Florida Department of Transportation Contract BDV31-977-133

Florida ATMA Pilot Demonstration and Evaluation

Final Report

Prepared by:
University of Florida

Principal Investigator: Dr. Nithin Agarwal
Director, UFTI-T2 Center
University of Florida Transportation Institute
2100 NE Waldo Rd
Gainesville, FL 32609
Phone: (352) 273-1674
Email: nithin.agarwal@ufl.edu

FDOT Project Manager: Tim Ruelke
State Materials Office
Florida Department of Transportation
5007 NE 39th Avenue
Gainesville, FL 32609
Phone: (352) 955-6600
Email: timothy.ruelke@dot.state.fl.us

March 2021

Disclaimer

Metric Conversion Table

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
LENGTH				
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	Km
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
AREA				
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
VOLUME				
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
NOTE: Volumes greater than 1000 L shall be shown in m^3.				

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Florida ATMA Pilot Demonstration and Evaluation		5. Report Date March 2021
		6. Performing Organization Code
7. Author(s) Nithin Agarwal, Roozbeh Rahmani, and Tilak Nagaraju		8. Performing Organization Report No.
9. Performing Organization Name and Address University of Florida Transportation Institute 2100 NE Waldo Rd Gainesville, FL 32609		10. Work Unit No. (TRAIS)
		11. Contract or Grant No. BDV31-977-133
12. Sponsoring Agency Name and Address Florida Department of Transportation 605 Suwannee Street, MS 26 Tallahassee, FL 32399		13. Type of Report and Period Covered Final Report Jan. 2020–March 2021
		14. Sponsoring Agency Code

15. Supplementary Notes
Mr. Tim Ruelke from the Florida Department of Transportation served as project manager for this project.

16. Abstract
Autonomous truck-mounted attenuators (ATMAs) promise transformative changes in mobile work zone operations by eliminating the need for a worker to operate an impact protection vehicle. The goal of this project was to pilot a demonstration of the ATMA technology, conduct an evaluation and assessment of the operational and safety functions of ATMA vehicle in a closed loop course, and test the feasibility of ATMA in active mobile work zones. For the active mobile work zone, the ATMA was used for a pavement testing operation using a falling weight deflectometer (FWD) on different facility types. This report provides a review of the ATMA safety and operational functions, the user training and feedback, the testing scheme for closed loop tests, and observations of test runs on active mobile work zones. This report also provides a benefit-cost analysis for procurement of ATMA technology.

17. Key Word Autonomous vehicles; Evaluation and assessment; Feasibility analysis; Pilot studies; Truck-mounted attenuators; Work zone safety; Work zone traffic control; mobile work zone; ATMA; AIPV; FWD	18. Distribution Statement No restrictions

19. Security Classify. (of this report) Unclassified	20. Security Classify. (of this page) Unclassified	21. No. of Pages 200	22. Price

Executive Summary

Work zone crash data from the National Institute for Occupational Safety and Health (NIOSH) indicate that for over 15 years (2003–2017) Florida has ranked second highest in fatal work zone crashes in the nation [1]. Data reveal that workers were present in the work zone in 35 percent of the fatal crashes and in an additional 44 percent of crashes resulting in serious injuries. The Florida Department of Transportation (FDOT) aims to achieve zero fatalities by leveraging the capabilities of the latest technology available to improve the safety of workers and the traveling public. This project leased an automated truck-mounted attenuator (ATMA), designed closed loop and open road tests, collected and analyzed data, and shared the findings and lessons learned. The ATMA was deployed to shield the falling weight deflectometer (FWD) equipment which tests the strength of the pavement. From the data and field observations, it was concluded that ATMA has the potential to improve work zone safety; however, several measures related to system enhancements, user training, and extended testing are needed in order to achieve market penetration and address stakeholder concerns.

E1. Synthesis of ATMA-Related Information

It is recognized that the ATMA technology is relatively new, with the first demonstration and deployment in the U.S. in 2017. There are ongoing efforts in various states related to testing and deployment of ATMA, including Missouri, Virginia, Tennessee, Colorado, California, North Dakota, and Minnesota. In addition, ATMAs have been explored and deployed in limited capacity in other countries, including England, Russia, Japan, Germany, and the Netherlands. The following table provides an overview of the ATMA deployment status within U.S.

Table E1. Summary of ATMA synthesis in the U.S.

State	Procure-ment	Application	Environment	Other Information
California	Purchased (ongoing)	Shadow vehicle for highway maintenance operations	Closed track + public roadways	Currently being evaluated by DMV to approve for open road testing
Colorado	Purchased	Painting; also considered other operations, including cone placement and patching work	Closed track + public roadways	Approved for statewide deployment as standard equipment and operated over 200 miles of open road. First system is being operated in the Denver area, and the second system is being procured for the Durango area.
Florida	Leased	Shadow vehicle for GPS seed file collection to support ITS operations in Milton, FL	Public roadway	Operated 28 miles across Santa Rosa County on US-90

Table E1. Summary of ATMA synthesis in the U.S. (continued)

State	Procure-ment	Application	Environment	Other Information
Minnesota	Purchased (planned)	Shadow vehicle for highway maintenance operations	Closed track + public roadways	Deployment delayed to summer 2021 due to COVID-19
Missouri	Purchased (ongoing)	Shadow vehicle for highway maintenance operations	Closed loop + public roadways	Completed 32-hr continuous operation on closed road; next phase of testing is 250 continuous hours on open road

E2. ATMA System Overview

Leader Kit Instrumentation on FDOT Vehicle: Royal Truck, in partnership with Kratos Defense, was contracted for the leasing of an ATMA system. An FDOT F350 truck was delivered to the Kratos facility in Fort Walton Beach where the leader kit was installed, calibrated, and tested. The kit included an operator control unit and a PC-based system for system activation, navigation, and emergency stop functions. External components of the kit included a V2V communications system, GPS receivers, a rear-facing video camera, and other components. The system is powered through a connection to the truck's battery.

