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Autonomous Truck Mounted Attenuator (ATMA) Pilot

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DISCLAIMER

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16. Abstract

The objective of this research was to provide the Tennessee Department of Transportation (TDOT) an evaluation on the performance of an autonomous truck mounted attenuator (ATMA) system(s), based on previous relevant research projects and on actual testing of the equipment during a demonstration pilot. A set of testing scenarios were developed in close collaboration with TDOT to better understand the feasibility and applicability of the ATMA system to improve safety on work zones in Tennessee. The ATMA pilot demonstration testing in Tennessee concluded primarily that the ATMA system is better suited for work zone operations that require continuous movement for longer periods of time. Retracing or installation of pavement markings and roadway sweeping are examples of such operations. Based on the pilot results, the tested ATMA system warrants further development and testing for work zones requiring stop-and-go applications. Pothole patching, weed spraying and trash pick-up on the roadway shoulder are examples of such operations. The ATMA system presents technological advancements that increase safety in work zones. It can be further enhanced by future refinement and implementation of additional system functionalities.

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Executive Summary

Work Zone safety is a major concern to federal, state and local agencies. Periodic maintenance of roadways requires workers to be exposed to hazardous conditions, often working next to traffic traveling at high rates of speed. The Tennessee Department of Transportation (TDOT), in its continuous efforts to target the reduction of work zone fatalities and to provide safe working conditions to its employees, decided to explore the applicability of an Autonomous Truck Mounted Attenuator (ATMA) to improve work zone safety. The main benefit of such a system is the enhanced operational safety provided by the removal of the Truck Mounted Attenuator (TMA) driver from harm's way. In addition, an ATMA system is designed to maintain the proper buffer distance to the service vehicle with greater accuracy than a human driver, therefore providing additional worker safety. In operation, the Leader Vehicle (LV) system transmits its position, speed, and heading to the ATMA follower vehicle in a sequential series of Vehicle-to-Vehicle (V2V) "*e-Crumb"* electronic crumb messages. The ATMA then maneuvers from one *e-Crumb* to the next precisely following the path of the LV at a user-defined vehicle-gap.

A Literature Review was conducted, but due to the novel concept of the ATMA system, the information available was limited. A few state DOT's provided feedback to a request of information. The Colorado Department of Transportation has performed validation tests on the system and has undertaken a phased approach with the deployment of the ATMA. Currently, in Colorado, the ATMA system is authorized to operate on roads with AADT of less than 5,000 vehicles per day and is used for painting stripping typically on long, flat, rural roadways.
The research team contacted TDOT representatives from the Occupational Health and Safety Division to learn about current TDOT practice regarding TMAs. We learned that TDOT provides comprehensive periodic training on TMAs and work zones and that maintaining consistent follow and roll ahead distances was identified as an important desired ATMA system asset. Meanwhile, the research team recommended TDOT to explore the use of rangefinders with laser technology to minimize the aforementioned concern.

The ATMA testing in Tennessee was conducted during a pilot demonstration in coordination with TDOT, where a set of twenty-four case scenarios analyzed the various operational components of the system. It concluded primarily that the ATMA system is better suited for work zone operations that require continuous movement for longer periods of time, due to its speed/gap

algorithm configuration. The ATMA system tested is not currently designed to accommodate stop-and-go applications, like pothole patching for example. In addition, the system demonstrated the capability to operate in Global Positioning System (GPS) denied locations, but only for a short period of time. Therefore, the tested ATMA system requires additional refinement for operations at locations with overpasses, heavy foliage, tunnels and any other locations with long periods of sustained loss of GPS signal. Furthermore, due to the "*e-crumb*" following technology, the testing pointed to the current inability of the ATMA system to consistently shadow/protect the service vehicle at all times. When the leader/service vehicle encroaches in the lane from a shoulder, for example, the autonomous follower vehicle will not immediately shift to the lane behind the service vehicle, having to follow the *e-crumbs* laid out by the service vehicle first. The ability to offset the follower vehicle from the leader vehicle "*on the fly*" is necessary to accommodate such scenario. Since the pilot testing in Tennessee, an offset functionality has been developed for the system. Extensive training and practice is imperative to assure the safe operation of the ATMA system.

Finally, the ATMA system is an innovative and promising asset to improve work zone safety for all users. The aforementioned issues can potentially be minimized by the continuous fine tuning the ATMA system algorithm, by implementation of additional functionalities and further testing, greatly enhancing the system capabilities.

List of Acronyms

Acronym	Description
AES	Advanced Encryption Standard
AHMCT	Advanced Highway Maintenance & Construction Technology Research Center
AIPV	Autonomous Impact Protection Vehicle
AMT	Autonomous Maintenance Technology
A-Stop	Automatic Stop
ATMA	Autonomous Truck Mounted Attenuator
CDOT	Colorado Department of Transportation
CTE	Cross Track Error
e-Crumbs	Electronic Crumbs
ESR	Electronic Scanning Radar
E-Stop	Emergency Stop
FLW	Follower Vehicle
GUI	Graphic User Interface
GPS	Global Positioning System
IMU	Inertial Monitoring Unit
INS	Inertial Navigation System
KML	Keyhole Markup Language
LTSC	Long Term Servicing Channel
LV	Leader Vehicle
MODOT	Missouri Department of Transportation
NDDOT	North Dakota Department of Transportation
NLOS	Non-Line of Sight
OCU	Operator Control Unit
PTQ	Protect-the-Queue
RF	Radio Frequency
SOG	Standard Operating Guidelines
TDOT	Tennessee Department of Transportation

TDSTC	Tennessee Department of Safety Training Center
TIM	Traffic Incident Management Training Facility
TMA	Truck Mounted Attenuator
V2V	Vehicle-to-Vehicle

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Chapter 1: Introduction

Work Zone safety is a major concern to federal, state and local agencies. Periodic maintenance of roadways requires workers to be exposed to hazardous conditions, often working next to traffic traveling at high rates of speed. The 2017 TDOT Work Zone Safety and Mobility Manual (*5*) states that it is the agency's goal to maximize safety in all its work zones to reduce fatality, injury and property damage crashes statewide. According to the National Work Zone Safety Information Clearinghouse, in the last 10 years, 147 fatalities have taken place in work zones in the State of Tennessee where 51 work zone workers lost their life. The Tennessee Department of Transportation (TDOT), in its continuous efforts to target the reduction of work zone fatalities and to provide safe working conditions to its employees, decided to explore the use of autonomous technology to improve work zone safety.

Truck mounted attenuators (TMAs) are energy-absorbing devices attached to the rear of trucks to reduce the severity of potential rear-end crashes by traffic mistakenly entering a work zone. Unfortunately, highway workers are routinely being placed at risk driving these trucks "designed to be hit," and are constantly exposed to potential death or lifelong injuries incurred by the operation of these vehicles. The introduction of connected and autonomous vehicle technology provides an opportunity to address the problem. The Autonomous Truck Mounted Attenuator or ATMA is an innovative system that removes the TMA driver from harm's way and promises to maintain accurate proper buffer distance, as required by standard work zone operation procedures. The ATMA system uses a leader-follower concept shown in Figure 1. The leader truck or service truck, operated by a human driver, is equipped with Global Positioning System (GPS), which drop virtual electronic crumbs (e-Crumbs) containing its position information for the follower. The follower vehicle equipped with an attenuator, is designed to operate autonomously following those e-Crumbs at a configured gap distance.

The objective of this report is to validate the various operational components of an ATMA system and to determine its applicability to TDOT, based on previous relevant research projects and on actual testing of the equipment during a demonstration pilot. In coordination with TDOT, a set of relevant scenarios were developed in several categories, including safety, following accuracy, typical applications, detection, communication and additional miscellaneous testing. Data from the week-long pilot demonstration was analyzed based on accuracy, ease of use and applicability to TDOT.

Figure 1 - ATMA's Leader Follower Concept

The report is structured in 7 Chapters, including the introduction, a literature review, a discussion on current TDOT practices, the pilot testing procedures, the ATMA system equipment specifications provided by the system supplier, the ATMA system equipment analysis, the pilot testing data analysis and the conclusions and recommendations chapter, followed by references and the appendix.

Chapter 2: Literature Review

2.1 State DOT's Testing of ATMA Systems

Autonomous Truck Mounted Attenuators (ATMA) systems or Autonomous Impact Protection Vehicles (AIPV) systems have first been demonstrated in 2014 in Pennsylvania. The following year, the equipment was also tested in London, England, aimed to enhance work zone protection due to an increase in deaths in their highway work force related to drunk and distracted drivers. Colorado DOT (CDOT) through its "RoadX – Accelerating Technology" project launched their test program of the first ATMA system used in conjunction with a striping operation. The Autonomous TMA truck completed a striping operation on the highway on August, 2017 in Fort Collins, Colorado. CDOT also hosted an FHWA Peer Exchange directed toward their experience of testing and adopting this Autonomous TMA technology. A live demonstration on Route 34 outside the CDOT Greeley Headquarters was provided at the end of the 2nd day of the exchange. Here is some available footage: https://www.youtube.com/watch?time_continue =145&v=xBd6CmTGjFk.

CDOT's interest in the ATMA system started from the fact that there were 171 fatalities in Colorado work zones between 2000 and 2014. High-level DOT interest in the safety of highway workers was exemplified by Shailen Bhatt (*2*), (former) Executive Director of CDOT who said: "Just in the last four years, there have been 26 incidents where a member of the traveling public struck a CDOT impact protection vehicle — that's almost seven per year. This is a dangerously high number when you consider that in some instances, a CDOT employee is sitting in the driver's seat of the vehicle that was hit. By using self-driving technology, we're able to take the driver out of harm's way while still effectively shielding roadside workers." Colorado, in conjunction with the Transportation Pooled Fund Program, created a solicitation called Autonomous Maintenance Technology (AMT) aimed at investigating and developing other platforms for this technology. Additional information can be found at [http://www.csits.colostate.edu/autonomous-maintenance-technology.html.](http://www.csits.colostate.edu/autonomous-maintenance-technology.html)

CDOT has tested the ATMA a few times since the initial demonstration. The first validation test (featuring approximately 30 different scenarios tested) occurred during the summer of 2018 on a closed course testing (4,000 feet airstrip) and also on an open, public roadway (with a human operator behind the wheel of the ATMA). The second validation test occurred on October 2019, after CDOT received a significant hardware and software technology upgrade on the vehicle. CDOT repeated the validation test (16 scenarios tested) on the closed course, and then repeated a selection of tests on the public roadway prior to the system being approved to operate in automated mode on the public roadway. CDOT researchers informed that in general, the ATMA gap control functionality worked as expected. Documentation on system challenges during the CDOT testing will be made available on a toolkit released by the Autonomous Maintenance Technology Pooled fund. Furthermore, CDOT has undertaken a phased approach with the deployment of the ATMA to mitigate risk to the public, to CDOT staff, and provide ample room to understand all aspects and considerations to deployment prior to expanding the program. Initial deployment has occurred on roads with AADT of less than 2,500 vehicles per day. Currently, in Colorado, the ATMA system is authorized to operate on roads with AADT of less than 5,000 vehicles per day and is used for painting stripping typically on long, flat, rural roadways. The research team received from Kratos Defense two ATMA validation reports from July 2017 (*7*) and September 2017 (*8*), prepared for internal use only for the Colorado Department of Transportation (CDOT). It detailed a few of the system's capabilities and provide interpretations of a set of testing procedures done on the original version of the ATMA system.

The research team contacted a few other locations that have undergone testing of the ATMA system. The University of California Davies have tested the equipment in the beginning of 2020 and have around 40 hours of autonomous operation time. Almost all of the testing was done on flat roadways. The need for a more responsive gap control was mentioned and testing under an overpass was not successful. Researchers agreed that the ATMA is most useful in moving mainline highway maintenance operations, like sweeping and lane striping. They also reported that the ATMA system being tested had control and sensing systems upgraded providing better functionality and fewer failures. The Advanced Highway Maintenance & Construction Technology Research Center (AHMCT) at UC Davies is currently under contract to evaluate the ATMA purchased for Caltrans use. The available report was not available for sharing at the time of this report.

Furthermore, the North Dakota Department of Transportation (NDDOT) was contacted and have tested the ATMA system in the second semester of 2020 and will continue to test it in the spring of 2021. Testing occurred on relatively flat terrain, on a low volume frontage road and on a low volume state road. No reports were available for the testing at this time. Researchers mentioned a few GPS connection issues that led to the loss of connectivity between the leader and the follower vehicle a few times, but that were solved during the testing. Preliminary information on gap control was that it seemed to work really well.

The University of Florida Transportation Institute has also tested the ATMA system and has no report available for sharing at the time of this report. A comprehensive set of tests were conducted in the demonstration location, including the automated stopping function, the emergency stop feature, accuracy of following in terms of both distance and path, lane-changing, vehicle intruding between leader and follower, object recognition, and many others. In addition, six test sites were selected that represented a range of Florida highways types on urban and rural environments, including testing of the ATMA system as it navigates through a series of signalized intersections.

Missouri DOT (MODOT) was also contacted and the information on their testing of the ATMA system was not yet available at the time of this report.

2.2 Benefits of ATMA Systems

Truck mounted attenuators (TMAs) are energy-absorbing devices attached to the rear of trucks to reduce the severity of rear-end crashes. TMAs are deployed on shadow vehicles in work zones to mitigate the effects of errant vehicles that strike the vehicle, either by smoothly decelerating the vehicle to a stop when hit head-on or by redirecting the errant vehicle (Cottrell). A Virginia Research Council study (*9*) identified potential hazards associated with mobile and short duration maintenance operations and the probable underlying causational factors. It was found that worker safety was one of the primary hazards due to worker exposure, worker complacency and attentiveness.

According to Royal Truck and Equipment Inc. and Kratos Defense, the ATMA shadows a lead vehicle, typically a slow-moving maintenance vehicle, such as a line painting truck or street sweeper. The lead vehicle drops "electronic GPS based breadcrumbs" that the ATMA picks up via a wireless link between vehicles, this allows the "crash cushion" vehicle to be unmanned and removes the driver from harm's way. The two companies add that there are primary and secondary benefits to the ATMA system:

- The primary benefit is the removal of the driver from harm's way, including potential death or lifelong injury.
- The human instinct for self-preservation is removed with the driver; automated vehicles will not flee oncoming errant vehicles as human drivers have been shown to do, leaving the lead vehicle unprotected.
- Human error is also removed with the driver; automated vehicles maintain the proper buffer distance with perfect accuracy; human drivers will often come too close to their protected vehicle thereby endangering them with a secondary impact.

In addition, according to Royal Trucking and Equipment Inc. it is claimed that the ATMA will save time, money, and improve quality in four areas. First, by repurposing the driver to a safer task, employment efficiencies will be created: a TMA truck driver can now be retrained to perform a higher skilled job of monitoring the autonomous vehicle's status, functions, and operation from the safety of the lead vehicle cab. Second, by removing the TMA driver from a dangerous location, the dark cloud of lifelong injury, including huge medical claims and workman's compensation payments are removed—this potential for great liability is mitigated.

Third, there is a psychological impact upon this class of workers that must report daily. The fear of potential catastrophe affects not only the worker, but the worker's family, and if they get hit: their community of support. Fourth, quality will be improved because the autonomous vehicle will not flee the scene. Take the human out and the driver will not forget to hit the brakes upon impact. Take the human out and the driver will not daydream and ride too close to the vehicle it is protecting. Automation is urgently needed to answer this important yet dangerous job.

The value of this system to state DOTs is that it introduces use of autonomous technology without any infrastructure improvements. This system relies solely on military grade GPS technology. Many states have fast-track programs to encourage innovations and new technologies that make their state highways safer. The ATMA is well suited for such programs. Transportation departments and the general public can easily accept use of this "icebreaker" autonomous technology because, 1) it is used in highly controlled mobile work zone environments, (not just out there driving around) and 2) it will save the lives of the traveling public and highway workers. In addition, if just one life is saved by an ATMA system, its investment costs far outweigh the "economical value of a statistical life," that according to the US Department of Transportation was valued in $9.6 million in 2016.

Chapter 3: Current TDOT Practice

The research team contacted TDOT representatives from the Occupational Health and Safety Division to learn about current TDOT practice regarding Truck Mounted Attenuators (TMAs). TDOT currently owns 220 TMA units statewide. TDOT Standard Operating Guidelines (SOG) states that maintenance forces (internal, TDOT employees) utilize TMAs on all roadways with a speed greater than 45mph (basically, 50mph and above). This accounts for approximately 56% of state routes and all interstates. TDOT plans to further expand their inventory to approximately 250 TMA units over the next couple of years. They will then revise the SOG to include roadways with a speed of 45mph and above, which accounts for approximately 86% of state routes. All contract work uses Protect-the-Queue (PTQ) equipment, which currently consists of TMAs. Figure 2 is an example of the vehicles used in the PTQ program. TDOT is currently developing specifications for queue warning systems that include sensors and message and notification dissemination. The program will still utilize TMAs when queues extend past the deployed devices.

Figure 2 - TMA used in TDOT's Protect-the-Queue Program

TDOT Regional Safety staff conducts training for TMA operators using a TMA manual recently developed in 2019. A laminated one page front-and-back condensed guide summarizes important information from the manual is kept aboard each TMA equipped vehicle. The document highlights pre-trip inspection steps, important considerations and placement and roll-ahead distances based on roadway type. Additionally, TDOT periodically conducts tailgate talks related to specific topics and answers questions that arise during operation. TDOT reviews TMA crashes on a case-by-case basis to determine if changes in procedure are warranted and is to determine the effectiveness of newly issued TMA guidance and implementation. The TDOT Work Zone Field Manual for Maintenance Operations (*6*) (https://www.tn.gov/content/dam/tn/tdot/traffic-engineering/Work%20Zone%20Field%20Manual%20-%20Final%204-29-2019.pdf) is currently under revision and is planned to be updated with additional guidance on TMA use and placement, TMA use during specific activities plus work activity and duration types.

While driving on Interstate (I)-40 from Knoxville to the ATMA Pilot testing locations, the research team drove through several roadway maintenance operations utilizing TMAs. It was noticeable that, even though the maintenance service being performed as well as speed limits were similar in each location, the spacing between the service vehicles and the TMAs differed. This triggered a specific question to TDOT personnel on how TMA operators maintain the required follow distance. Similar to practices in other DOT's around the country, TDOT TMA operators rely on dashed pavement markings as a guide for follow distance. The follow distance can be quickly estimated by counting the number of pavement markings between the vehicles. Pavement markings are typically 10 feet long with 30 feet spacing, for a total of 40 feet. Nevertheless, TDOT personnel pointed out that TMA operators are encouraged to consider roadway geometry, visibility, weather (sun glare), type of facility, traffic volumes and local knowledge of driver comfort to prevent encroachment into the roll ahead zone between the TMA and the work area.

Currently, TDOT's TMAs or contracted TMAs do not have a system (eg.: GPS with timestamp) that tracks the positioning of the TMA in relationship to the other service vehicles involved in the work zone operation. Two-way radios are the primary means of communication used by TMA operators. TMA operators also rely on truck horns as an alarm to warn other work zone personnel of hazardous conditions or operator distraction. TDOT supervisors didn't identify specific distractions (cell phone use, etc) noticed during field operations but were concerned with driver complacency. These concerns are more significant in interstate operations. High volumes of traffic locations require concentration, attentiveness and alertness, opposed to locations with lower traffic volumes.

Figure 3 - Typical TDOT TMA Operation

TDOT personnel were asked what asset that would most significantly improve TDOT's typical TMA operations (Figure 3) with the use of the ATMA system (other than TMA driver safety). They identified this asset as the ability to maintain consistent TMA follow and roll ahead distances. It was added that the human element would still be required to adjust for geometry, sight distance and driver encroachment.

Based on this information, the research team recommends TDOT to explore the use of rangefinders with laser technology (Figure 4). This device would allow a TMA operator to better estimate and maintain the follow and roll ahead distance between a TMA and a service vehicle. Currently available laser technology allows for precise distance measurements up to 500 yards.

These devices can compensate for slope and weather conditions (temperature and barometric pressure) at an estimated cost of less than $750 per unit.

Figure 4 - Rangefinder

Chapter 4: Pilot Testing Procedures

Preliminary ATMA pilot testing procedures designed to validate the various system's operational components were developed by the research team, and discussed with TDOT representatives from the Traffic Operations Division and the Occupational Health and Safety Division. Testing emulating typical applications of TMA's was requested by TDOT and incorporated to the final testing procedures. The set of case scenarios is presented in Table 1. Detailed description of each case scenario is presented in Chapter 6.

Autonomous Truck Mounted Attenuator (ATMA) Testing Scenarios		
Test Scenario #	**Test Category**	**Description**
1	Safety	Automatic Stop (A-Stop) - Leader Vehicle Internal Button
2	Safety	Emergency Stop (E-Stop) - Leader Vehicle Internal Button
3	Safety	Emergency Stop (E-Stop) - ATMA External Button
4	Safety	Emergency Stop (E-Stop) – ATMA Internal Button
5	Following Accuracy	Following Accuracy on Straight Line
6	Following Accuracy	Following Accuracy on Slalom Course
7	Following Accuracy	Following Accuracy on Lane Change
8	Following Accuracy	Adjusting Following Distance
9	Typical Applications	Trash Pick-up
10	Typical Applications	Herbicide Application
11	Typical Applications	Pothole Patching
12	Detection	Obstacle Detection - FRONT
13	Detection	Vehicle Intrusion
14	Detection	Sensitivity to Passing Vehicles
15	Detection	Object Recognition
16	Detection	Headlights
17	Detection	Cone Detection
18	Miscellaneous	Speed Test
19	Miscellaneous	Braking – Leader Vehicle
20	Miscellaneous	Bump Test
21	Miscellaneous	Leader Reverse
22	Miscellaneous	Turning at I-840
23	Miscellaneous	Tight Turn Radius
24	Communication	Loss of Communication

Table 1 – Testing Scenarios

The pilot took place November 4-8, 2019, from 8am to 4pm each day. Test locations were selected based on roadway characteristics that would provide access control and a wide variety of geometric and topographic conditions for the testing. The following are the two selected locations.

Location 1 – West end of I-840 in Dickson County, TN – 1,800 feet of straightaway in flat terrain with good pavement conditions, two 12 foot lanes plus a 10 foot shoulder and an unpaved turnaround under an overpass connecting to an additional 700 feet of similar roadway conditions. Figures 5 and 6 illustrate location 1.

