have implemented Leader-Follower TMAs

Questions 5 through 7 of the survey asked respondents about types of operations and facilities and number of Leader-Follower TMA units. As shown in Table 3-5, 75 percent of the agencies who viewed this question use Leader-Follower TMA systems for lane striping, while half of the agencies use them for pothole patching and sweeping. Regarding facility types, 75 percent of the four agencies deploy Leader-Follower TMA systems on urban or rural freeways, while half of the agencies use them on multi-lane highways or rural two-lane highways (Table 3-6). In response to Question 7, half of the agencies indicated that they have one Leader-Follower TMA unit, while the other half has two to three units (Table 3-7).

Table 3-5. Survey results for types of operations for Leader-Follower TMA systems (Question 5)

Type of operation	Response
Pavement testing	0%
Pothole patching	50%
Striping	75%
Sweeping	50%
Trash pick-up	0%
Weed spraying	0%
Other (please describe)	0%
No Response	0%

Number of respondents who viewed question = 4

Table 3-6. Survey results for facility types for Leader-Follower TMA systems (Question 6)

Facility Type	Response
Arterials	0%
Multi-lane highways	50%
Rural freeways	75%
Rural two-lane highways	50%
Urban freeways	75%
Other (please describe)	0%
No Response	0%

Number of respondents who viewed question = 4

Table 3-7. Survey results for number of Leader-Follower TMA units (Question 7)

Number of Leader-Follower TMA Units	Response
1	50%
2 to 3	50%
4 to 5	0%
6 or more	0%
No Response	0%

Number of respondents who viewed question = 4

As shown in Table 3-8, 75 percent of the four agencies have developed test plans or training materials to support their implementation of Leader-Follower TMA systems. Other resources developed include evaluation studies, operational guidelines, and performance specifications.

Table 3-8. Survey results for resources developed to support implementation of Leader-Follower TMA systems (Question 8)

Resource	Response
Evaluation studies	50%
Operational guidelines	25%
Performance specifications	50%
Test plan	75%
Training materials	75%
My agency has not developed any resources to support implementation of Leader-Follower TMA systems	25%
Other (please describe)	0%
No Response	0%

Number of respondents who viewed question = 4

Questions 9 through 11 asked the four agencies that have implemented Leader-Follower TMAs about various aspects of performance, including performance ratings, performance measures, and types of data used to evaluate performance. As shown in Table 3-9, 75 percent of the four agencies rated the performance of the system as a 4 out of 5, while the remaining agency gave a performance rating of 2 due to some issues with getting the system up and running. This results in an average performance rating of 3.5 out of 5. The survey results for Question 10 (Table 3-10) show that various performance measures are utilized to assess implementation of Leader-Follower TMA systems, with longitudinal accuracy, worker injuries, and worker perception of the system being the most frequently used. As shown in Table 3-11, the most frequently used types of data for evaluating the performance of Leader-Follower TMA systems are operator feedback and system log files.

Table 3-9. Survey results for performance ratings for Leader-Follower TMA systems (Question 9)

Rating*	Response
1	0%
2	25%
3	0%
4	75%
5	0%
No Response	0%

* 1 = Highly Ineffective, 5 = Highly Effective
Number of respondents who viewed question = 4

Table 3-10. Survey results for use of performance measures to assess implementation of Leader-Follower TMA system (Question 10)

Performance Measure	Response
Benefit-cost analysis	0%
Emergency stops	25%
Lateral accuracy	25%
Longitudinal accuracy	50%
Loss of communications	25%
Loss of GPS signal	25%
Obstacle detection and avoidance	25%
Turning capabilities	25%
Worker injuries	50%
Worker perception of the system	50%
Other (please describe)	0%
No response	25%

Number of respondents who viewed question = 4

Table 3-11. Survey results for types of data collected to evaluate the performance of Leader-Follower TMA systems (Question 11)

Types of data	Response
Field observations	50%
Operator feedback	75%
System log files	75%
Video data	25%
Other (please describe)	0%
No response	25%

Number of respondents who viewed question = 4

Questions 12 through 14 of the survey asked about implementation challenges, interest in possible system enhancements, and willingness to participate in a follow-up interview. As shown in Table 3-12, the highest ranked challenges to implementation include lack of agency buy-in, maintenance cost of the system, and technology cost. Factors not viewed as significant challenges to implementation include contracting considerations, lack of perceived need, legislative authority, and training needs. Half of the four agencies indicated an interest in enhancements or additional features for Leader-Follower TMA systems (Table 3-13). Three of the four agencies responded that they were willing to participate in a follow-up interview (Table 3-14).

Table 3-12. Survey responses for challenges to the implementation of Leader-Follower TMAs (Question 12)

Concern	Rank = 1	Rank = 2	Rank = 3	No ranking of 1, 2, or 3
Contracting Considerations	0%	0%	0%	100%
Funding Constraints	0%	0%	50%	50%
Lack of Agency Buy-In	25%	0%	0%	75%
Lack of Availability of Personnel	0%	25%	0%	75%
Lack of Perceived Need	0%	0%	0%	100%
Legislative Authority	0%	0%	0%	100%
Maintenance Cost of System	25%	0%	0%	75%
Performance Measures	0%	0%	25%	75%
Technology Cost	25%	25%	0%	50%
Training Needs	0%	0%	0%	100%
Unable to Achieve Desired Technical Performance	0%	25%	0%	75%
Other (Please describe)	0%	0%	0%	100%

Number of respondents who viewed question = 4
Number of responses = 4

Table 3-13. Survey results for interest in enhancements or additional features for Leader-Follower TMA systems (Question 13)

Answer Choice	Response
Yes	50%
No	50%
No Response	0%

Number of respondents who viewed question = 4

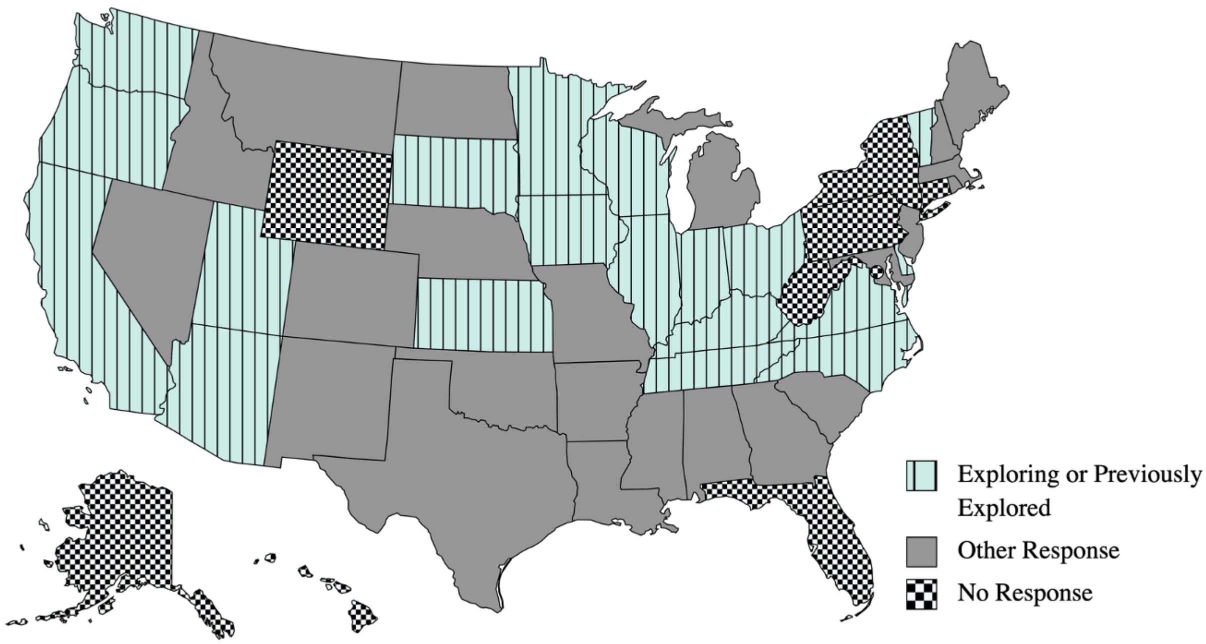
Table 3-14. Survey results for willingness to participate in follow-up interview to discuss implementation practices for Leader-Follower TMA systems (Question 14)

Answer Choice	Response
Yes	75%
No	0%
No response	25%

Number of respondents who viewed question = 4

Agencies Exploring Leader-Follower TMA Systems

Questions 15 through 19 of the survey were shown to the 19 agencies who responded that they are exploring or have previously explored implementation of Leader-Follower TMA systems. A map of these agencies is shown in Figure 3-4. These questions covered various topics related to exploration, such as status of exploration, development of resources, and performance measures.



(Ohio DOT = Exploring or Previously Explored)
(Map created with mapchart.net ©)

Figure 3-4. Map showing agencies that are exploring or have previously explored implementation of Leader-Follower TMAs

Question 15 asked agencies about the status of their exploration of Leader-Follower TMA systems. As shown in Table 3-15, approximately half of the agencies are in the process of gathering information, while 21 percent of the agencies are planning and conducting pilot testing or previously explored Leader-Follower TMA systems and decided not to implement them. Other responses included creation of a specifications sheet and participation in the Autonomous Maintenance Technology Pooled Fund.

Table 3-15. Survey results for status of exploration of Leader-Follower TMA systems (Question 15)

Status	Response
Gathering information	47%
Developing specifications/procurement documents	0%
Planning or conducting pilot testing	21%
Previously explored and decided not to implement	21%
Other (please describe)	11%
No Response	0%

Number of respondents who viewed question = 19

In response to Question 16, nearly two thirds of the agencies exploring the use of Leader-Follower TMA systems indicated that they have not developed any resources in support of potential implementation (Table 3-16). Approximately one quarter of the agencies have prepared evaluation or feasibility studies. Some agencies have also developed performance specifications or test plans.

Table 3-16. Survey results for development of resources to support potential implementation of Leader-Follower TMA systems (Question 16)

Resource	Response
Evaluation or feasibility studies	26%
Operational guidelines	0%
Performance specifications	11%
Test plan	16%
My agency has not developed any resources in support of potential implementation of Leader-Follower TMA systems	63%
Other (please describe)	0%
No Response	11%

Number of respondents who viewed question = 19

As shown in Table 3-17, agencies are interested in seeing data for a wide range of performance measures to help increase their comfort level with the Leader-Follower TMA technology. Agencies are most interested in reviewing performance data for loss of communications, loss of GPS signal, and obstacle detection and avoidance. Other responses included real costs.

Table 3-17. Survey results for interest in performance measures for Leader-Follower TMA systems (Question 17)

Performance Measure	Response
Benefit-cost analysis	58%
Emergency stops	63%
Lateral accuracy	63%
Longitudinal accuracy	68%
Loss of communications	79%
Loss of GPS signal	79%
Obstacle detection and avoidance	79%
Turning capabilities	58%
Worker injuries	42%
Worker perception of the system	47%
Other (please describe)	26%
No Response	5%

Number of respondents who viewed question = 19

Question 18 of the survey asked about challenges to potential implementation of Leader-Follower TA systems, and the results are shown in Table 3-18. The highest ranked challenges include an inability to obtain the desired performance, funding constraints, and the need for data on performance. Challenges ranked the lowest are other initiatives as a higher priority, lack of agency buy-in, and lack of perceived need. Other challenges noted included operations policy and procedures.

Table 3-18. Survey responses for challenges to the potential implementation of Leader-Follower TMAs (Question 18)

Concern	Rank = 1	Rank = 2	Rank = 3	No ranking of 1, 2, or 3
Contracting Considerations	11%	0%	5%	84%
Funding Constraints	21%	5%	0%	74%
Lack of Agency Buy-In	0%	0%	11%	89%
Lack of Availability of Personnel	11%	11%	0%	79%
Lack of Perceived Need	0%	5%	5%	89%
Legislative Authority	11%	0%	5%	84%
Maintenance Cost of System	0%	21%	5%	74%
Need for Data on Performance	0%	26%	11%	63%
Other Initiatives are Higher Priority	0%	5%	0%	95%
Technology Cost	0%	5%	21%	74%
Unable to Achieve Desired Technical Performance	32%	0%	11%	58%
Other (Please describe)	5%	5%	5%	84%

Number of respondents who viewed question = 19

As shown in Table 3-19, 79 percent of the agencies exploring the use of Leader-Follower TMA systems indicated that they would be willing to participate in a follow-up interview to discuss their experiences with exploring Leader-Follower TMA systems.

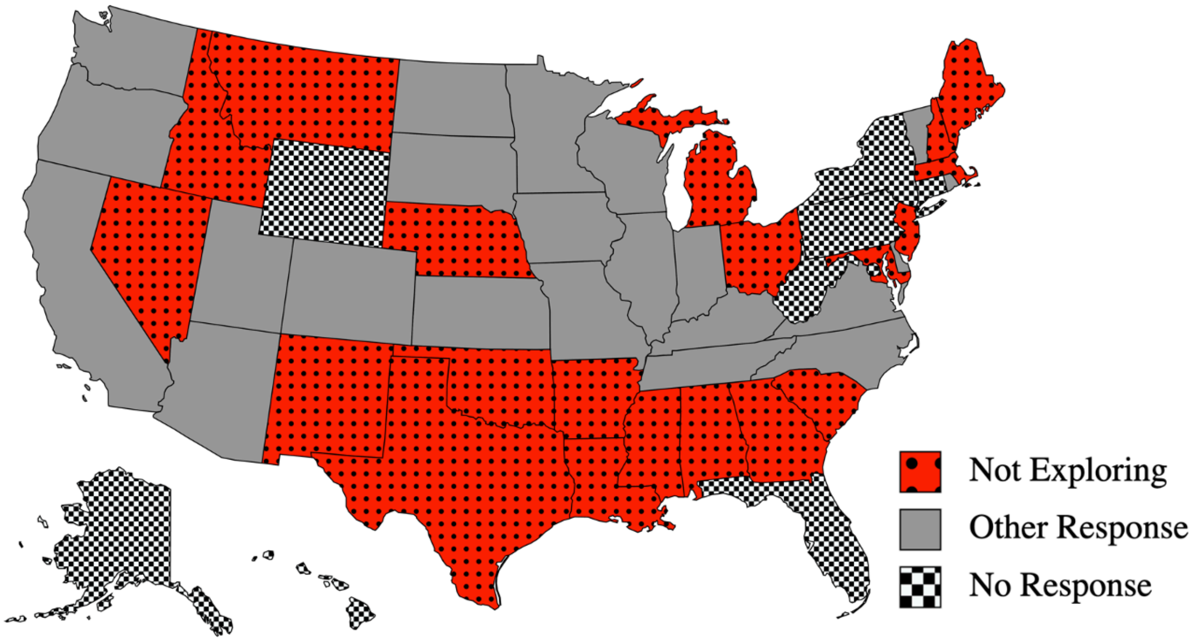
Table 3-19. Survey results for willingness to participate in a follow-up interview to discuss exploration of Leader-Follower TMA systems (Question 19)

Answer Choice	Response
Yes	79%
No	16%
No response	5%

Number of respondents who viewed question = 19

Agencies Not Implementing or Exploring Leader-Follower TMA Systems

Question 20 of the survey was shown to the 20 agencies who responded that they are not exploring the use of Leader-Follower TMA systems. A map of these agencies is shown in Figure 3-5. This survey question sought information regarding the reasons that these agencies are not exploring Leader-Follower TMA systems, and the results are shown in Table 3-20. These results indicate that the most frequently cited reasons are lack of data on system performance and other initiatives are a higher priority. Lack of available personnel and legislative authority were the least frequently cited reasons. Lack of awareness of the technology was also mentioned by three responding agencies in the “Other” responses. Other reasons cited by respondents include a lack of need due to primarily using flagger operations in work zones and a focus on other devices.



(Ohio TA = Not Exploring)
(Map created with mapchart.net ©)

Figure 3-5. Map showing agencies that are not exploring Leader-Follower TMA systems

Table 3-20. Survey results for reasons why agencies are not exploring Leader-Follower TMA systems (Question 20)

Reason	Response
Cost	20%
Lack of availability of personnel	15%
Lack of identified funding	20%
Lack of information regarding the technology	0%
Lack of data on system performance	30%
Lack of legislative authority	10%
Lack of perceived need	20%
Other initiatives are higher priority	25%
Other (please describe)	35%
No Response	0%

Number of respondents who viewed question = 20

General Comments

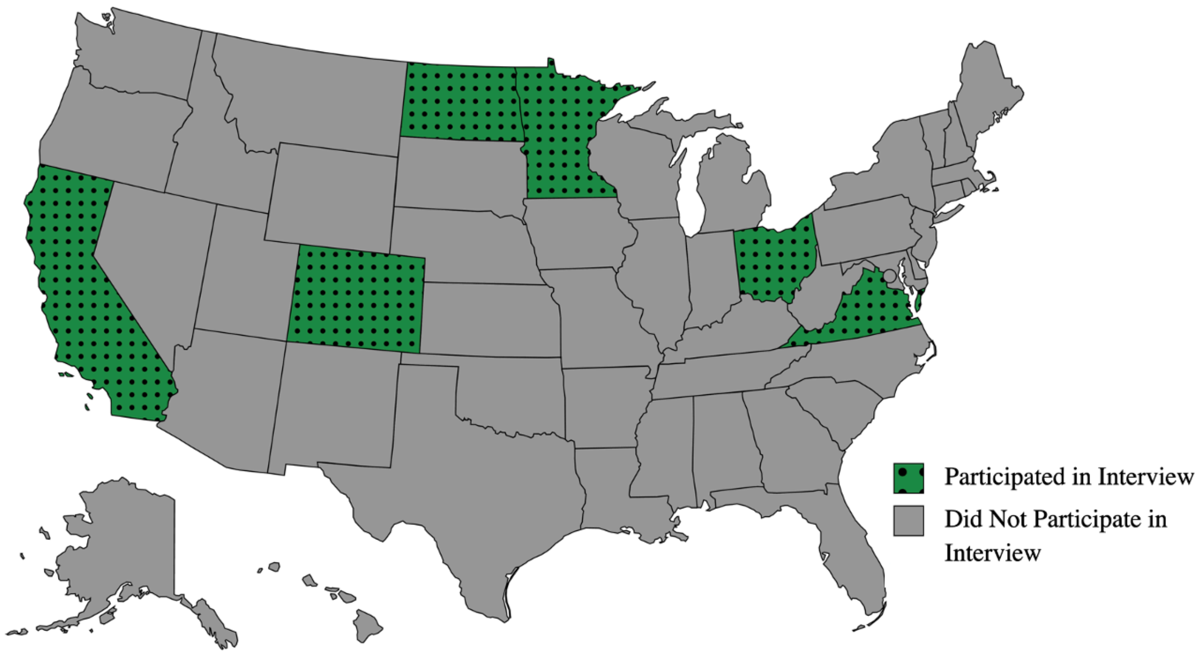
The final question of the survey gave all respondents an opportunity to provide additional comments. In general, the comments indicated interest in the system as a tool to help improve worker safety. A full list of the comments received for this question is provided in Appendix C.