ATMA Technical Overview: This project facilitated operator training in two parts. First was an online introduction to the ATMA system, its components, and their functions and use. Eighteen attendees completed the training. The training materials may be found in Appendix A. A post-training survey was administered to assess the quality of the training content, which was overall positive. The second part of the training included hands-on training which was administered in-person during the demonstration day.

ATMA Equipment Overview*:* The ATMA system comprises a leader truck and a follower truck. The follower truck can operate as a connected vehicle to precisely follow the leader truck. For this project, FDOT loaned a truck which was delivered to Kratos for installation of the necessary equipment to act as a leader truck. A fully equipped autonomous follower truck-mounted attenuator (ATMA) was leased from Kratos. The follower truck is guided by digital "crumbs," a series of GPS locations provided by the leader truck. Cameras on the follower vehicle provide visual feedback to the leader driver, who can also monitor aspects of the follower's performance on the operator control unit. However, the follower does not blindly follow; it is equipped with a variety of sensors to detect vehicles or other possible interferences. The sensors can cause the follower to stop in order to prevent a collision if, for example, a vehicle should enter the space between the leader and follower. The external control is an emergency stop (E-stop) activator, and the internal controls include steering actuator ring, steering tabs, and steering fingers; brake and accelerator cable system; and operator control unit.

Falling Weight Deflectometer and Maintenance of Traffic Requirements: The falling weight deflectometer (FWD) testing is a mobile stop-and-go operation that requires intermittent stops at predetermined intervals to perform pavement testing. FDOT adopts MUTCD indexes 607 and 619 for two-lane and multi-lane operation. The ATMA was used to shield the FWD operation in the field tests.

E3. Site Selection and Testing Plan

The scope of this project included two main testing scenarios. The first scenario was in a closed loop setting where the operational and safety features could be tested along with trial runs. The second scenario was the open road test where we deployed the ATMA for an active work zone application. UF coordinated with FDOT State Materials Office to select the sites for the live testing on public roadways. There were several factors that were considered, including facility type (vehicle mix, speed limit, number of lane, land use), maintenance of traffic (MOT) crew availability, typical operation of FWD, and safety considerations.

Closed Loop (CL) Sites: There were two locations for closed loop tests: the FDOT Maintenance Office in Gainesville, FL, and the Gainesville Regional Transit System (RTS) bus depot, also in Gainesville. Initially, the location selected for the closed loop testing had issues with the tree canopy that interfered with the GPS signal for the ATMA. After several unsuccessful attempts, the team then moved away from the tree canopy where the ATMA was successful in establishing the GPS network required to operate the autonomous mode; however, when the ATMA negotiated the north side of the section near the tree canopy, the ATMA lost signal, would throw an "e-crumb" error, and could not operate in autonomous mode. The closed loop testing was then moved east of the location, clear of any adjacent trees or other obstructions, and then the testing proceeded without any issues. The table below provides the summary of locations selected for the testing. The first location was the closed loop testing, and the remaining locations were on public roadways.

Table E2. Summary of sites selected for testing

Test Setup	ID	SR/Interstate	Roadway ID	Milepost	Annual Average Daily Traffic (AADT)
1	CL	FDOT D-2 Gainesville Maintenance and RTS Bus Depot			
2	FT-1	US-441	26010000	7.700 to 9.700	13,900
3	FT-2	I-75	26260000	10.500 to 12.500	73,203
4	FT-3	SR-222	26005000	6.500 to 8.000	22,914
5	FT-4	SR-26	26130000	6.400 to 8.000	10,788
6	FT-5	SW 2nd Ave	-	-	7,651
7	FT-6	SR-24 Waldo Rd	-	-	16,273

E4. Data Collection

With the demonstration and testing scheme designed for a two-week period, it was critical for the team to develop a data collection plan which included high resolution log file data from the ATMA recorder, which captures all the vehicular characteristics and attributes of the leader and follower vehicles. For validation, the ground truth data were collected using dash camera videos, and in specific cases, external cameras, drone, and manual inspections were adopted. Table E3 below provides a summary of the data collection methods and their purposes.

Table E3. Data collection methods

Equipment or method	Data or purpose
Dashcam	Time stamp, location of vehicle (latitude, longitude), velocity of the vehicle, video of front of vehicle
ATMA log file	Variety of leader and follower vehicles' attributes listed in the below section
Drone (for selected scenarios)	Traffic characteristics and driver behavior of other vehicles in the vicinity of the ATMA
Manual Inspection	Stopping distance, vehicle behavior (user experience for lead vehicle driver and as safety driver in ATMA), other vehicle behavior around ATMA, traffic characteristics

Data Repository: All of the data collected are stored and catalogued by test number and titles. The quality control process included reviewing the data and eliminating, truncating, or filtering to retain only the useful data. This dataset is stored in an external hard disk to be submitted as a media deliverable (USB) along with the final report. These data are also available to download from the UFTI-T2 website: https://techtransfer.ce.ufl.edu/florida-atma-demonstration-and-evalution/.

E5. Data Analysis

For closed loop testing, 26 test cases were designed in seven focus areas: safety functions, following accuracy, lateral accuracy, turning requirements, obstacle detection, operational tests, and communication tests. Field testing was conducted on five roads in the Gainesville, FL, area, ranging from urban streets to state roads to an Interstate highway. For each test, the objective and expectations were established. The result aimed at quantifying if the objective and expectations were met – this was achieved by analyzing the data logs from ATMA, visually certifying the results in the field, or post-processing the data logs and deriving the performance measures.