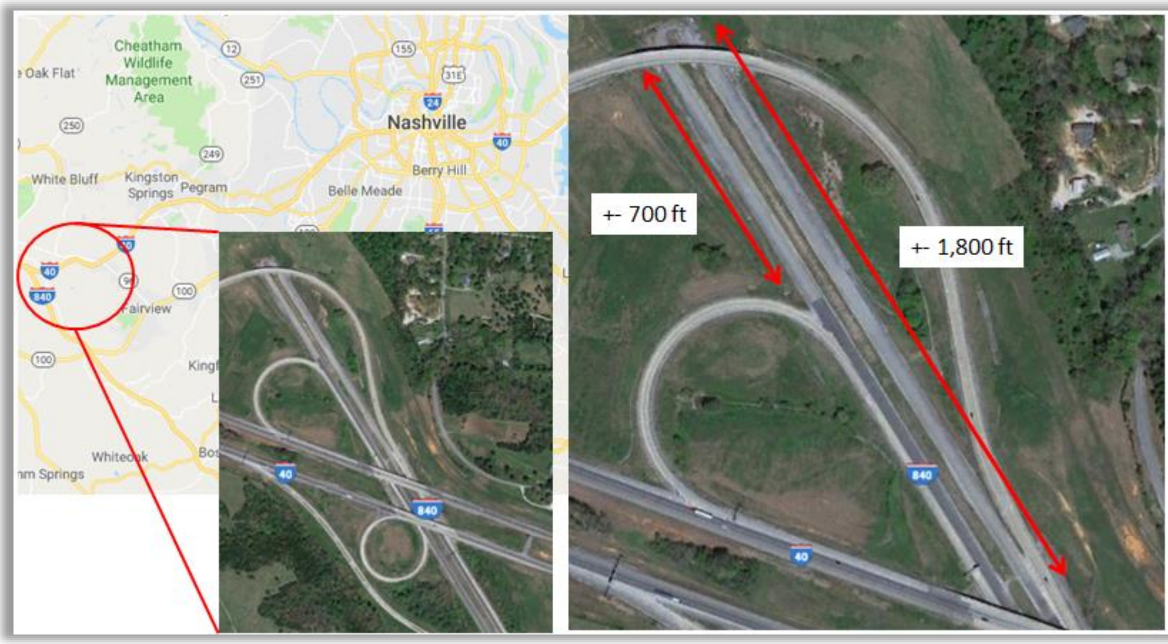


Figure 5 - Pilot testing location at I-840 in Dickson County, TN

Figure 6 - Straightaway and Turnaround at I-840

Location 2 – Tennessee Department of Safety Training Center (TDSTC) / Traffic Incident Management Training Facility (TIM) – 1,800 foot loop in hilly terrain, with varying width, intersections with tight turn radii, and tree cover on portions of the track. Figures 7 and 8 illustrate location 2.

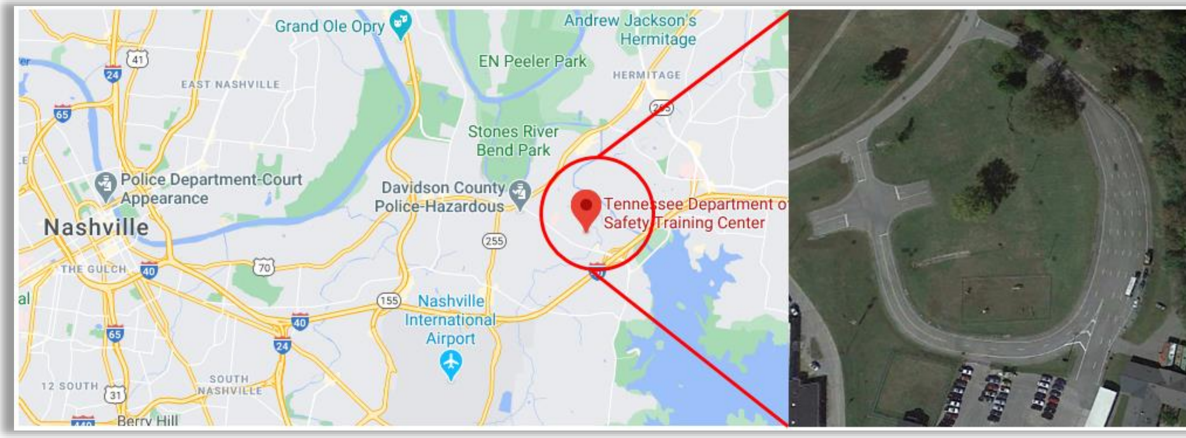


Figure 7 - *TN Department of Safety Training Center / Traffic Incident Management Training Facility*

Figure 8 - TDSTC / TIM

Chapter 5: Pilot Testing Equipment Specification and Analysis

The NextGen Autonomous Truck Mounted Attenuator (ATMA) Leader/Follower system developed by Kratos Defense and Royal Trucking was used for the pilot testing. This system is based on the original ATMA system tested by the Colorado DOT with added enhancements described in *Chapter 5.1*. The system is also known as the NextGen Autonomous Impact

Protection Vehicle (AIPV). The following sections present information on the ATMA/AIPV equipment and were provided by the system developers and collected during the pilot testing.

5.1 – The NextGen ATMA Performance Specification

The information presented in this section was provided by Kratos Defense.

In operation, the Leader Vehicle (LV) system transmits its position, speed, and heading to the ATMA follower vehicle in a sequential series of Vehicle-to-Vehicle (V2V) "*e-Crumb*" messages. The ATMA then maneuvers from one *e-Crumb* to the next precisely following the path of the LV at a user-defined vehicle-gap. The system is based on the original ATMA, but with added enhancements that include; GPS-Denied operation, encrypted redundant V2V communications, redundant frontal obstacle detection/avoidance, side view obstacle detection, and a computer based Graphic User Interface panel (GUI). These enhancements are detailed in the following sections.

5.1.1 - Safety

NextGen ATMA features multiple layers of redundancy to mitigate single point failures and ensure safety incorporating multiple Primary and Backup systems. The first layer of redundancy is provided with Backup navigation, V2V communications, obstacle detection and emergency stopping systems offering seamless automatic switchover from the Primary systems. The second layer of redundancy involves the ability to stop the vehicle and is enabled by an Automatic Stop (A-Stop) feature that is used if a Backup system fails. The A-Stop can be initiated manually by hitting a large red button in the LV and also initiated automatically under conditions that include; loss of V2V, loss of Navigation, exceeded gap distance, detected obstacles, an ATMA impact, a system fault, etc. The A-Stop engages the braking system through the mission computer to bring the vehicle to a controlled stop. The A-Stop can be stopped/started as many times as needed and reset remotely through the GUI without exiting the LV. The third layer of redundancy is a Backup system to the A-Stop provided by a manual independent Emergency Stop (E-Stop) operating on an independent dedicated V2V communication system initiated remotely by hitting a second large red button in the LV. The E-Stop engages the E-Stop braking actuator directly, engaging the brakes and stopping the vehicle immediately. It shuts down the engine which can only be manually reset by reinitializing the system from inside the AIPV. Lastly, a forth layer of redundancy is a Backup to the E-Stop provided by two large red E-Stop buttons located external to the ATMA on each side that shut down the engine, engage brakes, and immediately stop the vehicle.

For added safety, the NextGen ATMA system includes redundant primary and backup forward-looking obstacle detection sensors that simultaneously detect objects up to 200 feet from the ATMA within a ±10° field of view. If an object is detected by either sensor within one lane width of any received e-Crumb for .5 seconds or longer and the object is closer to the ATMA than the LV, the ATMA initiates an A-Stop for collision avoidance. To enhance obstacle detection at short range, the long range system was augmented with forward-looking ultrasonic sensors that initiate an A-Stop when people and other objects are detected at distances from 0 to 20 feet. This provides an extra layer of safety for workers, pedestrians, and motorists who might venture in front of the ATMA. Furthermore, the NextGen ATMA system also includes ultrasonic sensors on each side of the ATMA to provide side-view obstacle detection to further enhance the operational safety of the system. When the sensors detect an obstacle, the system notifies the operator by flashing a warning on the GUI cautioning of obstacles present on the side of the ATMA. The operator can then determine how best to maneuver the LV such that the ATMA is clear from any potential issues.

The GUI includes a “pause” feature enabling a remote LV operator to initiate a command that automatically brings the ATMA to a temporary stop where the pause was initiated allowing the LV to clear a sight distance concern such as before a curve or near a hill. While the ATMA is paused, the LV can slow down, stop, or continue driving to a maximum set gap distance. When initiated, a pause automatically shifts the ATMA transmission to neutral, releases the throttle, and applies the brakes. When the pause is then disengaged, the ATMA shifts into Drive, the brakes release, and throttle engages, capable of speeds up to 20 mph, to the specified gap distance behind the LV following the e-Crumbs as it catches up.

The ATMA system contains a longitudinal accelerometer that is continuously monitored for a rear impact by the control system. Upon sensing a rear impact, the control system immediately applies full force to the brake pedal, shuts off the engine, and turns on the hazard lights. The system remains in this state until it is manually reset. The default threshold for detecting an impact force is one gravity unit in the forward direction for a period of one second or longer which can easily be adjusted as desired.

Cybersecurity precautions include a combination of technologies, processes, and practices protecting the network, computers, and data from attack, damage, or unauthorized access. The system computers and V2V communications are prevented from accessing any internal/external vehicle interfaces. Additionally, there are no Wi-Fi, Bluetooth, or cellular interfaces installed on the system, completely isolating it from external wireless networks to minimize cyber-attack vulnerabilities. Cybersecurity risks are further mitigated by limited physical access, vulnerability management, and system hardening techniques. The user interface software was developed using secure coding practices and Windows 10 Long Term Servicing Channel (LTSC) providing a stable Operating System with 10 years of support for security updates. Maintenance activities and vulnerability management is provided through limited administration access using strict password controls managed by a designated system administrator.

5.1.2 - V2V Communication Systems

The V2V communications system uses a robust radio frequency (RF) link providing greater operating efficiency and longer range operation as compared to broadband video streaming navigation systems. The system also includes V2V communication system redundancy using Primary and Backup transponders in LV and ATMA. This enables, both V2V communication systems to transmit and receive the same data simultaneously on different RF channels, allowing the system to select the best redundant signal and preventing single point failure disruptions.

An extremely high level of security is integrated into the V2V communication system by using frequency hopping and data encryption. The radios selected for all V2V systems are “frequency hoppers” capable of changing channels within a frequency band using a pre-programmed pseudo-random sequence, making it extremely difficult to intercept, decipher, or hijack offering a high level of security. The system is capable of rapidly hopping among up to 50 different frequency channels preventing it from being ‘stuck’ on a single channel being used by another radio. This shields data throughput from being severely degraded by RF interference from other radios on the same frequency. Additional security is provided through encryption of all V2V communications using the Advanced Encryption Standard (AES) 128/256-Bit AES Encryption.

Kratos/MSI has performed a link budget analysis of the V2V communication system which shows it can withstand as much as 35 decibels (dB) of additional RF path loss without degradation of the V2V link. This path loss can result from foliage, buildings, or other obstacles between the LV and ATMA providing the worst-case Non-Line of Sight (NLOS) operating environment that can be reliably tolerated. Higher RF path loss scenarios due to more severe obstructions such as large hills, extremely dense foliage, solid metal structures, etc., could possibly degrade the V2V communications link to varying degrees.

5.1.3 – Navigation System

The primary navigation system uses a high precision GPS with centimeter-level accuracy to measure the ATMA position relative to the LV. These precise position measurements allow the ATMA to laterally track the LV path to an accuracy of ±6 inches without requiring any operator offset adjustments/calibrations. The backup navigation system seamlessly engages when in GPS-Denied environments.

An Inertial Navigation System (INS) enables GPS-Denied operation when driving under overpasses, under dense overhead foliage, etc. as a backup to the primary GPS system. Under GPS-denied conditions, the ATMA continues seamless accurate maneuvering using the backup INS-based navigation system. The system uses a precision Inertial Measurement Unit (IMU) to continuously calculate the ATMA's position with respect to the last valid GPS position obtained before GPS was lost. The LV and ATMA each have backup navigation systems enabling continuous navigation to a lateral accuracy of ±6 inches from the point where GPS is lost to the point where it is back. This INS navigation system offers a drift rate of .14% of the distance traveled which, if the vehicle is at 7.5 mph, enables the system to a maintain ±6 inch lateral accuracy for up to 35 seconds. Once GPS returns, the primary GPS navigation system seamlessly takes back over.

Immediately after a GPS outage is detected by the LV, it begins issuing e-Crumbs using position updates from the backup INS system. The ATMA also begins using its backup INS system ensuring the transition from the primary GPS navigation system to the backup INS navigation system is continuous/seamless requiring no external intervention or interruption to operation.

5.1.4 - Follow Distances

The system includes a user interface consisting of a vehicle mounted 10" High Definition (HD) touchscreen tablet computer in the LV with Graphical User Interface (GUI) software. The display provides clear images in all lighting conditions. The GUI enables the operator in the LV to remotely set the Gap (Follow) Distance between the LV and ATMA to prescribed distances using a slider-bar touchscreen control.

Figure 9 - Graphic User Interface (GUI) device located on Leader Vehicle

The tablet quickly mounts/dismounts in the LV using a standard windshield-mount device and is powered from the vehicle 12VDC electrical system for continuous daily operation. The software on the GUI is a straightforward Human Machine Interface similar to a smartphone app designed with intuitive ergonomic controls and "Status-At-A-Glance" system feedback. The GUI with conceptual software layout is shown in Figure 9. Function transitions are fast and clear, the layout is simple and meaningful, and the controls are large and easy to operate.

Follow distances system are set remotely from the GUI in the LV to any discrete value from the following list: 25', 100', 165', and 200' - 1500' in 100' increments measured from the rear of the LV to the front of the ATMA. Once set, the system measures the actual gap using the GPS locations of the LV and ATMA.

The Follow Distance accuracy is controlled by a speed/gap algorithm that maintains the ATMA at the gap distance set by the operator from the GUI. The vehicles remain within ±15 feet of the set point distance during typical driving conditions and acceleration/deceleration rates similar to previously deployed ATMA's. In GPS-Denied environments the gap is measured using the INS module.

5.1.5 - Data Recording

The system includes the ability to record up to 24 hours of vehicle performance data including time stamped velocity, location, heading, inter-vehicle gap, actuator commands, system/sensor status, and an array of other parameters, as desired, that can be downloaded off of the LV and ATMA computers and analyzed using standard Microsoft Excel graphing, printing, and data reduction tools.

5.2 – Pilot Testing Equipment Analysis

The information presented in this section was observed and collected during the initial inspection of the system components and during the five days of testing. It covers specifics on the vehicle instrumentation, introduces the different operating system modes, explains procedures necessary for the operation of the system, discusses the system's speed/gap algorithm and details the data logs.

5.2.1 – Vehicle Instrumentation

A Ford F550 was used as the leader vehicle (LV). Dimensions are 25'L x 8'6"W and the GPS units were located 11'4" from the front. A HINO 268 truck was used as the follower vehicle (FLW). Dimensions are 32'5"L x 8'9"W and the GPS units were located 9'9" from the front. The AIPV was equipped with a Scorpion truck mounted attenuator that measured 15'2" when deployed. Figure 10 presents the LV and the FLW (AIPV). For the purpose of this report, AIPV (Autonomous Impact Protection Vehicle) is used to denote the follower vehicle and the term ATMA system is used to denote the LV plus the AIPV.

Figure 10 - Leader (LV) and Follower (FLW/AIPV) Vehicles

A kit of components is installed in the LV and AIPV that facilitates the autonomous mode. The following illustrates the necessary instrumentation.

Figure 11 presents the Operator Control Unit (OCU) installed internally in the LV that controls the two modes of operation: IDLE and GO mode. In IDLE mode the safety operator of the ATMA system is in control of the AIPV instead of the autonomous system. In GO mode the AIPV operates autonomously. The OCU also controls the manually activated Automatic Stop (A-Stop), red button to the left. The E-Stop independent initiator controls the Emergency Stop (E-Stop), red button to the right. The main operational difference between the two types of Stop control is that the A-Stop does not kill the AIPV engine and can be reset from the LV. The A-Stop can also be initiated automatically by the ATMA system as explained in *Section 5.1.1*.

Figure 11 - Leader Vehicle Internal A-Stop and E-Stop Buttons

Two testing scenarios (detailed in Chapter 6) were used to demonstrate the applicability of the A-Stop and E-Stop buttons. The equipment worked as expected.

Figure 12 presents the equipment installed outside of the AIPV that controls the manually activated Emergency Stop (E-Stop). There are two large red buttons, one on each side of the AIPV.

Figure 12 - AIPV External E-Stop Button

One testing scenario (detailed in Chapter 6) was used to demonstrate the applicability of the E-Stop buttons. The equipment worked as expected.

The AIPV also has an OCU controlling the IDLE or GO mode of operation, with a red E-Stop button that can be manually activated (Figure 13). The applicability of the internal E-Stop on the AIPV may be considered limited but the equipment worked as expected as demonstrated in a testing scenario (detailed in Chapter 6). The yellow button is used for the parking brakes.

Figure 13 - AIPV Internal E-Stop Button

The AIPV vehicle has an E-Stop Controller unit that activates and releases the E-Stop (Figure 14). *Section 5.2.3* details its use on the restart procedure after E-Stop.

Figure 14 - AIPV E-Stop Controller Unit

Figure 13 also shows the equipment installed below the steering wheel that is used to control the vehicle autonomously, the Multi-Platform Appliqué Kit or M-PAK™ Steering Wheel Actuator / Smartmotor Assembly. The research team noticed it as a potential inconvenience, since it limits the space available for sitting. The ATMA system developer discourages users of the system to remove the steering wheel actuator on the AIPV, to prevent damage, misalignment and improper installation. The research team was informed that, in response to user feedback, the steering wheel actuator design has been modified after the testing procedures took place, to allow greater flexibility, during the installation process, and to increase clearance for the driver when the vehicle is being manually operated.

One of the mechanisms used to control the autonomous braking and acceleration of the AIPV is a series of control linkages interfaced to the vehicle control paddles. There are two control linkages connected to the braking paddle, one for the E-Stop actuator and the other used for regular braking. The research team noticed a short response lag during the testing of the E-Stop features and learned that the AIPV braking can be configured to a customer preference, with an abrupt or a soft braking setting. A braking/accelerating actuator panel is where the control actuators are mounted and the actuators can be adjusted for harder or softer braking response. There are three separate actuators that include one for primary braking, one for backup brake control, and one for throttle control of the AIPV.

The LV and the AIPV are equipped with a pair of GPS antennas each (Figure 15), that collect absolute data from 15 to 18 satellites at any given moment. *Section 5.2.2* describes a GPS lining up procedure executed before each test case scenario.

Figure 15 - GPS Antennas

The radio system described in *Section 5.1.2* for the V2V communications between the LV and the AIPV. There were 3 radios active in each vehicle for the testing, one 315Mhz and two 2.4 Ghz. A fourth radio with 915 MHz was installed but not in use for this deployment. The system provider demonstrated the equipment to TDOT personnel with knowledge in radio communications. No major issues or concerns were pointed out.

The forward-looking obstacle detection sensors mentioned in *Section 5.1.1* are installed in the AIPV. Light and radar is used for obstacle detection. The top sensor in Figure 16 is a Lidar unit and the bottom sensor is a Delphi ESR (Electronic Scanning Radar).

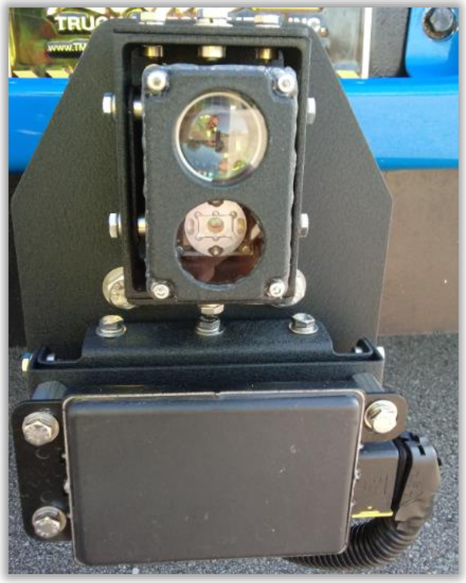


Figure 16 - Forward-looking Obstacle Detection Sensors

Three testing scenarios (detailed in Chapter 6) were used to demonstrate the applicability of the sensors. The equipment worked as expected.

Ultrasonic sensors mentioned in *Section 5.1.1* were installed in the front and on both sides of the AIPV (Figure 17). These sensors enhanced the forward looking obstacle detection system and provide side-view obstacle detection further enhancing the operational safety of the system. When the sensors detected an obstacle, the system notified the operator by flashing a warning on the GUI (Figure 17).

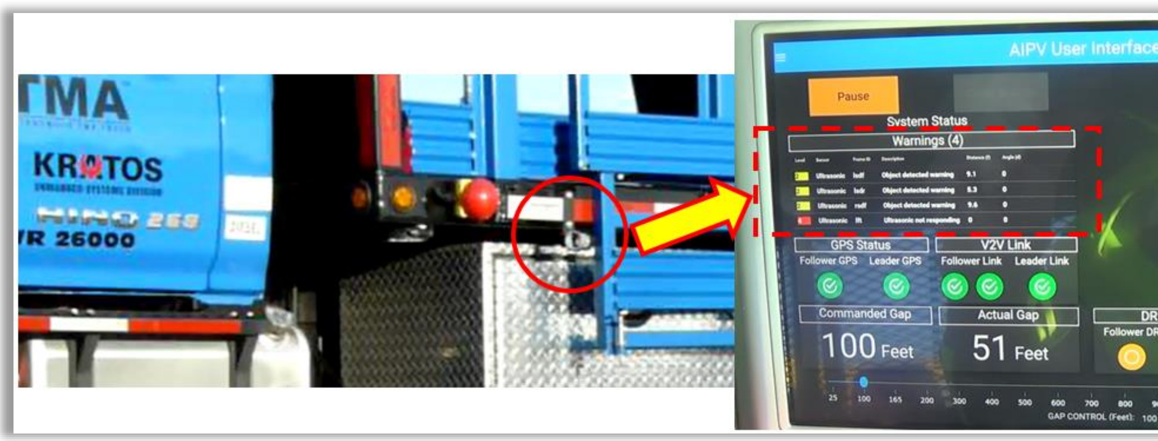


Figure 17 – Side-view Obstacle Detection Sensors

One testing scenario (detailed in Chapter 6) was used to demonstrate the effectiveness of the sensors. There were six sensors in total in the AIPV vehicle, two in front and two on each side of the vehicle. The sensors were extremely sensitive. They occasionally relayed false object-detected warnings to the GUI. This issue was noticeable in all test scenarios. The equipment failed to work as expected.