Pennsylvania DOT and Pennsylvania Turnpike Commission did not respond to the survey but provided some information by email. Pennsylvania DOT indicated that they have not yet procured a Leader-Follower TMA system due to budget impacts from the Covid-19 pandemic. Pennsylvania Turnpike Commission indicated that they were waiting for deployment and evaluation from Pennsylvania DOT.

DOT Interviews

Overview of DOT Interviews

In addition to the survey, follow-up interviews were conducted with six DOTs (Figure 3-6) to learn more about their implementation or exploration of Leader-Follower TMA systems. Two of the interviewees have implemented Leader-Follower TMA systems, and four interviewees are exploring or have previously explored Leader-Follower TMA systems. Criteria for selection included status of implementation or exploration, geographic diversity, and willingness to participate in a follow-up interview as indicated by the survey.



(Map created with mapchart.net ©)

Figure 3-6. Map showing DOTs that participated in follow-up interviews

Results from DOT Interviews

This section presents the results of the interviews for each state DOT.

California

Caltrans completed a research phase for Leader-Follower TMA systems and is preparing to do road testing on a long section of I-8 in 2023. The research phase included closed course testing using a test plan with 23 scenarios (Esfandabadi 2019). An issue encountered during the research phase was the tendency of the follower vehicle to lose signal and swerve abruptly when the leader vehicle was passing under long bridges. This concern was resolved by the vendor.

Caltrans is interested in potentially using the system in the future for all moving operations, such as lane striping, sweeping, and mowing. A major challenge to full implementation is a state law that requires a safety driver in the vehicle. A change in legislation is needed to allow the follower vehicle to operate without a safety driver or operator in the vehicle. Caltrans is also concerned about a scenario where the driver needs to exit the leader vehicle to reset the system after an E-Stop that could occur if another vehicle comes between the leader and follower vehicles. Caltrans would like to see if the follower vehicle could be remotely started in this scenario. Generally, Caltrans employees are supportive of the system, although there are some concerns about employees being replaced by an automated system. Caltrans would like to learn more about the plans of other state DOTs for the system. Looking to the future, Caltrans is interested in seeing if a Leader-Follower TMA system with zero emissions could be developed.

Colorado

CDOT uses the Leader-Follower TMA system shown in Figure 3-7 for lane striping on highways with annual daily traffic (ADT) less than 5,000 vpd in Regions 4 and 5. The follower vehicle is driverless, and the safety driver operates the system console from the leader vehicle while facing the follower vehicle. CDOT has taken a phased approach to implementation, with an initial deployment limited to striping on roads in Region 4 with ADT less than 2,500 vpd (Colorado DOT 2020). The initial interest in the technology originated from CDOT management. The original implementation process included procurement of a Hino TMA from Royal Truck and equipment, installation of leader and follower kit, and validation testing and training. The second set up uses a new International Truck body TMA vehicle that matches CDOT's fleet program build. The validation testing for Region 5 consisted of 15 scenarios, such as follow distance, lane change, and GPS-denied environment (Colorado DOT 2022b). As part of the Region 5 deployment, CDOT developed its own training, including two days of classroom and hands on-training, group exercises, and an exam. CDOT is the lead state for the AMT pooled fund, which is developing a community for the state of the practice (Colorado DOT 2022e).

(Colorado DOT 2022a)

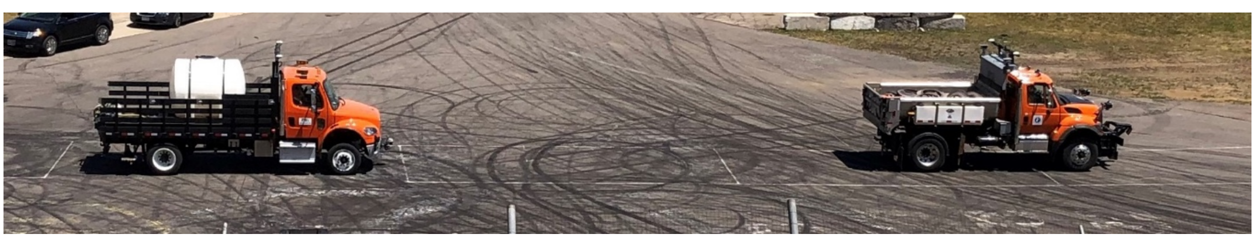
Figure 3-7. Leader and Follower TMAs used by Colorado DOT

Overall, CDOT finds the system to be effective. Performance measures tracked by CDOT include the number of hours and miles of use. Feedback from the public and news media has been positive. CDOT is interested in exploring future expansion of the system to incorporate other CDOT regions, higher traffic volumes, and other operations such as sweeping or mowing. As noted by CDOT personnel, the challenges are not always technical and can include procurement, operations, and legislation. CDOT found bringing together a multidisciplinary team for implementation to be beneficial, as CDOT implementation efforts started with maintenance and operations. CDOT also noted the importance of building trust with the operator crew and having patience when working through system challenges.

The research team also obtained operator feedback from CDOT personnel regarding training, initial learning curve, and system performance. The operator feedback indicated that the training, which covered operating systems for both the lead and follower vehicles, was very thorough and beneficial. The operators found the initial learning curve to be very challenging, but their level of comfort increased as they gained more experience with the system. The operators noted the safety benefits of removing the driver from the follower vehicle, although they indicated a concern with the driver walking from the leader vehicle to the follower vehicle if there is an issue with the follower vehicle. The operators rated the overall system performance as 7 out of 10 and expressed interest in seeing operations expanded to include tunnel washing and mowing. The operators noted some challenges with the system. They indicated that sharp curves and excessive dips or bumps can cause communication issues between the leader and follower vehicle. In addition, establishing the initial link between the leader and follower vehicles can sometimes take a lot of time. General advice from the operators for other users of the system includes checking the system components regularly, follow the training, trust in the system, and maintain a positive outlook.

<u>Minnesota</u>

The Minnesota Department of Transportation (MnDOT) is in the process of testing a Leader-Follower system (Figure 3-8) from Kratos (Minnesota DOT 2021). After acceptance, there will be a 28-month warranty period with ongoing on-call support. Since MnDOT utilizes the same vehicle for winter operations, the system needs to be de-commissioned at the end of the season and re-commissioned in the spring. MnDOT participates in the AMT pooled fund. A change in Minnesota state law is needed to allow the driver to be removed from the follower vehicle.



(Minnesota DOT 2021)

Figure 3-8. Leader-Follower TMA configuration for Minnesota DOT

MnDOT began testing the system in 2021 on a closed course, followed by testing on a county road and then on MnDOT facilities. Initial training in 2021 and refresher training for software updates in 2022 were provided. In 2021, the system was tested for shoulder repair and guardrail repair in Lakeville. MnDOT is testing the system for lane striping in District 6 (Rochester) in 2022 to gain experience in a more rural context.

MnDOT generates performance measures from the log data but finds developing ways to estimate the safety benefits of the system to be challenging. MnDOT has had some success with the system performance, although there have been some issues. The follower vehicle had trouble with picking up E-Crumbs at very low speeds (under 3 mph) for the guardrail repair. The vendor resolved the issue by adding a sensor to monitor the drive shaft. The follower vehicle also tended to veer to the left when deprived of GPS in the shop, and this issue was also resolved by the vendor. MnDOT continues to experience issues with GPS limiting deployments.

Feedback from MnDOT employees included suggested use on lower volume roads, the need for a larger screen in the leader truck, and concerns regarding fast acceleration of the follower vehicle when catching up, bringing vehicles closer for ramps or turn lanes, and interactions with emergency vehicles (Minnesota DOT 2021).

North Dakota

The North Dakota Department of Transportation (NDDOT) has implemented one Leader-Follower TMA unit from Kratos in the Fargo District. The unit was acquired in 2020 using funds from the Accelerated Innovation Deployment (AID) Demonstration Program. NDDOT has logged approximately 50 to 60 hours of use with the system, including training. Initial testing was performed on a closed course and then Old Highway 10. NDDOT has used the system for slow moving operations such as sweeping on I-29. NDDOT has not implemented the Leader-Follower system for lane striping because it contracts lane striping operations. An employee is still in the seat of the follower vehicle for testing. NDDOT uses data from the system log files to assess performance.

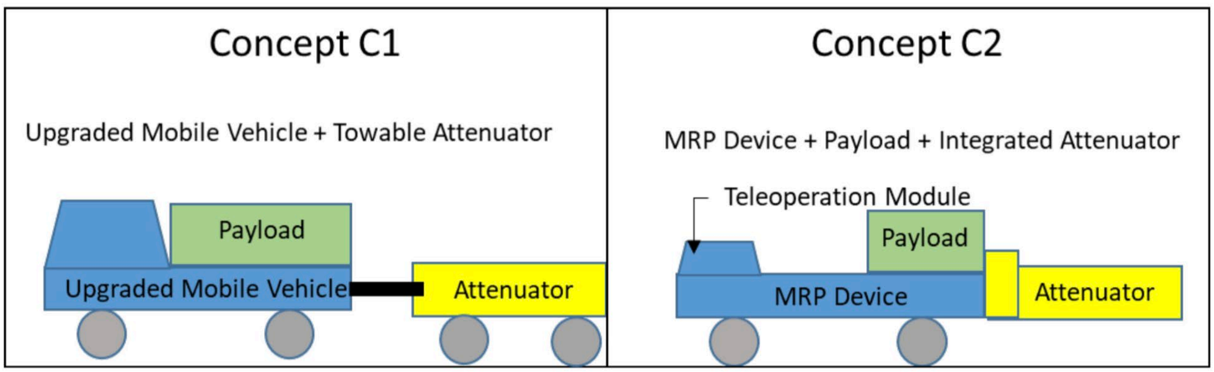
NDDOT finds value in the system, and employees generally feel comfortable using it. Media outreach to increase awareness of the system was received positively. NDDOT would like to see some improvements in the reliability of the system, especially with regard to losing GPS signal. NDDOT sometimes finds it difficult to get the system to connect during the initialization procedure. In addition, some connectors needed to be replaced. NDDOT has also found the need for a champion at the district level to be a challenge to implementation.

Ohio

The Ohio Department of Transportation (ODOT), which participates in the AMT pooled fund, sponsored a research study that developed functional requirements for two types of systems: Upgraded Mobile Vehicle and Mobile Remote Platform (Mandokhot et al. 2022). As shown in Figure 3-9, the Upgraded Mobile Vehicle with a towable attenuator would be driven by the operator to the work zone and then function in the work zone without a driver, while the Mobile Remote Platform with an attached attenuator would be driven or towed to the work zone and operated remotely. The scope of the study included three major tasks: ODOT Work Zone

Analysis, Market Survey, and Specification Development. A Request for Information (RFI) was issued to obtain vendor feedback. An analysis of work zone crashes from 2016 to 2020 found that 166 crashes could potentially have benefited from the system. The study found the system to be technically feasible and developed a tool to help assess the economic feasibility of the system.

ODOT plans to pursue a second phase of the study to move towards implementation of the system. However, ODOT has not been able to proceed with Phase 2 of the study due to a lack of researcher availability to undertake the study. ODOT would also like to find newer trucks to host the system. ODOT personnel seem to be very interested in the system. ODOT has gained valuable information on the system from the AMT pooled fund and is interested in information on any performance measures developed through the pooled fund.

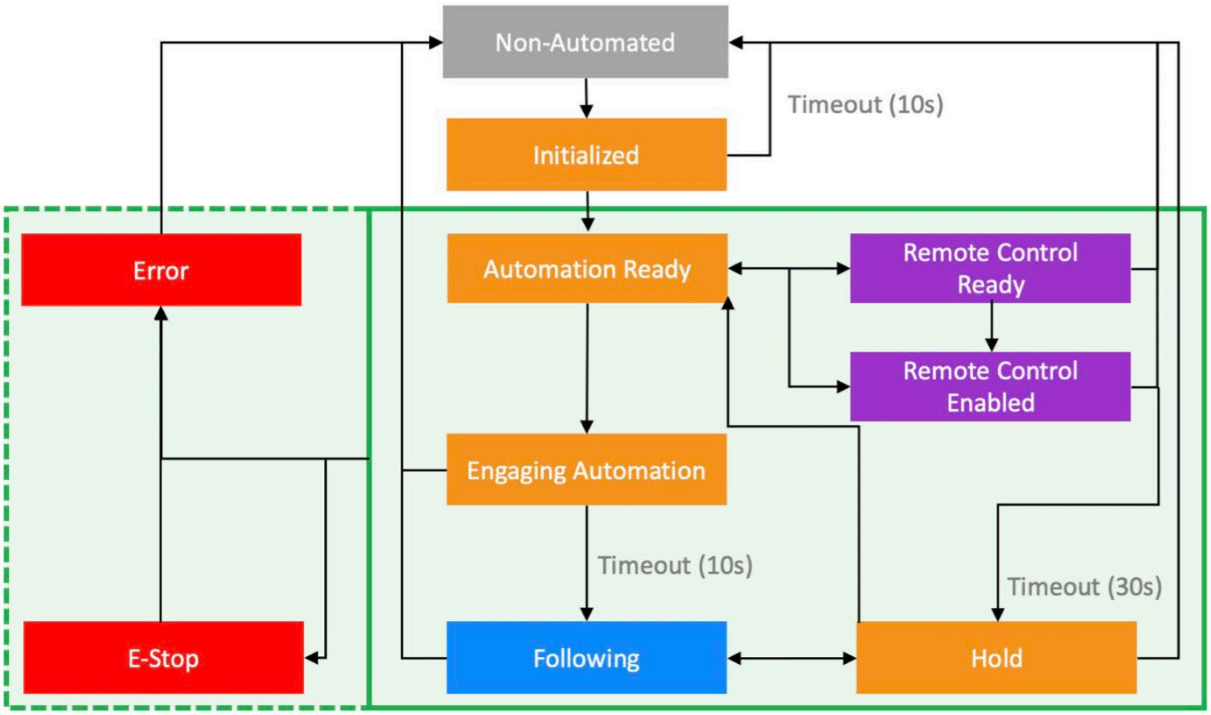


(Mandokhot et al. 2022)

Figure 3-9. Proposed concepts of alternative vehicle for ODOT study

<u>Virginia</u>

In Virginia, a Leader-Follow TMA system was developed through a collaborative consortium comprised of VTTI, VDOT, dBi Services, and Transurban. As discussed in Chapter 2 of this report, a Phase 1 study, including testing on a closed track, was completed in 2021 (White et al. 2021). Study results indicated that the system operated successfully for the following conditions: speeds of 15 mph or less, reliable GPS signal present, following distances between 50 feet and 400 feet, and lateral offsets of plus or minus 12 feet. A diagram showing system states is shown in Figure 3-10. The system also uses LiDAR for detection of obstacles and includes an HMI tablet that allows the lead operator to control the follower vehicle. In addition, the system can be operated remotely with a joystick with a range of 1600 feet.



(White et al. 2021)

Figure 3-10. System states for Virginia Leader-Follower TMA

Following some delays due to a change in ownership of the equipment, a consortium consisting of VTTI, VDOT, and DeAngelo Contracting Services began a Phase 2 study in 2022. The Phase 2 study is exploring operation in a GPS-denied environment using a higher performance LiDAR unit and a camera-based perception system. It has a goal of implementation of the system on higher speed facilities (45 mph or less). In addition, the study is also investigating improvements to sensing and localization components, an enhanced rear radar system to monitor traffic, optimization of equipment to make it less expensive to manufacture and run, and ways to commercialize the system. Real world testing on highway facilities is anticipated in 2023.

Implementation challenges for VDOT include system performance in a GPS-denied environment, the change in ownership of the equipment which led to delays, and the lack of a law related to automated operation of the vehicle. The Phase 2 study is expected to address the operation in a GPS-denied environment through the use of a supplementary system.

Summary of Agency Practices

Agency practices regarding the implementation or exploration of Leader-Follower TMA systems are summarized below.

- Among the 43 agencies that completed the survey, the breakdown of implementation or exploration status is as follows: four agencies have implemented Leader-Follower TMA systems, 19 agencies are exploring or have previously explored Leader-Follower TMA systems, and 20 agencies are not exploring the potential use of Leader-Follower TMA systems.
- Agencies are currently using Leader-Follower TMA systems for pothole patching, lane striping, and sweeping on various types of facilities, including freeways, multi-lane highways, and rural two-lane highways.
- Various performance measures are used to assess implementation of Leader-Follower TMA systems, with longitudinal accuracy, worker injuries, and worker perception of the system being the most frequently used. Most agencies that have implemented the system are generally satisfied with the system. There are some concerns regarding reliability of the system, especially with regard to losing GPS signal.
- Among the four DOTs that have implemented Leader-Follower TMA systems, the highest ranked challenges to implementation in the survey include lack of agency buy-in, maintenance cost of the system, and technology cost. Other non-technical challenges, such as procurement, operations, legislation, were also noted.
- Two Leader-Follower TMA systems have been evaluated by agencies: the Kratos system and the system developed by the consortium in Virginia.
- Approximately half of the agencies exploring the potential use of Leader-Follower TMA systems are in the process of gathering information.
- Agencies that are exploring the potential use of Leader-Follower TMA technology are most interested in reviewing performance data for loss of communications, loss of GPS signal, and obstacle detection and avoidance.
- In the survey, agencies exploring the potential use of Leader-Follower TMA technology ranked an inability to obtain the desired performance, funding constraints, and the need for data on performance as the highest challenges to implementation.
- The survey results identified lack of data on system performance and other initiatives being a higher priority as the most frequently cited reasons agencies are not exploring the use of Leader-Follower TMA systems.
- In some states, a change in legislation is needed to allow the follower vehicle to operate without a safety driver or operator in the vehicle.

4. FIELD STUDY

This chapter presents the methodology and results for the field study of Leader-Follower TMA systems. The field study included observations of the system in operation, collection of video data, and analysis of system log data.