Table E4. List of Closed Loop Tests

Closed Loop Test Cases	
Focus area 1 – Safety	
TC-1	Automatic stop (A-stop) – Leader vehicle internal button (OCU)
TC-2	Emergency stop – ATMA internal button (OCU)
TC-3	Emergency stop – ATMA external button
TC-4	Emergency stop – Leader independent E-stop button (initiator)
Focus area 2 – Following Accuracy	
TC-5	Follow distance set by user interface (UI) panel
TC-6	Following accuracy on straight line (A&H)
TC-7	Following accuracy on slalom course (A&H)
Focus area 3 – Lateral Accuracy	
TC-8	Lane-changing accuracy (A&H)
TC-9	Lateral offset

Table E4. List of Closed Loop Tests

Focus area 4 – Turning	
TC-10	Minimum turn radius
TC-11	Obstacle detection – Front
TC-12	Simple Curve
TC-13	U-turns
Focus area 5 – Obstacle	
TC-14	Bump test
TC-15	Obstacle detection – Front
TC-16	Vehicle intrusion
TC-17	Object recognition
Focus area 6 – Operational tests	
TC-18	Speed test (A&H)
TC-19	Braking – Leader vehicle (A&H)
TC-20	ATMA human driver takeover (A&H)
TC-21	Leader reverse
TC-22	Acceleration/deceleration
Focus area 7 – Communication	
TC-23	Loss of sensor (radar, LIDAR)
TC-24	Loss of GPS
TC-25	Loss of communication (single V2V radio)
TC-26	Loss of communication (both V2V radios)

E6. Benefit-Cost Analysis Tool

This project also aimed to quantify the benefit and cost of the ATMA deployments and documented the process adopted.

Benefit Calculations: The first step in calculating the benefit is to find the crash types that can be mitigated by ATMA. In this study, these crashes were considered as TMA-related crashes in which a DOT worker was injured or killed. The user is required to input the average yearly number of work-zone-related crashes associated with their agency (AYWZ crashes).

- TMA crashes = AYWZ crashes × 1.134%
- TMA fatal injury crashes involved DOT workers = TMA crashes × 19.658%

The developed tool calculates the benefit and cost of adding one ATMA to an agency's set of equipment. To find the number of crashes that could be mitigated per one TMA, the TMA fatal injury crashes involving DOT workers should be divided into the number of TMA vehicles in the network.

$$Mitigatable\ crashes\ per\ TMA = \frac{TMA\ fatal\ injury\ crashes\ involving\ DOT\ workers}{N+1}$$

$$Mitigatable\ crashes\ per\ TMA = \frac{AYWZ\ Crashes * 1.134\% * 19.658\%}{N+1}$$

where N is the number of TMAs in the agency. The +1 in the formula is for adding one ATMA into the network.

The benefit is quantified by multiplying the unit crash cost by the crashes that will be mitigated. The average crash cost for fatal and injury crashes was extracted and/or calculated from the Florida Department of Transportation's (FDOT) *Design Manual*. This study assumed that ATMAs are going to be used on all facility types. The weighted average fatal and injury (WAFI) crash cost is as follows:

$$WAFI\ crash\ cost = \frac{\$10{,}670{,}000 \times 0.007 + \$872{,}612 \times 0.041 + \$174{,}018 \times 0.124 + \$106{,}215 \times 0.217}{0.007 + 0.041 + 0.124 + 0.217}$$

$$WAFI\ crash\ cost = \$398{,}699.2$$

The benefit of adding one ATMA to the set of agency's set of TMAs is equal to:

$$ATMA\ benefit\ per\ vehicle = Mitigatable\ crashes\ per\ TMA \times WAFI\ crash\ cost$$

$$ATMA\ benefit\ per\ vehicle = \frac{AYWZ\ Crashes * 1.134\% * 19.658\%}{N+1} \times \$398{,}699$$

The benefit is calculated based on yearly mitigated crashes. To convert the yearly benefits to present value, the annuity factor must be used. By using an annuity factor of 0.07, the present value of benefits is as follows:

$$Present\ value\ of\ benefits = ATMA\ benefit\ per\ vehicle \times \frac{1-(1+0.04)^{-(Life\ Cicle)}}{0.04}$$

Cost Calculations: The ATMA system includes a leader and a follower truck. The assumption of the study is that an agency has the leader and follower trucks and there is no need for investment. However, the user can fill in any other value. The other costs include technology procurement of $250,000, the deployment cost of $40,000, and the yearly cost of maintenance. These are numbers suggested by the vendor (Kratos) and can be updated by the user. The yearly cost should be converted to the present value using the annuity factor. The user chooses the life cycle of technology. The default value is 5 years.

Benefit-Cost Analysis Tool: The tool calculates the present value of benefit and cost, and then benefit-cost ratio as output. In an example with 50 TMAs (N=50), the average yearly number of Florida work zone crashes (AYWZ crash = 3,520), and using the default values, the benefit-cost ratio was calculated as 0.76. This tool is also available to download from the UFTI-T2 website: https://techtransfer.ce.ufl.edu/florida-atma-demonstration-and-evalution/.

E7. Data Analysis Results

Closed Loop Test Results: A total of 26 testing scenarios was completed, with multiple runs for each test. Among the 26 tests, the ATMA performed as expected in 23 scenarios. In three tests, there were exceptions, and in one scenario, there was a critical error as summarized below.