The GUI described in *Section 5.1.4* was mounted in the LV on the passenger side, not interfering with the driver ability to control the vehicle but within easy reach. The screen was easily readable at all light conditions. The process to disconnect and reconnect the GUI to its bracket and communications cables was not cumbersome and took less than 3 minutes. A video of the procedure can be found here: https://youtu.be/G_Fxtkbuezw. Figure 18 presents a screenshot of the GUI.

The overall ATMA system status presented in the GUI includes:

- warnings from the side-view obstacle detection ultrasonic sensors;
- the AIPV and LV GPS status;
- the AIPV and LV V2V communication link status;
- the Commanded Gap (desired gap spacing between vehicles);
- the Actual Gap (actual gap spacing between vehicles);
- the AIPV and LV INS status (GPS denied locations);
- the Gap Control slide bar for the selection of the Commanded Gap; and
- a video of the AIPV from the back of the LV.

Specific warning messages pop up at the top of the screen and promptly warn the driver of a system malfunction. An example of an E-crumb error (where the AIPV was not able to locate the LV next data point position) can be found here: https://youtu.be/Tbiy2FyXjNg. It is necessary to note that the Gap Control slide bar does not accommodate for all potential following distances required by TDOT's Work Zone Field Manual for Maintenance Operations (eg.:175 feet, 225 feet). No other GUI issues were noticed during the testing procedures.

Figure 18 – Graphic User Interface (GUI) Panel

Overall, the systems installed in the vehicles have no effect on normal manned TMA operations, except for the potential steering wheel actuator issue mentioned earlier. Similarly, installed system components do not interfere with warning lights, the arrow board or the attenuator itself.

5.2.2 – Line-Up Procedure before Engaging Autonomous Mode

The research team was informed by the ATMA system developer that during the equipment installation, a system alignment procedure is performed that ensures the GPS devices are properly aligned and tuned to support a Leader-Follower configuration. The tested ATMA system requires a series of pre-operational checks before the user can get the autonomous mode engaged. If the user does not properly perform these steps the AIPV vehicle will not rollout and the AIPV GUI panel will show an error message that the vehicles are not aligned. This is an operator performance requirement that is stressed during the training provided by the vendor.

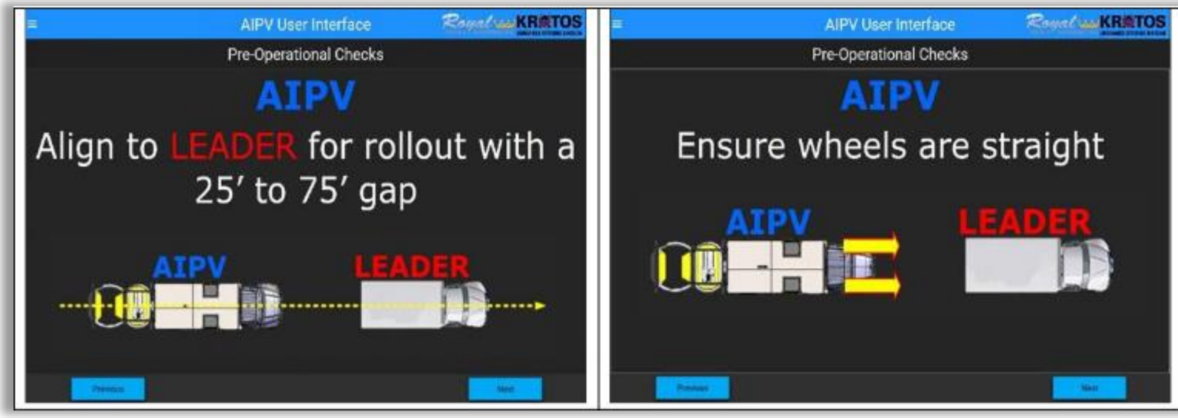


Figure 19 – Pre-operational Checks – Alignment Procedure – GUI Panel

Figure 19 illustrates the pre-operational check for the alignment procedure presented on the AIPV GUI panel. First, it is necessary to position the AIPV exactly behind the LV with a 25 feet to 75 feet gap. That is done by visually aligning the center of the AIPV with the center of LV. Second, the front wheels on the AIPV need to be pointing straight, in line towards the LV. That sets the steering wheel actuator to position "zero". For example, if the autonomous mode is engaged with the AIPV front wheels pointing to the left, as the LV starts moving straight forward, the AIPV would move to the left. Figure 20 illustrates the line-up process during the testing procedures.

Figure 20 – LV and AIPV during Line-up Procedure

The line-up process had to be repeated for each run of each test case scenario. This became a time consuming process, with many of the line-up procedures taking more than 10 minutes. In day-to-day applications, the line-up procedure is also required before the system is engaged in autonomous mode, but is not considered a major operational concern.

Furthermore, the ATMA system has three modes of operation: IDLE, manually controlled by the operator, ROLLOUT, beginning of autonomous plan and RUN, operating on autonomous mode. After the initial alignment discussed above, the ATMA system developers also pointed to the need to keep the maximum distance between the LV and the AIPV before ROLLOUT around 75 feet to 200 feet, with a maximum limit of 246 feet (75 meters). If the ROLLOUT range is exceeded, the AIPV will not move and the user will be informed with an error on the GUI panel. There are a couple of reasons for the ROLLOUT limitation. First, the system developers wanted to limit how far the AIPV needs to drive in straight line to reach the LV's rollout point. On rollout, the AIPV first beeline the point where the LV started and then gets on the LV path. If the LV is too far, the AIPV operator may not be able to judge the straight line path before reaching the LV. This is typically not a problem if both the LV and the AIPV start on a roadway, but it can be a potential issue if the vehicles start the rollout procedure on the shoulder, maneuvering around a guard rail or a turn. Second, the LV is also limited to be within four degrees of error from zero degree azimuth of the AIPV on rollout. This prevents large heading corrections for the AIPV. Basically, it is easier to line up the heading when the LV and the AIPV are closer to each other.

5.2.3 – Restart Procedure after E-Stop

The Emergency Stop (E-Stop) is a safety feature of the ATMA system that stops the vehicle and kills the engine of the AIPV once activated. Personnel operating the ATMA system need to follow a stepwise procedure to release the E-Stop and reset the system. The following list indicates the steps presented in the GUI panel for the LV and the AIPV to recover from an E-Stop (see Appendix for GUI screenshots):

1. Set the OCU to IDLE (LV).
2. Apply parking break (AIPV).
3. Shift into neutral, if applicable (AIPV).
4. Set E-Stop bypass to on (AIPV).
5. Release all E-Stop switches (AIPV).
6. Set OCU to IDLE (AIPV).
7. Set OCU to off (AIPV).
8. Remove cause of E-stop, then select next (AIPV).
9. Start the engine (AIPV).
10. Go through the alignment process (AIPV and LV).

11. Set OCU to on (AIPV).
12. Once the GPS LED is solid green, select next (AIPV).
13. Once READY LED is blinking green, select next (AIPV).
14. Once E-Stop LED is green, switch Bypass to off (AIPV).
15. Set OCU to GO (AIPV).
16. Release parking break (AIPV).
17. Shift into drive (AIPV).
18. Verify system controls brake and if vehicle maintains position, then select next (AIPV).
19. Leave the AIPV and enter the LV as system monitor (AIPV).
20. Set OCU to GO (LV).
21. If ready for ROLLOUT, select complete. If all following status indicators are green, select start. (LV).

5.2.4 – Inertial Navigation Operation.

When the GPS system is having GPS signal issues due to overhead gantry, bridges, or crowding due to building or trees, the navigation system switches to INS-based navigation which uses a IMU and wheel odometer. The GPS system gives not only the accurate positioning, but it also gives the accurate heading. However, overhead structures can cause the heading accuracy data to degrade slowly. To get better accuracy, the ATMA system have an overhead Lidar unit which detects gantries, bridges, and trees and forces switching to INS navigation even before the heading starts to degrade. Essentially, the ATMA system switches to INS navigation in two ways: a forced INS, which can be caused by the overhead Lidar detection of a structure or, a natural INS which can be caused by degraded GPS signal due to weather.

When the ATMA system first switches to INS, vehicles take the heading information of the vehicle from the GPS at that point and then start tracking the heading changes from that point on using the IMU. The wheel odometer gives the distance travelled. Using the vector value of heading and distance, a very good approximation of Latitude and Longitude values can be generated. Both the leader and the follower vehicles use the approximate values until the GPS is back online. Then, the ATMA system switches back to GPS navigation. However, there are small amounts of random errors that can creep into the IMU as INS navigation time progress and these errors cannot be predicted easily. Therefore, it is necessary to limit how long the INS system is allowed to operate before the accumulated errors become significant. Currently, a simple 45 seconds time limit is in place. When the time limit is reached and the GPS does not come back online, an A-STOP is initiated on the AIPV with “INS time limit reached” error. The GUI indicates which vehicle is under INS navigation.

5.2.5 – Speed / Gap Algorithm Functionality

In *Section 5.1.2*, the ATMA system specifications mention that the follow distance accuracy is controlled by a speed/gap algorithm that maintains the AIPV at the gap distance set by the operator from the GUI. The vehicles remain within ±15 feet of the set point distance during typical driving conditions and acceleration/deceleration rates similar to previously deployed ATMA’s.

After analysis of the testing procedures, the ATMA system demonstrated an inability to maintain the follow distance set on the GUI for stop-and-go operation scenarios. Upon further discussion with the ATMA system developers, the research team learned that the current ATMA system algorithm was coded to allow the LV operator to control the AIPV by adjusting its own speed. In other words, the AIPV tries to adjust its speed to the LV’s. The AIPV stops when the LV stops, without considering the gap distance. When the LV speeds up, the AIPV takes a few seconds to get up to the target speed. Therefore, when the actual gap between the LV and the AIPV is longer than the command gap set on the GUI, the algorithm only adds a little more gain to the control, requiring extra running time to shorten the distance. It is also important to notice, that the ATMA system was originally designed for striping of pavement markings and cone deployment, scenarios that typically run for longer distances and longer periods of time. This explains the mentioning on the system specifications above “*…during typical driving conditions and acceleration/deceleration rates similar to previously deployed ATMA’s*.” Nevertheless, the ATMA system developers pointed to a plan to update the system so that the user can move the AIPV to close the gap even when the LV is not moving.

5.2.5 – Data Logs

As mentioned in *Section 5.1.5*, the ATMA system records several data parameters from the LV and FLW vehicles. The vehicle data logs are formatted as a comma separated value (CSV) file format. Data was collected in a tenth of a second increments. A new log file was created using a time stamp as the file name when the system was power cycled. The following is an example of a log file name: *2019-11-05_19-38-54_log.*

The LV and the FLW data were included in each file. The research team had to manually separate the information for analysis.

The following is an example of the data collected for the LV:

TIMESTAMP	VEH	CRUMB	STAMP	LAT	LON	ALT	HEADING	VELOCITY	COURSE	NEAREST_CRUMB	TOTAL_CRUMBS
17:43.7	LDR	100	14174350	36.0234	-87.2663	197.43	328.921	1.26	330.5	100	4

where,

- TIMESTAMP, Time in UTC (HH:MM:ss,ms)
- VEH Type, vehicle LDR (Leader)
- CRUMB, ecrumb id (Just an integer value to identify)
- STAMP, Timestamp integer value used by GPS
- LAT, Latitude in degree
- LON, Longitude in degree
- ALT, Altitude in meters above sea level
- HEADING, Vehicle heading in degree
- VELOCITY, Speed (velocity) in miles per hour
- COURSE, Track heading generated by GPS (not used)
- NEAREST_CRUMB, closest ecrumb id in list
- TOTAL_CRUMBS, Total ecrumbs in list

The following is an example of the data collected for the FLW:

TIMESTAMP	VEH	CRUMB	STAMP	LAT	LON	ALT	HEADING	HDG(Desired)	VELOCITY	VEL(Desired)
17:43.7	FLW	0	14174360	36.0231	-87.2661	196.898	328.233	0	0.01	0

GAP	GAP(Desired)	#SATS	VALID	CTE	ACCEL	STEER	STATE
29.64	0	11	1	0	-100	0	ROLLOUT

where,

- TIMESTAMP, Time in UTC (HH:MM:ss,ms)
- VEH Type, vehicle FLW (Follower)
- CRUMB, ecrumb id (Just an integer value to identify)
- STAMP, Timestamp integer value used by GPS

- LAT, Latitude in degree
- LON, Longitude in degree
- ALT, Altitude in meters above sea level
- HEADING, Vehicle heading in degree
- HDG (Desired), Where the vehicle wants to go for heading in degree
- VELOCITY, Speed (velocity) in miles per hour
- VEL (Desired), The speed that the vehicle is trying to get to
- GAP, Gap distance in meters
- GAP (Desired), the gap the vehicle is trying to reach in meters
- #SATS, number of satellites (count)
- VALID, Position state value (1=good, other values related to GPS codes)
- CTE, Cross Track Error in meters
- ACCEL, Acceleration / braking (negative) percent
- STEER, Steering (left/right) percent
- STATE, Navigation state (IDLE, manually controlled by the operator, ROLLOUT, beginning autonomous plan, RUN, autonomous mode, ASTOP, automatic stop)

Chapter 6: Pilot Testing Data Analysis

The information in this chapter details the procedures and analysis results for each test case scenario performed during the pilot testing of the ATMA system. For safety, a driver was inside the AIPV at all times, except for demonstration purposes during a visit from TDOT personnel. Tools used in the analysis include a Python programming language script, provided by the system developer that converts original log files to LV and AIPV paths in keyhole markup language (KML). The KML output files were used with Google Earth to view paths traveled by the LV and AIPV. In addition, Microsoft Excel was used to plot data for analysis. Data was plotted using x-y scattered charts, with time used in the x-axis. For dual axis data with different scale, a secondary axis is used to demonstrate the relationship. Lastly, picture and video documentation supplement the data log analysis. Table 2 provides a summary of the pilot testing results.

Autonomous Truck Mounted Attenuator (ATMA) Testing Results					
Test Scenario #	Test Category	Description	Location	Results	
1	Safety	Automatic Stop (A-Stop) - Leader Vehicle Internal Button	I-840		
2	Safety	Emergency Stop (E-Stop) - Leader Vehicle Internal Button	I-840		
3	Safety	Emergency Stop (E-Stop) - ATMA External Button	I-840		
4	Safety	Emergency Stop (E-Stop) – ATMA Internal Button	I-840		
5	Following Accuracy	Following Accuracy on Straight Line	I-840	CTE	GAP
6	Following Accuracy	Following Accuracy on Slalom Course	I-840	CTE	GAP
7	Following Accuracy	Following Accuracy on Lane Change	I-840	CTE	GAP
8	Following Accuracy	Adjusting Following Distance	I-840		
9	Typical Applications	Trash Pick-up	I-840		
10	Typical Applications	Herbicide Application	I-840		
11	Typical Applications	Pothole Patching	I-840	Detection	GAP
12	Detection	Obstacle Detection - FRONT	I-840		
13	Detection	Vehicle Intrusion	I-840		
14	Detection	Sensitivity to Passing Vehicles	I-840		
15	Detection	Object Recognition	TDSTC / TIM		
16	Detection	Headlights	TDSTC / TIM		
17	Detection	Cone Detection	TDSTC / TIM		
18	Miscellaneous	Speed Test	I-840		
19	Miscellaneous	Braking – Leader Vehicle	I-840		
20	Miscellaneous	Bump Test	TDSTC / TIM		
21	Miscellaneous	Leader Reverse	TDSTC / TIM		
22	Miscellaneous	Turning at I-840	I-840		
23	Miscellaneous	Tight Turn Radius	TDSTC / TIM		
24	Communication	Loss of Communication	TDSTC / TIM		

Table 2 – Summary of Testing Results

Tests that completely achieved the expected results were coded green. Tests that not consistently achieved expected results were coded yellow and tests that did not achieve expected results were coded red.

An initial system malfunction at the beginning of the testing session was diagnosed and fixed by the ATMA system operators, but delayed most of the first day morning testing session. The ATMA system performed as expected in the Safety category, where the Automatic Stop (A-Stop) and the Emergency Stop (E-Stop) were tested. The Following Accuracy testing had two components that were analyzed, the Cross Track Error (CTE) that demonstrates the lateral accuracy of the system, and the Gap Distance Control, that demonstrates the ability of the system to maintain the selected gap distance between the LV and the AIPV. The ATMA system was not able to consistently maintain the specified ± 6 inches of lateral accuracy between the LV and the AIPV, most notably when testing was not on a straight path. Further analyses of CTE for testing scenarios in other categories yielded similar results. A summary table of the CTE analyses can be found in the APPENDIX. The ATMA system was able to maintain the specified ± 15 feet of gap distance control for tests number 5, 6 and 7 for the Following Accuracy category. Test number 8 exposed an issue of the ATMA system related to the speed/gap algorithm. The system was not able to maintain the specified gap control distance on test scenarios that included stop-and-go operation. *Section 5.2.5* provides additional details. Similarly, tests number 9 and 11 from the Typical Application category, emulated a stop-and-go operation, leading to the ATMA system not being capable to maintain the selected gap control distance. Test number 10 exposed the inability of the ATMA system to consistently shadow/protect the service vehicle at all times, since the tested system had no offset capability required for the tested operation. Overall, the testing performed on the ATMA system detection yielded acceptable results. Test number 13 tested the ability of the ATMA system to detect a vehicle intrusion between the LV and the AIPV, with the system not being able to consistently detect the intrusion. The tested system had ultrasonic detection on the AIPV that did not work as expected, as test number 15 details. A set of miscellaneous tests were performed, with the ATMA system not being able to consistently maintain the CTE accuracy on Test number 20. Test number 21 pointed to an issue on the ATMA system algorithm, where the AIPV rolled forward as the LV was reversing. Test number 22 demonstrated the ability of the ATMA system to momentarily operate without the GPS signal, but the system was unable to completely navigate the required turn. The ATMA system was unable to navigate a really tight turn in test number 23. Lastly, the communication system of the ATMA was inspected by TDOT experts and the V2V redundant link was tested, not presenting any issues. The following presents a detailed discussion on each individual test.

6.1 – TEST CASE SCENARIO 1 - Automatic Stop (A-Stop) – Leader Vehicle Internal Button

Category: Safety.
Location: TDSTC/TIM.
Objective: Observe the response of the ATMA system to a request of A-Stop from the LV.
Test procedure: The command gap was set to 100 feet on the GUI. The LV and the AIPV were activated. The LV operator was asked to drive in a straight line at a target speed of 10 mph. Once the AIPV reached a pre-determined location in the test track, the A-Stop button in the LV OCU was pressed upon a radio command from the UT team member. The stopping distance and stopping time of the ATMA system were recorded for two runs, using a measuring wheel and a stopwatch. The test was repeated at a target speed of 15 mph. The status of the engine and braking lights were observed.
Expected result: The AIPV should stop and its engine should stay on.
Results: Table 3 presents the recorded data. The AIPV stopped as expected on all 4 runs. The

AIPV braking lights were activated and the AIPV engine stayed on.

	Speed - 10mph		Speed - 15mph	
	RUN 1	RUN 2	RUN 3	RUN 4
Command Gap set (ft):	100	100	100	100
Stopping Distance:	40'5"	35'5"	75'8"	66'8"
Stopping Time:	4.03 sec	3.68 sec	6.25 sec	5.56 sec
FLW brake lights status:	ON	ON	ON	ON
FLW engine status:	ON	ON	ON	ON

Table 3 – A-Stop – Leader Vehicle Internal Button Test

Video file: https://youtu.be/AgBeNkgMIhw

Additional information: The A-Stop, as explained in *Section 5.1.1*, can be initiated manually, like in this testing case, or is initiated automatically due to a system fault, loss of communication, obstacle detection, etc. The A-Stop engages the braking system through the mission computer to bring the vehicle to a controlled stop. Throughout the week long testing of the system, the research team was able to observe several instances where the A-Stop initiated automatically. The main reason pointed by the system owner was for detecting a cone on the vehicle path. The A-Stop can be cleared by the system operator from the LV, since it does not kill the engine of the AIPV, allowing for the continuation of normal system operation.

Also, the ATMA system was not operating normally during the initial testing procedures, according to the system operator personnel present in the testing site. A recalibration process of the system was performed (Figure 21). A system relay was exchanged and after the lengthy testing delay, the system was deemed ready for testing. The testing schedule was affected.

Figure 21 – ATMA System Recalibration Process

6.2 – TEST CASE SCENARIO 2 - Emergency Stop (E-Stop) – Leader Vehicle Internal Button

Category: Safety.

Location: TDSTC/TIM.

Objective: Observe the response of the ATMA system to a request of E-Stop from the LV.

Test procedure: The command gap was set to 100 feet on the GUI. The LV and the AIPV were activated. The LV operator was asked to drive in a straight line at a target speed of 10 mph. Once the AIPV reached a pre-determined location in the test track, the E-Stop button in the LV E-Stop initiator was pressed upon a radio command from the UT team member. The stopping distance and stopping time of the ATMA system were recorded for two runs, using a measuring wheel and a stopwatch. The test was repeated at a target speed of 15 mph. The status of the engine and braking lights were observed.

Expected result: The AIPV should stop and its engine should be shut down.

Results: Table 4 presents the recorded data. The AIPV stopped as expected on all 4 runs. The AIPV braking lights were activated and the AIPV engine was shut down.

	Speed - 10mph		Speed - 15mph	
	RUN 1	RUN 2	RUN 3	RUN 4
Gap set (ft):	100	100	100	100
Stopping Distance:	54'8"	41'10"	68'10"	96'
Stopping Time:	3.90 sec	3.43 sec	4.09 sec	4.12 sec
FLW brake lights status:	ON	ON	ON	ON
FLW engine status:	OFF	OFF	OFF	OFF

Table 4 – E-Stop – Leader Vehicle Internal Button Test

Video file: https://youtu.be/pghXMuCHYa8

Additional information: The E-Stop, as explained in *Section 5.1.1*, can only be initiated manually. Since the engine was shut down in the process it was necessary to manually reset the system from the inside of AIPV after each test run. The process of restarting the system after an E-Stop is explained in *Section 5.2.3.*

It is noticeable that the stopping distances recorded for the E-Stop are longer in three of the runs when compared to the A-Stop stopping distances on Section 6.1. The reason for that is that the E-Stop engages the E-Stop braking actuator directly to stop the AIPV and the actuator had a slack on the E-Stop cable, as explained in *Section 5.2.1*, denoting the softer braking response experienced during the testing.