Field Study Methodology

Field Study Overview

The field study included observations of the Leader-Follower TMA system in operation in both the Southwest and Kansas City Districts. The research team made three field visits to the Southwest District and one field visit to the Kansas City District. The first visit to Southwest District office in Springfield occurred on May 23, 2022. MoDOT employees provided an overview of the system and demonstrated the process for initializing the system in a parking lot. The initialization process, which involved going through a series of pre-operational checks on a tablet, appeared to be straightforward. An example pre-operational check is shown in Figure 4-1. The user interface after initialization is shown in Figure 4-2. The research team also observed the Leader-Follower TMA system in operation from the shoulder on US 65, as shown in Figure 4-3.

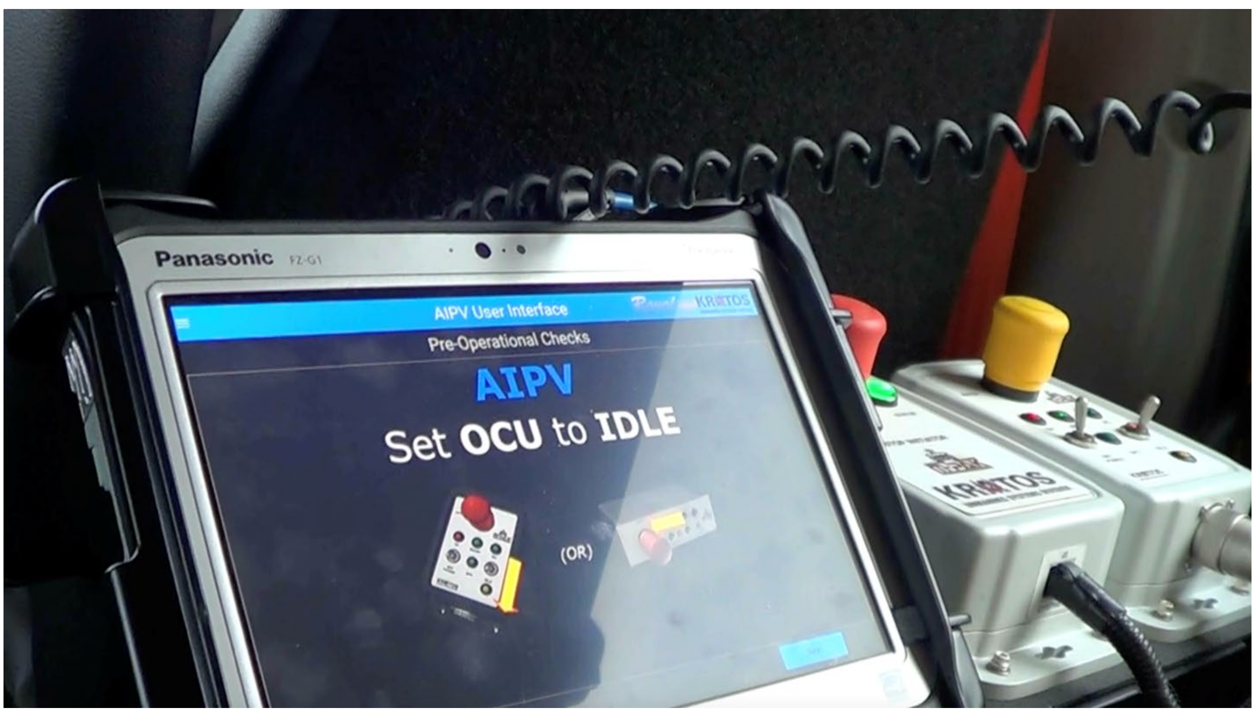


Figure 4-1. Example pre-operational check for Leader-Follower TMA system

Figure 4-2. User interface for Leader-Follower TMA system after initialization

Figure 4-3. Leader-Follower TMA system traveling on US 65 near Branson, Missouri

The research team made a second field visit to the Southwest District on June 21, 2022, to set up and test the instrumentation for the collection of video data. Details of this instrumentation are provided in subsequent sections of this report. The research team did not ride in the leader or follower vehicles but collected several hours of video data on MO 13 just north of Springfield.

The research team rode along with MoDOT employees in the leader and follower vehicles during nighttime lane striping work on US 65 in Springfield on July 10 and 11, 2022. Two researchers rode in the leader vehicle, and one researcher traveled in the follower vehicle. Thus, the researchers were able to observe the system in operation from the vantage point of MoDOT employees. In addition, approximately seven hours of video data were collected. During this shift, there were two trips back to the Southwest District garage to reload paint and beads.

The research team also rode along with MoDOT employees in the leader and follower vehicles during daytime lane striping work on US 50 near Kansas City on October 14, 2022. Again, there were two researchers in the leader vehicle and one researcher in the follower vehicle. Approximately three hours of video data were collected.

Overview of Data Log Files

The Leader-Follower TMA system collects data including the state of the system, GPS coordinates, lateral offset, desired lateral offset, heading, desired heading, velocity, desired velocity, gap distance, and desired gap distance for both leader vehicle and follower ATMA per

0.05 second. The system uploads to the Kratos server which helps to access the log files remotely.

Methodology for Analysis of Data Log Files

The log files recorded the status of the Leader-Follower TMA system in operation, and then they were uploaded to Kratos for remote analysis and support. The log files were shared with the research team by Kratos to further analyze each case for A-stops and DRs, time to reconnect to the system, the difference between actual gap distance and desired gap distance, and the difference between actual speed and desired speed. The raw log files on the day of the field study were compiled into one spreadsheet and cleaned to ensure format consistency.

The spreadsheet file structure was as follows:

> TIMESTAMP, VEH, STATE, NAV_STATE, STAMP, GPS_LAT, GPS_LON, ALT, #SATS, VELOCITY, VEL(Desired), GAP, GAP(Desired), NOTES.

Where,

> TIMESTAMP = Time in UTC (HH:MM:SS.ms)
>
> VEH = Vehicle (FLW = Follower; LDR = Leader)
>
> STATE = System state (IDLE = manually controlled by operator; ROLLOUT = beginning autonomous plan; RUN = autonomous mode; RUN_PAUSE = temporarily pause automatic mode; ASTOP = automatic stop)
>
> NAV_STATE = Navigation state (READY = the navigation system is ready; DEADRECKONING = the navigation system is in DR mode)
>
> GPS_LAT = GPS latitude in degrees
>
> GPS_LON = GPS longitude in degrees
>
> ALT = Altitude in meters above sea level
>
> #SATS = Number of satellites acquired (count)
>
> VELOCITY = Speed (velocity) in miles per hour

VEL (DESIRED) = The speed of the leader TMA vehicle

GAP = Gap distance in meters

GAP(DESIRED) = The gap the vehicle is trying to maintain

NOTES = Notes of warning information (e.g., Adjacent object detected on left side LIDAR.##)

The details of A-Stops and DRs (i.e., TIMESTAMP, GPS_LAT, GPS_LON, and STATE) were screened out first. Then, the possible cause of A-Stops and DRs were identified with the use of field video data and street view in Google Earth Pro. Secondly, the durations of A-Stops and DRs were calculated between the first timestamp and the last timestamp of the same state (i.e., ASTOP and DEADRECKONING), while the time to reconnect to the system was measured by the duration of the "IDLE" state of the system until the system changed to “GO” mode. Thirdly, the gap measures were filtered one more time to avoid the sudden changes due to ROLLOUTS and RUN_PAUSE. Before rollout, the leader and follower TMAs need to line up and stop at a recommended gap distance of 200 feet. When the leader TMA began the rollout process, the actual gap was always around 200 feet. However, the value of desired gap was set by the operator (from 25 feet to 1400 feet) and the difference between actual and desired gap distance could suddenly increase. On the other hand, if the operator paused the follower TMA at a location to enhance its visibility to alert drivers, the desired gap would be the same, but the actual gap was continuedly increasing while the autonomous mode was paused. The gap measures were analyzed by calculating the average, verifying the maximum and the minimum value, and standard deviation. Average and standard deviation indicated how the system maintains the actual value compared to the desired value in general operation. All measurements for the gap distance analysis were applied to speed data analysis.

A summary of the Measures of Effectiveness (MOEs) is provided below:

- MOE 1 relates to A-Stops, including the number of A-Stops initiated in total observation, the time to reconnect to the system after an A-Stop initiated, and rollout time after the reconnection.
- MOE 2 concerns instances of DRs, including the number, duration, location, and potential causes for each DR.
- MOE 3 relates to gap distance, including average actual gap distance, average desired gap distance, and the difference between actual and desired gap distance.
- MOE 4 concerns speed, including average actual speed, average desired speed, and the difference between actual and desired speed.

Setup for Video Data Collection

The research team installed a video system consisting of four cameras to record the Leader-Follower TMA system, traffic, and roadway conditions during the operation. The locations and directions of the four cameras are shown in Figure 4-4.

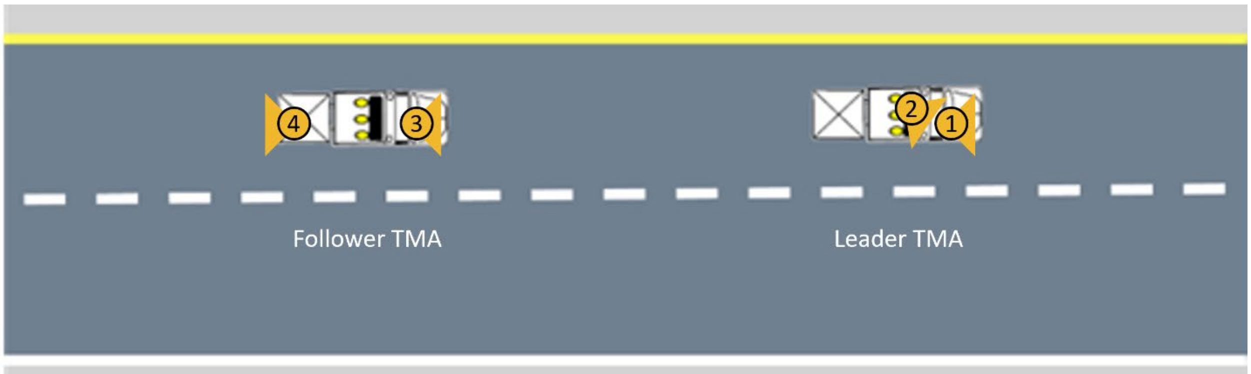


Figure 4-4. Camera locations and directions for video data collection

The setup and field of view (FOV) of the video system are shown in Figure 4-5. Cameras #1 and #3 were mounted near the passenger side windshields inside the leader and follower TMAs using a double suction camera mount and towards the vehicle's direction. These compact cameras could steadily record a FOV of 150 degrees to capture more traffic and roadway conditions without distracting drivers. The videos collected were used to validate the accuracy of vehicle speed and trajectory in the data log file and identify the potential causes of DR, such as bridges, sign structures, and other objects.

Camera #2 was mounted on the rear window inside the leader TMA's cab facing the Leader-Follower TMA console and screen behind the passenger seat. This camera had a tracking focus function to record the information on the screen and the operator's actions. The videos were used to verify the operator's actions and the information from the data log files.

Camera #4 was mounted at the rear end of the follower TMA toward the approaching traffic from behind. Since this camera was installed outside the driving cab, the research team used a camera bracket with two metal loops to hold it tightly. In addition, the camera was set up under the work zone warning sign, so it does not distract any driver behind the follower TMA. The recording videos were used to report any ATMA-related crashes, near calls, and unsafe driving behaviors of following drivers.

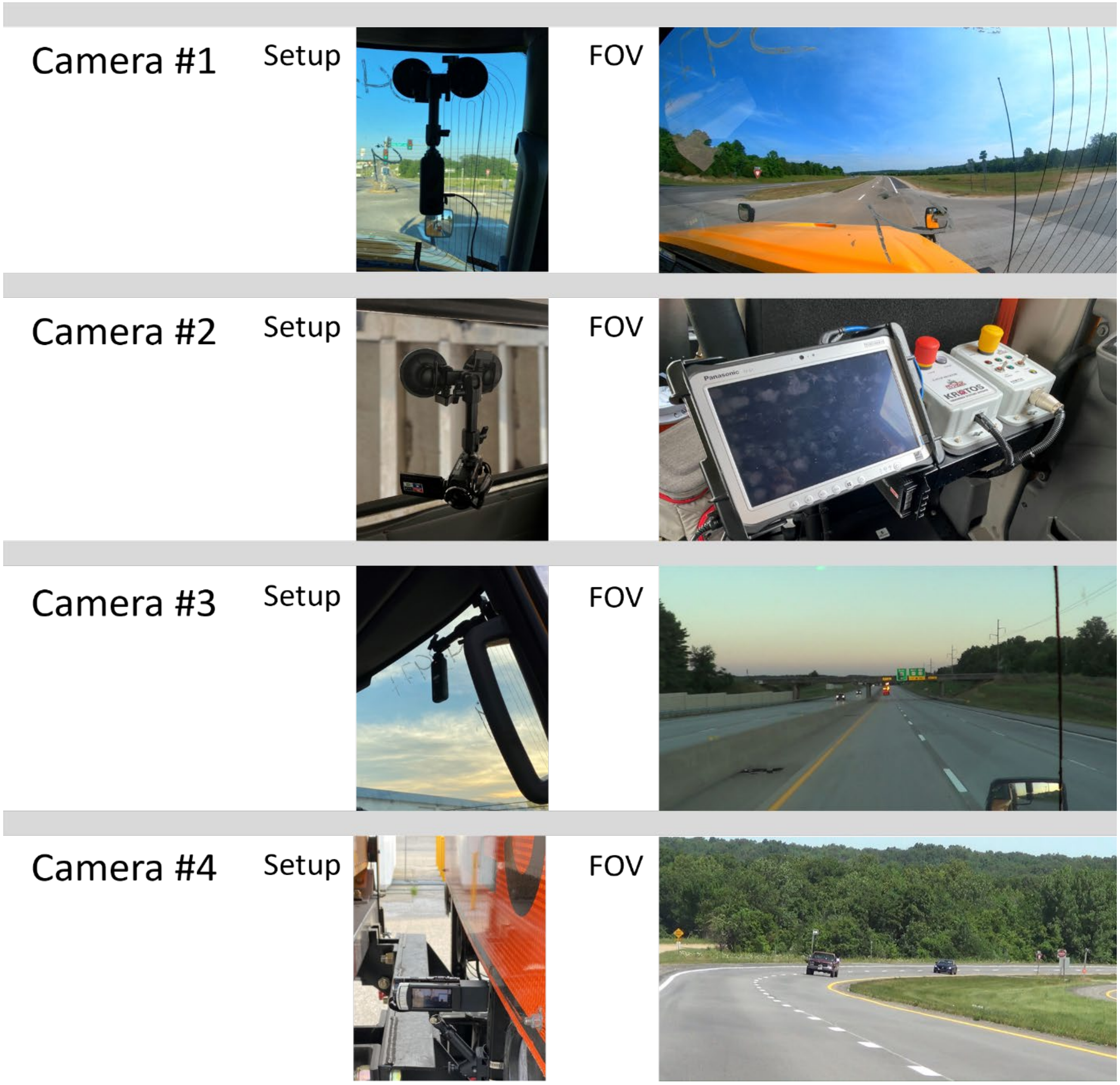


Figure 4-5. Camera setup and FOV

Field Study Results

Results from Log Data

<u>Results from Southwest District Log Data (July 10-11, 2022)</u>

For the first field study, the research team accompanied MoDOT personnel during lane striping work in the Southwest District on US 65 near Springfield from July 10, 2022, at 7:24 pm to July 11, 2022, at 2:57 am. The lane striping crew returned to the garage twice to refill the paint and beads. Therefore, the total duration of the work zone was 5 hours and 13 minutes. Six A-Stops were recorded during the whole shift which comes out as 1.15 A-stops per hour. Four of the A-Stops were triggered by exceeding the time limit of GPS signal loss. By observing the corresponding video, bridge structures were defined as the main issue for these four cases. One other A-Stop happened while rebooting the system after returning from the garage. And the last A-stop happened while reconnecting the system after recovering from one of the A-stops caused by GPS signal loss. These A-Stops took 1 minute and 11 seconds on average to reconnect the system and return to "Go" mode.

The location, probable reason, and duration for each DR instance were identified. Video data and Google Earth were utilized to specify the location with given coordinates to verify the reason for the signal loss. In some cases, DR was triggered twice when both the leader vehicle and follower TMA passed by the same location. In total, 71 DRs were recorded: 31 DRs by bridge structures, 26 DRs by sign trusses, and 14 DRs for unknown reasons. Overall, 13.61 DRs per hour occurred during the whole shift. The average duration to recover the V2V connection and GPS signal was 25.63 seconds.

The Southwest District field data results for gap distance are shown in Table 4-1. The average actual gap distance was 701.39 feet. The average for desired gap distance was 686.02 feet. The standard deviation for desired gap distance was 23.63 feet. Values for desired gap distance ranged from 49.87 feet to 700.16 feet. The average gap distance difference between the actual and desired value was 15.38 feet. The average absolute value of the gap distance difference was 22.03 feet. The maximum gap distance difference was recorded as 429.81 feet which means the actual gap was 429.81 feet longer than the desired gap distance. The minimum gap distance difference was recorded as -148.96 feet which means the actual gap distance was shorter by 148.96 feet compared to the desired gap distance. The standard deviation for the gap distance difference was 16.79 feet.

Table 4-1. Southwest District field data results for gap distance

Parameter	Value
Average gap difference (actual – desired) (feet)	15.38
Average absolute value of gap difference (actual-desired) (feet)	22.03
Maximum gap difference (actual – desired) (feet)	429.81
Minimum gap difference (actual – desired) (feet)	-148.96
Gap difference standard deviation (actual – desired) (feet)	16.79
Average actual gap distance (feet)	701.39
Average desired gap distance (feet)	686.02
Standard deviation of desired gap distance (feet)	23.63
Maximum desired gap distance (feet)	700.16
Minimum desired gap distance (feet)	49.87
Number of observations	69,361

The Southwest District field data results for speed are shown in Table 4-2. The average actual speed was 4.79 mph. The average desired speed was 5.18 mph. The standard deviation of the desired speed was 4.08 mph. Values for desired speed ranged from -14.12 mph (during rollout when the actual speed was 0 mph) to 12.43 mph. The average speed difference between the actual and desired value was -0.39 mph. The average absolute value of the speed difference was 1.097 mph. The maximum speed difference was recorded as 14.12 mph which means the actual speed was 14.12 mph faster than the desired speed. The minimum speed difference was recorded as -8.02 mph which means the actual speed was 8.02 mph slower than the desired speed. The standard deviation for the speed was 2.64 mph.