Table E5. Overview of closed loop test results

Test Cases		
ID	Scenario	Performed as Expected?
TC-1	Automatic stop (A-stop) – Leader vehicle internal button (OCU)	Yes
TC-2	Emergency stop – ATMA internal button (OCU)	Yes
TC-3	Emergency stop – ATMA External Button	Yes
TC-4	Emergency stop – Leader independent E-stop button (initiator)	Yes
TC-5	Follow distance set by user interface (UI) panel	Yes
TC-6	Following accuracy on straight line (A&H)	Yes
TC-7	Following accuracy on slalom course (A&H)	Yes
TC-8	Lane changing accuracy (A&H)	Yes
TC-9	Lateral offset	Yes
TC-10	Minimum turn radius	Exception
TC-11	Simple curve (A&H)	Yes with critical error
TC-12	Roundabouts	Exception
TC-13	U-turns	Yes
TC-14	Bump test	Yes
TC-15	Obstacle Detection – FRONT	No
TC-16	Vehicle intrusion	Yes
TC-17	Object recognition	Yes
TC-18	Speed test (A&H)	Yes
TC-19	Braking – leader vehicle (A&H)	Yes
TC-20	ATMA human driver takeover (A&H)	Yes
TC-21	Leader Reverse	Exception
TC-22	Acceleration/deceleration	Yes
TC-23	Loss of sensor (RADAR, LIDAR)	Yes
TC-24	Loss of GPS	Yes
TC-25	Loss of communication (single V2V radio)	Yes
TC-26	Loss of communication (both V2V radios)	Yes

Exceptions: Three scenarios had exceptions: TC-10, the minimum turn radius test; TC-12, the roundabout negotiating test; and TC-21, the leader reverse test. For TC-10, initially the minimum turn radius was set at 25 feet, which the ATMA could not negotiate. Further experiments revealed that the system was able to negotiate a turn with a radius of 45 ft. However, the ATMA was successful in three of the four runs at 45 feet.

For the roundabout scenario (TC-12), the test was unsuccessful with multiple attempts. It was noted that the system was designed to negotiate a roundabout with minimum internal diameter of 130 feet or a radius of 65 feet, which could not be simulated in the testing area. This scenario is reported as an exception because the scenario could not be validated. Supplemental efforts were made to negotiate roundabouts in an open road scenario; however, the roundabouts that the ATMA navigated had an inner diameter of less than 65 feet, and hence, it was unable to negotiate successfully. Based on several tests and attempts, it was concluded that system enhancements are needed in order for the ATMA to negotiate a roundabout successfully.

For TC-21, when the leader vehicle reversed its course towards the ATMA, the expectation was that ATMA would make an emergency stop. However, it did not, and to the contrary, the ATMA moved forward towards the leader vehicle. It is acknowledged that this scenario is atypical and that the system was not designed to negotiate such scenarios.

Critical Errors: There were two critical errors observed during the two-week testing period. The first observation was failure to make an emergency stop even after the sensor detected an obstacle in a closed loop test. The second observation was abrupt deviation of the ATMA from the intended path – both in closed loop testing and the open road field test.

Failure to Stop after Detecting an Obstacle: Test Case 15 tested the vehicle's ability to detect an obstacle in its path and make an emergency stop. After seven successful attempts, the ATMA failed to identify the object in Run 8. The safety operator in the ATMA (driver) applied brakes to avoid hitting the obstacle because there was not enough stopping distance available. The team then re-tested the last run by placing the same barrel in a horizontal position (3' width and 1'8" height). The safety officer in the ATMA had to manually apply brake to avoid hitting the barrel. The object was recognized by the ATMA lidar at a 3.6-ft distance. This test indicated that the sensor location and configuration is critical in recognizing obstacles with height of less than 1 ft. System enhancement or user guidance needs to be made in order for the sensor to detect and for the system to react appropriately.

Abrupt Deviation from Paths: Two events were recorded where the ATMA abruptly deviated from its path. The first occurrence was during the closed loop test. In this case, the ATMA traveled from the paved road onto to a grassy area over a bump. When it encountered the bump, the ATMA deviated from its path, and the safety driver manually overrode the system to a stop. The second was during the field test at SR-222 as explained below.

Field Test Results: Table E6 provides a summary of field test results. Three tests completed as expected; however, there were exceptions to three others.

Table E6. Overview of field test results

Test ID	SR/Interstate	AADT	Performed as Expected?
FT-1	US-441	13,900	Y
FT-2	I-75	73,203	Y
FT-3	SR-222	22,914	Exception
FT-4	SR-26	10,788	Exception
FT-5	SW 2nd Ave	7,651	Exception
FT-6	SR-24 Waldo Rd	16,273	Y

Field Test 3 – SR-222:

- The ATMA drifted off the intended path. In one instance, the ATMA drifted toward the outside lane, and the control was overridden by the Kratos safety officer. Even though the exact cause was not determined, it was suspected that it may have been due to improper engagement of

the steering lock.
- The system misreported a hard brake event as a collision, and the safety operator (Kratos staff) was required to change to Idle mode. Kratos staff mentioned that this can be eliminated by system upgrades or enhancements.
- At intersections, driver training is critical to understand the implications of ATMA operation, e.g., the FWD test was being performed downstream of the intersection, and the work platoon blocked the left-turning traffic. This may cause a traffic bottleneck at the intersection (Figure 6-133) and, in some cases, safety concerns.

Field Test 4 – SR-26:
The testing was performed in the EB direction only; however, it was terminated early due to increased traffic and safety reasons. This was a two-vehicle operation. This exception was not due to system limitation exclusively because two-lane operations are challenging even in a manual operation scenario. However, the ability to quickly move onto the shoulder to let traffic pass and then swiftly return to testing is something that the ATMA is lacking currently. This may improve with system enhancements and operator experience.

Field Test 5 – SW 2nd Avenue:
This section was selected due to the presence of multiple roundabouts. The roundabout had a small inner diameter, and as such, the ATMA was unable to negotiate any of the roundabout. It was observed that any turning movement less than a 65-ft radius was a challenge for the ATMA.

E8. Lessons Learned from Field Observations and Data Analysis

1. Operator training is essential and critical.

The lead vehicle driver essentially paves the path for the follower ATMA. As such, every decision the lead vehicle driver makes affects the operational and safety performance of the ATMA and the traveling public around the work platoon. The lead vehicle driver must be trained in several aspects, including conducting a route survey before the planned work in order to:

- Check GPS connectivity
- Scout start location for pre-checks
- Check for available distance for initial rollout
- Test obstacle detection and calibrate
- Check and plan for intersections along the routes
- Check and prepare for overhead signs and other structures for potential loss of connectivity
- Check potential bumps or road condition issues
- Check roadway alignments
- Check weather conditions
- Check traffic conditions.