6.3 – TEST CASE SCENARIO 3 - Emergency Stop (E-Stop) – AIPV External Button

Category: Safety.

Location: TDSTC/TIM.

Objective: Observe the response of the ATMA system to a request of E-Stop using the external buttons on the AIPV.

Test procedure: The command gap was set to 100 feet on the GUI. The LV and the AIPV were activated. The LV operator was asked to drive in a straight line at a target speed of 5 mph. Once the AIPV reached a pre-determined location in the test track, the UT team member would press the external E-Stop button on the AIPV. The stopping distance and stopping time of the ATMA system were recorded using a measuring wheel and a stopwatch. A total of four test runs were performed, two runs on the driver's side E-Stop buttons and two runs on the passenger side E-Stop buttons. The status of the engine and braking lights were observed.

Expected result: The AIPV should stop and its engine should be shut down.

Results: Table 5 presents the recorded data. The AIPV stopped as expected on all 4 runs. The AIPV braking lights were activated and the AIPV engine was shut down.

	Speed - 5mph			
	RUN 1	RUN 2	RUN 3	RUN 4
Gap set (ft):	100	100	100	100
Stopping Distance:	14'1"	22'8"	22'7"	26'2"
Stopping Time:	3.00 sec	2.96 sec	3.25 sec	3.28 sec
Driver Side	x	x		
Passenger Side			x	x
FLW brake lights status:	ON	ON	ON	ON
FLW engine status:	OFF	OFF	OFF	OFF

Table 5 – E-Stop – AIPV External Button Test

Video file: https://youtu.be/Nnim4oH5MhQ

Additional information: Since the E-Stop was initiated manually and the engine was shut down in the process it was necessary to manually reset the system from the inside of AIPV after each test run. The process of restarting the system after an E-Stop is explained in *Section 5.2.3.*

6.4 – TEST CASE SCENARIO 4 - Emergency Stop (E-Stop) – AIPV Internal Button

Category: Safety.

Location: TDSTC/TIM.

Objective: Observe the response of the ATMA system to a request of E-Stop using the internal button on the AIPV.

Test procedure: The command gap was set to 100 feet on the GUI. The LV and the AIPV were activated. The LV operator was asked to drive in a straight line at a target speed of 10 mph. Once the AIPV reached a pre-determined location in the test track, the E-Stop button inside the AIPV was pressed upon a radio command from the UT team member. The stopping distance and stopping time of the ATMA system were recorded for two runs, using a measuring wheel and a stopwatch. The test was repeated at a target speed of 15 mph. The status of the engine and braking lights were observed.

Expected result: The AIPV should stop and its engine should be shut down.

Results: Table 6 presents the recorded data. The AIPV stopped as expected on all 4 runs. The AIPV braking lights were activated and the AIPV engine was shut down.

	Speed - 10mph		Speed - 15mph	
	RUN 1	RUN 2	RUN 3	RUN 4
Gap set (ft):	100	100	100	100
Stopping Distance:	30'2"	34'9"	46'2"	51'2"
Stopping Time:	3.37 sec	3.56 sec	3.37 sec	3.81 sec
FLW brake lights status:	ON	ON	ON	ON
FLW engine status:	OFF	OFF	OFF	OFF

Table 6 – E-Stop – AIPV Internal Button Test

Video file: N/A

Additional information: Since the E-Stop was initiated manually and the engine was shut down in the process it was necessary to manually reset the system from the inside of AIPV after each test run. The process of restarting the system after an E-Stop is explained in *Section 5.2.3.* The applicability of the internal E-Stop on the unmanned AIPV is considered limited since it would be difficult for the button to be reached in case of an emergency.

6.5 – TEST CASE SCENARIO 5 - Following Accuracy on Straight Line

Category: Following Accuracy.

Location: I-840.

Objective: Collect data to determine if the AIPV maintains the lateral accuracy of ± 6 inches from the LV path, as specified in *Section 5.1.3* and if the AIPV maintains the following gap distance of ± 15 feet, as specified in *Section 5.1.4*, on a straight line.

Test procedure: The command gap was set to 100 feet on the GUI. The LV and the AIPV were activated. The LV operator was asked to drive in a straight line at a target speed of 10 mph and stay centered in the lane. Data was collected for two runs. Figure 22 presents the plotted path of the test, with the orange line representing the LV and the blue line representing the AIPV.

Figure 22 – Test Path – Following Accuracy on Straight Line Test

Expected result: The AIPV maintains the lateral accuracy of ± 6 inches from the LV path and the following gap distance of ± 15 feet between the LV and the AIPV.

Files used for analysis: 2019-11-05_21-21-05_log and 2019-11-05_20-59-06_log

Results: The cross track error (CTE) data was analyzed from the logs. Table 7 presents the range of values for each run. CTEs that fell outside the expected result value were coded red. The AIPV was not able to maintain the expected lateral accuracy on Run 2.

	Speed - 10mph			
	RUN 1		RUN 2	
Gap set (ft):	100		100	
Cross Track Error (in)	-3.70	1.38	-6.96	0.00

Table 7 - Cross Track Error (CTE) Range – Following Accuracy on Straight Line Test

Figure 23 plots the speed vs the cross track error, having the speed change on the primary Y-axis as a function of time on the x-axis. A secondary y-axis plots the CTE of the AIPV. The plot for Run 2 is in the APPENDIX.

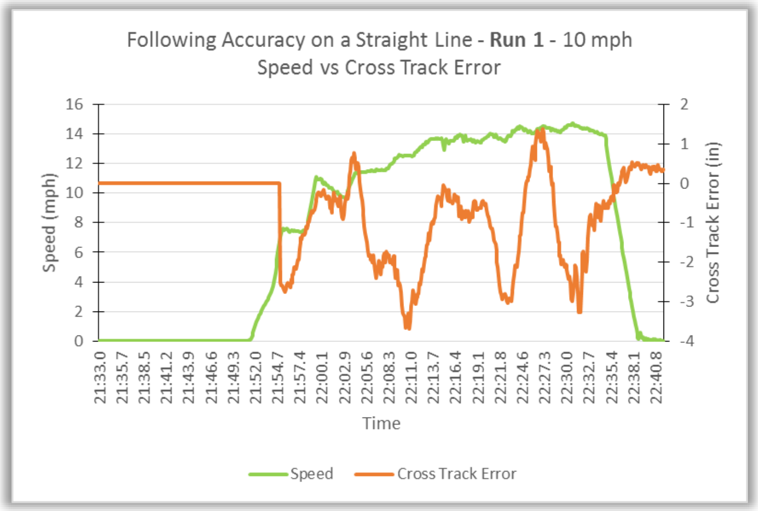


Figure 23 – Speed Vs Cross Track Error – Following Accuracy on Straight Line Test

According to the specifications in *Section 5.1.4* the follow distance accuracy is controlled by a speed/gap algorithm that maintains the AIPV at the command gap distance set by the operator from the GUI, with the vehicles remaining within ±15 feet of the set point distance. Table 7 presents the gap analysis results. The gap distance at rollout indicates the distance between the LV and the AIPV at the start of the test, when the LV started to move. The minimum, maximum and average gap values were collected from the moment the AIPV first accelerated during the test to the moment the AIPV started decelerating to a final stop. Gap values that fell outside the expected result value were coded red. Table 8 also presents information about the elapsed time (from the moment data started to be recorded) for IDLE mode (Safety operator on the LV has control of the ATMA system), ROLLOUT (Autonomous mode is engaged) and RUN (Autonomous mode is operational). The AIPV was able to maintain the expected gap accuracy on both runs, based on the average gap results.

	Speed - 10mph			
	RUN 1		RUN 2	
Gap set (ft):	100		100	
Gap dist at ROLLOUT (ft)	72.40		105.64	
Min Gap / Difference (ft)	72.67	-27.33	100.26	0.26
Max Gap / Difference (ft)	108.60	8.60	116.47	16.47
Avg Gap / Difference (ft)	99.17	-0.83	111.94	11.94
IDLE TIME	00:37.1		00:16.1	
ROLLOUT TIME	00:06.7		00:06.9	
RUN TIME	00:52.0		00:54.5	

Table 8 - Gap Analysis – Following Accuracy on Straight Line Test

Figure 24 plots the speed vs the gap distance between the LV and the AIPV, with the speed change on the primary Y-axis as a function of time on the x-axis. A secondary y-axis plots the gap of the AIPV in relationship to LV. The plot for Run 2 is in the APPENDIX.

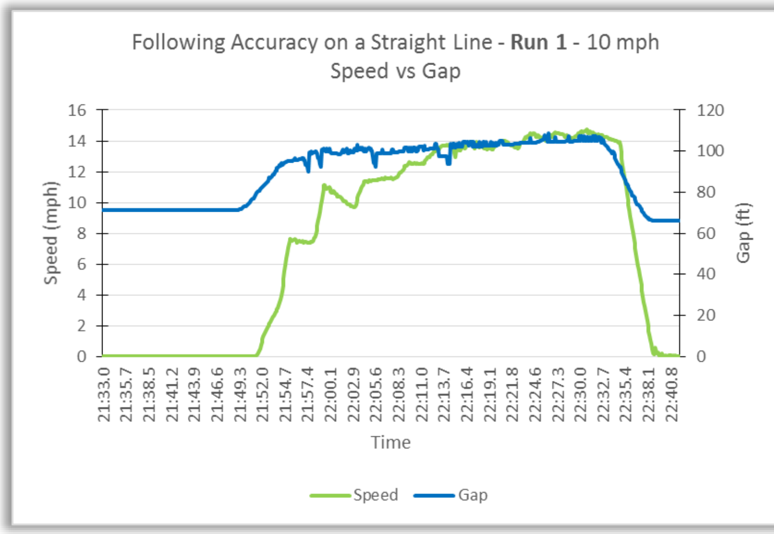


Figure 24 – Speed vs Gap – Following Accuracy on Straight Line Test

Video file: https://youtu.be/7uAMsteWQzk

Additional information: On Run 1 (Table 7), the minimum gap fell outside the expected value of ±15 feet. Notice that he gap distance at ROLLOUT was 72.40 feet and that the AIPV started moving before the actual gap reached the command gap of 100ft, leading to the minimum gap value falling outside the expected range. Figure 25 compares the speed of the LV and the AIPV during the test. The 10 mph speed set for the test procedure was exceeded and is dependent on the ability of the LV driver to maintain such speed. It is important to notice that the AIPV speed profile follows pretty closely the LV speed profile for this test, as discussed in *Section 5.2.5*. The plot for Run 2 is in the APPENDIX.

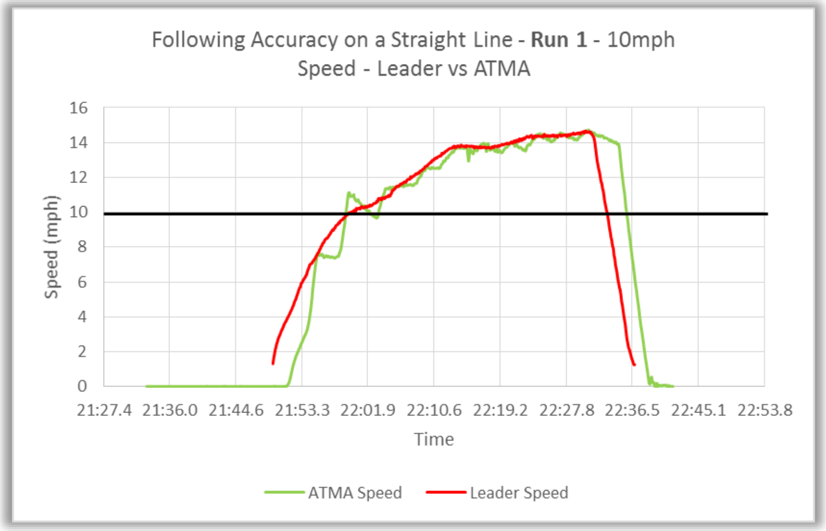


Figure 25 – Speed Profiles – Following Accuracy on Straight Line Test

6.6 – TEST CASE SCENARIO 6 - Following Accuracy on Slalom Course

<u>*Category:*</u> Following Accuracy.

<u>*Location:*</u> I-840.

<u>*Objective*</u>*:* Collect data to determine if the AIPV maintains the lateral accuracy of ± 6 inches from the LV path, as specified in *Section 5.1.3* and if the AIPV maintains the following gap distance of ± 15 feet, as specified in *Section 5.1.4*, on a slalom course.

<u>*Test procedure:*</u> A slalom course was set by positioning 5 cones 100 feet apart between the two lanes on I-840. The command gap was set to 100 feet on the GUI. The LV and the AIPV were activated. The LV operator was asked to drive at a target speed of 5 mph in a zig-zag pattern from one lane to another going through the cones. Data was collected for two runs. Figure 26 presents the plotted path of the test, with the orange line representing the LV and the blue line representing the AIPV.

Figure 26 – Test Path – Following Accuracy on Slalom Course Test

Expected result: The AIPV maintains the lateral accuracy of ± 6 inches from the LV path and the following gap distance of ± 15 feet between the LV and the AIPV.

Files used for analysis: 2019-11-05_17-32-22_log and 2019-11-05_17-43-41_log

Results: The cross track error (CTE) data was analyzed from the logs. Table 9 presents the range of values for each run. CTEs that fell outside the expected result value were coded red. Data for run 2 was not recorded on the log file. The AIPV was not able to maintain the expected lateral accuracy on Run 1.

	Speed - 5 mph			
	RUN 1		RUN 2	
Gap set (ft):	100		100	
Cross Track Error (in)	-8.98	9.80	N/A	N/A

Table 9 - Cross Track Error (CTE) Range – Following Accuracy on Slalom Course Test

Figure 27 plots the speed vs the cross track error, having the speed change on the primary Y-axis as a function of time on the x-axis. A secondary y-axis plots the CTE of the AIPV.

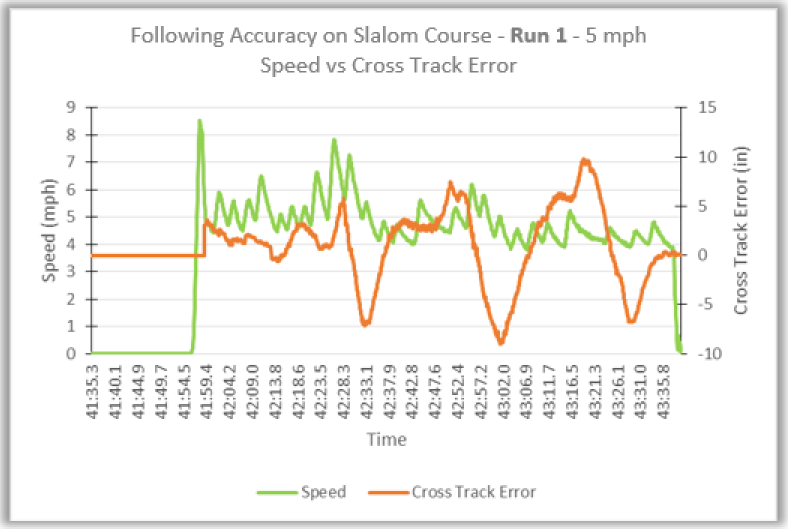


Figure 27 – Speed vs Cross Track Error – Following Accuracy on Slalom Course Test

According to the specifications in *Section 5.1.4* the follow distance accuracy is controlled by a speed/gap algorithm that maintains the AIPV at the command gap distance set by the operator from the GUI, with the vehicles remaining within ±15 feet of the set point distance. Table 10 presents the gap analysis results. The gap distance at rollout indicates the distance between the LV and the AIPV at the start of the test, when the LV started to move. The minimum, maximum and average gap values were collected from the moment the AIPV first accelerated during the test to the moment the AIPV started decelerating to a final stop. Gap values that fell outside the expected result value were coded red. Table 10 also presents information about the elapsed time (from the moment data started to be recorded) for IDLE mode (Safety operator on the LV has control of the ATMA system), ROLLOUT (Autonomous mode is engaged) and RUN (Autonomous mode is operational). Data for run 2 was not recorded on the log file. The AIPV was able to maintain the expected gap accuracy on run 1, based on the average gap results.

	Speed - 5 mph			
	RUN 1		RUN 2	
Gap set (ft):	100		100	
Gap dist at ROLLOUT (ft)	104.46		N/A	
Min Gap / Difference (ft)	94.78	-5.22	N/A	N/A
Max Gap / Difference (ft)	110.96	10.96	N/A	N/A
Avg Gap / Difference (ft)	100.93	0.93	N/A	N/A
IDLE TIME	09:22.6		N/A	
ROLLOUT TIME	00:09.4		N/A	
RUN TIME	01:44.8		N/A	

Table 10 - Gap Analysis – Following Accuracy on Slalom Course Test

Figure 28 plots the speed vs the gap distance between the LV and the AIPV, with the speed change on the primary Y-axis as a function of time on the x-axis. A secondary y-axis plots the gap of the AIPV in relationship to LV.

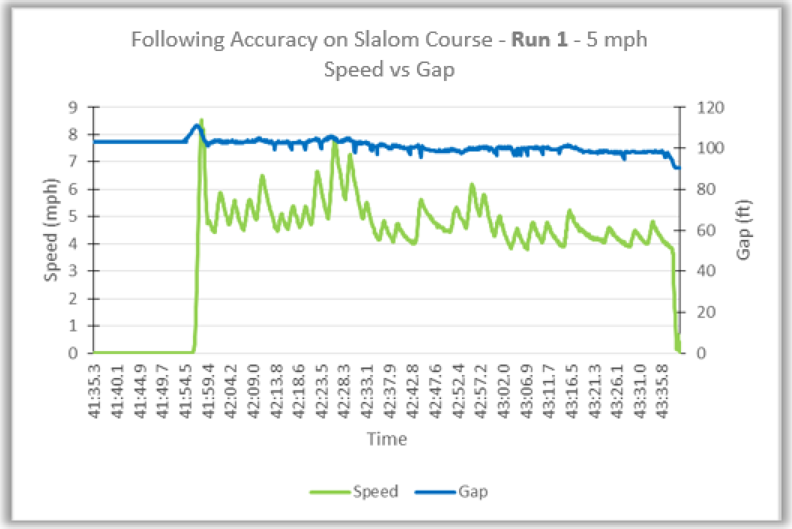


Figure 28 – Speed vs Gap – Following Accuracy on Slalom Course Test

<u>*Video file:*</u> https://youtu.be/St3F05r7GwI

<u>*Additional information:*</u> Figure 29 compares the speed of the LV and the AIPV during the test. The 5 mph speed set for the test procedure was reasonably maintained and is dependent on the ability of the LV driver to maintain such speed. It is important to notice that the AIPV speed profile follows pretty closely the LV speed profile for this test, as discussed in *Section 5.2.5.*

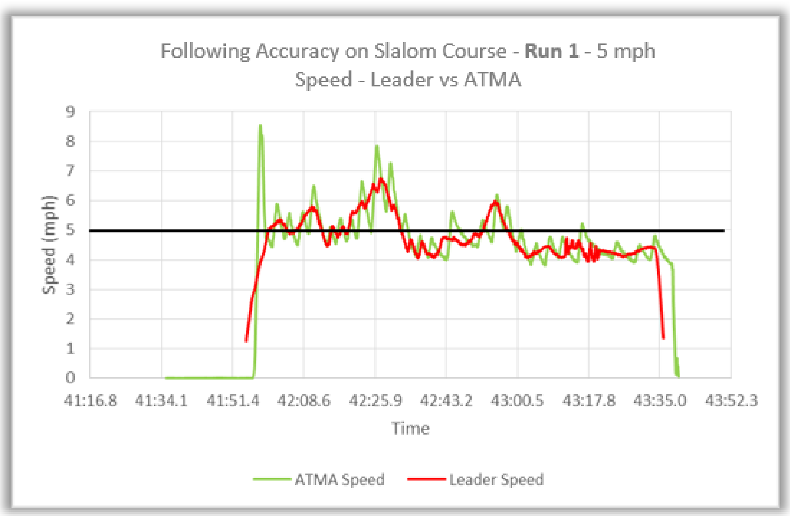


Figure 29 – Speed Profiles – Following Accuracy on Slalom Course Test

6.7 – TEST CASE SCENARIO 7 - Following Accuracy on Lane Change

Category: Following Accuracy.

Location: I-840.

Objective: Collect data to determine if the AIPV maintains the lateral accuracy of ± 6 inches from the LV path, as specified in *Section 5.1.3* and if the AIPV maintains the following gap distance of ± 15 feet, as specified in *Section 5.1.4*, while changing lanes.

Test procedure: Using the 2 lanes of I-840, the right side lane was tapered from the shoulder to the left most lane, between 200 feet and 400 feet. After a 100 feet straight segment another taper was created from the left most lane back to the shoulder, between 500 feet to 700 feet. The command gap was set to 100 feet on the GUI. The LV and the AIPV were activated. The LV operator was asked to drive at a target speed of 10 mph, navigating the lane change described above. The test was repeated at a target speed of 15 mph. Data was collected for a total of four runs. Figure 30 presents the plotted path of the test, with the orange line representing the LV and the blue line representing the AIPV.

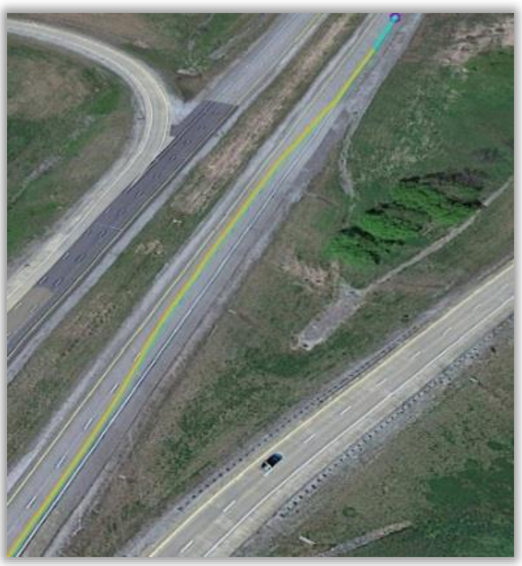


Figure 30 – Test Path – Following Accuracy on Lane Change Test

Expected result: The AIPV maintains the lateral accuracy of ± 6 inches from the LV path and the following gap distance of ± 15 feet between the LV and the AIPV.