Table 4-2. Southwest District field data results for speed

Parameter	Value
Average speed difference (actual – desired) (mph)	-0.39
Average absolute value of speed difference (actual-desired) (mph)	1.097
Maximum speed difference (actual – desired) (mph)	14.12
Minimum speed difference (actual – desired) (mph)	-8.02
Speed difference standard deviation (actual – desired) (mph)	2.64
Average actual speed (mph)	4.79
Average desired speed (mph)	5.18
Standard deviation of desired speed (mph)	4.08
Maximum desired speed (mph)	12.43
Minimum desired speed (mph)	-14.12
Number of observations	69,361

Results from Kansas City District Log Data (July 22, 2022)

During interviews with the research team, some MoDOT employees mentioned that software upgrades increased the stability of the system. The research team confirmed with Kratos that a software upgrade was provided in August 2022 for the Kansas City District. A similar upgrade was provided to the Southwest District in April 2022. To assess the impacts of the software upgrade in the Kansas City District, the research team also analyzed the data log file recorded on July 22, 2022 for lane striping work on MO 152 near Sherrydale, Missouri. The total duration of this data was 3 hours 38 minutes, but the system was connected for only 2 hours 36 minutes.

Two A-Stops were triggered, but the written information for the errors on the log file was not available since it was before the software upgrade. Only the coordinates were available, and the potential reason for the first A-stop was DR caused by GPS signal loss due to a bridge structure. After the first A-Stop, the system could not recover until the end of the data collected. The second A-Stop happened while the system was disconnected.

For 2 hours 36 minutes of driving time while the system was connected, 24 DRs were counted which results in 9.23 DRs per hour. Potential causes for DRs were 16 bridges, 5 sign trusses, and 3 undefined instances. There were 26 DRs during the 1 hour and 2 minutes of disconnected time (25.2 DRs per hour).

The Kansas City field data results for gap distance on July 22, 2022, are shown in Table 4-3. The average actual gap distance was 203.58 feet. The average desired gap distance was 191.21 feet. The standard deviation of the desired gap distance was 0.48 feet. The maximum desired gap distance was 200.14 feet, and the minimum desired gap distance was 174.88. The average gap distance difference between the actual and desired value was 12.37 feet. The average absolute value of gap difference was 19.60 feet. The maximum gap distance difference was recorded as 147.65 feet. The minimum gap distance difference was recorded as -92.85 feet. The standard deviation for the gap distance difference was 7.82 feet.

Table 4-3. Kansas City District log data results for gap distance for July 22, 2022

Parameter	Value
Average gap difference (actual – desired) (feet)	12.37
Average absolute value of gap difference (actual – desired) (feet)	19.60
Maximum gap difference (actual – desired) (feet)	147.65
Minimum gap difference (actual – desired) (feet)	-92.85
Gap difference standard deviation (actual – desired) (feet)	7.82
Average actual gap distance (feet)	203.58
Average desired gap distance (feet)	191.21
Standard deviation of desired gap distance (feet)	0.48
Maximum desired gap distance (feet)	200.14
Minimum desired gap distance (feet)	174.88
Number of observations	43,903

Regarding results for speed (Table 4-4), the average actual speed was 6.50 mph. The average desired speed was 6.51 mph. The standard deviation of the desired speed was 2.45 mph. The maximum desired speed was 10.86 mph, and the minimum desired speed was 0.11 mph. The average speed difference between the actual and desired value was -0.006 mph. The average absolute value of speed difference was 0.303 mph. The maximum speed difference was recorded as 2.87 mph. The minimum speed difference was recorded as -7.88 mph. The standard deviation for the speed difference was 0.91 mph.

Table 4-4. Kansas City District log data results for speed for July 22, 2022

Parameter	Value
Average speed difference (actual – desired) (mph)	-0.006
Average absolute value of speed difference (actual – desired) (mph)	0.303
Maximum speed difference (actual – desired) (mph)	2.87
Minimum speed difference (actual – desired) (mph)	-7.88
Speed difference standard deviation (actual – desired) (mph)	0.91
Average actual speed (mph)	6.50
Average desired speed (mph)	6.51
Standard deviation of desired speed (mph)	2.45
Maximum desired speed (mph)	10.86
Minimum desired speed (mph)	0.11
Number of observations	43,903

<u>Results from Kansas City Log Data (October 14, 2022)</u>

For the second field study, the research team also accompanied MoDOT for lane striping work on US 50 near Lee's Summit, Missouri. in the Kansas City District on October 14, 2022, from 8:19 am to 11:27 am. The total duration in the work zone was 3 hours and 8 minutes. Only one A-Stop was activated by a GPS error, which is an average of 0.32 A-stops per hour. The follower truck was manually paused while maintaining the set gap distance with the leader vehicle to protect curves on the highway. The follower truck held on to its location before entering the curve, and after the leader vehicle passed through curves, the follower truck set free to make up the gap distance. Since the follower truck was facing a curve, the camera system could not detect the leader vehicle by sight. Therefore, an A-Stop can easily be triggered by GPS signal loss or V2V connection failure. This GPS error was caused by this process when the gap distance exceeded 1100 feet. The system was disconnected for 50 seconds. It took 20 seconds to reconnect and 11 seconds to roll out. The total time to reconnect after the disconnection was 1 minute 21 seconds.

There were 19 DRs during this time period, or an average of 6.06 DRs per hour. The potential causes for these DRs were 12 bridges, 5 sign trusses, and 2 undefined instances. The average duration for all DRs was 18.78 seconds.

There were fewer DRs per hour compared to the Southwest District data, and the main difference between the two districts was desired gap distance. The Kansas City District sets the gap distance to 175 feet while the Southwest District sets the gap distance to 700 feet. The Kansas City District field data results for gap distance on October 14, 2022, are shown in Table 4-5. The average actual gap distance was 171.76 feet. The average desired gap distance was 174.98 feet. The standard deviation of the desired gap distance was 7.78 feet. Values for the desired gap distance ranged from 100.07 feet to 200.14 feet. The average gap distance difference between the actual and desired value was -3.21 feet. The average absolute value of gap distance difference was 12.90 feet. The maximum gap distance difference was recorded as 457.37 feet when the gap distance was intentionally increased to protect curves. The minimum gap distance difference was recorded as -126.32 feet. The standard deviation for the gap distance difference was 10.38 feet.

Table 4-5. Kansas City District field data results for gap distance for October 14, 2022

Parameter	Value
Average gap difference (actual – desired) (feet)	-3.21
Average absolute value of gap difference (actual – desired) (feet)	12.90
Maximum gap difference (actual – desired) (feet)	457.37
Minimum gap difference (actual – desired) (feet)	-126.32
Gap difference standard deviation (actual – desired) (feet)	10.38
Average actual gap distance (feet)	171.76
Average desired gap distance (feet)	174.98
Standard deviation of desired gap distance (feet)	7.78
Maximum desired gap distance (feet)	200.14
Minimum desired gap distance (feet)	100.07
Number of observations	63,480

The Kansas City District field data results for speed on October 14, 2022, are shown in Table 4-6. The average actual speed was 5.73 mph. The average desired speed was 5.89 mph. The standard deviation of the desired speed was 1.91 mph. The maximum desired speed was 9.04 mph, and the minimum desired speed was 1.17 mph. The average speed difference between the actual and desired value was -0.17 mph. The average absolute value of speed difference was 0.59 mph. The maximum speed difference was recorded as 4.0 mph. The minimum speed difference was recorded as -10.71 mph. The standard deviation for the speed difference was 1.68 mph.

Table 4-6. Kansas City District field data results for speed for October 14, 2022

Parameter	Value
Average speed difference (actual – desired) (mph)	-0.17
Average absolute value of speed difference (actual – desired) (mph)	0.59
Maximum speed difference (actual – desired) (mph)	4.00
Minimum speed difference (actual – desired) (mph)	-10.71
Speed difference standard deviation (actual – desired) (mph)	1.68
Average actual speed (mph)	5.73
Average desired speed (mph)	5.89
Standard deviation of desired speed (mph)	1.91
Maximum desired speed (mph)	9.04
Minimum desired speed (mph)	1.17
Number of observations	63,480

Summary of Log Data Results

The Leader-Follower TMA system collects the operational data and records it on the internal Kratos server. Logs of the system were analyzed for four MOEs related to A-stops, DRs, gap distance, and speed. Three log files were processed: Southwest District on July 10-11, 2022; Kansas City District on October 14, 2022; and Kansas City District on July 22, 2022. The Southwest District work field was during the nighttime, and the desired gap distance was set to 700 feet most of the time. The Kansas City District log data was for daytime, and the desired set gap distance was 175 feet to 200 feet. The software was upgraded in the Kansas City District in August 2022. To verify the effectiveness of this software upgrade, log data from July 22, 2022, was analyzed.

A summary of the field data results for A-stops is shown in Table 4-7. Six A-stops were counted from Southwest District, while one and two A-stops were recorded from the Kansas City District in October and July, respectively. In general, the number of A-stops was higher in the Southwest District than in the Kansas City District. The average disconnected time for the A-stop was less than 1 minute and 30 seconds, although the system could not recover the data analyzed from the Kansas City District for July 22, 2022.

Table 4-7. Summary of field data results for A-stops

District	Count	Per hour	Duration	Average disconnected time per A-stop
Southwest	6	1.15	5 hours 13 minutes	1 minute 11 seconds
Kansas City (July)*	1	0.38	2 hours 36 minutes	System unable to recover
Kansas City (Oct.)	1	0.32	3 hours 8 minutes	1 minute 21 seconds

* Excludes 1 additional A-stop during additional 1 hour 2 minutes when system was disconnected

A summary of the results for DRs is shown in Table 4-8. Overall, 71 DRs were triggered in the Southwest District, while 19 DRs were recorded from the Kansas City District in October and 24 DRs from the Kansas City District in July. The number of DRs was higher in the Southwest District than in the Kansas City District. This result could be due to the longer gap distance set by the Southwest District personnel. In addition, the Southwest District work zone was more urbanized than the Kansas City work zone. The average duration of the DRs was less than 40 seconds for all three dates. As shown in Table 4-9, most of the DRs were associated with bridges and sign trusses. The number of satellites acquired was also reported in the log files of Southwest District's July and Kansas City districts' October field study. If the number of satellites is less than 6-7, the GPS status light on the OCU will go off (Agarwal et al. 2021) and a forced DR will be initiated. There were instances recorded of the system transitioning to DR while connected to as many as 18 satellites. However, the Leader-Follower TMA system was able to on average locate 22 satellites' signals during the field study, even in the status of DR. The change in the number of satellites was not a leading cause of a DR.

Table 4-8. Summary of field data results for DRs

District	Count	Per hour	Duration	Average disconnected time per DR
Southwest	71	13.61	5 hours 13 minutes	25.63 seconds
Kansas City (July)*	24	9.23	2 hours 36 minutes	31.25 seconds
Kansas City (Oct.)	19	6.06	3 hours 8 minutes	18.78 seconds

* Excludes additional 1 hour 2 minutes when system was disconnected

Table 4-9. Summary of features associated with DRs

Associated Feature	Southwest District	Kansas City District (July)	Kansas City District (Oct.)	Total Percent of DRs
Bridge	31	16	12	51.8%
Sign Truss	26	5	5	31.6%
Unknown	14	3	2	16.7%
Total	**71**	**24**	**19**	**100.0%**

As shown in Table 4-10 and Table 4-11, the system was generally effective in managing gap distance and speed. Regarding gap distance, the system was most effective at maintaining the set gap distance for the Kansas City District in October. The average gap distance difference between actual and desired was -3.21 feet from the Kansas City District in October compared to 15.38 feet from the Southwest District and 12.37 feet from the Kansas City District in July. This result indicates the possible benefits of the software upgrade in the Kansas City District. The average gap difference for the Southwest District was higher than the average gap difference for the Kansas City District, possibly due to the larger desired gap distance used by the Southwest District. The differences in speed data were minor for all three days of data collection, with average speed differences of -0.39 mph (Southwest District), -0.17 mph (Kansas City District on October 14, 2022), and -0.006 mph (Kansas City District on July 22, 2022). The Southwest District data shows more variation in the desired gap distance and speed. The Southwest District sometimes gradually increased the desired gap distance during rollout, while the Kansas City District tended to use a more consistent value for the desired gap.

Table 4-10. Summary of field data results for gap distance

Parameter	Southwest District	Kansas City District (July)	Kansas City District (Oct.)
Average gap difference (actual – desired) (feet)	15.38	12.37	-3.21
Average absolute value of gap difference (actual-desired) (feet)	22.03	19.60	12.90
Maximum gap difference (actual – desired) (feet)	429.81	147.65	457.37
Minimum gap difference (actual – desired) (feet)	-148.96	-92.85	-126.32
Gap difference standard deviation (actual – desired) (feet)	16.79	7.82	10.38
Average actual gap distance (feet)	701.39	203.58	171.76
Average desired gap distance (feet)	686.02	191.21	174.98
Standard deviation of desired gap distance (feet)	23.63	0.48	7.78
Maximum desired gap distance (feet)	700.16	200.14	200.14
Minimum desired gap distance (feet)	49.87	174.88	100.07
Number of observations	69,361	43,903	63,480

Table 4-11. Summary of field data results for speed

Parameter	Southwest District	Kansas City District (July)	Kansas City District (Oct.)
Average speed difference (actual – desired) (mph)	-0.39	-0.006	-0.17
Average absolute value of speed difference (actual – desired) (mph)	1.097	0.303	0.59
Maximum speed difference (actual – desired) (mph)	14.12	2.87	4.00
Minimum speed difference (actual – desired) (mph)	-8.02	-7.88	-10.71
Speed difference standard deviation (actual – desired) (mph)	2.64	0.91	1.68
Average actual speed (mph)	4.79	6.50	5.73
Average desired speed (mph)	5.18	6.51	5.89
Standard deviation of desired speed (feet)	4.08	2.45	1.91
Maximum desired speed (mph)	12.43	10.86	9.04
Minimum desired speed (mph)	-14.12	0.11	1.17
Number of observations	69,361	43,903	63,480

The main differences between the three log datasets were the desired gap distance and the software upgrade that was provided to the Kansas City District in August 2022. The lower desired gap distance set by the Kansas City District seemed effective in reducing the number of A-stops and DRs. The software upgrade was associated with a lower gap distance in the Kansas City District.

Results from Video Data

From the Southwest District night shift video data, one instance of unusual follower TMA behavior was observed. During the 45 seconds of following the E-Crumb data after a loss of signal, the follower TMA drifted slightly to the left. It did not cross the adjacent lane but did travel over the fresh paint. No other unusual driving behavior in traffic, close calls, or ATMA-related crashes were recorded. The video data was also utilized to verify the causes of DRs and A-Stops.

The circumstances for the only A-Stop that happened in the Kansas City District during the field work on October 14, 2022, were observed from the video recording. The gap distance between the leader and follower vehicle was intentionally increased to protect the curve, but this could not prevent the passing traffic from cutting into the protected lane. Several other attempts to protect the curves by increasing the gap were observed, but there was no system disconnect or unusual behavior observed for these instances.

5. FEEDBACK FROM MODOT PERSONNEL

This chapter presents the methodology and results from interviews conducted with MoDOT personnel regarding the Leader-Follower TMA system. The results are organized by topic.

Methodology for Interviews with MoDOT Personnel

The research team conducted interviews with four MoDOT employees from the Southwest District and three MoDOT employees from the Kansas City District to learn about their perceptions of the Leader-Follower TMA system. The interview participants were the system operators and were selected by MoDOT. The interviews took place on August 17, 2022, at the Southwest District and on October 14, 2022, at the Kansas City District. The interviews were conducted individually and covered various topics regarding the system, such as level of experience, training, performance, and suggested improvements. A list of the interview questions is provided in Appendix E.

Results from Interviews with MoDOT Personnel

MoDOT Employee Experience with Leader-Follower TMA System

In general, the MoDOT employees indicated that they had gained experience with all three positions (driver of leader truck, driver of follower truck, and system operator) and rotated between the three positions. Some employees expressed a preference for one of the three positions. The number of hours of experience with the system varied from 16 to 80 hours per employee. Some employees were unsure of the number of hours they had spent using the system. There was some prior limited experience in the Kansas District beginning in 2019.

Training and Initial Learning Curve

The MoDOT employees generally believed that the training they received for the system was adequate. Initial training was provided by Kratos in the Kansas District in 2019 and in the Southwest District in 2022. MoDOT provided refresher training in the Kansas City District in 2022. The training incorporated both classroom learning and hands-on-experience on closed courses (e.g., fairgrounds and airport) and the open road. The training also included troubleshooting, and employee questions about the systems were addressed. The employees found the system checklist provided to be beneficial.

The employees also indicated that the initial learning curve was generally smooth. Employees found that the system was fun to learn although it took some time to learn how to drive the leader TMA, avoid making sharp turns, and troubleshoot issues such as DRs, antenna, wires, and truck stoppages. The employees indicated that they generally could operate the system efficiently after the initial learning curve, except for some issues such as the truck stopping after going under bridges and trusses.

Performance of Leader-Follower TMA System

The MoDOT employees were asked about their perceptions of the safety of the system. In general, the employees indicated that the system functions properly within the work zone as intended, although concerns were noted about loss of GPS signal and maintaining the distance between the leader and follower vehicles on a hill. The employees also indicated that the system operates safely with some minor issues, such as false alarms for A-Stops from shadows and abrupt acceleration after the follower vehicle restarts from a stop. There were significant differences in responses when the employees were asked about their perception of mobile work zone safety with the system versus without the system, including yes, no, and about the same. Reasons cited for yes responses include the benefits of eventually taking the driver out of the follower vehicle and, in the meantime, the ability of the driver of the follower vehicle to concentrate more on watching traffic. Employees who answered no to this question expressed concerns that the follower vehicle cannot speed up to avoid a crash or stop on hill crests. In addition, there were some concerns regarding the reset of the follower vehicle for driverless operation, which would require the leader vehicle to drive down the highway, turn around, and return to the follower vehicle so that the system operator could initiate a reset in the follower vehicle.

The employees indicated that they have not experienced any TMA strikes while the system was in operation. However, there have been many close calls where vehicles have gotten too close to the TMA. Examples of these close calls include a truck locking up its brakes and the driver of the follower vehicle sounding the horn when a vehicle came within 100 feet of the follower vehicle. The employees noted that these types of close calls also occur with a regular TMA. Some employees noted that the system allows them to pay more attention to traffic when they are driving the follower vehicle.