2. Review FHWA STSDM guidelines; and DOT could consider development of ATMA specific guidelines for TTC.

Short-term, short-duration, and mobile (STSDM) operations have unique characteristics, and with ATMA evolving and finding new applications, DOT may consider developing guidelines specifically for ATMA operation. For instance, the American Traffic Safety Services Association (ATSSA) STSDM guide describes some common work site characteristics that often create challenges and could require field adjustments and possible mitigation strategies to address them. Since the conditions and strategies may not be applicable for every work site characteristic, some guidance on how to alleviate safety challenges and suit field conditions is helpful. In addition, it is recommended that standard plans and guidance for ATMA operations would ensure consistency and enhance safety for DOT staff and contractors.

3. Avoid roundabout or untraditional intersection designs.

The testing revealed that the current system configuration is challenged when navigating a roundabout or making U-turns. Any intersection design such as roundabout, median U-turn (RCUT), etc. should be avoided until further testing to successfully navigate such a pathway is documented.

4. System enhancements for stop-and-go operation

Currently, the ATMA system aims to achieve the desired fixed gap as long as there is enough time and space for the leader and follower to travel. However, in some instances, such as stop-and-go operation or even a stop-controlled intersection, this constant gap distance may hinder the operation. If the system has capability to reduce the gap when the leader is stopped to achieve a new gap and then resume the following pattern, that would be helpful in several scenarios. In addition, steps to mitigate atypical scenarios such as leader vehicle in reverse (Test Case 21) can be addressed.

5. Leverage the lateral offset feature in ATMA.

One of the latest enhancements of the ATMA system is the ability to maintain a lateral offset of up to 12 feet. The users must be trained to leverage this feature and function in field operation when applicable.

6. Test with no safety operator in ATMA.

All the testing was performed with a safety operator in ATMA; however, the intent of the ATMA is to eliminate the injuries and fatalities of TMA drivers. Therefore, testing needs to be performed for ATMA without a safety operator in ATMA. It is acknowledged that this testing was conducted beyond the standard system design in that the leader kit was retrofitted in the FDOT truck. It is recommended that further calibration and testing be conducted without a safety officer for more data points to quantify the feasibility of ATMA in open road operation.

7. Longitudinal testing and data repository

Since ATMA is a new technology, having a clearinghouse and data repository would be beneficial for DOT and other agencies to track and quantify the performance over time. A list of performance measures can be identified for longitudinal analysis.

Table of Contents

Contents

List of Figures

List of Tables

Chapter 1 – Introduction

1.1 Background Statement

Data from the National Institute for Occupational Safety and Health (NIOSH) indicate that for over 15 years (2003–2017) Florida has ranked second highest in fatal work zone crashes in the nation [1]. Data reveal that workers were present in the work zone in 35 percent of the fatal crashes and in an additional 44 percent of crashes resulting in serious injuries. While work zone fatalities make up approximately three percent and two percent of all traffic fatalities and serious injuries, respectively, with FDOT's "Driving Down Fatalities" initiative [2], safe and efficient flow of traffic through work zones is an ongoing priority for Florida's transportation and traffic safety partners because as seen in Figure 1 below, the crash frequency and work zone fatalities trend is on the rise.

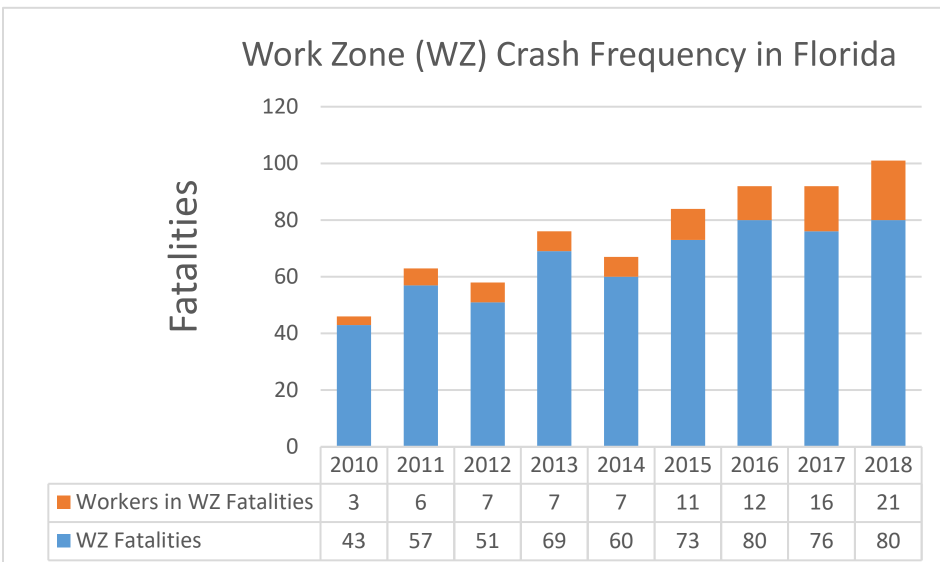


Figure 1-1. Florida work zone crash frequency

In order to alert the traveling public to active work zones, the *Manual on Uniform Traffic Control Devices* (MUTCD) provides the basic principles of design and use of traffic control devices for streets and highways. Part 6 of the 2009 MUTCD [3] provides guidance related to work zone Temporary Traffic Control (TTC). The primary function of TTC is to accommodate the safe and efficient movement of road users through or around work zones, while providing protection for other road users and workers. TTC guidance can vary based on the type and duration of work. Short-term stationary, short duration, and mobile (STSDM) work zones require a simple process and highly visible TTC to enable quick implementation and removal processes. The MUTCD defines mobile work as that which moves continuously or intermittently, rarely stopping for more than a few minutes at a time. For mobile operations, shadow vehicles are deployed to protect the work vehicles. Based on the *Roadside Design Guide* (RDG) and the MUTCD, USDOT, FHWA, and the American Traffic Safety Services Association (ATSSA) have developed field guides for the use and placement of shadow vehicles in work zones.