Files used for analysis: 2019-11-05_14-13-53_log, 2019-11-05_14-26-17_log, 2019-11-05_14-38-02_log and 2019-11-05_21-52-20_log.

Results: The cross track error (CTE) data was analyzed from the logs. Table 11 presents the range of values for each run. CTEs that fell outside the expected result value were coded red. The AIPV was not able to maintain the expected lateral accuracy on all runs.

	Speed - 10mph				Speed - 15mph			
	RUN 1		RUN 2		RUN 3		RUN 4	
Gap set (ft):	100		100		100		100	
Cross Track Error (in)	-1.93	8.62	-5.67	13.54	0.00	14.37	-8.93	3.54

Table 11 - Cross Track Error (CTE) Range – Following Accuracy on Lane Change Test

Figure 31 plots the speed vs the cross track error, having the speed change on the primary Y-axis as a function of time on the x-axis. A secondary y-axis plots the CTE of the AIPV. The plot for the additional runs are in the APPENDIX.

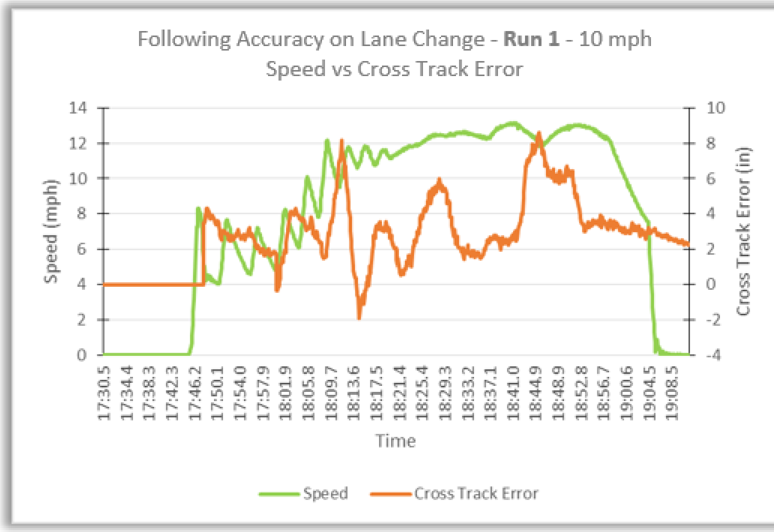


Figure 31 – Speed vs Cross Track Error – Following Accuracy on Lane Change Test

According to the specifications in *Section 5.1.4,* the follow distance accuracy is controlled by a speed/gap algorithm that maintains the AIPV at the command gap distance set by the operator from the GUI, with the vehicles remaining within ±15 feet of the set point distance. Table 12 presents the gap analysis results. The gap distance at rollout indicates the distance between the LV and the AIPV at the start of the test, when the LV started to move. The minimum, maximum and average gap values were collected from the moment the AIPV first accelerated during the test to the moment the AIPV started decelerating to a final stop. Gap values that fell outside the expected result value were coded red. Table 12 also presents information about the elapsed time (from the moment data started to be recorded) for IDLE mode (Safety operator on the LV has control of the ATMA system), ROLLOUT (Autonomous mode is engaged) and RUN (Autonomous mode is operational). The AIPV was able to maintain the expected gap accuracy on runs 1, 3 and 4, based on the average gap results. During run 2, an A-Stop brought the AIPV to a stop, disrupting its ability to maintain the command gap distance appropriately, as can be seen on Figure 33 around the 27:23.0 seconds mark.

	Speed - 10mph				Speed - 15mph			
	RUN 1		RUN 2		RUN 3		RUN 4	
Gap set (ft):	100		100		100		100	
Gap dist at ROLLOUT (ft)	96.12		99.27		96.03		91.53	
Min Gap / Difference (ft)	93.43	-6.57	82.94	-17.06	84.81	-15.19	86.05	-13.95
Max Gap / Difference (ft)	113.75	13.75	206.89	106.89	110.37	10.37	111.87	11.87
Avg Gap / Difference (ft)	105.95	5.95	131.28	31.28	102.65	2.65	100.68	0.68
IDLE TIME	03:46.3		00:12.1		01:14.4		00:10.9	
ROLLOUT TIME	00:03.4		00:04.9		00:05.1		00:06.9	
RUN TIME	01:27.5		01:44.3		00:54.6		00:55.0	

Table 12 - Gap Analysis – Following Accuracy on Lane Change Test

Figure 32 plots the speed vs the gap distance between the LV and the AIPV, with the speed change on the primary Y-axis as a function of time on the x-axis. A secondary y-axis plots the gap of the AIPV in relationship to LV. The plot for the additional runs are in the APPENDIX.

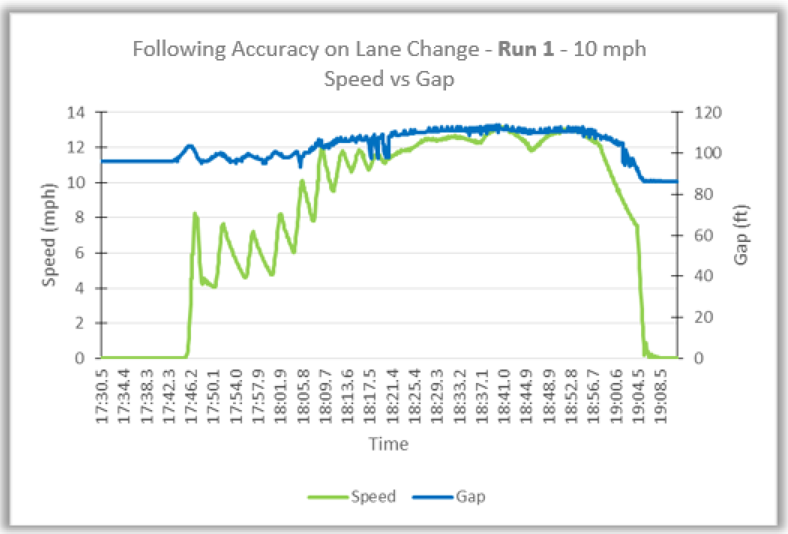


Figure 32 – Speed vs Gap – Following Accuracy on Lane Change Test

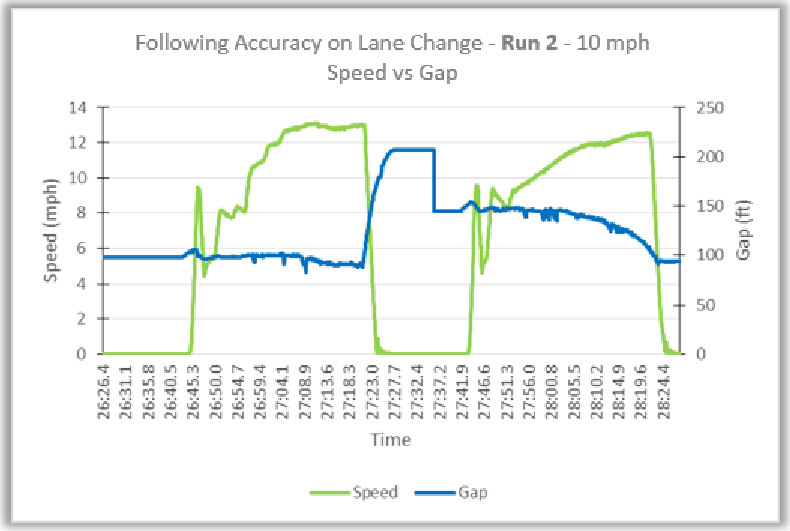


Figure 33 – Speed vs Gap – A-Stop – Following Accuracy on Lane Change Test

Video file: https://youtu.be/3nwkJPKiUf4

Additional information: Figure 34 compares the speed of the LV and the AIPV during the test. The 10 mph speed set for the test procedure was exceeded and is dependent on the ability of the LV driver to maintain such speed. It is important to notice that the AIPV speed profile follows pretty closely the LV speed profile for this test, as discussed in *Section 5.2.5*

The plot for the additional runs are in the APPENDIX.

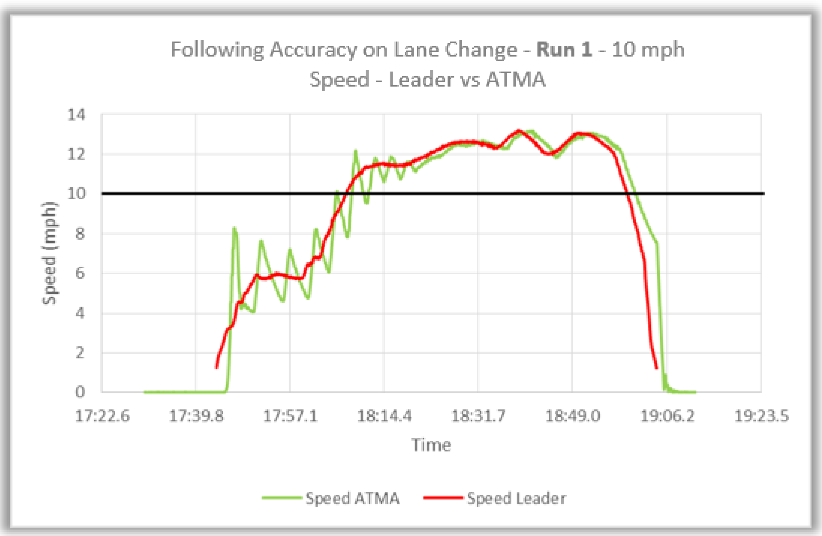


Figure 34 – Speed Profiles – Following Accuracy on Lane Change Test

6.8 – TEST CASE SCENARIO 8 – Adjusting Following Distance

Category: Following Accuracy.

Location: TDSTC/TIM.

Objective: Collect data to determine if the AIPV is able to adjust to a new command gap distance set on the GUI and the system maintains the following gap distance of ± 15 feet, as specified in *Section 5.1.4*.

Test procedure: The command gap was set to 100 feet on the GUI. The LV and the AIPV were activated. The LV operator was asked to drive at a target speed of 10 mph. After the initial gap distance stabilized, the command gap was increased to 200 feet on the GUI panel. The test was repeated with the command gap increased to 300 feet. Data was collected for a total of four runs. Figure 35 presents the plotted path of the test, with the orange line representing the LV and the blue line representing the AIPV.

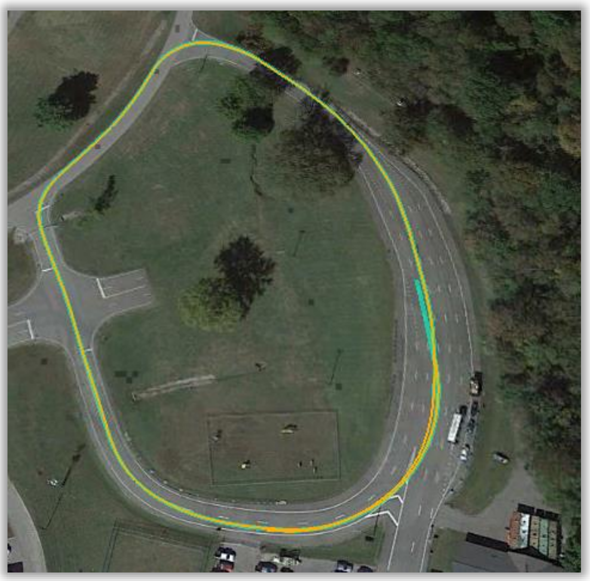


Figure 35 – Test Path – Adjusting Following Distance Test

Expected result: The AIPV is able to adjust to a new command gap distance set on the GUI and maintains the following gap distance of ± 15 feet between the LV and the FLW.

Files used for analysis: 2019-11-08_15-51-36_log, 2019-11-08_16-03-06_log, 2019-11-08_17-04-51_log and 2019-11-08_17-19-34_log.

Results: According to the specifications in *Section 5.1.4* the follow distance accuracy is controlled by a speed/gap algorithm that maintains the AIPV at the command gap distance set by the operator from the GUI, with the vehicles remaining within ±15 feet of the set point distance.

Table 13 presents the gap analysis results. The gap distance at rollout indicates the distance between the LV and the AIPV at the start of the test, when the LV started to move. The minimum, maximum and average gap values were collected from the moment the AIPV first accelerated during the test to the moment the AIPV started decelerating to a final stop. Gap values that fell outside the expected result value were coded red. Table 13 also presents information about the elapsed time (from the moment data started to be recorded) for IDLE mode (Safety operator on the LV has control of the ATMA system), ROLLOUT (Autonomous mode is engaged) and RUN (Autonomous mode is operational). The AIPV was able to adjust to a new command gap set on the GUI but was not able to maintain the expected gap accuracy based on the average gap results.

	Speed - 10mph							
	RUN 1		RUN 2		RUN 3		RUN 4	
Initial gap setting (ft):	100		100		100		100	
Final gap setting (ft):	200		200		300		300	
Gap dist at ROLLOUT (ft)	76.83		101.77		68.40		69.61	
Min Gap / Difference (ft)	83.39	-116.61	173.91	-26.09	82.05	-217.95	81.69	-218.31
Max Gap / Difference (ft)	260.26	60.26	255.05	55.05	437.59	137.59	445.96	145.96
Avg Gap / Difference (ft)	215.74	15.74	224.58	24.58	327.96	27.96	332.56	32.56
IDLE TIME	00:19.9		00:15.1		00:34.3		00:10.9	
ROLLOUT TIME	00:08.5		00:05.3		00:06.9		00:07.0	
RUN TIME	03:45.7		02:37.2		03:15.4		03:13.8	

Table 13 - Gap Analysis – Adjusting Following Distance Test

Figure 36 plots the speed vs the gap distance between the LV and the AIPV, with the speed change on the primary Y-axis as a function of time on the x-axis. A secondary y-axis plots the gap of the AIPV in relationship to LV. After the initial gap distance stabilized, the command gap was increased to 200 feet, as can be seen at 4:06.3 seconds. The AIPV stopped until it reached the 200 feet gap distance, at 4:12.7, and then moved again, but was unable to consistently maintain the new gap distance set. The test was conducted on a loop track that demanded the LV to slow down while turning right on two tight radius turns (North of the track). The speed/gap algorithm is not well suited for such speed variations, as discussed in *Section 5.2.5*, leading to an inconsistent gap between the LV and the AIPV. The plot for the additional runs are in the APPENDIX.

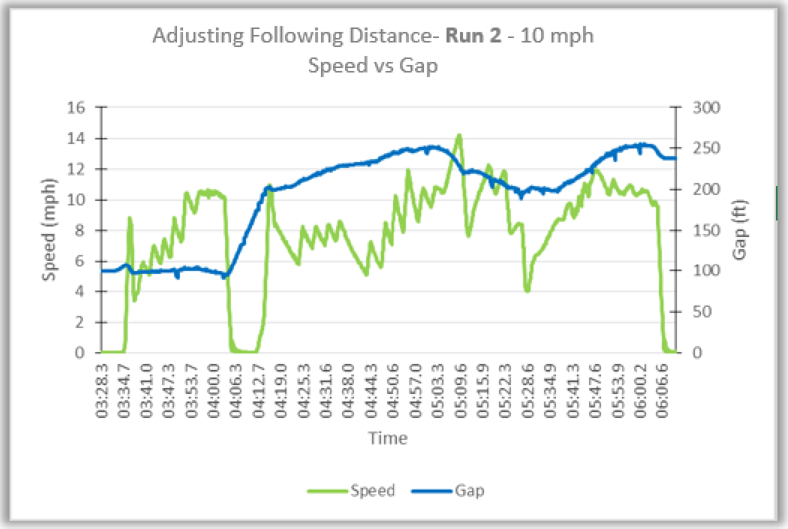


Figure 36 – Speed vs Gap – Adjusting Following Distance Test

Video file: https://youtu.be/kVh-bmRdoic and https://youtu.be/KEROlxBO9AA

Additional information: The subject test was initially scheduled for I-840, which was considered a more conducive testing location due to its straight geometry and the ability of the ATMA system to operate on a non-stop-and-go environment (no slowing down for turning, etc), as discussed in *Section 5.2.5*. The adjusting following distance test was postponed to the TDSTC/TIM, to maintain the testing schedule due to the ATMA system issues mentioned in *Section 6.1*. Figure 37 compares the speed of the LV and the AIPV during the test at TDSTC/TIM. Again, the AIPV stopped when the new command gap distance was selected, and then moved again when the 200 feet was achieved. It followed pretty closely the LV speed profile for the rest of the test, except after 4:48.0, when the AIPV speed was higher than the LV, leading to the actual gap being closer to the command gap set. Towards the end of the test, the LV speed was higher than the AIPV, leading to an increase in the actual gap distance once again. This clearly exemplifies the discussion in *Section 5.2.5*. The plot for the additional runs are in the APPENDIX.

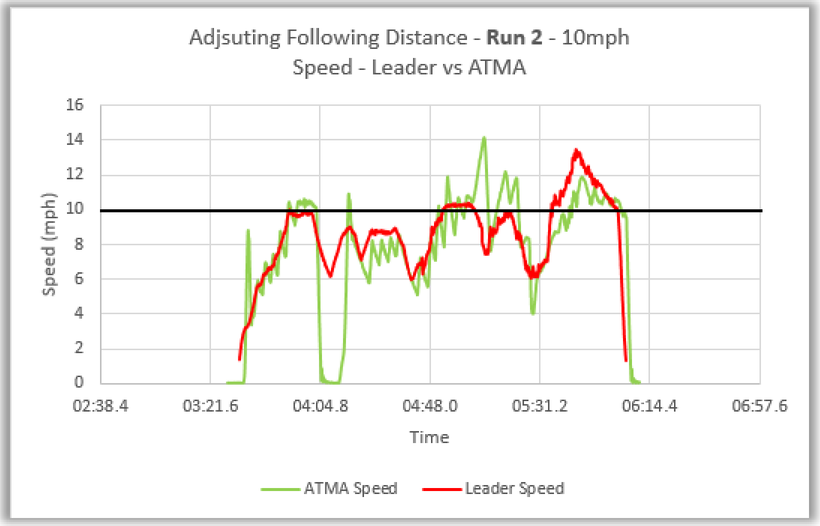


Figure 37 – Speed Profiles – Adjusting Following Distance Test

6.9 – TEST CASE SCENARIO 9 - Trash Pick-up

Category: Typical Application.

Location: I-840.

Objective: Collect data to determine if the AIPV maintains the following gap distance of ± 15 feet, as specified in *Section 5.1.4*, while emulating a typical trash pick-up operation at a multi-lane divided highway with posted speed limit of 65 mph.

Test procedure: The LV and the AIPV operated on the shoulder. The command gap was set to 300 feet on the GUI. The LV and the AIPV were activated. The LV operator was asked to drive at a target speed of 10 mph along the shoulder to the first predetermined stopping location. After the first stop, the LV moved 200 feet to the second predetermined stopping location. Data was collected for two runs. Figure 38 presents the plotted path of the test, with the orange line representing the LV and the blue line representing the AIPV.

Figure 38 – Test Path – Trash Pick-up

Expected result: The AIPV maintains the following gap distance of ± 15 feet between the LV and the AIPV.

Files used for analysis: 2019-11-05_19-23-47_log and 2019-11-05_19-30-56_log

Results: According to the specifications in *Section 5.1.4* the follow distance accuracy is controlled by a speed/gap algorithm that maintains the AIPV at the command gap distance set by the operator from the GUI, with the vehicles remaining within ±15 feet of the set point distance.

Table 14 presents the gap analysis results. The AIPV was not able to maintain the command gap distance set to the LV. On the first run, the AIPV was 367 feet away from the LV after the first stop, and 405 feet away from the LV after the second stop. The results were repeated on the second run. The stop-and-go operation of the testing inhibits the ability of the current speed/gap algorithm to work appropriately, as discussed in *Section 5.2.5*. Table 14 also presents information about the elapsed time (from the moment data started to be recorded) for IDLE mode (Safety operator on the LV has control of the ATMA system), ROLLOUT (Autonomous mode is engaged) and RUN (Autonomous mode is operational).

	Speed - 10mph			
	RUN 1		RUN 2	
Gap set (ft):	300		300	
	1st stop	2nd stop	1st stop	2nd stop
Distance between LV and FLW (ft)	367.00	405.00	362.00	404.00
IDLE TIME	00:57.7		00:17.3	
ROLLOUT TIME	00:07.7		00:10.2	
RUN TIME	01:42.3		01:18.1	

Table 14 - Gap Analysis – Trash Pick-up Test

Figure 39 plots the speed vs the gap distance between the LV and the AIPV, with the speed change on the primary Y-axis as a function of time on the x-axis. A secondary y-axis plots the gap of the AIPV in relationship to LV. During ROLLOUT, the AIPV waited for the gap distance to reach 300 feet before it started moving. Once the AIPV moved forward, the speed/gap algorithm was unable to maintain the command gap distance because of the stop-and-go operation (see *Section 5.2.5*), and the gap between the LV and the AIPV continued to grow. Basically, the AIPV ability to stabilize the gap distance is dependent on the run time and distance, with longer periods of running time being necessary to allow the speed/gap algorithm to adjust properly. The plot for the additional runs are in the APPENDIX.

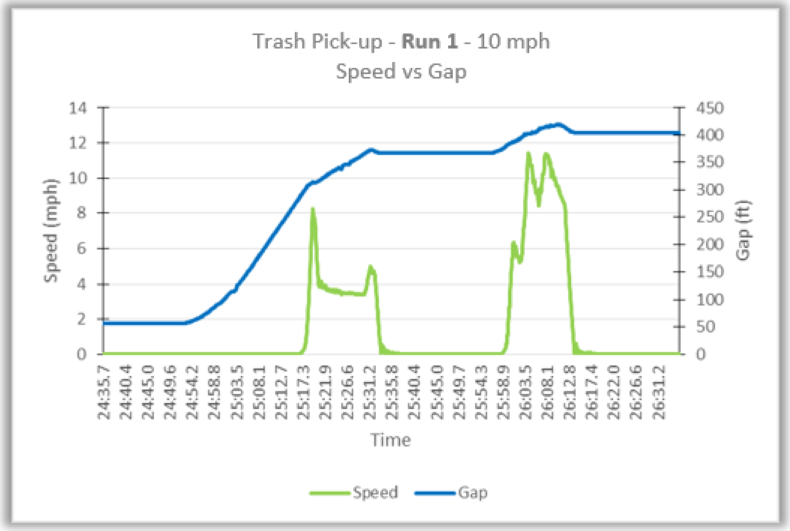


Figure 39 – Speed vs Gap – Trash Pick-up Test

Video file: https://youtu.be/ZLOLOFKdK_o

Additional information: The test procedure required a command gap distance of 225 feet, based on the Temporary Traffic Control Distance Charts from the TDOT Work Zone Field Manual for Maintenance Operations (*6*). The required distance was not available on the Command Gap slide bar on the GUI, and a 300 feet Command Gap was used instead.