The MoDOT employees were asked to rate the performance of the system on a scale of 1 to 10 and to describe any issues they have encountered that hindered the effective operation of the system. Performance ratings (1 = lowest, 10 = highest) ranged from 6 to 9, with an average rating of 7.4 and standard deviation of 1.1. The interviewers did notice that the responses provided aligned with the perceptions of the operations role each person took most often even though they have performed each function of the system. Employees indicated that the system performance has significantly improved since the initial rollout in 2019 and since Kratos has installed software updates. As described by the employees, some of the issues that have hindered effective operation of the system are described below:

- E-Crumb errors can occur if the gap is too far (1500 feet) or speed is over 15 to 20 mph.

- E-Crumb errors vary in frequency.
- Sudden loss of GPS signal can take place at certain features (e.g., bridges, overhead signs, trees, fog). A noteworthy example in the Kansas City District was at a steel truss bridge on MO 291 over the Missouri River (Figure 5-1) where the follower could not get out of DR and began to veer off.
- An instance of the follower vehicle going off to an exit ramp on I-435, for no apparent reason, was noted.
- The follower sometimes veers to the left and goes over fresh paint or into the ditch after going into DR. *Note: This phenomenon was also observed by the researchers during the field work in the Southwest District on July 10-11, 2022, which was after the software upgrade in April 2022.*
- The time to reconnect if the system cannot get out of DR can be significant.
- The initialization in parking lot on some occasions takes a significant amount of time.
- False A-Stops can sometimes occur.

Figure 5-1. Steel truss bridge on MO 291 over the Missouri River in Sugar Creek, Missouri

Suggested Improvements to Leader-Follower TMA System

The MoDOT employees provided several suggestions for potential improvements to the system, as listed below:

- Addition of a feature to remotely reset the follower vehicle from the leader vehicle when there is not a driver in the follower vehicle.
- Additional cameras (e.g., front, rear, side) on the follower vehicle to help the operator in the leader vehicle to monitor traffic.
- Camera improvements for use during nighttime.
- A remote alarm trigger for the operator in the leader vehicle to alert traffic that is coming too close to the follower vehicle.
- The ability to drop a pausing breadcrumb to instruct the follower vehicle to stop at a specified location (e.g., top of hill or corner).
- The addition of a supplementary system (e.g., lane sensors) to help prevent the follower vehicle from driving on wet paint.
- Notifications to provide information regarding which sensor detected an object when a stoppage occurs to assist with troubleshooting.
- A more stable stand for the tablet in the follower vehicle.
- Designation of a closed course by MoDOT for training purposes.

The MoDOT employees indicated that the system could be considered for use in other mobile operations, such as trash pickup, street sweeping, pothole patching, and shoulder maintenance. Further, investigating the potential use of the system on corridors with more frequent signals was also suggested.

Summary of Feedback from MoDOT Personnel

Overall, the MoDOT employees generally had a positive perception of the system and believed that it improves work zone safety. The primary areas of concern regarding the system were loss of GPS signal and logistical considerations for the follower vehicle (e.g., stopping at the top of a hill and alerting vehicles in close proximity). Suggested solutions to address these concerns include a supplementary lane assist system, additional cameras on the follower vehicle, and a remote alarm for alerting traffic.

6. ECONOMIC ANALYSIS

The research team developed an economic analysis tool to quantify the benefits and costs of the Leader-Follower TMA deployments and documented the calculation process.

Methodology for Economic Analysis

Cost Calculations

The costs of using the Leader-Follower TMA system mainly include three parts: the system integration cost on existing trucks and TMAs, the training cost, and the maintenance and support cost. The study assumes that the Leader-Follower TMA system is upgraded from trucks and TMAs already operated and owned by MoDOT. Therefore, there is no need to procure new trucks and TMAs. The system integration cost for existing equipment is $298,245/unit, based on the cost data of MoDOT Southwest District Leader-Follower TMA project. The system integration cost was converted to the equivalent annual value using Equation 6.1, where i is the annual interest rate and n is the expected life cycle of the Leader-Follower TMA system. The research team assumed that the expected life cycle of the Leader-Follower TMA system is ten years, and the annual interest rate is 2%.

$$Equivalent\ annual\ value\ of\ the\ system\ integration\ cost = system\ integration\ cost \times \frac{i(1+i)^n}{(1+i)^n - 1} \qquad \textit{Equation 6.1}$$

The vendor of the Leader-Follower TMA system provides a week-long training module for MoDOT staff who are new to the Leader-Follower TMA system. As the training module is complimentary and can be offered by MoDOT engineers, the training cost primarily includes the staff time of trainees. As four MoDOT staff were trained together for each Leader-Follower TMA unit in the Kansas City and Southwest Districts, the training cost per unit was estimated using Equation 6.2.

$$Training\ cost\ per\ unit = 4 workers/unit \times 40\ hrs \times Hourly\ Rate \qquad \textit{Equation 6.2}$$

Besides system integration and training costs, the annual maintenance and support costs are budgeted as $1,000/unit, which was used in the study by Florida DOT (Agarwal et al. 2021).

Benefit Calculations

As the Leader-Follower TMA system can relocate the driver of the follower TMA to the leader TMA and allow the driver to control it remotely, the primary benefit is to eliminate the costs of worker injuries (i.e., staff time, lost wages, and medical bills) caused by TMA hits. The benefit can be estimated based on the data for TMA hits, average crash injury costs, and the follower TMA risk factor.

Based on Tracker, MoDOT's performance management tool, the 4-year average TMA hits from 2018 to 2021 is 44 hits/year. Over the last three years, a total of 67 MoDOT workers involved in 159 TMA hits sought medical attention (MoDOT 2022b). If the current trends continue, there will be approximately 18.54 worker injuries per year (44×67/159) in TMA hits.

The benefit of using the Leader-Follower TMA system was calculated based on the crash severity distribution and comprehensive crash cost. As shown Table 6-1, the crash severity distribution for Missouri was estimated based on Missouri Highway Safety Manual Recalibration study (Sun et al. 2018) and the assumptions that all Leader-Follower TMAs will be used as TMAs on all facility types and have the same crash severity distribution as other vehicles. The estimated combined probability of disabling injury and minor injury (26.8%) is close to the observed total injury rate (23.7%) from the TMA-related crash analysis between 2011 and 2016 (Feng 2018).

Table 6-1. Crash severity distribution for Missouri (adapted from Sun et al. 2018)

Type Facility	Fatal	Disabling Injury	Minor Injury	Property Damage Only
Rural Roadways, Two-lane Undivided	0.020	0.084	0.266	0.630
Rural Roadways, Multilane Divided	0.014	0.043	0.245	0.698
Urban Arterials, Two-lane Divided	0.008	0.039	0.235	0.718
Urban Arterials, Four-lane Divided	0.003	0.024	0.228	0.745
Urban Arterials, Five-lane Undivided	0.003	0.021	0.250	0.726
Freeways, Rural Four-lane	0.009	0.035	0.148	0.808
Freeways, Urban Four-lane and Six-lane	0.004	0.022	0.216	0.759
All Roadways	0.009	0.041	0.228	0.722

Missouri comprehensive crash cost (Table 6-2) was estimated based on FHWA Crash Costs for Highway Safety Analysis (Harmon et al. 2018) using state cost of living adjustment factors (0.882) and the ratio of the consumer price index (CPI) for 2022. As the benefit of Leader-Follower TMA system does not include eliminating the cost of property damage only (PDO) crash, the comprehensive crash injury cost was developed by deducting the PDO cost from the comprehensive crash cost of each crash severity for the benefit calculation.

Table 6-2. Missouri comprehensive crash injury cost in 2022 (Harmon et al. 2018)

Severity	Comprehensive Crash Cost	Comprehensive Crash Injury Cost
Fatal	$12,221,135	$12,208,260
Disabling Injury	$708,682	$695,807
Minor Injury	$175,331	$162,456
Property Damage Only	$12,875	-

With the comprehensive crash injury cost and the probability of each crash severity, the weighted average comprehensive crash injury cost (WACCIC) for one injured MoDOT employee was calculated using Equation 6.3.

$$WACCIC = \frac{\sum_1^i (comprehensive\ crash\ injury\ cost\ for\ severity(i) \times probability\ of\ severity(i))}{\sum_1^i probability\ of\ severity(i)} = \frac{\$12{,}208{,}260 \times 0.009 + \$695{,}807 \times 0.041 + \$162{,}456 \times 0.228}{0.009 + 0.041 + 0.228} = \$631{,}087 \qquad \text{Equation 6.3}$$

The benefit is also decided by the follower TMA hit rate. The follower TMA is always used in mobile work zone as the last TMA on the main road, which is also called as hot-seat due to the highest danger level. Based on the TMA-related crash reports between 2011 and 2016, 84.2% of TMA hits happened in mobile work zones and 69.1% of these hits occurred with the last TMA (Feng 2018). Therefore, if all mobile work zones use the Leader-Follower TMA system, the follower TMA can reduce the number of TMA hits and worker injury by 58.2% (=0.691*0.842).

MoDOT currently owns more than 500 TMAs and can use them in 250 mobile work zones, as each mobile work zone requires an average of two TMAs. If one of mobile work zones is equipped with a Leader-Follower TMA system, the probability of worker injuries avoided should be 1 out of 250 (0.4%). The benefit of adding one Leader-Follower TMA to the current TMA fleet can be calculated using Equation 6.4.

$$Leader - Follower\ TMA\ benefit = \frac{number\ of\ Leader - Follower\ TMAs}{number\ of\ mobile\ work\ zones} \times number\ of\ workers\ injuried\ in\ TMA\ hitts\ per\ year \times follower\ TMA\ hit\ rate \times WACCIC \qquad \text{Equation 6.4}$$

The Leader-Follower TMA benefit was converted to the equivalent annual benefit with the use of the annual interest rate of 2%. The project life cycle was assumed to be the same as the Leader-Follower TMA life cycle (10 years). The BCR is calculated using Equation 6.5.

$$BCR = Leader - Follower\ TMA\ equivalent\ annual\ benefit / (Equivalent\ annual\ value\ of\ the\ system\ integration\ cost + training\ cost + maintenance\ cost) \quad \text{Equation 6.5}$$

Results from Economic Analysis

The research team developed a user-friendly spreadsheet (https://bit.ly/atmabcr) to calculate the BCR. MoDOT can adjust the values in yellow to calculate a new BCR in different situations. The results of the current BCR analysis are shown in Figure 6-1. The BCR was 0.83, which indicated the current Leader-Follower TMA project would not be financially successful. However, the BCR results will be improved to 1.0, if the system integration cost is reduced to $243,304. There is potential for the system cost to decrease due to economies of scale with the purchase of additional units.

Input	
Agency Size	
Number of TMAs owned by MoDOT	500
Number of TMAs upgraded to Leader-Follower TMAs	1
System Cost and Characteristics	
Leader-Follower TMA life cycle (years)	10
Follower TMA risk rate	0.582
System integration cost per unit	$298,245
Support and maintenance/unit/year	$1,000
MoDOT worker hourly rate	$14.00
Training cost/unit	$2,240
Annuity factor	0.02
TMA Crashes	
Average annual number of TMA hits	44
Possibility of a worker injured in a TMA hit	0.42

Output	
Number of crashes involved with Leader-Follower TMAs	0.102432
Number of workers injured mitigated by Leader-Follower TMAs	0.043
Benefit	$30,326.24
Total Cost	$36,442.58
BCR	0.83

Editable input
Read-only output

Figure 6-1. Results from economic analysis

7. CONCLUSIONS

This chapter presents the overall conclusions of the research, organized by topic.

Implementation

- Based on the survey results, four state DOTs (Colorado, Missouri, North Dakota, and Rhode Island) have implemented Leader-Follower TMA systems.
- The implementing agencies are currently using Leader-Follower TMA systems for pothole patching, striping, and sweeping on various types of facilities, including freeways, multi-lane highways, and rural two-lane highways.
- Three of the four implementing agencies have developed test plans or training materials to support their implementation of Leader-Follower TMA systems.
- The Kratos system is the only known commercially available system as of January 2023. Another system is under development by a Virginia consortium.
- Based on the survey results, 19 agencies are exploring the potential use of Leader-Follower TMA systems. Approximately half of these agencies are in the process of gathering information. Caltrans, MnDOT, and VDOT are in the process of evaluating Leader-Follower TMA systems for possible implementation.
- Prior research studies have investigated various implementation aspects of Leader-Follower TMA systems, such as operational parameters, human factors, and response to a Leader-Follower TMA incident.
- MoDOT employees generally indicated that the training they received on the system was adequate.

Performance

- Six state DOTs (California, Colorado, Florida, Missouri, Ohio, and Tennessee) have completed feasibility or evaluation studies of Leader-Follower TMA systems. Results generally show that the system performed as expected, with some challenges related to GPS-denied environment, tight turns, and path deviations.
- The four implementing agencies gave an average performance rating of 3.5 out of 5. One agency noted some issues with getting the system up and running. The average performance rating from MoDOT employees was 7.4 out of 10.
- Results from the field evaluation conducted in this research study indicated that the system generally performed as expected, with some concerns related to DRs and loss of GPS signal. The system was generally effective in managing gap distance and speed.
- There was a wide range of perceptions of MoDOT employees regarding mobile work zone safety with the system versus without the system. Some employees noted the benefits of eventually taking the driver out of the follower vehicle and, in the meantime, the ability of the driver of the follower vehicle to concentrate more on watching traffic. Performance

concerns mentioned by the MoDOT employees included loss of GPS signal, false A-stops, abrupt acceleration after the follower vehicle restarts from a stop, the inability of the follower vehicle to speed up to avoid a crash or stop on hill crests, and the need for the leader vehicle to circle back to the follower vehicle if a reset is required during driverless operation.

- Various performance measures are utilized by implementing agencies for Leader-Follower TMA systems, with longitudinal accuracy, worker injuries, and worker perception of the system being the most frequently used.
- Agencies exploring Leader-Follower TMA systems are most interested in reviewing performance data for loss of communications, loss of GPS signal, and obstacle detection and avoidance.

Economic Feasibility

- Prior economic evaluations have found benefit-cost ratios (BCRs) of 0.76 (Agarwal et al. 2021) and 1.01 (Mandokhot et al. 2022).
- The research team developed a user-friendly spreadsheet to calculate the BCR. MoDOT can adjust the values in yellow to calculate a new BCR in different situations. A BCR of 0.83 was calculated in this research study. There is potential for the system cost to decrease due to economies of scale with the purchase of additional units or with the addition of new products in the market.

Challenges to Implementation

- The highest ranked challenges to implementation from implementing agencies, as indicated by the survey results, include lack of agency buy-in, maintenance cost of the system, and technology cost. As mentioned in a DOT interview, the challenges are not always technical and can include procurement, operations, and legislation.
- The highest ranked challenges to implementation noted by exploring agencies in the survey are an inability to obtain the desired performance, funding constraints, and the need for data on performance.
- The 20 agencies that are not exploring the use of Leader-Follower TMA systems identified lack of data on system performance and other initiatives being a higher priority as the most frequently cited reasons for not exploring the use of Leader-Follower TMA systems. Other reasons cited by respondents include cost, a lack of awareness of the technology, and a lack of perceived need.
- In some states, a change in legislation is needed to allow the follower vehicle to operate without a safety driver or operator in the vehicle.

Possible Enhancements to Leader-Follower TMA Systems

- A Phase 2 study for the system developed by a consortium in Virginia is exploring operation

in a GPS-denied environment using a higher performance LiDAR unit and a camera-based perception system.
- The vendor (Kratos) for the system used by MoDOT and other DOTs has made several improvements to the system to address operational concerns from other state DOTs such as low speeds and the tendency of the follower vehicle to lose signal and swerve abruptly when the leader vehicle was passing under long bridges. MoDOT employees indicated that the system performance has significantly improved since the initial rollout in 2019 and since the installation of software updates.
- Suggested enhancements from MoDOT employees include a supplementary lane assist system, additional cameras on the follower vehicle, and a remote alarm for alerting traffic.
- Ongoing research for the Autonomous Maintenance Technology (AMT) pooled fund includes projects on development of deployment guidelines, documentation for promotion and deployment, cost-benefit analysis, literature review of current and potential applications, and system effects of a crash impact (Colorado DOT 2022c).

Implementation Considerations

In assessing whether to proceed further with the Leader-Follower TMA system, there are some aspects of implementation that MoDOT may want to consider, especially regarding driverless operation. One consideration involves procedures for resetting the follower vehicle after an A-stop when there is no driver in the follower vehicle. With the system as configured and no operator in the follower vehicle, the driver of the leader vehicle would need to travel down the highway, turn around, and return to the follower vehicle so that the system operator could initiate a reset in the follower vehicle. The addition of a remote reset feature could address this situation. Other implementation considerations for driverless operation concern how to provide situational awareness (e.g., hills, curves, drivers getting too close to the follower vehicle) for the system operator. Possible solutions could include additional cameras on the follower vehicle and a remote alarm system to warn drivers of the TMA. Finally, given the difference in desired gap distance used by the Southwest and Kansas City Districts, MoDOT may want to consider developing guidance for setting the desired gap, including special situations such as curves and hills.

Summary of Findings

Overall, the study findings indicate that the Leader-Follower TMA has the potential to be an effective tool in improving safety for workers in mobile work zones. With the system, the driver can be removed from the follower vehicle, thus reducing exposure to risk. If the driver is still in the follower vehicle, the system allows the driver to focus more on traffic. Challenges to implementation are both technical (e.g., GPS signal loss, need for situational awareness of hills and curves, need for performance data, and need for procedures to reset the system when there is no driver in follower vehicle) and non-technical (e.g., legislation, policy, procurement, competing priorities, and lack of awareness of the system and its capabilities). The vendor has been able to resolve some of the technical issues faced by other states. Potential enhancements to help address some of the remaining technical challenges include a supplementary guidance system for loss of GPS signal, a remote reset feature, additional cameras, and a remote alarm trigger. Bringing together a multidisciplinary team has been found to be beneficial in helping to address some of the non-technical challenges to implementation of the system.

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APPENDIX A. SUMMARY OF EXISTING LITERATURE AND RESOURCES FOR LEADER-FOLLOWER TMAS

Table A-1. Summary of existing literature for Leader-Follower TMAs

State	Title	Reference	Summary
-	Identification of Operational Design Domain for Autonomous Truck Mounted Attenuator System on Multilane Highways	Tang et al. 2021b	This research study investigated the traffic conditions for deployment of Leader-Follower TMA systems and recommended a maximum value of 40,000 vehicles per day as the operating threshold.
-	Development of Operation Guidelines for Leader–Follower Autonomous Maintenance Vehicles at Work Zone Locations	Tang et al. 2022	Performed analysis for three system requirements: car-following distance, critical lane-changing gap distance, and intersection clearance time. Researchers suggested the following system parameters: a minimum car-following distance of 100 feet, a minimum gap distance of 912 feet, and 15 seconds for intersection clearance time.
-	Implementation, Benefits, and Challenges of Autonomous Truck-Mounted Attenuator	Tian et al. 2022	The researchers interviewed four project managers and two researchers from four state DOTs to learn about their perspectives regarding implementation of Leader-Follower TMA technology. The study found that the major challenges to implementation are loss of GPS signal, the need for regular training, and regulatory concerns.
California	Evaluation of Autonomous TMA Trucks for Use in Caltrans' Operations	Bennett and Lasky 2021	Included the development of a purchase specification and closed course testing of the Kratos system. Closed course testing included 26 categories in safety and performance. Results indicated that all the safety and performance scenarios were completed successfully. The researchers suggested limiting initial implementation to sweeping operations.