Shadow vehicles are usually moving trucks, equipped with an integral attenuator, spaced a short distance from a moving work operation. These vehicles offer physical protection to workers in case of errant traffic entering the work zone from the rear. In some cases, the shadow vehicle is equipped with a trailer-mounted attenuator. In addition to shadow vehicles, advance warning vehicles, equipped with appropriate signs and warning lights, may be used upstream of the work space to warn road users of downstream work activity. There are several factors that determine the use of shadow vehicles, including driver sight distance and reaction time along with speed and the type of work activity. For short-term, intermediate, and long-term stationary work zones, a shadow vehicle may be used in the work space in advance of work operations to protect workers from vehicle intrusions. When equipped with a truck-mounted attenuator or trailer-mounted attenuator, it protects occupants of intruding vehicles from impacts with work vehicles and equipment. When equipped with a lighted arrow panel or static signing, shadow vehicles used in mobile operations also serve to warn road users prior to entering the activity area.

ATSSA developed a guide [4] that outlines shadow vehicle considerations for mobile freeway and non-freeway applications (Figure 2). In general, in high risk situations or activities where workers may be exposed to traffic or working in a high speed environment, shadow vehicles are recommended.

Mobile Freeway Applications

The following guidelines are applicable to freeways **with no stationary lane closures (NoLC) or with no stationary shoulder closures (NoSC).**

If the type of activity involves:	The priority for use of shadow vehicles is:	The priority for use of a TMA on the vehicle is:
Exposed personnel – crack pouring, patching, utility work, striping, coning (No LC)	Very highly recommended	Very highly recommended
Exposed personnel – pavement repair, pavement marking, delineator repair (No SC)	Highly recommended	Highly recommended
No exposed personnel – sweeping, chemical spraying (No LC)	May be justified based on the specific project need if it would lessen impacts	Very highly recommended
No exposed personnel – open excavation, temporarily exposed bridge pier (No SC)	May be justified based on the specific project need if it would lessen impacts	Highly recommended

Mobile Non-Freeway Applications

The following guidelines are applicable to roadways (other than freeways) that have **no stationary lane closures (NoLC) or with no stationary shoulder closures (NoSC).**

If the type of activity involves:	The priority for use of shadow vehicles is:	And, if the speed is:	The priority for use of a TMA on the vehicle is:
Exposed personnel – crack pouring, patching, utility work, striping, coning (No LC)	Very highly recommended	50 mph	Highly recommended
		45 mph	Recommended
		40mph or less	Desirable
Exposed personnel – pavement repair, pavement marking, delineator repair (No SC)	Highly recommended	50 mph	Recommended
	Recommended	45 mph	
	Recommended	40mph or less	
No exposed personnel – sweeping, chemical spraying (No LC)	May be justified based on the specific project need if it would lessen impacts	50 mph	Highly recommended
		45 mph	Recommended
		40mph or less	Desirable
No exposed personnel – open excavation, temporarily exposed bridge pier (No SC)	May be justified based on the specific project need if it would lessen impacts	50 mph	Recommended
		45 mph	Desirable
		40mph or less	May be justified based on the project

Figure 1-2. ATSSA guidance on shadow vehicle consideration for mobile applications

Even with the use of crash cushions that are installed on trucks, also known as truck-mounted attenuators (TMA), to reduce the severity of rear-end crashes, when an errant vehicle strikes the TMA, it could result in serious injuries to the driver and occupants of these trucks. The autonomous truck-mounted attenuator (ATMA) aims to solve this problem by removing drivers from behind the wheel of TMA vehicles. The driverless ATMA system operates in a multi-vehicle leader-follower configuration where the TMA truck is retrofitted with an electromechanical system and a fully integrated telematics and sensor suite that enables its autonomous capability. In the leader-follower configuration, the system enables the leader vehicle to transmit navigation data via encrypted vehicle-to-vehicle (V2V) communications to the follower ATMA vehicle.

The driverless ATMA is operated in the leader-follower configuration where the human-driven leader vehicle (i.e., maintenance vehicle, lane stripping vehicle, etc.) is followed by the unmanned follower vehicle (i.e., the ATMA) in a multi-vehicle operation. The follower TMA truck is retrofitted with an electromechanical system to allow autonomous operation and a fully integrated telematics and sensor suite to follow the path of the leader vehicle. The leader vehicle includes a navigation computer, V2V communications system, an operator control unit with system termination or kill switch, user interface tablet computer, and rear-facing video camera. The follower vehicle (ATMA) includes the same components as the leader vehicle along with actuators for controlling steering, braking, and acceleration as well as sensors for obstacle detection, external E-stop system termination or kill switches, forward-facing video camera, and an independent remote E-stop system as an added backup safety system. Chapter 3 provides the detailed information of the ATMA system.

1.2 Project Objectives

The main objective of the research project was to evaluate the performance of an autonomous truck-mounted attenuator (ATMA) system based on:

a. Ongoing or completed projects by other agencies that adopted ATMA

b. Actual testing of the equipment during a demonstration pilot in Gainesville, FL.

The goal of this project was to provide an opportunity to experience ATMA operation in a closed testbed as well as on an active work zone and conduct testing under different scenarios to validate the functions of the ATMA and understand the feasibility or applicability of the autonomous system to enhance operational or safety benefit on work zones in Florida.

1.3 Document Organization

This following chapters are as follows:

- Chapter 2 includes a synthesis of related ATMA initiatives and deployments.
- Chapter 3 provides a review of ATMA functions and the demonstration event.
- Chapter 4 provides a summary of site selection and testing plan that were implemented.
- Chapter 5 details the data collected during the demonstration and the closed loop testing.
- Chapter 6 details the data analysis performed.
- Chapter 7 summarizes the benefit-cost analysis approach and the tool developed.
- Chapter 8 summarizes the results from the data analysis tasks.
- Chapter 9 provides the conclusions from the project findings.