Figure 40 compares the speed of the LV and the AIPV during the test. It can be noticed that the AIPV was not able to adjust its speed profile and therefore was unable to maintain the set gap distance, as discussed in *Section 5.2.5*.

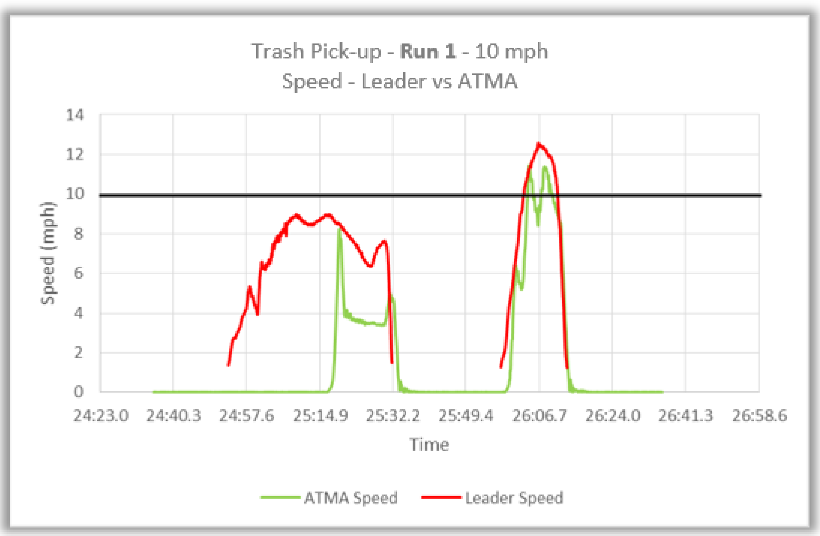


Figure 40 – Speed Profiles – Trash Pick-up Test

6.10 – TEST CASE SCENARIO 10 - Herbicide Application

Category: Typical Application.

Location: I-840.

Objective: Observe if the ATMA system is capable to continuously shadow/protect the service vehicle during a typical herbicide application operation at a multi-lane divided highway with posted speed limit of 45 mph.

Test procedure: The LV and the AIPV operated on the shoulder. The command gap was set to 200 feet on the GUI. The LV and the AIPV were activated. The LV operator was asked to drive at a target speed of 10 mph along the shoulder, encroach on the adjacent lane at a predetermined location in the test track and return to the shoulder. Data was collected for two runs. Figure 41 presents the plotted path of the test, with the orange line representing the LV and the blue line representing the AIPV.

Figure 41 – Test Path – Herbicide Application

Expected result: The AIPV is capable to continuously shadow/protect the service vehicle (LV).

Files used for analysis: 2019-11-05_19-38-54_log and 2019-11-05_19-47-19_log

Results: As mentioned in *Chapter 5*, when in operation, the LV transmits its position, speed, and heading to the AIPV vehicle in a sequential series of Vehicle-to-Vehicle (V2V) "*e-Crumbs*" messages. The AIPV then maneuvers from one e-Crumb to the next following the path of the LV at a user-defined vehicle-gap. Figure 42 presents the moment the service vehicle (LV) encroached in the adjacent lane during the testing. From that point, for the next 19 seconds, the AIPV was unable to shadow the service vehicle as required. The AIPV simply continued to follow the e-Crumbs laid out by the LV on the shoulder. While the LV returned to the shoulder, the AIPV followed the e-Crumbs laid out by the LV on the adjacent lane. The ATMA system was not capable of continuously shadow/protect the service vehicle (LV).

Figure 42 – Unprotected Service Vehicle – Herbicide Application Test

Video file: https://youtu.be/61BR3lsYY2M

Additional information: The ATMA system developer representative mentioned during the testing procedures that the company was aware of the issue and was developing an offset system that would give the ability for the LV operator, from the GUI, to move the AIPV over to the encroached lane at the same time as the LV.

6.11 – TEST CASE SCENARIO 11 – Pothole Patching

Category: Typical Application.

Location: I-840.

Objective: Collect data to determine if the AIPV maintains the following gap distance of ± 15 feet, as specified in *Section 5.1.4*, while emulating a typical pothole patching operation at a multi-lane divided highway with posted speed limit of 55 mph. In addition, observe the ATMA system while a person walks towards the AIPV.

Test procedure: The command gap was set to 200 feet on the GUI. The LV and the AIPV were activated. The LV operator was asked to drive at a target speed of 10 mph to the first predetermined stopping location. After the first stop, the LV moved to the second predetermined stopping location. After the second stop, a UT team member walked towards the AIPV. Data was collected for two runs. Figure 43 presents the plotted path of the test, with the orange line representing the LV and the blue line representing the AIPV.

Figure 43 – Test Path – Pothole Patching

Expected result: The AIPV maintains the following gap distance of ± 15 feet between the LV and the AIPV and detects a person walking towards the AIPV, generating an A-Stop.

Files used for analysis: 2019-11-05_20-00-01_log and 2019-11-05_20-12-49_log

Results: According to the specifications in *Section 5.1.4* the follow distance accuracy is controlled by a speed/gap algorithm that maintains the AIPV at the command gap distance set by the operator from the GUI, with the vehicles remaining within ±15 feet of the set point distance.

Table 15 presents the gap analysis results. The AIPV was not able to maintain the command gap distance set to the LV, due to the stop-and-go operation, as discussed in *Section 5.2.5*. On the first run, the AIPV was 231 feet away from the LV after the first stop, and 273 feet away from the LV after the second stop. The results were repeated on the second run. The ATMA system detected a person 91’7” and 92’2” (run 1 and run 2, respectively) away from the AIPV, and generated an A-Stop. Table 15 also presents information about the elapsed time (from the moment data started to be recorded) for IDLE mode (Safety operator on the LV has control of the ATMA system), ROLLOUT (Autonomous mode is engaged) and RUN (Autonomous mode is operational).

	Speed - 10mph			
	RUN 1		RUN 2	
Gap set (ft):	200		200	
	1st stop	2nd stop	1st stop	2nd stop
Distance between LV and FLW (ft)	231.00	273.00	226.00	232.00
Distance ATMA detect person in between vehicles	91'7"		92'2"	
IDLE TIME	00:49.3		00:18.2	
ROLLOUT TIME	00:06.1		00:04.4	
RUN TIME	02:08.5		01:09.0	

Table 15 - Gap Analysis – Pothole Patching Test

Figure 44 plots the speed vs the gap distance between the LV and the AIPV, with the speed change on the primary Y-axis as a function of time on the x-axis. A secondary y-axis plots the gap of the FLW in relationship to LV. During ROLLOUT, the AIPV waited for the gap distance to reach 200 feet before it started moving. Once the AIPV moved forward, the speed/gap algorithm was unable to maintain the command gap distance because of the stop-and-go operation (as discussed in *Section 5.2.5*), and the gap between the LV and the AIPV continued to grow. Basically, the AIPV ability to stabilize the gap distance is dependent on the run time and distance, with longer periods of running time being necessary to allow the speed/gap algorithm to adjust properly. The plot for the additional runs are in the APPENDIX.

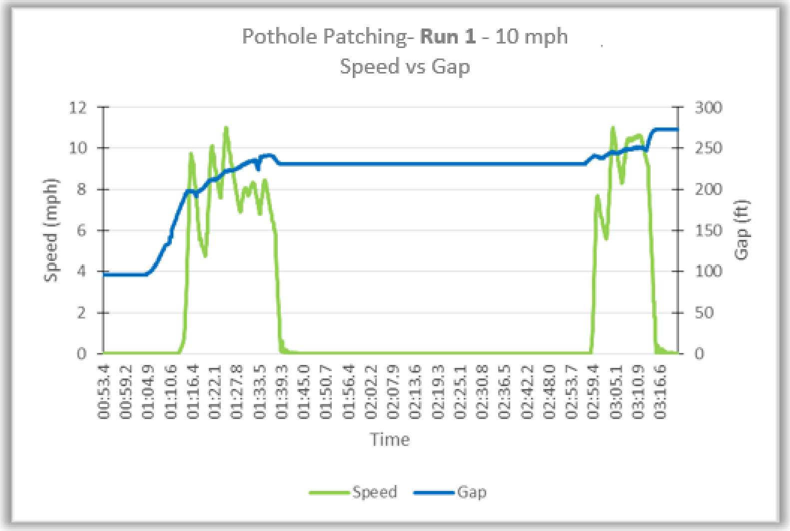


Figure 44 – Speed vs Gap – Pothole Patching Test

<u>*Video file:*</u> https://youtu.be/axcY0Oj2ck8

<u>*Additional information:*</u> The test procedure required a command gap distance of 175 feet, based on the Temporary Traffic Control Distance Charts from the TDOT Work Zone Field Manual for Maintenance Operations (*6*). The required distance was not available on the Command Gap slide bar on the GUI, and a 200 feet Command Gap was used instead.

Figure 45 compares the speed of the LV and the AIPV during the test. It can be noticed that the AIPV was not able to adjust its speed profile and therefore was unable to maintain the set gap distance, as discussed in *Section 5.2.5*.

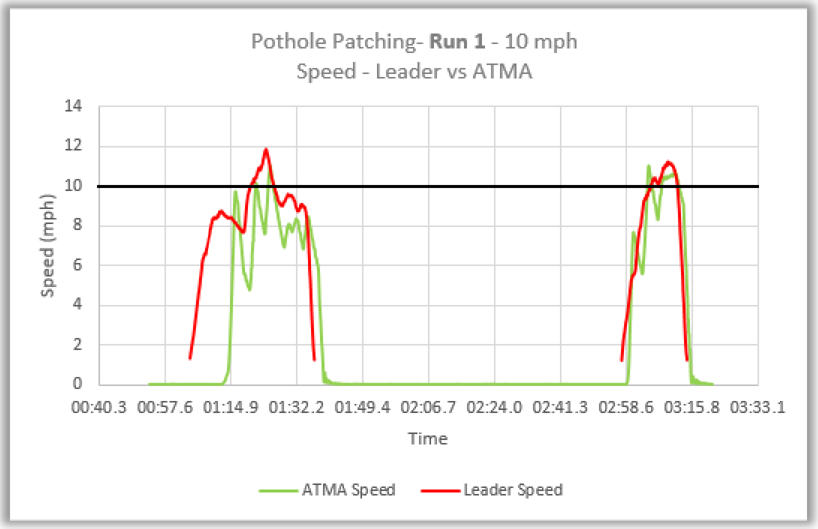


Figure 45 – Speed Profiles – Pothole Patching Test

6.12 – TEST CASE SCENARIO 12 – Obstacle Detection - Front

<u>Category:</u> Detection.

<u>Location:</u> I-840.

<u>Objective</u>: Observe if the ATMA system detects an object pulled in front of the AIPV during autonomous operation. Record the distance from the AIPV the object was detected and the distance between the front of the AIPV and the traffic barrel after the AIPV stops.

<u>Test procedure:</u> The command gap was set to 200 feet on the GUI. The LV and the AIPV were activated. The LV operator was asked to drive in a straight line at a target speed of 10 mph. Once the LV cleared a pre-determined location in the test track, a traffic barrel connected to a rope was pulled in front of the AIPV. Data was collected for two runs. Figure 46 presents the plotted path of the test, with the orange line representing the LV and the blue line representing the AIPV.

Figure 46 – Test Path – Obstacle Detection - Front

Expected result: The AIPV detects the traffic barrel and executes an A-Stop.

Files used for analysis: 2019-11-05_15-17-53_log and 2019-11-05_15-01-01_log

Results: The type of radar and the range detected message was analyzed from the logs. Table 16 presents the values for each run. The AIPV detected the traffic barrel and executed an A-Stop.

	Speed - 10mph	
	RUN 1	RUN 2
Gap set (ft):	200	200
Actual speed of FLW when object detected	10.08 MPH	10.95 MPH
Object detection range	159' 4"	163' 3"
Dist. from object when FLW stops	69' 6"	66' 2"

Table 16 - Detection Distances – Object Detection (Front) - Test

Video file: https://youtu.be/b3RB6x4FccQ

Additional information: N/A.

6.13 – TEST CASE SCENARIO 13 – Vehicle Intrusion

Category: Detection.

Location: I-840.

Objective: Observe if the ATMA system detects a vehicle driving between the LV and the AIPV, a potential hazardous condition to the service vehicle operator.

Test procedure: The command gap was set to 300 feet on the GUI. The LV and the AIPV were activated. The LV operator was asked to drive in a straight line at a target speed of 10 mph. A UT research team member drove a vehicle alongside the AIPV and then moved in front of the AIPV, positioning the vehicle between the LV and the AIPV. Data was collected for two runs. Figure 47 presents the plotted path of the test, with the orange line representing the LV and the blue line representing the AIPV.

Figure 47 – Test Path – Vehicle Intrusion

Expected result: The AIPV detects the vehicle in its path and executes an A-Stop.

Files used for analysis: 2019-11-05_16-21-37_log and 2019-11-05_16-37-28_log

Results: On run 1, the AIPV executed an A-Stop and took 5.1 seconds to totally stop (data collected from log file). During an A-Stop, the LV operator receives a message on the GUI informing that the AIPV has stopped. That in itself is a safety feature that can potentially safeguard the LV operator (the service vehicle) from a hazardous condition. On run 2, the AIPV did not execute an E-Stop. The main difference between run 1 and run 2 was how close to the AIPV the vehicle encroached into the operational lane on run 1. Ideally, the ATMA system would execute an A-Stop independent of the distance a vehicle encroaches between the LV and the AIPV.

Video file: https://youtu.be/mSw-8bLXbH8

Additional information: N/A.

6.14 – TEST CASE SCENARIO 14 – Sensitivity to Passing Vehicles

Category: Detection.

Location: I-840.

Objective: Observe the response of the ATMA system when a vehicle drives on an adjacent lane, going away and towards the AIPV.

Test procedure: The command gap was set to 100 feet on the GUI. The LV and the AIPV were activated. The LV operator was asked to drive in a straight line at a target speed of 10 mph. A UT research team member drove a vehicle on an adjacent lane to the AIPV, going away and towards the autonomous vehicle. Data was collected for two runs. Figure 48 presents the plotted path of the test, with the orange line representing the LV and the blue line representing the AIPV.

Figure 48 – Test Path – Sensitivity to Passing Vehicles

Expected result: The ATMA system detects the vehicles on the GUI but does not execute an A-Stop.

Files used for analysis: 2019-11-05_21-12-52_log and 2019-11-05_21-00-33_log

Results: The ATMA system detected the vehicle passing the AIPV on both runs and did not execute an A-Stop.

Figure 49 – GUI Display during Sensitivity to passing Vehicles Test

Video file: https://youtu.be/mSw-8bLXbH8

Additional information: Figure 49 presents the GUI display as the vehicle was driving alongside the AIPV, going away from the autonomous vehicle. The ultrasonic sensors detection can be noticed at the top left of the screen, with two warning messages.

6.15 – TEST CASE SCENARIO 15 – Object Recognition

Category: Detection.

Location: TDSTC/TIM.

Objective: Observe the response of the ATMA system when the AIPV drives near parked vehicles.

Test procedure: The command gap was set to 100 feet on the GUI. The LV and the AIPV were activated. The LV operator was asked to drive at a target speed of 10 mph and stay in the lane adjacent to the parked vehicles. Data was collected for two runs. Figure 50 presents the plotted path of the test, with the orange line representing the LV and the blue line representing the AIPV.

Figure 50 – Test Path – Object Recognition

Expected result: The ATMA system detects the vehicles on the GUI but does not execute an A-Stop.

Files used for analysis: 2019-11-08_14-30-18_log and 2019-11-08_14-46-56_log

Results: The ATMA system was not able to consistently detect and recognize the parked vehicles. The ATMA system did not execute an A-Stop.

Figure 51 – GUI Display during Object Recognition Test

Video file: https://youtu.be/DYz2wl9bm4M

Additional information: Figure 51 presents the GUI display as the AIPV was driving alongside the parked vehicles. The screenshot to the left is during ROLLOUT and several warnings messages from the ultrasonic sensors can already be noticed at the top left, even though there were no vehicles/objects nearby. The screenshot to the right is during the RUN, and the ultrasonic sensors generated several warning messages as the AIPV drove by. Even though having sensors monitoring the side of the AIPV is beneficial, the warning messages were considered not useful due to the inconsistent relay of information.

6.16 – TEST CASE SCENARIO 16 – Headlights

Category: Detection.

Location: TDSTC/TIM.

Objective: Observe the response of the ATMA system to vehicle headlights towards the AIPV.

Test procedure: The command gap was set to 100 feet on the GUI. The LV and the AIPV were activated. The LV operator was asked to drive at a target speed of 10 mph. A UT team member drove a vehicle towards the AIPV and flashed the headlights. Data was collected for two runs. Figure 52 presents the plotted path of the test, with the orange line representing the LV and the blue line representing the AIPV.

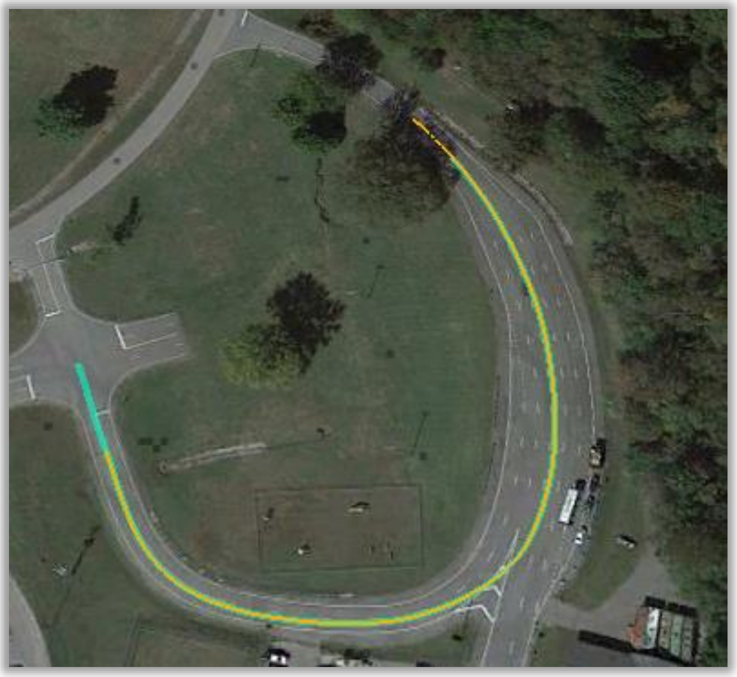


Figure 52 – Test Path - Headlights

Expected result: The ATMA system would not detect the vehicle's headlights and would not execute an A-Stop.

Files used for analysis: 2019-11-07_19-40-52_log and 2019-11-07_19-45-41_log

Results: The ATMA system was not affected by the flashing headlights. The ATMA system did not execute an A-Stop.

Figure 53 – ATMA System during Headlights Test

Video file: https://youtu.be/ujGGrFrsyBU

Additional information: During the week long testing of the ATMA system, a few A-Stop events happened without a readily known reason. The events were apparently generated by the obstacle detection system. Therefore this test was designed "on the fly" to learn if potential sources of light would disturb the detection components of the AIPV. Notice that it was raining during the test (Figure 53), what generated pavement glare as well towards the system.

6.17 – TEST CASE SCENARIO 17 – Cone Detection

Category: Detection.

Location: TDSTC/TIM.

Objective: Observe the response of the ATMA system while driving through a line of reflective cones.

Test procedure: The command gap was set to 100 feet on the GUI. The LV and the AIPV were activated. The LV operator was asked to drive at a target speed of 10 mph on a lane delineated with reflective cones on both sides. Data was collected for two runs. Figure 54 presents the plotted path of the test, with the orange line representing the LV and the blue line representing the AIPV.

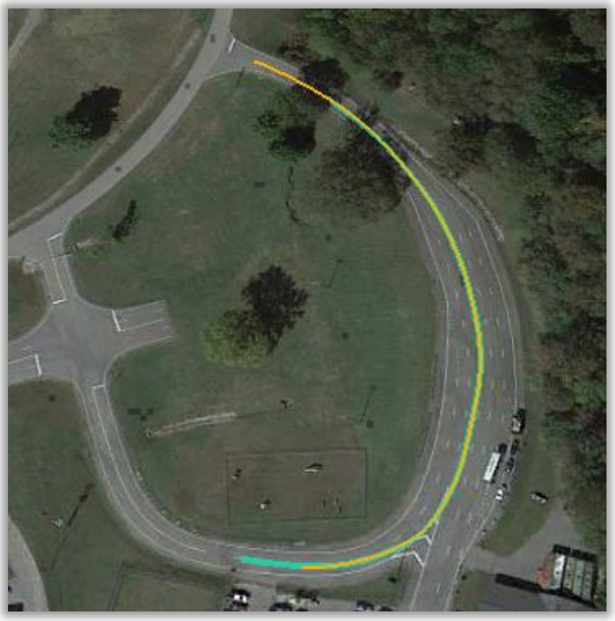


Figure 54 – Test Path – Cone Detection

Expected result: The ATMA system would not detect the reflective cones and would not execute an A-Stop.

Files used for analysis: 2019-11-07_20-28-41_log and 2019-11-07_20-10-15_log

Results: The ATMA system did not detect the reflective cones. The ATMA system did not execute an A-Stop.

Figure 55 – ATMA System during Cone Detection Test

Video file: https://youtu.be/Q5bcTiH_RuE

Additional information: During the week long testing of the ATMA system, a few A-Stop events happened without a readily known reason. The events were apparently generated by the obstacle detection system. Therefore this test was designed "on the fly" to learn if typical work zone objects, like reflective traffic ones, would disturb the detection components of the AIPV (Figure 55).

6.18 – TEST CASE SCENARIO 18 – Speed

Category: Miscellaneous.

Location: I-840.

Objective: Collect data to determine the maximum speed of the AIPV during a gap adjustment procedure.