State	Title	Reference	Summary
Colorado	Autonomous Truck Mounted Attenuator-Validation Test Report for Region 5	Colorado DOT 2022b	Validation testing for Region 5. Included 15 scenarios on various aspects of Leader-Follower TMA operation, such as follow distance, collision avoidance, braking, lane changes, automatic and emergency stops, following accuracy on curves, and the offset feature.
Colorado	Autonomous Truck Mounted Attenuator (ATMA)Incident Response - CSU Data Report	Daily et al. 2022	Provided recommendations for data and security in case of an incident with a Leader-Follower TMA, such as improving data attribution, developing clear data download procedures, development of a tool to analyze log files, and adding the capability for data logging after an E-Stop.
Colorado	Evaluating the Human-Automated Maintenance Vehicle Interaction for Improved Safety and Facilitating Long-Term Trust	Miller and Pourfalatoun 2021	This study focused on workers' perceptions of working with a Leader-Follower TMA system. 13 DOT workers were surveyed. Workers with more experience and training showed higher confidence with the technology. Some workers expressed concerns about operating the system in more complicated situations. Both groups agreed to the importance of training to increase trust and confidence with the system. Workers did not believe that the system caused issues with their workload.
Colorado	Autonomous Traffic Mobile Attenuator (ATMA) Tabletop Exercise 2021 Summary Report	Morehead and Peterson 2021	Summary of a tabletop exercise conducted in Colorado to assess the immediate and long-term response to an incident in which a motorist strikes the Leader-Follower TMA during striping. The exercise included four modules: initial actions at the crash scene, arrival of response partners at the crash scene, start of the collision investigation, and the continuing investigation. Suggestions for the After-Action Report/Improvement plan included development of a checklist for contacts to be notified, provision of accident packets, and developing procedures for documentation and data collection.

State	Title	Reference	Summary
Florida	Florida ATMA Pilot Demonstration and Evaluation	Agarwal et al. 2021	The study included two testing scenarios (closed loop setting and open road test). Data collection methods included log file and drone. Data regarding time stamp, longitude, latitude of the vehicle, velocity, traffic characteristics and driver behavior in the vicinity of the Leader-Follower TMA was collected. Benefit-cost analysis for the system was performed, and a benefit-cost ratio of 0.76 was calculated. The system performance met expectations for 23 of the 26 scenarios, and there were three exceptions (minimum turn radius, roundabouts, and leader reverse) and two critical errors (not stopping for obstacle and suddenly deviating from path).
Missouri	Evaluation Methodology of Leader-Follower Autonomous Vehicle System for Work Zone Maintenance	Tang et al. 2021a	Developed methodology to assess performance of Leader-Follower TMA system. Field testing evaluated system performance with respect to following distance and accuracy, obstacle detection, and emergency situations. Results indicated that the system performance consistently met expectations.
Ohio	Design of an Alternative Work Zone Attenuator Device	Mandokhot et al. 2022	Research study focused on work zone analysis (e.g., analysis of work zone crashes, economic analysis, and Ohio DOT needs assessment), market survey, and specification development. Results from an economic analysis found that the system was feasible with a benefit-cost ratio of 1.01. The market survey included concepts for two types of systems: Upgraded Mobile Vehicle and Mobile Remote Platform. The market review identified 25 vendors who could meet at least some of the specified system requirements. Functional specifications were developed for both concepts.

State	Title	Reference	Summary
Tennessee	Autonomous Truck Mounted Attenuator (ATMA) Pilot	Kohls 2020	Evaluation study of the Kratos system sponsored by Tennessee DOT that included 24 scenarios at two locations. In general, the system performed as expected. The system could function in a GPS-denied environment for only a limited time. The researcher concluded that ATMA is suited for work zones with continuous movement but needed more development or testing for work zones that need to repeat stop-and-go. The system was unable to maintain the set gap distance for trash pick-up and pothole patching scenarios.
Virginia	Automated Truck Mounted Attenuator (ATMA) Integration Plan	VTTI 2021	Provides recommendations for testing using a phased approach, performance metrics, and an overview of suggested training for management and system operators.
Virginia	Design and Development of an Automated Truck Mounted Attenuator	White et al. 2021	A consortium collaborated to design, build, test and demonstrate a prototype Leader-Follower TMA system. System features include LiDAR sensors for object detection, three computer systems, emergency stop functions, communications links, and a human-machine interface (HMI) tablet. The system was tested on a 2.2-mile long test track under different conditions. The study results demonstrated that the system operated successfully for the following conditions: speeds of 15 mph or less, reliable GPS signal present, following distances between 50 feet and 400 feet, lateral offsets of plus or minus 12 feet, clear weather, and night and day conditions.

APPENDIX B. QUESTIONS FOR AGENCY SURVEY

MISSOURI DEPARTMENT OF TRANSPORTATION

AMR LEADER-FOLLOWER SYSTEM TMA EVALUATION

SURVEY

LETTER TO THE RESPONDENT

Dear Participant,

The Missouri Department of Transportation is sponsoring a research study titled "AMR Leader-Follower System TMA Evaluation." The research is being performed by the University of Missouri. The project objectives are to evaluate MoDOT's pilot program for Leader Follower-TMAs in two of its seven Districts, to synthesize practices of other state DOTs regarding Leader-Follower TMAs, and to identify obstacles to implementation faced by other state DOTs. With the Leader-Follower TMA System (shown in Figure 1 below), the driver can be removed from the follower vehicle, and connected vehicle technology is used to guide the follower vehicle to follow the path of the leader vehicle.

Figure 1. Leader-Follower TMA system (Source: MoDOT)

Attainment of the project objectives will help MoDOT to assess the potential for continued implementation of the Leader-Follower TMA system beyond its pilot study and facilitate identification of challenges to implementation faced by other state DOTs.

Your cooperation in completing this survey will help to ensure the success of this research project. This survey is being sent to one person from each state DOT and two turnpike authorities. You have been identified as the appropriate person at your agency to complete this survey. The survey link that you received for completing the survey is unique for your agency. If it would be more appropriate for someone else at your agency to take this survey, please forward the email with the survey link to them or send their name and email address to Henry Brown (brownhen@missouri.edu). Additional instructions are provided at the beginning of the survey. If you would like to download a PDF version of the survey for informational purposes, please click here.

Please complete this survey by June 7, 2022. Depending on your agency's experience and level of involvement with Leader-Follower TMA systems, the survey includes 6 to 15 questions, and we estimate that the survey will take approximately 5 to 20 minutes to complete. If you have any questions, please contact Henry Brown at (573) 882-0832 or brownhen@missouri.edu. Any supporting materials may be sent by email to Henry in lieu of providing URLs. Thank you for participating in this survey!

SURVEY INSTRUCTIONS

1. To begin the survey, click the forward arrow at the bottom of this page.
2. To view and print the entire survey for informational purposes, click on this survey link and download and print the document.
3. To save your partial answers and complete the survey later, close the survey. Answers are automatically saved upon closing the browser window. To return to the survey later, open the original email from Henry Brown and click on the survey link.
4. To pass a partially completed survey to a colleague, close the survey and forward the original email from Henry Brown to a colleague. Note that only one person may work on the survey at a time; the survey response should only be active on one computer at a time.
5. To view and print your answers after completing the survey, submit the survey by clicking "Submit" on the final page. Download and print the PDF on the following page which contains a summary of your responses.
6. To submit the survey, click on "Submit" on the last page.

SURVEY TIPS

1. Survey navigation is conducted by selecting the forward and back arrows at the bottom of each page.
2. If you are unable to complete the survey in a single session, you can return to the survey at any time by reentering through the survey link.

QUESTIONS

Contact Information

Name ___________________
State ___________________
Job Title ___________________
Phone Number _____________________
Email Address ______________________

Section 1: Initial Screening Questions

1. Is worker safety a significant concern at your agency?

    - ☐ Yes
    - ☐ No

Comments:

____

2. Does your agency have any data on worker-related work zone concerns or incidents?

    - ☐ Yes
    - ☐ No

Comments:

____

3. Which of the following devices/technologies has your agency implemented or considered implementing in work zones to help improve worker safety? Please select all that apply.

    - ☐ Automated Flagger Assistance Device (AFAD)
    - ☐ Automated Work Zone Speed Enforcement
    - ☐ End of Queue Warning System
    - ☐ Leader-Follower TMA System
    - ☐ Notification of Construction Equipment Entering/Existing System
    - ☐ Radar Speed Display Feedback Signs
    - ☐ Temporary Rumble Strips
    - ☐ Wearable Technologies
    - ☐ Work Zone Intrusion Alarm

☐ Other (please describe) ____________

Comments:

____

4. Which of the following best describes your agency's current level of experience with Leader-Follower TMA systems?

   ☐ My agency has implemented Leader-Follower TMA systems *(continue to Question No. 5)*
   ☐ My agency is currently exploring or has previously explored the potential use of Leader-Follower TMA systems *(skip to Question No. 15)*
   ☐ My agency is not currently exploring the potential use of Leader-Follower TMA systems *(skip to Question No. 20)*

Section 2: My agency has implemented Leader-Follower TMA systems

5. For which of the following types of operations does your agency currently use Leader-Follower TMA systems? Please select all that apply.

   ☐ Pavement testing
   ☐ Pothole patching
   ☐ Striping
   ☐ Sweeping
   ☐ Trash pick-up
   ☐ Weed spraying
   ☐ Other (please describe) ____________

Comments:

____

6. For which of the following facility types does your agency currently use Leader-Follower TMA systems? Please select all that apply.

   ☐ Arterials
   ☐ Multi-lane highways
   ☐ Rural freeways
   ☐ Rural two-lane highways
   ☐ Urban freeways

☐ Other (please describe) ____________

Comments:

____

7. How many Leader-Follower TMA units (One unit = Leader TMA plus Follower TMA) does your agency currently operate?

   ☐ 1
   ☐ 2 to 3
   ☐ 4 to 5
   ☐ 6 or more

Comments:

____

8. Which of the following resources has your agency developed to support implementation of Leader-Follower TMA systems? Please select all that apply.

   ☐ Evaluation studies
   ☐ Operational guidelines
   ☐ Performance specifications
   ☐ Test plan
   ☐ Training materials
   ☐ My agency has not developed any resources to support implementation of Leader-Follower TMA systems
   ☐ Other (please describe) ____________

If you selected any resources and are willing to share them, please provide URL(s) for the relevant documents in the box below or email files to brownhen@missouri.edu:

____

Comments:

____

9. On a scale of 1 to 5 (1 = Highly Ineffective, 5 = Highly Effective), how would you rate the

performance of your agency's Leader-Follower TMA system?

- ☐ 1
- ☐ 2
- ☐ 3
- ☐ 4
- ☐ 5

Comments:

____

10. What performance measures does your agency currently use to evaluate the performance of its Leader-Follower TMA system? Please select all that apply.

- ☐ Benefit-cost analysis
- ☐ Emergency stops
- ☐ Lateral accuracy
- ☐ Longitudinal accuracy
- ☐ Loss of communications
- ☐ Loss of GPS signal
- ☐ Obstacle detection and avoidance
- ☐ Turning capabilities
- ☐ Worker injuries
- ☐ Worker perception of the system
- ☐ Other (please describe) ____________

Comments:

____

11. What types of data does your agency collect to evaluate the performance of its Leader-Follower TMA system? Please select all that apply.

- ☐ Field observations
- ☐ Operator feedback
- ☐ System log files
- ☐ Video data
- ☐ Other (please describe) ____________

Comments:

____

12. A list of possible challenges to the implementation of Leader-Follower TMA systems is provided below. Please rank the top **three** challenges based on the degree to which you believe that they have hindered your agency's efforts to implement Leader-Follower TMA systems (1 = greatest challenge, 2 = 2nd greatest challenge, 3 = 3rd greatest challenge)?

Concern	Ranking
Contracting Considerations	
Funding Constraints	
Lack of Agency Buy-In	
Lack of Availability of Personnel	
Lack of Perceived Need	
Legislative Authority	
Maintenance Cost of System	
Performance Measures	
Technology Cost	
Training Needs	
Unable to Achieve Desired Technical Performance	
Other (Please describe) _____	

Comments:

____

13. Are there any enhancements or additional features that your agency would like to see added to Leader-Follower TMA systems?

☐ Yes
☐ No

If you answered Yes, please briefly describe the suggested enhancements or additional features in the box below.

____

14. Would you be willing to participate in a follow-up interview to discuss in greater detail your agency's use of Leader-Follower TMA systems?

☐ Yes
☐ No

(skip to Question No. 21)

Section 3: My agency is currently exploring or has previously explored the potential use of Leader-Follower TMA systems

(Display questions in this section only if Question No. 4 Answer = My agency is currently exploring or has previously explored the potential use of Leader-Follower TMA systems)

15. Which of the following best describes the current status of your agency's exploration of the use of Leader-Follower TMA systems?

☐ Gathering information
☐ Developing specifications/procurement documents
☐ Planning or conducting pilot testing
☐ Previously explored and decided not to implement
☐ Other (please describe) ____________

Comments:

____

16. Has your agency developed any of the following resources in support of its potential implementation of Leader-Follower TMA systems? Please select all that apply.

☐ Evaluation or feasibility studies
☐ Operational guidelines

- ☐ Performance specifications
- ☐ Test plan
- ☐ My agency has not developed any resources in support of potential implementation of Leader-Follower TMA systems
- ☐ Other (please describe) ____________

If you selected any resources and are willing to share them, please provide URL(s) for the relevant documents in the box below or email files to brownhen@missouri.edu:

____

Comments:

____

17. For which of the following performance metrics would you like to see data to increase your agency's comfort level with the use of Leader-Follower TMA systems? Please select all that apply.

- ☐ Benefit-cost analysis
- ☐ Emergency stops
- ☐ Lateral accuracy
- ☐ Longitudinal accuracy
- ☐ Loss of communications
- ☐ Loss of GPS signal
- ☐ Obstacle detection and avoidance
- ☐ Turning capabilities
- ☐ Worker injuries
- ☐ Worker perception of the system
- ☐ Other (please describe) ____________

Comments:

____

18. A list of possible challenges to the implementation of Leader-Follower TMA systems is provided below. Please rank the top **three** challenges based on the degree to which you believe that they hinder your agency's efforts to implement Leader-Follower TMA systems (1 = greatest challenge, 2 = 2nd greatest challenge, 3 = 3rd greatest challenge)?

Concern	Ranking
Contracting Considerations	
Funding Constraints	
Lack of Agency Buy-In	
Lack of Availability of Personnel	
Lack of Perceived Need	
Legislative Authority	
Maintenance Cost of System	
Need for Data on Performance	
Other Initiatives are Higher Priority	
Technology Cost	
Unable to Achieve Desired Technical Performance	
Other (Please describe) _____	

Comments:

____

19. Would you be willing to participate in a follow-up interview to discuss in greater detail your agency's exploration of the use of Leader-Follower TMA systems?

☐ Yes
☐ No

(skip to Question No. 21)

Section 4: My agency is not currently exploring the potential use of Leader-Follower TMA systems

(Display questions in this section only if Question No. 4 Answer = My agency is not currently exploring the potential use of Leader-Follower TMA systems)

20. Which of the following is a reason for why your agency is currently not exploring the potential use of Leader-Follower TMA systems? Please select all that apply.

- ☐ Cost
- ☐ Lack of availability of personnel
- ☐ Lack of identified funding
- ☐ Lack of information regarding the technology
- ☐ Lack of data on system performance
- ☐ Lack of legislative authority
- ☐ Lack of perceived need
- ☐ Other initiatives are higher priority
- ☐ Other (please describe) ____________

Section 5: All respondents

21. Please provide any additional comments that you may have regarding Leader-Follower TMA systems.

____
____
____

SUBMITTAL INSTRUCTIONS

To complete the survey and record your answers, please click the "Submit" button.

Please note that once you click the "Submit" button, you will not be able to modify your answers. To save your partial answers and complete the survey later, close the survey. Answers are automatically saved upon closing the browser window. To return to the survey later, open the original email from Henry Brown and click on the survey link. To pass a partially completed survey to a colleague, close the survey and forward the original email from Henry Brown to a colleague. Note that only one person may work on the survey at a time; the survey response should only be active on one computer at a time. To review your answers before submitting, please select the forward and back arrows at the bottom of each page.

END OF SURVEY

Thank you for completing this survey. Your efforts are greatly appreciated. Your responses are very important, and your feedback is welcome. For your information, a copy of your responses is provided below. You may download your responses in pdf format using the "Download pdf" link shown below. If you have any questions or comments, please contact the principal investigator, Henry Brown:

Henry Brown, P.E.
E2509 Lafferre Hall
University of Missouri
Columbia, MO 65211
(573) 882-0832
brownhen@missouri.edu

Your responses have been recorded, and you may now close your browser.

APPENDIX C. SURVEY RESPONSES BY AGENCY

Table C-1. Survey responses for Question 1 (significance of worker safety as a concern)

Respondent	Response Text
Alabama	Yes
Alaska	-
Arizona	Yes
Arkansas	Yes
California	Yes
Colorado	Yes
Connecticut	-
Delaware	Yes
District of Columbia	-
Florida	-
Georgia	Yes
Hawaii	-
Idaho	Yes
Illinois	Yes
Indiana	Yes
Iowa	Yes
Kansas	Yes
Kentucky	Yes
Louisiana	Yes
Maine	Yes
Maryland	Yes
Massachusetts	Yes
Michigan	Yes
Minnesota	Yes
Mississippi	Yes
Missouri	Yes
Montana	Yes
Nebraska	Yes
Nevada	Yes
New Hampshire	Yes
New Jersey	Yes
New Mexico	Yes

Respondent	Response Text
New York	-
North Carolina	Yes
North Dakota	Yes
Ohio	Yes
Ohio Turnpike	Yes
Oklahoma	Yes
Oregon	Yes
Pennsylvania	-
Pennsylvania Turnpike	-
Rhode Island	Yes
South Carolina	Yes
South Dakota	Yes
Tennessee	Yes
Texas	Yes
Utah	Yes
Vermont	Yes
Virginia	Yes
Washington	Yes
West Virginia	-
Wisconsin	Yes
Wyoming	-

Table C-2. Survey comments for Question 1 (significance of worker safety as a concern)

Comment
We have been purchasing more and more trailer mounted attenuators for our maintenance crews to use.
This is not a fair question. Who would say "no" until all workers are off the road.
Our motto is "We put Safety in Everything We Do." Safety of our employees and motorists is very important to our DOT.
There are so many things in worker safety that we need to improve but worker safety is my number 1 goal.
Our DOT and the state Asphalt Paving Association have a working group that meets regularly on the subject, and our DOT has made changes in work zone guidance based on committee discussions.
Worker safety is paramount in both our Contracted projects and our internal operations.
Safety is always a concern during the formulation of traffic control plans for both design and maintenance related projects.
We want to provide the safest work environment we can for our employees. We don't have that many attenuators hit but felt this was a good use of technology to remove a driver from an unsafe position.