Chapter 2 – Synthesis of ATMA-Related Information

The project team first explored existing work related to ATMA in the U.S. as well as abroad. This chapter provides an overview of the information gathered related to ATMA. The team conducted a literature search (projects, publications, and reports) on the Transportation Research Board's (TRB) TRID database [5] with various permutations of keywords related to autonomous truck-mounted attenuator and autonomous impact protection vehicles and their abbreviations. The TRID result yielded one TRB publication (submission) and two ongoing projects as of June 2020. Further, the research team reached out to state agencies, university research centers, and ATMA vendors to learn from their deployments.

It should be recognized that the ATMA technology is relatively new. The first demonstration and deployment in the U.S. was in 2017 [6]. Even though there has not been any official government report available on the Internet related to ATMA, there are ongoing efforts in various states, including Missouri, Virginia, Tennessee, Colorado, California, North Dakota, and Minnesota [7]. In addition, ATMAs have been explored and deployed in limited capacity in other countries, including England, Russia, Japan, Germany, and the Netherlands [8].

The Colorado Department of Transportation (CDOT) was an early adopter of ATMA technology in the U.S. and is currently at the forefront of research and implementation activities with respect to ATMA. CDOT procured the ATMA system and installed the leader vehicle kit on a paint truck. CDOT currently approves the ATMA for statewide deployment as standard equipment, operating on over 200 miles of public road. The first ATMA system is operating in the Denver area, and the second system is currently being procured for the Durango area. The CDOT staff and Colorado State University are leading the pool fund study to unify the learning efforts on ATMA and its application [9].

The Missouri Department of Transportation (MoDOT) is currently working with Micro Systems, Inc., to provide a National Cooperative Highway Research Program (NCHRP) 350 Level 3 compliant leader-follower TMA system capable of operating a driverless advanced warning follower truck in mobile highway operations as described in Traffic Application TA-35a [10]. Tang et al. from Missouri University of Science and Technology [11] conducted 31 test scenarios to evaluate system performance in a controlled environment. The same research team is also currently conducting a 250-hour continuous test of ATMA deployment and operation. In order to recommend deployment strategies, the team is working on developing a tool [12] to recommend input requirements, including roadway network GIS shapefile, traffic counts, and ATMA system characteristics. It is recognized that the leader-follower system design of the ATMA imposes more requirements on lead truck (LT) drivers in order to ensure a safe and smooth system operation. Because the drivers are required to undertake driving decisions for both the lead truck as well as the shadow ATMA truck, Missouri [13] is working on developing training material for lead vehicle drivers in various scenarios such as end of green phase at signals and gap acceptance in turn movements at intersections.

The Virginia Tech Transportation Institute [14] is currently working on developing an automated control system for TMA vehicles using a short following distance, a leader-follower control concept which will remove the driver from the at-risk TMA vehicle.

The University of Tennessee at Knoxville [15] conducted a demonstration for the Tennessee Department of Transportation (TDOT) and is currently analyzing the data from the closed loop testing of the ATMA.

As a part of the Autonomous Maintenance Technology Pooled Fund research referenced earlier with CDOT, California DOT (Caltrans) is exploring the use of ATMA in its existing practice and also refining policy and operational procedures for autonomous work vehicles. Caltrans is also developing a data framework and data exchange platform for autonomous maintenance technology in general practices. Minnesota and North Dakota have planned demonstrations and procurement of ATMA.

Table 2-1 synthesizes the information on current ATMA applications in various states as derived from websites, phone calls, and vendor information.

Table 2-1. Summary of ATMA synthesis in the U.S.

State	Procure-ment	Application	Environment	Other Information
California	Purchased (ongoing)	Shadow vehicle for highway maintenance operations	Closed track + public roadways	Currently being evaluated by DMV to approve for open road testing
Colorado	Purchased	Painting; also considered other operations, including cone placement and patching work	Closed track + public roadways	Approved for statewide deployment as standard equipment and operated over 200 miles of open road. First system is being operated in the Denver area, and the second system is being procured for the Durango area.
Florida	Leased	Shadow vehicle for GPS seed file collection to support ITS operations in Milton, FL	Public roadway	Operated 28 miles across Santa Rosa County on US-90
Minnesota	Purchased (planned)	Shadow vehicle for highway maintenance operations	Closed track + public roadways	Deployment delayed to summer 2021 due to COVID-19
Missouri	Purchased (ongoing)	Shadow vehicle for highway maintenance operations	Closed loop + public roadways	Completed 32-hr continuous operation on closed road; next phase of testing is 250 continuous hours on open road.

Table 2-1. Summary of ATMA synthesis in the U.S. (continued)

State	Procure-ment	Application	Environment	Other Information
North Dakota	Purchase (planned)	Shadow vehicle for highway maintenance operations	Closed track + public roadways	Deployment planned for Aug–Sept 2020
Tennessee	Lease (ongoing)	Shadow vehicle for highway maintenance operations	Closed Loop	27 tests per testing plan
Virginia	Custom develop-ment	Various	Under development	None

Chapter 3 – ATMA System Overview

This chapter provides the details of ATMA system fabrication and customization made for the FDOT pilot study. To demonstrate and test the Kratos ATMA system, the stakeholders desired to create a system most resembling one that would actually be used in the field. The tested system comprised three vehicles: a standard work truck loaned to UF by FDOT, including a trailer carrying a falling weight deflectometer (FWD), which was retrofitted by Kratos to serve as a leader vehicle; the Kratos follower vehicle with the Scorpion attenuator; and a standard truck with an attenuator to be used between the leader and follower vehicle as a safety precaution in open-road testing.

The following section provides an overview of the Kratos ATMA leader and follower system and the FWD.