Test procedure: The command gap was set to 100 feet on the GUI. The LV and the FLW were activated. The LV operator was asked to drive in a straight line at a target speed of 10 mph and when the gap distance was reached, initiate a pause command on the GUI system (as specified in *Section 5.1.1*) to bring the AIPV to a temporary stop. The LV operator continued to drive at the same speed up to a gap distance of 300 feet. The pause command was then released, allowing the AIPV to start the process of catching up to the LV and stabilize at the command gap distance of 100 feet. Data was collected for two runs. Figure 56 presents the plotted path of the test, with the orange line representing the LV and the blue line representing the AIPV.

Figure 56 – Test Path – Speed Test

Expected result: The AIPV would not exceed 20 mph as specified in *Section 5.1.1*.

Files used for analysis: 2019-11-05_20-23-22_log and 2019-11-05_20-32-18_log

Results: The speed data was analyzed from the logs. Table 16 presents the values for each run. Table 17 also presents information about the elapsed time (from the moment data started to be recorded) for IDLE mode (Safety operator on the LV has control of the ATMA system), ROLLOUT (Autonomous mode is engaged) and RUN (Autonomous mode is operational). The AIPV did not exceed the 20 mph specified speed.

	Speed - 10mph	
	RUN 1	RUN 2
Gap set (ft):	100-300-100	100-300-100
FLW Max speed (mph)	13.77	16.43
Final Gap dist. (ft)	172.00	145.00
IDLE TIME	00:21.8	00:26.2
ROLLOUT TIME	00:04.2	00:09.3
RUN TIME 1	00:15.1	00:18.6
RUN PAUSED	00:17.1	00:10.8
RUN TIME 2	01:25.5	01:08.7

Table 17 - AIPV Maximum Speed Values – Speed Test

Figure 57 plots the speed vs the gap distance between the LV and the AIPV, with the speed change on the primary Y-axis as a function of time on the x-axis. A secondary y-axis plots the gap of the AIPV in relationship to LV. The plot for Run 2 is in the APPENDIX.

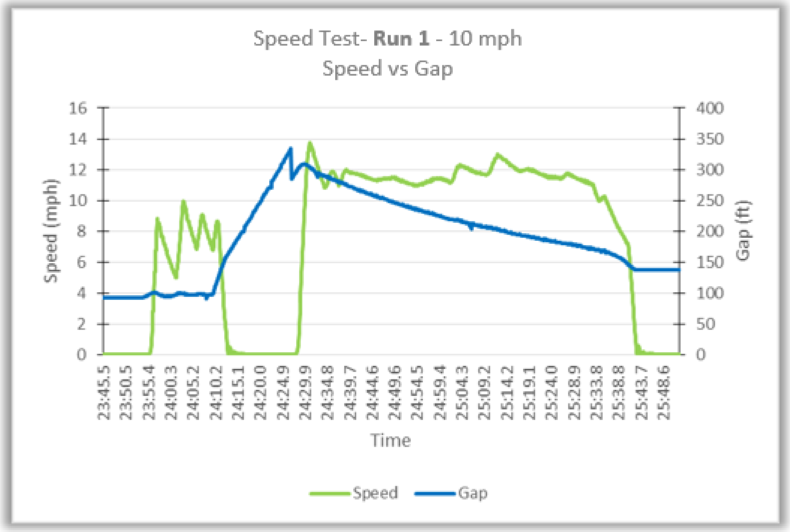


Figure 57 – Speed vs Gap – Speed Test

Video file: https://youtu.be/hCtExs8Hxds

Additional information: The gap data was analyzed from the logs. The pause command can be identified in Figure 57 from the 24:10.2 second mark to the 24:29.9 mark. The gap extended from 100 feet to more than 300 feet during the period. Once the pause command was released, the AIPV started to accelerate and began the catch-up process. The system developer limits the AIPV maximum speed to 20 mph for safety reasons. The final gap distance between the LV and the AIPV was 172 feet during run 1 and 145 feet during run 2. The ATMA system needed additional roadway length to be able to reach the command gap of 100 feet, as discussed in *Section 5.2.5*. Figure 58 compares the speed of the LV and the AIPV during the test. The speed of the AIPV was higher than the LV after the pause command release, allowing for the gap to be reduced. The plot for Run 2 is in the APPENDIX.

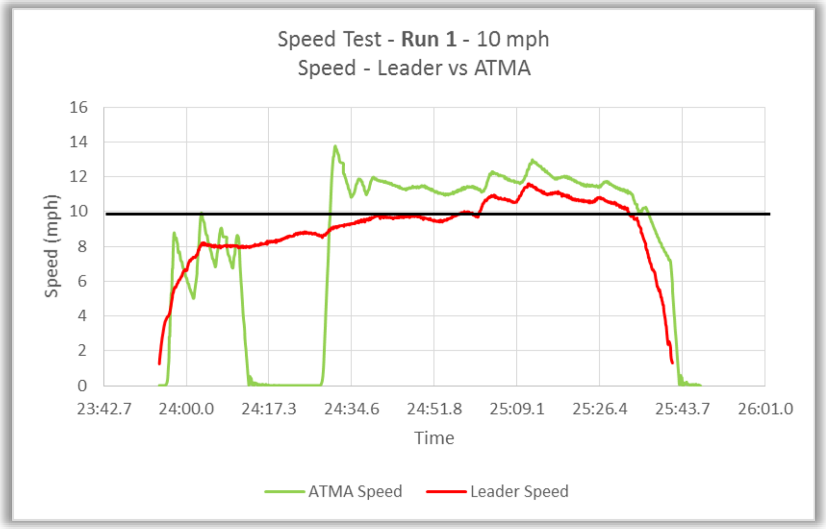


Figure 58 – Speed Profiles – Speed Test

6.19 – TEST CASE SCENARIO 19 – Braking

Category: Miscellaneous

Location: I-840.

Objective: Observe the response of the AIPV while the LV undergoes hard braking.

Test procedure: The command gap was set to 100 feet on the GUI. The LV and the AIPV were activated. The LV operator was asked to drive in a straight line at a target speed of 10 mph. Once the LV has reached a pre-determined location in the test track, the driver will engage the brake instantly. Data was collected for two runs. Figure 59 presents the plotted path of the test, with the orange line representing the LV and the blue line representing the AIPV.

Figure 59 – Test Path - Braking

Expected result: The AIPV should stop immediately within a safe distance from the LV.

Files used for analysis: 2019-11-05_20-43-40_log and 2019-11-05_20-47-10_log

Results: The gap data was analyzed from the logs. Table 17 presents the final actual gap values for each run. Table 18 also presents information about the elapsed time (from the moment data started to be recorded) for IDLE mode (Safety operator on the LV has control of the ATMA system), ROLLOUT (Autonomous mode is engaged) and RUN (Autonomous mode is operational). The AIPV stopped within a safe distance from the LV on both runs.

	Speed - 10mph	
	RUN 1	RUN 2
Gap set (ft):	100	100
Final Actual Gap (ft)	79	73
IDLE TIME	00:22.3	00:15.9
ROLLOUT TIME	00:08.7	00:03.3
RUN TIME	00:39.6	00:29.7

Table 18 - Final Actual Gap – Braking Test

Video file: https://youtu.be/gVsAQeHDkQ8

Additional information: N/A

6.20 – TEST CASE SCENARIO 20 – Bump

Category: Miscellaneous

Location: TDSTC/TIM.

Objective: Collect data to determine if the AIPV maintains the lateral accuracy of ± 6 inches from the LV path, as specified in *Section 5.1.3,* as it rides over an object on the roadway.

Test procedure: The command gap was set to 100 feet on the GUI. The LV and the AIPV were activated. The LV operator was asked to drive at a target speed of 5 mph. Once the LV has reached a pre-determined location in the test track, a UT team member pulled a 4x4 log into the AIPV path. The test was conducted on a straighter section of the test track and repeated on a curve. Data was collected for four runs. Figure 60 presents the plotted path of the test, with the orange line representing the LV and the blue line representing the AIPV.

Figure 60 – Test Paths – Bump Test

Expected result: The AIPV maintains the lateral accuracy of ± 6 inches from the LV path.

Files used for analysis: 2019-11-06_21-52-17_log, 2019-11-06_21-56-49_log, 2019-11-08_15-26-17_log and 2019-11-08_15-31-37_log

Results: The cross track error (CTE) data was analyzed from the logs. Table 19 presents the range of values for each run. CTEs that fell outside the expected result value were coded red. Table 18 also presents information about the elapsed time (from the moment data started to be recorded) for IDLE mode (Safety operator on the LV has control of the ATMA system), ROLLOUT (Autonomous mode is engaged) and RUN (Autonomous mode is operational). The AIPV was not able to maintain the expected lateral accuracy on all runs but did not present any adverse behavior as it moved over the bump obstacle.

	Speed - 5mph							
	RUN 1		RUN 2		RUN 3		RUN 4	
	Straight Line				Curve			
Gap set (ft):	100		100		100		100	
Cross Track Error (in)	-4.84	6.28	-7.72	2.68	-1.41	8.50	-1.29	11.73
IDLE TIME	00:10.8		00:10.0		00:10.6		00:17.4	
ROLLOUT TIME	00:05.5		00:00.3		00:09.9		00:03.4	
RUN TIME	00:49.2		01:28.8		00:48.6		00:52.7	

Table 19 - Cross Track Error (CTE) Range – Bump Test

Figure 61 plots the speed vs the cross track error, having the speed change on the primary Y-axis as a function of time on the x-axis. A secondary y-axis plots the CTE of the AIPV. The plot for the additional runs are in the APPENDIX.

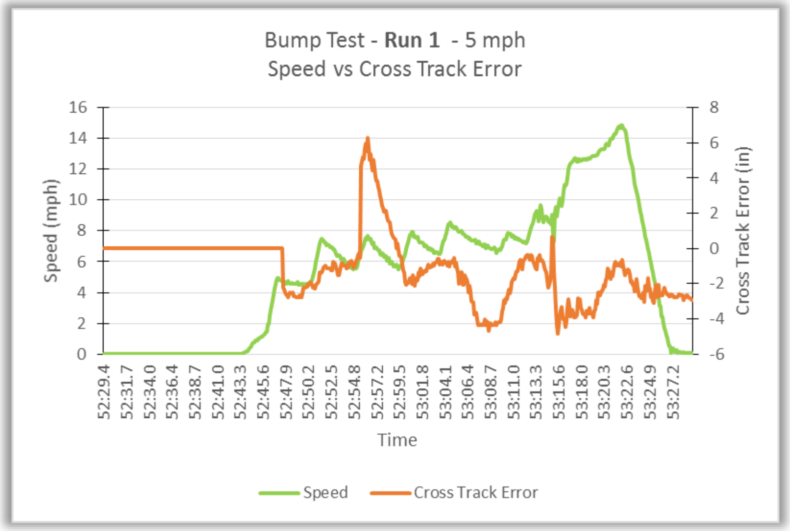


Figure 61 – Speed vs Cross Track Error – Bump Test

Video file: https://youtu.be/3hS7gFIxFIU and https://youtu.be/JZ7-AkswkZI

Additional information: The AIPV 5 mph speed set for the test procedure was exceeded in all runs but did not affect the testing. Notice it is dependent on the ability of the LV driver to maintain such speed.

6.21 – TEST CASE SCENARIO 21 – Leader Reverse

Category: Miscellaneous

Location: TDSTC/TIM.

Objective: Observe the response of the ATMA system while the LV reversed toward the AIPV.

Test procedure: The command gap was set to 100 feet on the GUI. The LV and the AIPV were activated. The LV operator was asked to drive in a straight line at a target speed of 10 mph and stop at a pre-determined location in the test track. Once the LV and the AIPV stopped, the LV driver would start reversing towards the AIPV. Data was collected for two runs. Figure 62 presents the plotted path of the test, with the orange line representing the LV and the blue line representing the AIPV.

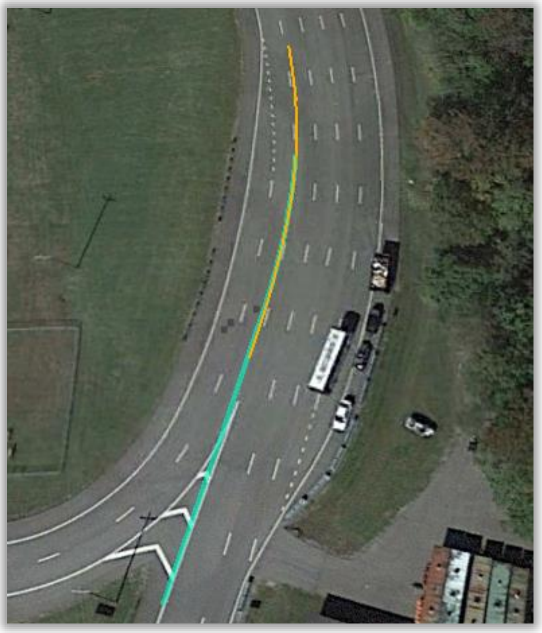


Figure 62 – Test Path – Leader Reverse

Expected result: The AIPV should start an A-Stop.

Files used for analysis: 2019-11-07_18-54-05_log and 2019-11-07_19-14-26_log

Results: On both runs, the AIPV started to roll forward as the LV was reversing towards it. The AIPV did not start an A-Stop and the test had to be aborted to avoid a collision between the vehicles.

Video file: https://youtu.be/gpUhfHfTmxc

Additional information: Testing the LV reversing towards the AIPV is not a typical scenario, but it demonstrated a fault on the ATMA system algorithm. Close inspection of the video also demonstrated that the actual gap on the GUI did not provide accurate information on the distance between vehicles.

6.22 – TEST CASE SCENARIO 22 – Turn Under Overpass

Category: Miscellaneous

Location: I-840.

Objective: Observe the response of the ATMA system while navigating under and overpass.

Test procedure: The command gap was set to 100 feet on the GUI. The LV and the AIPV were activated. The LV operator was asked to drive the semi-loop that connects the end of the testing track, under and overpass, at a target speed of 5 mph. Data was collected for one run. Figure 63 presents the plotted path of the test, with the orange line representing the LV and the blue line representing the AIPV.

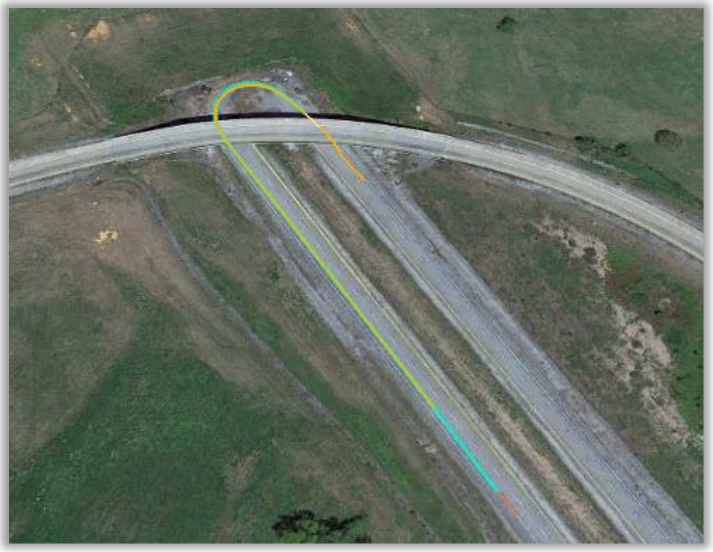


Figure 63 – Test Path – Turn under Overpass

Expected result: The ATMA system should be able to navigate under the overpass.

File used for analysis: 2019-11-05_22-07-04_log

Results: The ATMA system was able to navigate the turn, using the INS (as explained in *Section 5.2.4*) but an e-crumb error (where the AIPV was not able to locate the LV next data point position) caused an A-Stop towards the end of the testing.

Video file: https://youtu.be/toB7rJWndiE

Additional information: N/A

6.23 – TEST CASE SCENARIO 23 – Tight Turn Radius

Category: Miscellaneous

Location: TDSTC/TIM.

Objective: Test the ability of the ATMA system to navigate a tight turn.

Test procedure: The command gap was set to 100 feet on the GUI. The LV and the AIPV were activated. The LV operator was asked to execute a U-turn at a target speed of 5 mph. Data was collected for two runs. Figure 64 presents the plotted path of the test, with the orange line representing the LV and the blue line representing the AIPV.

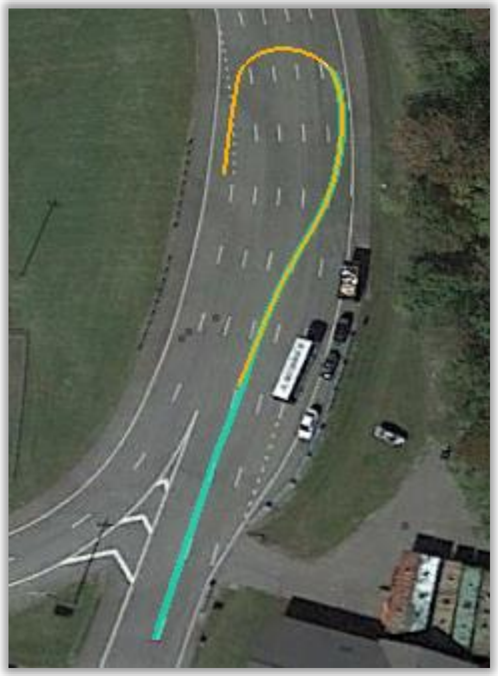


Figure 64 – Test Path – Tight Turn Radius

Expected result: The ATMA system should be able to navigate the tight turn radius.

Files used for analysis: 2019-11-08_19-29-16_log and 2019-11-08_19-21-35_log

Results: The ATMA system was not able to navigate the U-turn. An e-crumb error (where the AIPV was not able to locate the LV next data point position) caused an A-Stop on both testing runs.

Video file: https://youtu.be/MaILAYHR7PQ

Additional information: During the second run (see video file) the command gap distance was set to the minimum selectable on the GUI, 25 feet, as an attempt for the ATMA system to successfully navigate the U-turn. An e-crumb error prevented the movement to be completed.

6.24 – TEST CASE SCENARIO 24 – Loss of Communication

Category: Communication

Location: TDSTC/TIM.

Objective: Test the ability of the ATMA system to navigate with a single V2V communication link.

Test procedure: The command gap was set to 100 feet on the GUI. The LV and the AIPV were activated. The LV operator was asked to drive at a target speed of 10 mph on the test track while a

UT team member disconnected one of the V2V communication links to the AIPV. Data was collected for one run. Figure 65 presents the plotted path of the test, with the orange line representing the LV and the blue line representing the AIPV.

Figure 65 – Test Path – Loss of Communication

Expected result: The ATMA system should continue to navigate the testing track seamlessly without an A-Stop or E-Stop.

File used for analysis: 2019-11-08_19-57-58_log

Results: The ATMA system continued to navigate the testing track without any issues.

Video file: https://youtu.be/umaGSNDxKCQ

Additional information: The disconnected V2V link to the AIPV is part of the redundant system of communication that uses Primary and Backup transponders in the LV and AIPV, as explained in *Section 5.1.2*.

Chapter 7: Discussion and Conclusion

Work Zone safety is a major concern to federal, state and local agencies. Periodic maintenance of roadways requires workers to be exposed to hazardous conditions, often working next to traffic traveling at high rates of speed. The Tennessee Department of Transportation (TDOT), in its continuous efforts to target the reduction of work zone fatalities and to provide safe working conditions to its employees, decided to explore the applicability of an Autonomous Truck Mounted Attenuator (ATMA) system to improve work zone safety. Testing was conducted during a pilot demonstration in coordination with TDOT, where a set of case scenarios analyzed the various operational components of the system.

A Literature Review was conducted, but due to the novel concept of the ATMA system the information available was limited to demonstrations of the system. No reports were available for public sharing during the time of this research project. The supplier of the tested ATMA system provided an internal validation report done for the Colorado Department of Transportation in 2017, which pointed basically to initial insights of the system, mentioning that the cross track error was most of the time within an acceptable range and that higher speeds led to larger range gap values. A few state DOT's provided feedback to a request of information, pointing primarily to the need for a more responsive gap control on the ATMA system. Researchers from other State DOT's also agreed that the ATMA system is most useful in moving mainline highway maintenance operations, like sweeping and lane striping.

The ATMA system pilot demonstration in Tennessee concluded primarily that the tested Autonomous Truck Mounted Attenuator system is better suited for work zone operations that require continuous movement for longer periods of time, due to its speed/gap algorithm configuration. Retracing or installation of pavement markings and roadway sweeping are examples of such operations. In addition, the ATMA system was not able to consistently maintain the gap distance required between the leader vehicle and the follower vehicle during the stop-and-go operations testing of typical applications, like trash pick-up on the shoulder and pothole patching. Therefore, the current speed/gap algorithm warrants further development and testing to accommodate stop-and-go applications. Furthermore, the system demonstrated the capability to operate in GPS denied locations, but only for a short period of time and inconsistently. The system developer announced equipment improvements since the pilot demonstration in Tennessee, but further testing is required for operations at locations with overpasses, heavy foliage, tunnels and any other operations that undergo long periods of sustained loss of GPS signal. The testing also pointed to a flaw of the ATMA system regarding its inability to consistently shadow/protect the service vehicle at all times, when the leader/service vehicle encroaches in the lane from a shoulder, for example. The system tested lacked the capability of offsetting the follower vehicle from the leader vehicle to accommodate for such scenario. The research team learned that an offset feature has since been developed for the system. During the testing procedures in Tennessee, the ATMA system was not able to consistently maintain the specified ± 6 inches of lateral accuracy between the leader and the follower vehicle, most notably when testing was not on a straight path. There is a potential hazardous risk to this situation, when the follower vehicle deviates from the leader's path during operations near a ditch or during tight turning maneuvers. The crucial role of the leader vehicle driver became very apparent during the testing of the system. Extensive training and practice is imperative to assure the safe operation of the system. The leader vehicle driver requires understanding of how the follower vehicle reacts to his/her actions (wide turns and speed judgments near intersections, for example), to avoid potentially hazardous scenarios. With that said, most of the aforementioned issues can potentially be minimized by fine tuning the ATMA system algorithm, by implementation of additional functionalities and further testing.

Based on the analysis of current TDOT practice with TMA's, the research team recommends TDOT to explore the use of rangefinders with laser technology, to allow a TMA operator to better estimate and maintain the follow and roll ahead distance between a TMA and a service vehicle. Finally, the ATMA system is an innovative and promising asset to improve work zone safety for all users. As previously mentioned, it is currently safely suitable for a few typical TDOT applications, but future updates to the system has the potential to enhance applicability to a wider set of practices.