Table C-3. Survey responses for Question 2 (availability of data on worker-related work zone concerns or incidents)

Respondent	Response Text
Alabama	Yes
Alaska	-
Arizona	No
Arkansas	Yes
California	Yes
Colorado	Yes
Connecticut	-
Delaware	No
District of Columbia	-
Florida	-
Georgia	Yes
Hawaii	-
Idaho	Yes
Illinois	Yes
Indiana	Yes
Iowa	Yes
Kansas	No
Kentucky	Yes
Louisiana	Yes
Maine	Yes
Maryland	Yes
Massachusetts	Yes
Michigan	Yes
Minnesota	Yes
Mississippi	Yes
Missouri	Yes
Montana	Yes
Nebraska	Yes
Nevada	-
New Hampshire	Yes
New Jersey	No
New Mexico	No
New York	-

Respondent	Response Text
North Carolina	No
North Dakota	Yes
Ohio	Yes
Ohio Turnpike	No
Oklahoma	No
Oregon	Yes
Pennsylvania	-
Pennsylvania Turnpike	-
Rhode Island	No
South Carolina	Yes
South Dakota	No
Tennessee	Yes
Texas	-
Utah	Yes
Vermont	Yes
Virginia	Yes
Washington	Yes
West Virginia	-
Wisconsin	No
Wyoming	-

Table C-4. Survey comments for Question 2 (availability of data on worker-related work zone concerns or incidents)

Comment
We are in the process of developing a reporting application.
To my knowledge there is not a readily available form of work zone crashes, injuries, and fatalities; however, the crash reporting form was modified recently to include a field for work zones. Shortly, crash infomation in work zones should be able to be queried.
We track work zone crashes, work zone crashes with workers present, number of work zones, and number of work zone hours to develop crash rates per roadway system and route.
Our Traffic Operations division has data on work zone related incidents.
Mostly anecdotal
Interested in more data mainly close calls, but yes have crash data.
We have occupational safety records for incidents that occur within a DOT work zone that affects DOT employees and general information on vehicle crashes that occur within a work zone that may or may not affect workers that are present.
Depends what sort of data, but assuming crashes or other disturbances, then yes.
Yes, but not a lot.
I believe we do. I'm not sure which division collects and retains that information.
We try to manage work zones at the local level - one size doesn't necessarily fit all when it comes to traffic control. Concerns may come into play with crew sharing, where hazards can be: unfamiliar crews, roads, and traffic patterns. We have been blessed with few mobile impact attenuator accidents. Mobile work zones tend to be the most frequent for work zone accidents involving impact attenuators (i.e., striping operations).
Again, through the above-mentioned committee and reported crashes... National & State Traffic Data — Work Zone Safety Information Clearinghouse
We do not have a formal report but we do review all the work zone fatal crashes that occur.
We track incidents involving maintenance crews that occur in work zones. We have also started tracking TMA strikes in recent years.
Fortunately, worker related incidents are very rare in our state. We really do not have an official data base specifically aimed at capturing these incidents. We do, however, do accident reports of any accidents that occur in the work-zone and this information is kept by our State-run Traffic Management Center (TMC). If a worker was injured, this infomation would be captured in those reports.

Table C-5. Survey responses for Question 3 (use of devices and technologies)

Respondent	Automated Flagger Assistance Device (AFAD)	Automated Work Zone Speed Enforcement	End of Queue Warning System	Leader-Follower TMA System	Notification of Construction Equipment Entering/Existing System	Radar Speed Display Feedback Signs	Temporary Rumble Strips	Wearable Technologies	Work Zone Intrusion Alarm	Other (please describe)
Alabama	O	-	-	-	-	O	O	-	-	-
Alaska	-	-	-	-	-	-	-	-	-	-
Arizona	O	-	O	O	O	O	O	-	-	O
Arkansas	O	-	O	-	-	O	O	-	-	-
California	O	O	O	O	O	O	O	-	O	-
Colorado	-	-	O	O	-	-	-	-	-	-
Connecticut	-	-	-	-	-	-	-	-	-	-
Delaware	-	O	O	-	-	O	O	-	-	-
District of Columbia	-	-	-	-	-	-	-	-	-	-
Florida	-	-	-	-	-	-	-	-	-	-
Georgia	-	-	O	-	-	O	O	-	-	-
Hawaii	-	-	-	-	-	-	-	-	-	-
Idaho	O	-	O	-	-	O	O	-	-	-
Illinois	O	O	O	-	-	O	O	-	-	-
Indiana	O	-	O	O	-	O	O	-	O	-
Iowa	O	-	O	-	O	O	O	O	-	-
Kansas	O	-	-	-	-	-	O	O	-	-
Kentucky	O	-	O	-	O	O	-	-	-	-
Louisiana	O	-	O	-	O	O	O	-	-	-

Respondent	Automated Flagger Assistance Device (AFAD)	Automated Work Zone Speed Enforcement	End of Queue Warning System	Leader-Follower TMA System	Notification of Construction Equipment Entering/Existing System	Radar Speed Display Feedback Signs	Temporary Rumble Strips	Wearable Technologies	Work Zone Intrusion Alarm	Other (please describe)
Maine	O	O	-	-	O	O	O	-	-	-
Maryland	O	O	-	-	-	O	-	-	-	-
Massachusetts	-	-	O	-	-	O	O	-	-	-
Michigan	O	O	O	-	O	O	O	O	-	O
Minnesota	O	O	O	O	O	O	O	O	O	-
Mississippi	O	-	O	-	O	O	O	-	-	-
Missouri	O	-	O	O	-	O	O	-	O	-
Montana	-	-	O	-	-	O	O	O	O	-
Nebraska	O	-	O	-	-	O	-	-	-	-
Nevada	-	-	O	-	-	O	O	-	-	O
New Hampshire	O	-	O	-	-	O	O	O	-	-
New Jersey	-	-	-	-	-	-	-	-	-	O
New Mexico	O	-	-	-	-	O	O	-	-	-
New York	-	-	-	-	-	-	-	-	-	-
North Carolina	O	-	O	-	O	-	-	-	-	-
North Dakota	-	-	O	O	-	O	O	-	-	-
Ohio	O	-	-	-	-	-	O	O	-	O
Ohio Turnpike	-	O	O	-	-	O	O	-	-	-
Oklahoma	-	-	O	-	-	O	O	-	-	-
Oregon	O	O	O	-	-	O	O	-	-	-

Respondent	Automated Flagger Assistance Device (AFAD)	Automated Work Zone Speed Enforcement	End of Queue Warning System	Leader-Follower TMA System	Notification of Construction Equipment Entering/Existing System	Radar Speed Display Feedback Signs	Temporary Rumble Strips	Wearable Technologies	Work Zone Intrusion Alarm	Other (please describe)
Pennsylvania	-	-	-	-	-	-	-	-	-	-
Pennsylvania Turnpike	-	-	-	-	-	-	-	-	-	-
Rhode Island	-	-	-	O	-	O	-	-	-	-
South Carolina	O	-	O	-	O	-	O	-	-	-
South Dakota	O	-	O	-	-	O	O	-	-	O
Tennessee	O	O	O	O	O	O	O	O	O	O
Texas	-	-	O	-	-	O	-	-	-	-
Utah	O	-	-	O	-	-	O	O	O	-
Vermont	O	-	O	O	-	O	O	-	O	-
Virginia	O	O	O	O	O	O	O	O	O	-
Washington	O	-	-	-	-	O	O	-	-	O
West Virginia	-	-	-	-	-	-	-	-	-	-
Wisconsin	O	-	O	-	O	O	O	-	-	-
Wyoming	-	-	-	-	-	-	-	-	-	-

Table C-6. Survey comments for Question 3 (use of devices and technologies)

Comment
Digital Speed Signs are implemented on all Interstate paving projects. We use Smart Work Zones where appropriate and have begun using HAAS Alerts on Highway Service Patrols HELP Trucks, and we are considering expanding this to other vehicles queue protection vehicles.
Traffic Management: impacting mobility directly relates to safety. Detouring traffic around the work zone and eliminating the safety concern is preferred. Evaluating delay and adjusting signal timing....
We implement temporary rumble strips, law enforcement, and feedback signs. We are looking into smart work zone technologies.
We will shortly be implementing a Photo Speed Enforcement program in our long-term interstate and high-volume roadway projects.
Some of the technologies listed above have been used on a trial basis, so may have only been used one time.
Automated work zone speed enforcement has failed to pass in the legislature. We are currently involved in research projects with a university looking at work zone intrusion technologies and the use of driverless TMA vehicles, similar to what this study will be looking at. We also participate in the Automated Attenuator pool fund being run by Colorado DOT.
Automated enforcement can't be done yet but we are looking into the law to have it updated.
Our DOT has implemented the Automated Flagger System sparingly in the recent past. Temporary Rumble Strips and Radar Feedback signs have been used extensively.

Table C-7. Other text responses for Question 3 (use of devices and technologies)

Other - Text
We have also installed flashing "panic lights" on the rear of attenuators that are activated by the operator.
Smart Work Zones / Traffic Management
Uniform Traffic Control Officer - law enforcement presence
Smart work zone systems, Smart work zone devices, Work zone speed limit reductions
None of these items
Not Leader-Follower TMAs but standard TMAs
Temporary pavement marking improvements

Table C-8. Survey responses for Question 4 (current level of experience with Leader-Follower TMA systems)

Respondent	Response Text
Alabama	My agency is not currently exploring the potential use of Leader-Follower TMA systems
Alaska	-
Arizona	My agency is currently exploring or has previously explored the potential use of Leader-Follower TMA systems
Arkansas	My agency is not currently exploring the potential use of Leader-Follower TMA systems
California	My agency is currently exploring or has previously explored the potential use of Leader-Follower TMA systems
Colorado	My agency has implemented Leader-Follower TMA systems
Connecticut	-
Delaware	My agency is currently exploring or has previously explored the potential use of Leader-Follower TMA systems
District of Columbia	-
Florida	-
Georgia	My agency is not currently exploring the potential use of Leader-Follower TMA systems
Hawaii	-
Idaho	My agency is not currently exploring the potential use of Leader-Follower TMA systems
Illinois	My agency is currently exploring or has previously explored the potential use of Leader-Follower TMA systems
Indiana	My agency is currently exploring or has previously explored the potential use of Leader-Follower TMA systems
Iowa	My agency is currently exploring or has previously explored the potential use of Leader-Follower TMA systems
Kansas	My agency is currently exploring or has previously explored the potential use of Leader-Follower TMA systems
Kentucky	My agency is currently exploring or has previously explored the potential use of Leader-Follower TMA systems
Louisiana	My agency is not currently exploring the potential use of Leader-Follower TMA systems
Maine	My agency is not currently exploring the potential use of Leader-Follower TMA systems
Maryland	My agency is not currently exploring the potential use of Leader-Follower TMA systems
Massachusetts	My agency is not currently exploring the potential use of Leader-Follower TMA systems
Michigan	My agency is not currently exploring the potential use of Leader-Follower TMA systems
Minnesota	My agency is currently exploring or has previously explored the potential use of Leader-Follower TMA systems
Mississippi	My agency is not currently exploring the potential use of Leader-Follower TMA systems
Missouri	My agency has implemented Leader-Follower TMA systems
Montana	My agency is not currently exploring the potential use of Leader-Follower TMA systems
Nebraska	My agency is not currently exploring the potential use of Leader-Follower TMA systems
Nevada	My agency is not currently exploring the potential use of Leader-Follower TMA systems

Respondent	Response Text
New Hampshire	My agency is not currently exploring the potential use of Leader-Follower TMA systems
New Jersey	My agency is not currently exploring the potential use of Leader-Follower TMA systems
New Mexico	My agency is not currently exploring the potential use of Leader-Follower TMA systems
New York	-
North Carolina	My agency is currently exploring or has previously explored the potential use of Leader-Follower TMA systems
North Dakota	My agency has implemented Leader-Follower TMA systems
Ohio	My agency is currently exploring or has previously explored the potential use of Leader-Follower TMA systems
Ohio Turnpike	My agency is not currently exploring the potential use of Leader-Follower TMA systems
Oklahoma	My agency is not currently exploring the potential use of Leader-Follower TMA systems
Oregon	My agency is currently exploring or has previously explored the potential use of Leader-Follower TMA systems
Pennsylvania	-
Pennsylvania Turnpike	-
Rhode Island	My agency has implemented Leader-Follower TMA systems
South Carolina	My agency is not currently exploring the potential use of Leader-Follower TMA systems
South Dakota	My agency is currently exploring or has previously explored the potential use of Leader-Follower TMA systems
Tennessee	My agency is currently exploring or has previously explored the potential use of Leader-Follower TMA systems
Texas	My agency is not currently exploring the potential use of Leader-Follower TMA systems
Utah	My agency is currently exploring or has previously explored the potential use of Leader-Follower TMA systems
Vermont	My agency is currently exploring or has previously explored the potential use of Leader-Follower TMA systems
Virginia	My agency is currently exploring or has previously explored the potential use of Leader-Follower TMA systems
Washington	My agency is currently exploring or has previously explored the potential use of Leader-Follower TMA systems
West Virginia	-
Wisconsin	My agency is currently exploring or has previously explored the potential use of Leader-Follower TMA systems
Wyoming	-

Table C-9. Survey responses for Question 5 (types of operations for use of Leader-Follower TMA systems)

Respondent	Pavement testing	Pothole patching	Striping	Sweeping	Trash pick-up	Weed spraying	Other (please describe)
Colorado	-	-	O	-	-	-	-
Missouri	-	-	O	-	-	-	-
North Dakota	-	O	-	O	-	-	-
Rhode Island	-	O	O	O	-	-	-

Table C-10. Survey comments for Question 5 (types of operations for use of Leader-Follower TMA systems)

Comment
We plan to use it for sweeping and pothole patching to begin with. We have had it for a couple years but are still working through some issues. We hope to get it on the road more this summer.

Table C-11. Survey responses for Question 6 (types of facilities for use of Leader-Follower TMA systems)

Respondent	Arterials	Multi-lane highways	Rural freeways	Rural two-lane highways	Urban freeways	Other (please describe)
Colorado	-	-	O	O	O	-
Missouri	-	O	O	-	O	-
North Dakota	-	O	O	O	-	-
Rhode Island	-	-	-	-	O	-

Table C-12. Survey responses for Question 7 (number of Leader-Follower TMA units)

Respondent	1	2 to 3	4 to 5	6 or more
Colorado	-	O	-	-
Missouri	-	O	-	-
North Dakota	O	-	-	-
Rhode Island	O	-	-	-

Table C-13. Survey responses for Question 8 (resources developed to support implementation of Leader-Follower TMA systems)

Respondent	Evaluation studies	Operational guidelines	Performance specifications	Test plan	Training materials	My agency has not developed any resources to support implementation of Leader-Follower TMA systems	Other (please describe)
Colorado	O	O	O	O	O	-	-
Missouri	O	-	O	O	O	-	-
North Dakota	-	-	-	O	O	-	-
Rhode Island	-	-	-	-	-	O	-

Table C-14. Survey responses for Question 9 (performance rating for Leader-Follower TMA systems)

Respondent	Rating
Colorado	4
Missouri	4
North Dakota	2
Rhode Island	4

Table C-15. Survey comments for Question 9 (performance rating for Leader-Follower TMA systems)

Comment
Has been hard to get buy in from the staff to get it on the road. Each time they have tried to use it we have had minor and major issues getting it up and running which has discouraged them from wanting to use it.

Table C-16. Survey responses for Question 10 (use of performance measures for Leader-Follower TMA systems)

Respondent	Benefit-cost analysis	Emergency stops	Lateral accuracy	Longitudinal accuracy	Loss of communications	Loss of GPS signal	Obstacle detection and avoidance	Turning capabilities	Worker injuries	Worker perception of the system	Other (please describe)	No response
Colorado	-	-	-	-	-	-	-	-	-	O	-	-
Missouri	-	O	O	O	O	O	O	O	O	O	-	-
North Dakota	-	-	-	O	-	-	-	-	O	-	-	-
Rhode Island	-	-	-	-	-	-	-	-	-	-	-	O

Table C-17. Survey responses for Question 11 (types of data collected to evaluate performance of Leader-Follower TMA systems)

Respondent	Field observations	Operator feedback	System log files	Video data	Other (please describe)
Colorado	O	O	O	O	-
Missouri	O	O	O	-	-
North Dakota	-	O	O	-	-
Rhode Island	-	-	-	-	-

Table C-18. Survey responses for Question 12 (ranking of implementation challenges for Leader-Follower TMA systems)

Respondent	Contracting Considerations	Funding Constraints	Lack of Agency Buy-In	Lack of Availability of Personnel	Lack of Perceived Need	Legislative Authority	Maintenance Cost of System	Performance Measures	Technology Cost	Training Needs	Unable to Achieve Desired Technical Performance	Other (Please describe)
Colorado	-	3	-	-	-	-	-	-	1	-	2	-
Missouri	-	-	-	5	6	-	-	7	-	-	-	-
North Dakota	8	3	1	7	5	9	10	11	2	6	4	-
Rhode Island	-	-	-	2	-	-	1	3	-	-	-	-

Table C-19. Survey responses for Question 13 (interest in enhancements or additional features for Leader-Follower TMA systems)

Respondent	Response Text
Colorado	Yes
Missouri	No
North Dakota	Yes
Rhode Island	No

Table C-20. Text responses for Question 13 (interest in enhancements or additional features for Leader-Follower TMA systems)

Text
We would like it to be more reliable at the moment.

Table C-21. Survey responses for Question 14 (interest in participating in follow-up interview to discuss use of Leader-Follower TMA systems)

Respondent	Response Text
Colorado	Yes
Missouri	Yes
North Dakota	Yes
Rhode Island	-

Table C-22. Survey responses for Question 15 (status of exploration of Leader-Follower TMA systems)

Respondent	Gathering information	Developing specifications/procurement documents	Planning or conducting pilot testing	Previously explored and decided not to implement	Other (please describe)
Arizona	O	-	-	-	-
California	-	-	-	-	-
Delaware	-	-	-	O	-
Illinois	-	-	-	-	O
Indiana	-	-	O	-	-
Iowa	O	-	-	-	-
Kansas	O	-	-	-	-
Kentucky	O	-	-	-	-
Minnesota	-	-	O	-	-
North Carolina	O	-	-	-	-
Ohio	-	-	-	-	O
Oregon	-	-	-	O	-

Respondent	Gathering information	Developing specifications/procurement documents	Planning or conducting pilot testing	Previously explored and decided not to implement	Other (please describe)
South Dakota	-	-	-	O	-
Tennessee	-	-	-	O	-
Utah	O	-	-	-	-
Vermont	O	-	-	-	-
Virginia	-	-	O	-	-
Washington	O	-	-	-	-
Wisconsin	O	-	-	-	-

Table C-23. Survey comments for Question 15 (status of exploration of Leader-Follower TMA systems)

Comment
We have a research project underway with a university that will be looking at the use of a leader/follower TMA during crack sealing, pothole patching, and sweeping mobile operations.
The Virginia Tech Transportation Institute (VTTI) has developed an ATMA specification and is Beta testing the device on a closed course.
Our tests results indicated that the equipment tested was not ready for implementation without further development.
Looked into it a couple years ago, 2019, and decided the technology hadn't advanced to a point where it was usable.
We currently have a research study looking at the feasibility of ATMA implementation for our state.
We attended the peer exchange in 2017 with Colorado DOT's demo of Royal Trucks ATMA. At that time and future demos we found too many flaws along with secondary contract needs for our DOT. Our DOT doesn't have many long straight roadways which made it hard to justify. During the CDOT peer exchange I had discussions with other DOTs. We discussed that MODOT was looking to build their own ATMA. Unfortunately at the time, we didn't have the funds to contribute to the building. We are interested to see how far it's come.
Several years ago, we had looked into the Royal Trucking automated TMA, but in discussions with the company, it sounded like the build would be part of R&D instead of there being finished specs we could choose. Had heard that North Dakota DOT was already in the process of having one built and decided to hold off and see what ND received and how it went. Have not looked into this further in recent years.

Table C-24. Other text responses for Question 15 (status of exploration of Leader-Follower TMA systems)

Other - Text
We have created a spec sheet but the researcher was unable to move to 2nd phase and implement.
We are a member of the AMT Pooled Fund, which is developing specs, procurement documents, and best practices. Our state's legal code must change for us to pursue the technology further.

Table C-25. Survey responses for Question 16 (development of resources to support potential implementation of Leader-Follower TMA systems)

Respondent	Evaluation or feasibility studies	Operational guidelines	Performance specifications	Test plan	My agency has not developed any resources in support of potential implementation of Leader-Follower TMA systems	Other (please describe)
Arizona	-	-	-	-	-	-
California	O	O	O	O	-	-
Delaware	-	-	-	-	-	-
Illinois	-	-	-	-	O	-
Indiana	-	-	-	-	O	-
Iowa	-	-	-	-	O	-
Kansas	O	-	-	-	-	-
Kentucky	-	-	-	-	O	-
Minnesota	O	O	-	O	-	-
North Carolina	-	-	-	-	O	-
Ohio	-	-	-	-	O	-
Oregon	O	-	-	-	-	-
South Dakota	-	-	-	-	O	-
Tennessee	-	-	-	-	O	-
Utah	-	-	-	-	O	-
Vermont	-	-	-	-	O	-
Virginia	O	O	O	O	-	-
Washington	-	-	-	-	O	-
Wisconsin	-	-	-	-	O	-

Table C-26. Survey comments for Question 16 (development of resources to support potential implementation of Leader-Follower TMA systems)

Comment
Feasibility study is in the early stages at this time.
Development is currently in process with the research team at a university and the work being done by the pool fund.
While we have not developed any resources, we are actively participating in the AMT pooled fund that is developing resources for all members to use in implementing ATMA technology.

Table C-27. Survey responses for Question 17 (interest in performance metrics for Leader-Follower TMA systems)

Respondent	Benefit-cost analysis	Emergency stops	Lateral accuracy	Longitudinal accuracy	Loss of communications	Loss of GPS signal	Obstacle detection and avoidance	Turning capabilities	Worker injuries	Worker perception of the system	Other (please describe)
Arizona	-	-	-	-	-	-	-	-	-	-	O
California	-	O	-	-	-	O	-	-	-	O	-
Delaware	-	-	O	O	O	O	O	O	-	-	O
Illinois	O	O	O	O	O	O	O	O	-	-	-
Indiana	O	O	O	O	O	O	O	O	O	O	-
Iowa	O	-	O	O	-	-	-	O	O	O	-
Kansas	O	O	O	O	O	O	O	O	O	O	O
Kentucky	-	O	O	O	O	O	O	-	O	O	-
Minnesota	O	O	O	O	O	O	O	O	O	O	-
North Carolina	O	O	O	O	O	O	O	O	O	O	-
Ohio	-	-	-	-	-	-	-	-	-	-	-
Oregon	-	O	O	O	O	O	O	O	-	-	-
South Dakota	O	-	-	-	O	-	O	O	-	-	-
Tennessee	-	O	O	O	O	O	O	-	-	-	-
Utah	O	O	-	-	O	O	O	-	O	O	O
Vermont	O	-	-	O	O	O	O	O	-	-	-
Virginia	O	-	-	-	O	O	O	-	-	-	-
Washington	-	O	O	O	O	O	O	-	-	-	O
Wisconsin	O	O	O	O	O	O	O	O	O	O	-

Table C-28. Survey comments for Question 17 (interest in performance metrics for Leader-Follower TMA systems)

Comment
Lots of concerns overall with regards to the viability of this tech for maintenance work. For example, many of the states participating in the pooled fund have focused on painting/striping activities with this type of equipment. After spending a day with a paint crew there are concerns with private vehicles leap frogging between the lead and follow vehicles, which can widen the gap to the point the follow vehicle would just stop on the road. Someone would then have to go back and get the truck.
See our full report for some of the issues we found during our trial.
GPS communication, data security, and travel through roundabouts.

Table C-29. Other text responses for Question 17 (interest in performance metrics for Leader-Follower TMA systems)

Other - Text
Practicality and ease of use getting from a Maintenance Shed to an Autonomous sweeping route.
Real costs.
Need to be able to enter traffic before the leader; as a leader/follower, the leader needs to enter traffic first before the ATMA will enter to protect the leader.

Table C-30. Survey responses for Question 18 (ranking of challenges to potential implementation of Leader-Follower TMA systems)

Respondent	Contracting Considerations	Funding Constraints	Lack of Agency Buy-In	Lack of Availability of Personnel	Lack of Perceived Need	Legislative Authority	Maintenance Cost of System	Performance Measures	Technology Cost	Training Needs	Unable to Achieve Desired Technical Performance	Other (Please describe)
Arizona	-	-	-	-	-	-	-	-	-	-	-	1
California	-	-	-	-	-	1	-	2	-	-	-	3
Delaware	-	-	8	11	9	-	-	-	-	12	10	-
Illinois	-	2	-	-	-	1	-	-	-	3	-	-
Indiana	-	-	-	-	3	-	-	-	-	2	1	-
Iowa	10	1	6	11	7	9	2	3	4	5	8	12
Kansas	1	-	-	-	-	-	4	-	-	3	-	2
Kentucky	-	-	3	-	-	-	-	2	-	-	1	-
Minnesota	-	-	-	-	-	3	2	-	-	-	1	-
North Carolina	3	-	-	-	-	-	-	2	-	-	1	-
Ohio	1	-	-	2	-	-	-	-	-	-	-	-
Oregon	-	-	-	-	-	-	-	2	-	3	1	-
South Dakota	-	-	-	1	-	-	-	-	2	-	3	-
Tennessee	6	8	3	10	7	12	11	2	5	9	1	-
Utah	-	1	-	2	-	-	3	-	-	-	-	-
Vermont	-	1	-	-	2	-	-	3	-	-	-	-
Virginia	-	10	11	-	-	-	-	-	12	-	-	-
Washington	-	4	-	1	-	-	2	5	-	-	3	-
Wisconsin	6	1	8	10	7	4	2	9	5	3	11	12

Table C-31. Survey comments for Question 18 (ranking of challenges to potential implementation of Leader-Follower TMA systems)

Comment
The concept and reasoning sound great - removing a driver from the vehicle most likely to be hit and our agency probably has attenuator trucks hit 18-20 times a year, but we do not have a correlating set of serious injuries resulting from those hits. There is also a perception with ground crews that the person in the seat of that attenuator truck is an extra set of eyes to alert them of a potential intrusion into their work area and moving them out of that truck makes their work zone less safe.
Finding technically skilled workers/mechanics and equipment funding is presently difficult. Having good technical data showing consistent equipment performance is important.

Table C-32. Other text responses for Question 18 (ranking of challenges to potential implementation of Leader-Follower TMA systems)

Other - Text
Lack of employee buy in
All of the above
Operation policy and procedures

Table C-33. Survey responses for Question 19 (willingness to participate in interview to discuss potential implementation of Leader-Follower TMA systems)

Respondent	Response Text
Arizona	Yes
California	Yes
Delaware	Yes
Illinois	Yes
Indiana	Yes
Iowa	Yes
Kansas	Yes
Kentucky	Yes
Minnesota	Yes
North Carolina	Yes
Ohio	Yes
Oregon	Yes
South Dakota	No
Tennessee	-
Utah	Yes
Vermont	No
Virginia	Yes
Washington	Yes
Wisconsin	No

Table C-34. Survey responses for Question 20 (reasons for not exploring potential use of Leader-Follower TMA systems)

Respondent	Cost	Lack of availability of personnel	Lack of identified funding	Lack of information regarding the technology	Lack of data on system performance	Lack of legislative authority	Lack of perceived need	Other initiatives are higher priority	Other (please describe)
Alabama	O	O	O	O	O	O	O	-	-
Arkansas	-	-	-	O	-	-	-	-	-
Georgia	-	-	-	O	O	-	-	-	-
Idaho	-	-	-	-	-	-	-	-	O
Louisiana	-	O	-	-	-	-	-	O	-
Maine	-	O	-	-	-	-	-	O	O
Maryland	-	-	-	-	-	O	-	-	-
Massachusetts	-	-	O	O	O	-	-	-	-
Michigan	-	-	-	-	-	-	-	O	O
Mississippi	O	-	O	O	O	-	-	-	-
Montana	-	-	-	O	O	-	O	O	-
Nebraska	-	-	-	O	-	-	-	O	-
Nevada	O	-	-	-	-	-	O	-	-
New Hampshire	-	-	-	O	-	-	-	-	O
New Jersey	-	-	-	O	O	-	O	-	O
New Mexico	-	-	-	O	O	-	O	-	O
Ohio Turnpike	-	-	-	O	-	-	-	-	-
Oklahoma	O	-	O	-	-	O	-	-	-
South Carolina	-	-	-	O	-	-	-	-	-
Texas	-	-	-	-	-	-	-	-	O

Table C-35. Other text responses for Question 20 (reasons for not exploring potential use of Leader-Follower TMA systems)

Other - Text
Lack of awareness
It appears this issue is for a moving operation?
Our work mostly consists of flagger-controlled work sites, rarely have we used or specified a lead vehicle (Pilot car).
The major reason for the lack of a Follower - Leader TMA system is that the District Offices were not aware of it and there does seem to be some questioning of the need for it.
Have not heard of this.
In speaking with members of our traffic control committee, this has not even been brought up for consideration.
We are looking at a lot of devices and this is just not one on our list. We have talked about this just not something we are focusing on as a lead state at this time.

Table C-36. Survey comments for Question 21 (general comments)

Comment
This appears to be a great idea to improve safety of the follower vehicles. There is some interest in pilot cases.
I do expect in the future we will explore these systems, but at the current time, we are not. We would entertain this if a Contractor was to propose a Leader-Follower TMA system, based on work zone type and successful previous use by the Contractor.
We are interested in the outcome of your study!
The area that is going to create issues and concerns for me is the bridge and ramp locations. With a human driver there are times that the lead and follow spaces are adjusted based on roadway elements. You don't park a TMA under a bridge as it is hard to see as a driver so you stop before and then park after, this requires a different knowledge and follow distance from the driver. The location when passing by on and off ramps is another area of concern and how they handle these locations. Backing of the TMA or work vehicles. We don't promote or allow backing in most conditions but once again as an automated follow vehicle the lead driver can't operate as they normally would. On a simple section of roadway this can work but will there be more harm than good that can come out of this?
We saw this technology demonstrated (CTE meeting?) and we realize the safety value that it offers. We are interested to know what are the states that have implemented this system and what are their thoughts. And of course what costs would be per unit.
Very thankful and appreciative of the work that lead states are putting into this program.
Our DOT is participating in the ATMA Pool Fund study with other state DOTs.
Thanks, this was FUN! :)
This appears to be a decent technology we have been monitoring to see if it is relevant to our business needs
Our DOT Maintenance is working on this endeavor. If there is a follow-up conversation, I would need them to be involved.
Having never used it, or having never even considered it, our DOT really isn't positioned to provide comment. It would be interesting to hear how many states use it.
Leader-Follower TMA systems seem to have benefit for the safety of a work zone. Please keep our DOT informed as the study progresses.
Our DOT formed a group to look into current Leader Follower System TMA in/around 2019. The group decided the technology wasn't in an advanced state to be able to practically put into use. The main issues centered around the follower navigating highway accesses safely. System seemed good for segments of highways, but generally long segments of highways have less traffic, so the need for a TMA is less. Also worried about additional manpower of TMA, still requires a person to facilitate the use of the follower.

APPENDIX D. EXAMPLE QUESTIONS FOR DOT INTERVIEWS

This Appendix provides example questions for the DOT interviews. Questions for one DOT that has implemented Leader-Follower TMA systems (Colorado DOT) and one DOT that has explored Leader-Follower TMA systems (Ohio DOT) are shown. There was some customization of the questions for each DOT.

Questions for Colorado DOT

Questions for Central Office

1. What is the current status of CDOT's implementation of the Leader-Follower TMA system (e.g., Regions, applications, routes)?
2. What types of roadways and ADT ranges is the system used for?
3. Do you only use this for mobile operations? If so, specifically what types?
4. Have you used this in stationary applications? If so, what types of operations?
5. Is CDOT looking to expand the use of the system to other Regions or applications?
6. What led CDOT to pursue implementation of a Leader-Follower TMA system?
7. What process did CDOT use to assess the Leader-Follower TMA system for possible implementation?
8. What challenges did CDOT face in trying to implement a Leader-Follower TMA system? How did CDOT overcome those challenges?
9. What data does CDOT collect to evaluate the performance of its Leader-Follower TMA system? What performance measures does CDOT currently use to evaluate the performance of the Leader-Follower system?
10. How do you perceive the overall effectiveness of the Leader-Follower TMA system?
11. How is the Leader-Follower TMA system perceived by the public and news media?
12. Are there any major system issues or shortcomings of the system (in training or in the field) that new users or potential users of the system should be aware of?
13. Based on your experience with implementing the system, is there any advice that you would give to other DOTs who are considering implementing the system or just starting to implement the system?

Questions for Operators

1. What type of training did you receive on the system? Do you believe that you received sufficient training to operate the system?
2. What type of initial learning curve did you experience when first using the system?
3. Are you able to use the equipment efficiently after the initial learning curve?
4. How many hours did you have behind the wheel of the follower TMA under live traffic before going completely autonomous?

5. Once you switched to fully autonomous and all personnel were located in the leader TMA under live traffic, how long did it take to get accustomed to the setup?
6. Does the system operate overall within the work zone as intended?
7. Does the system operate safely?
8. Have you had any vehicles strike the follower TMA? If so, how did it perform during and afterwards?
9. What is your perception of mobile work zone safety with the Leader-Follower TMA system versus without the system?
10. How would you rate the overall performance of the system on a scale of 1 to 10?
11. Have you encountered any issues that have hindered the effective operation of the system?
12. Are there any improvements that could be made regarding the operation of the system?
13. Are there other applications for which you think that the system could be beneficial?
14. Based on your experience with using the system, is there any advice that you would give to an operator who is just beginning to use the system?

Questions for Ohio DOT

1. How extensively has your DOT explored Leader-Follower TMA systems?
2. What is the current status of your DOT's exploration of Leader-Follower TMA systems?
3. What types of roadways and ADT ranges is your DOT considering using the system for?
4. What factors currently limit your DOT's ability to implement Leader-Follower TMA systems?
5. Do personnel at your DOT have any concerns regarding the use of Leader-Follower TMA systems? If so, what are their concerns?
6. How is the Leader-Follower TMA system perceived by the public and news media?
7. Has your DOT performed any formal evaluations of Leader-Follower TMA systems? If so, what were the results?
8. What information regarding performance metrics for Leader-Follower TMA systems would you like to see?
9. What information regarding practices of other DOTs for Leader-Follower TMA systems could be beneficial to your DOTs efforts to implement Leader-Follower TMA systems?

APPENDIX E. QUESTIONS FOR MODOT EMPLOYEE INTERVIEWS

1. What has been your role in operating the system?
2. Approximately how many hours have you logged while operating the system in the field?
3. What type of training did you receive on the system? Do you believe that you received sufficient training to operate the system?
4. What type of initial learning curve did you experience when first using the system?
5. Are you able to use the equipment efficiently after the initial learning curve?
6. Overall, does the system function properly within the work zone as intended?
7. Does the system operate safely?
8. Have you had any vehicles strike the follower TMA? If so, how did it perform during and afterwards?
9. Have you had any close calls where vehicles almost struck the TMA? If so, please describe.
10. Have you ever had to walk between the leader and follower vehicles while the system was in operation? If so, please describe.
11. What is your perception of mobile work zone safety with the Leader-Follower TMA system versus without the system?
12. How would you rate the overall performance of the system on a scale of 1 to 10?
13. Have you encountered any issues that have hindered the effective operation of the system? If so, please describe.
14. Are there any improvements that could be made regarding the operation of the system?
15. Are there other applications for which you think that the system could be beneficial?
16. Based on your experience with using the system, do you have any suggestions for ways that MoDOT can improve its implementation of the system?