References

(1) Colorado Department of Transportation. (2017). *Autonomous TMA Truck (ATMA) Project Background*. Retrieved from https://www.workzonesafety.org/files/documents/SWZ/ATMA_project_background-Kyle.pdf

(2) Colorado Department of Transportation Drive Safety with World's First Self-Driving Work Zone Vehicle. Retrieved from https://www.codot.gov/news/2017-news/august/cdot-and-partners-drive-safety-with-world2019s-first-self-driving-work-zone-vehicle

(3) Kratos – From Strength to Success. (2017). *Kratos Deploys the World's First Autonomous Vehicle Utilized in Live Operation on Public Roadways*. Retrieved from http://ir.kratosdefense.com/releasedetail.cfm?releaseid=1040829

(4) Royal Truck and Equipment Inc (2017). *Autonomous TMA Truck* Retrieved from https://royaltruckandequipment.com/autonomous/

(5) TDOT Work Zone Safety and Mobility Manual. (2019 update). Retrieved from https://www.tn.gov/tdot/traffic-operations-division/traffic-operations-division-resources/work-zone-safety-and-mobility-manual.html

(6) TDOT Work Zone Field Manual for Maintenance Operations (2019 edition) Retrieved from https://www.tn.gov/content/dam/tn/tdot/traffic-engineering/Work%20Zone%20Field%20Manual%20-%20Final%204-29-2019.pdf

(7) Validation Data Report for the Colorado Department of Transportation – Autonomous Truck Mounted Attenuator Validation Event, July 2017, Micro Systems Inc.

(8) Validation Data Report for the Colorado Department of Transportation – Autonomous Truck Mounted Attenuator Second Validation Event, September 2017, Micro Systems Inc.

(9) Virginia Transportation Research Council - *Investigation of Truck Mounted Attenuator (TMA) Crashes in Work Zones in Virginia*. Benjamin H. Cottrell Jr.- October 2017.

Appendix

Restart Procedure after E-Stop (Section 5.2.3)


AIPV User Interface
EStop Recovery
AIPV
Once GPS LED is solid, select next
(OR)


AIPV User Interface
EStop Recovery
AIPV
Once Ready LED is blinking, select next
(OR)


AIPV User Interface
EStop Recovery
AIPV
Once ESTOP LED is green, switch Bypass to OFF


AIPV User Interface
EStop Recovery
AIPV
Set OCU to GO
(OR)

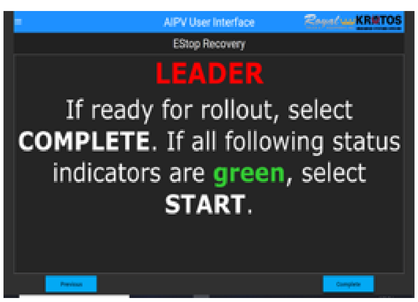

AIPV User Interface
EStop Recovery
AIPV
Release parking brake
(OR)
PUSH ON OFF


AIPV User Interface
EStop Recovery
AIPV
Shift into drive (if applicable)
PARK R N D L2 L1


AIPV User Interface
EStop Recovery
AIPV
Verify system controls brake and vehicle maintains position, then select next


AIPV User Interface
EStop Recovery
AIPV
Leave AIPV and enter LEADER as system monitor
AIPV
LEADER


AIPV User Interface
EStop Recovery
LEADER
Set OCU to GO
(OR)

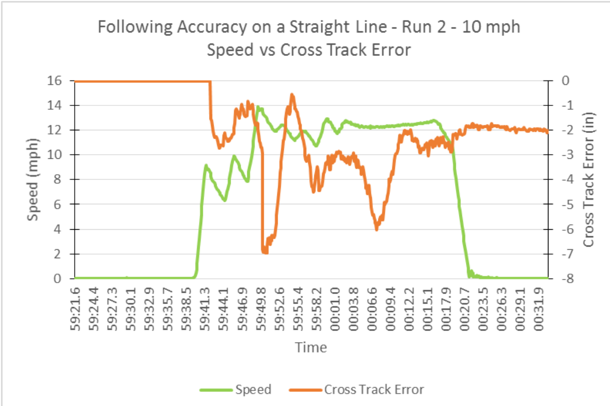

AIPV User Interface
EStop Recovery
LEADER
If ready for rollout, select COMPLETE. If all following status indicators are green, select START.

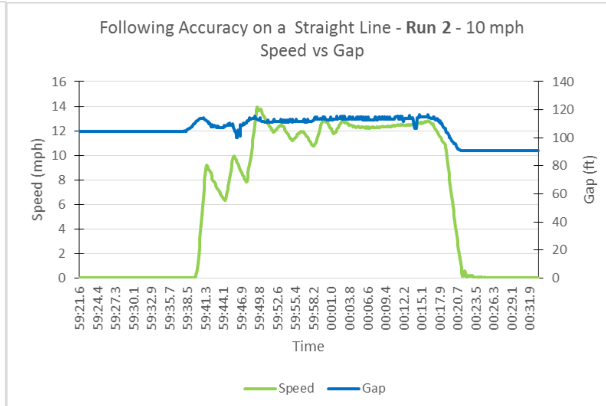
Summary Table of CTE Analysis (Chapter 6 Introduction)

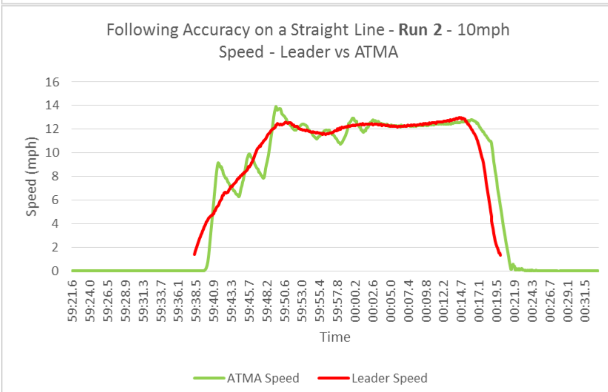
Autonomous Truck Mounted Attenuator (ATMA) Testing Results

		Cross Track Error -CTE - (in)																			
		5 MPH								10 MPH								15 MPH			
Test #	Description	RUN 1		RUN 2		RUN 3		RUN 4		RUN 1		RUN 2		RUN 3		RUN 4		RUN 1		RUN 2	
1	Automatic Stop (A-Stop) - Leader Vehicle Internal Button																				
2	Emergency Stop (E-Stop) - Leader Vehicle Internal Button																				
3	Emergency Stop (E-Stop) - ATMA External Button																				
4	Emergency Stop (E-Stop) - ATMA Internal Button																				
5	Following Accuracy on Straight Line									-3.70	1.38	-6.96	0.00								
6	Following Accuracy on Slalom Course	-8.98	9.80																		
7	Following Accuracy on Lane Change									-1.93	8.62	-5.67	13.54					0.00	14.37	-8.93	3.54
8	Adjusting Following Distance									-4.13	14.96	-12.24	22.08	-31.33	1.77	-31.85	3.58				
9	Trash Pick-up									-3.78	1.29	-5.31	0.00								
10	Herbicide Application									-6.45	0.63	-7.36	4.29								
11	Pothole Patching									-4.05	0.12	-12.16	0.63								
12	Obstacle Detection - FRONT									-2.63	5.98	-2.52	6.18								
13	Vehicle Intrusion									-2.40	5.91	0.00	5.94								
14	Sensitivity to Passing Vehicles									-3.70	1.38	-6.70	0.00	-12.20	0.00						
15	Object Recognition									0.00	17.24	0.00	28.22	0.00	22.95	0.00	20.78				
16	Headlights									-2.95	13.18	-3.74	15.07								
17	Cone Detection									-3.66	28.85	-4.88	10.70								
18	Speed Test																				
19	Braking - Leader Vehicle									-5.24	0.00	-4.72	1.30								
20	Bump Test	-4.84	6.28	-7.72	2.68	-1.41	8.50	-1.29	11.73												
21	Leader Reverse									-0.20	11.69	-1.77	8.62								
22	Turning at I-840	-8.58	26.61																		
23	Tight Turn Radius																				
24	Loss of Communication																				

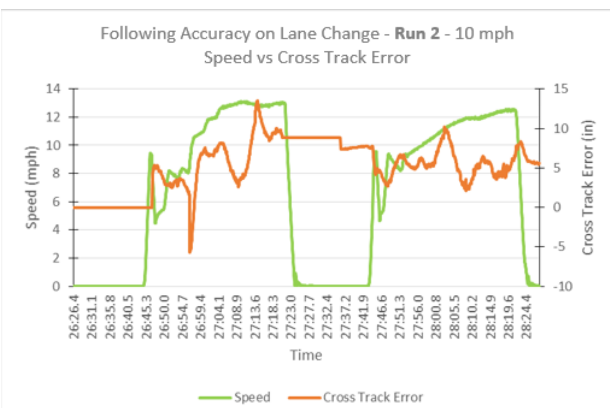
6.5 – TEST CASE SCENARIO 5 - Following Accuracy on Straight Line

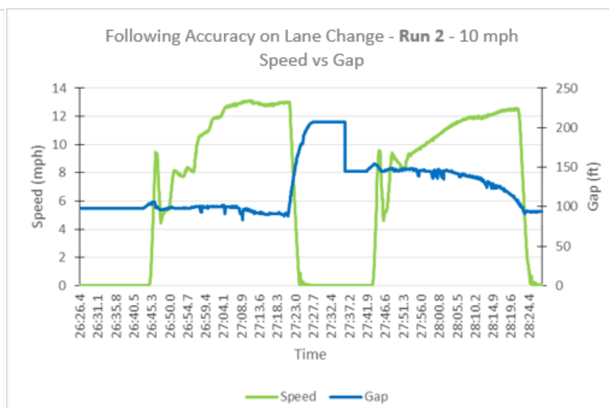


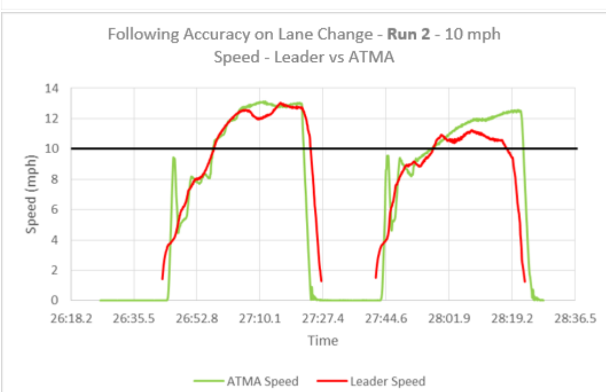


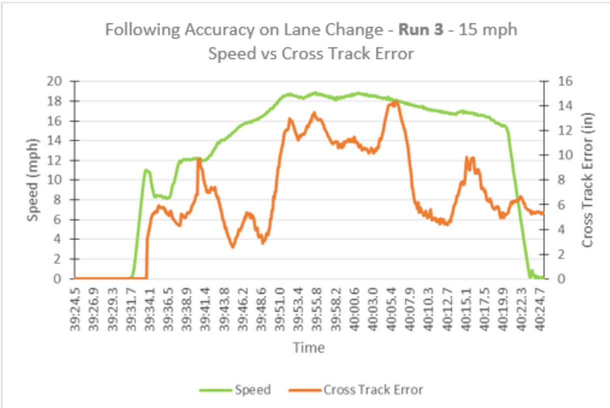


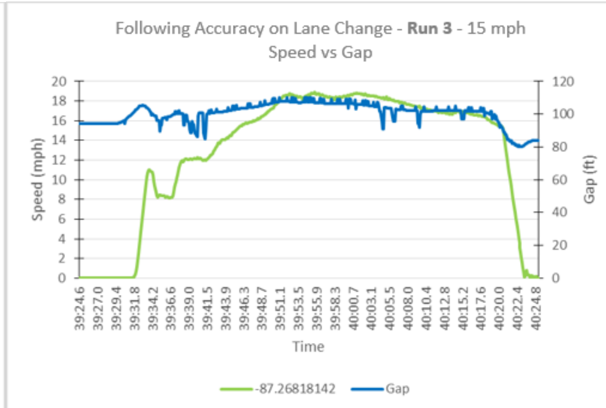
6.7 – TEST CASE SCENARIO 7 - Following Accuracy on Lane Change

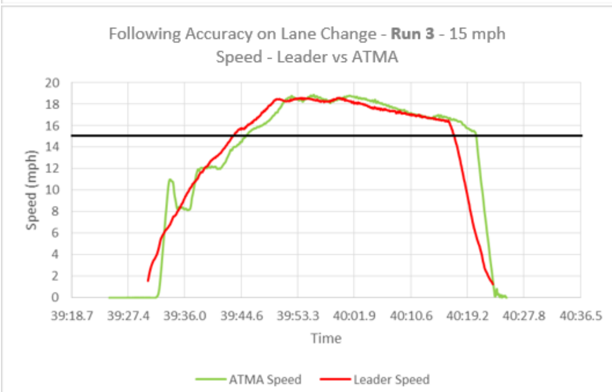


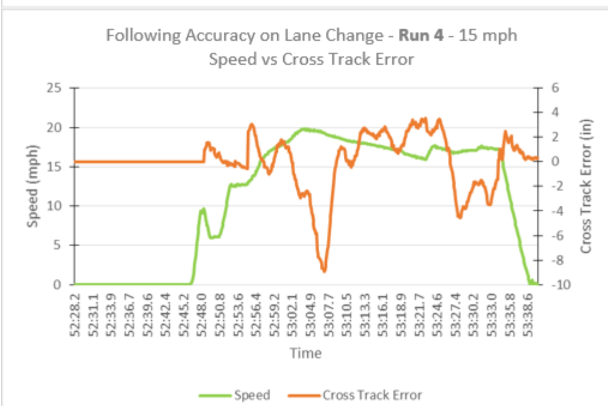


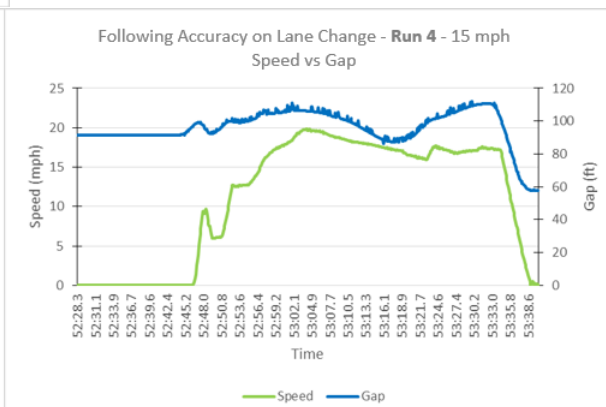


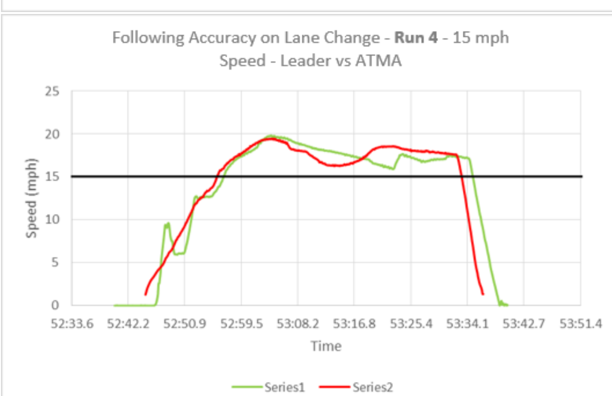

Following Accuracy on Lane Change - **Run 3** - 15 mph
Speed vs Cross Track Error
Speed (mph)
Cross Track Error (in)
Time
Speed
Cross Track Error


Following Accuracy on Lane Change - **Run 3** - 15 mph
Speed vs Gap
Speed (mph)
Gap (ft)
Time
-87.26818142
Gap

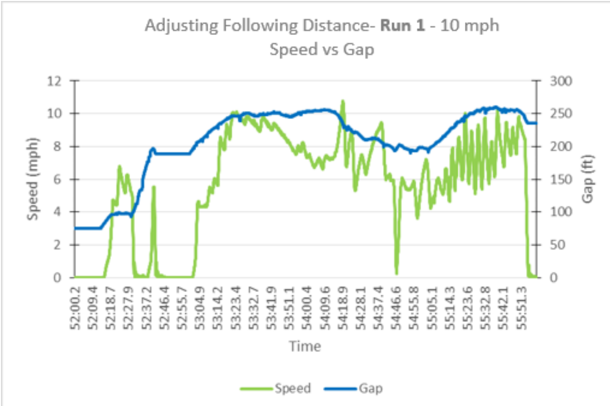

Following Accuracy on Lane Change - **Run 3** - 15 mph
Speed - Leader vs ATMA
Speed (mph)
Time
ATMA Speed
Leader Speed

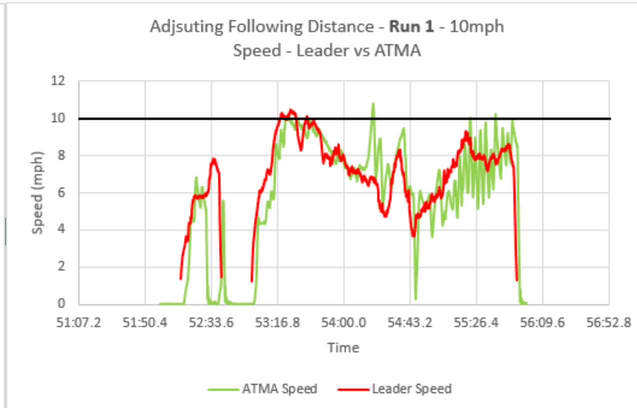

Following Accuracy on Lane Change - **Run 4** - 15 mph
Speed vs Cross Track Error
Speed (mph)
Cross Track Error (in)
Time
Speed
Cross Track Error

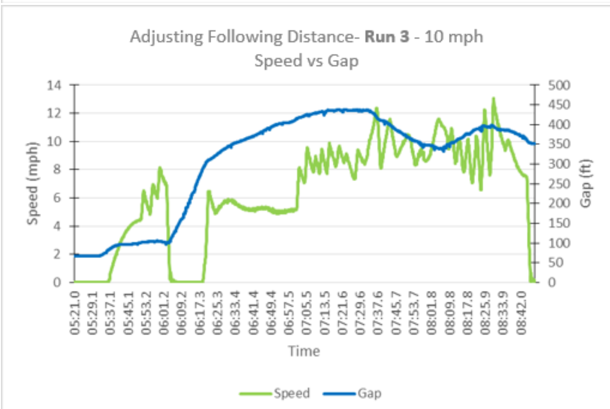

Following Accuracy on Lane Change - **Run 4** - 15 mph
Speed vs Gap
Speed (mph)
Gap (ft)
Time
Speed
Gap


Following Accuracy on Lane Change - **Run 4** - 15 mph
Speed - Leader vs ATMA
Speed (mph)
Time
Series1
Series2

6.8 – TEST CASE SCENARIO 8 – Adjusting Following Distance

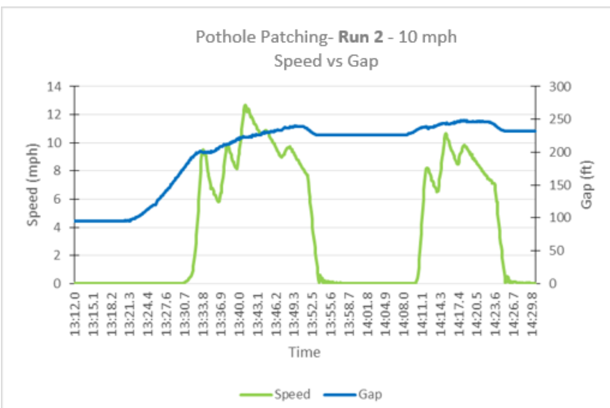


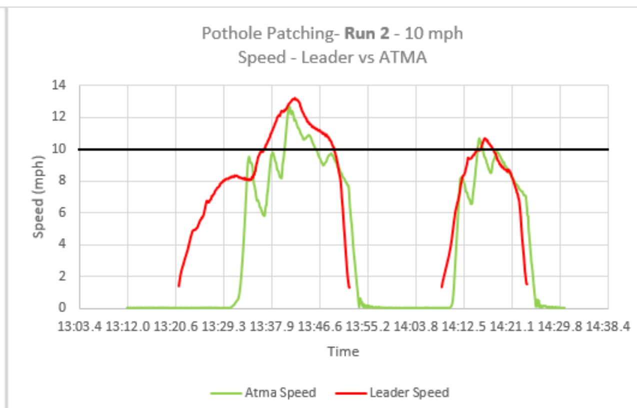




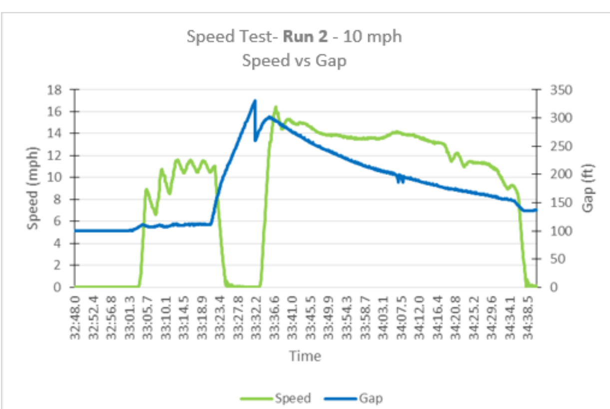
6.9 – TEST CASE SCENARIO 9 - Trash Pick-up

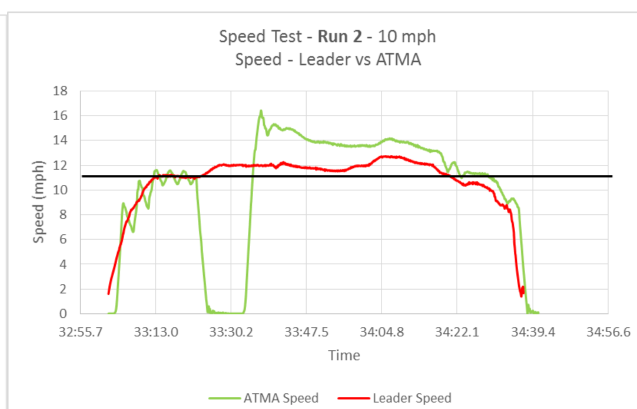
6.11 – TEST CASE SCENARIO 11 – Pothole Patching





6.18 – TEST CASE SCENARIO 18 – Speed





6.20 – TEST CASE SCENARIO 20 – Bump