3.1 Leader Kit Instrumentation on FDOT Vehicle

Royal Truck, in partnership with Kratos Defense, was contracted for the leasing of an ATMA system. An FDOT F350 truck was delivered to the Kratos facility in Fort Walton Beach on Tuesday, June 23, 2020. Kratos technicians installed the leader kit. The kit included an operator control unit, a PC-based system for system activation, navigation, and emergency stop functions. External components of the kit included a V2V communications system, GPS receivers, a rear-facing video camera, and other components. The system is powered through a connection to the truck's battery. System integration, calibration, and testing were conducted from June 23 through July 12. Figure 3-1 below shows the interior center console of FDOT F350 before and after the instrumentation. Figure 3-2 shows the modification to retrieve power from the F350 battery. Figure 3-3 shows the before and after of the exterior with the custom-fitted antenna and other equipment. Detailed description is provided in Section 3.3 of this report, which provides the overview of ATMA Demonstration.

Figure 3-1. Before and after leader kit installation on FDOT F350 leader vehicle center console

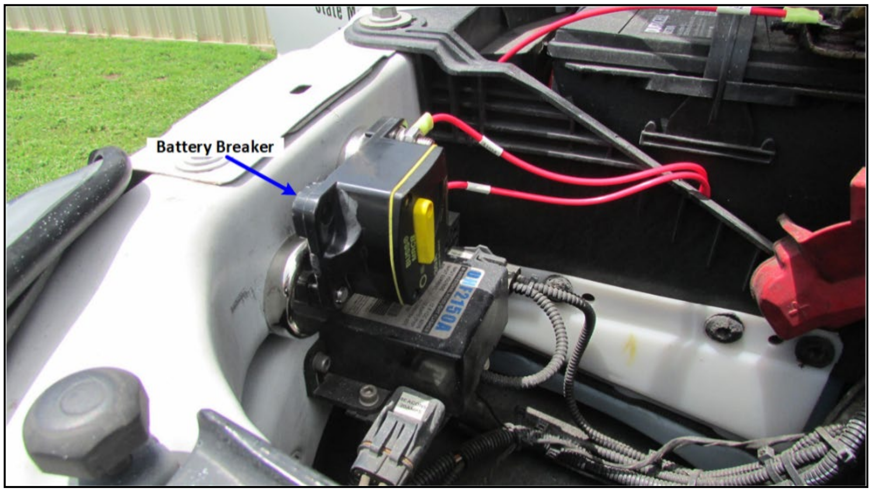


Figure 3-2. Battery breaker installed in the leader vehicle


Figure 3-3. Before and after installation of the exterior mount and equipment on FDOT leader vehicle

3.2 ATMA Technical Overview

On July 24, 2020, Kratos personnel conducted the first part of operator training: an online introduction to the ATMA system, its components and their functions and use. Eighteen attendees completed the training: 3 UF staff members, 1 Royal Truck and Equipment staff member, and 14 FDOT employees. The training materials may be found in Appendix A. A post-training survey was administered to assess the quality of the training content. Figure 3-4 below shows the eight responses received. Overall, feedback was positive regarding the content and delivery of the operator overview training presentation.

#	Field	Strongly agree	Somewhat agree	Neither agree nor disagree	Somewhat disagree	Strongly disagree	Total
1	I found the webinar easy to access and participate in.	100.00% 8	0.00% 0	0.00% 0	0.00% 0	0.00% 0	8
2	After participating in the webinar, I have a better understanding of how the ATMA works.	87.50% 7	12.50% 1	0.00% 0	0.00% 0	0.00% 0	8
3	After participating in the webinar, I have a better understanding of how to operate the ATMA.	37.50% 3	50.00% 4	12.50% 1	0.00% 0	0.00% 0	8
4	I am satisfied with the safety aspects of ATMA operation.	57.14% 4	42.86% 3	0.00% 0	0.00% 0	0.00% 0	7
5	I have enough knowledge to proceed to hands-on training with the ATMA.	37.50% 3	50.00% 4	12.50% 1	0.00% 0	0.00% 0	8
6	I had a good opportunity to ask questions and improve my understanding of the webinar information.	62.50% 5	25.00% 2	0.00% 0	12.50% 1	0.00% 0	8
7	I believe that the ATMA would improve the efficiency of work zone operations.	75.00% 6	12.50% 1	12.50% 1	0.00% 0	0.00% 0	8
8	I believe that the ATMA would improve the safety of work zone operations.	75.00% 6	25.00% 2	0.00% 0	0.00% 0	0.00% 0	8

Showing rows 1 - 8 of 8

Figure 3-4. ATMA operator training evaluation survey results

3.3 ATMA Equipment Overview

An in-person overview and training on the ATMA (Figure 3-5) and a demonstration of ATMA operation was conducted on Monday, July 23, 2020, between 8 a.m. and 10 a.m. at the FDOT Maintenance Facility in Gainesville, Florida. Attendees included State Materials Office staff, FDOT Maintenance Office staff, and UF staff. One FDOT staff member was trained in-person to operate the leader vehicle. The Kratos staff provided an overview of each system component, safety feature, and operational feature of both the leader and the follower vehicles, which is documented in the following sections.

Figure 3-5. Kratos staff providing in-person overview and training at FDOT facility

3.3.1 Overview of ATMA System and Controls

The ATMA system comprises a leader truck and a follower truck. The follower truck can operate as a connected vehicle to precisely follow the leader truck. For this project, FDOT loaned a truck which was delivered to Kratos for installation of the necessary equipment to act as a leader truck. A fully equipped autonomous follower truck-mounted attenuator (ATMA) was leased from Kratos.

Figure 3-6 shows the leader truck and follower truck in demonstration configuration. The FDOT leader truck is in the foreground with trailer attached. The trailer carries a falling weight deflectometer (FWD). The Kratos follower truck is in the background. The follower carries a Scorpion attenuator, shown in Figure 3-7.

Figure 3-6. ATMA trucks in demonstration configuration. The white truck in the foreground is the FDOT F350 truck retrofitted with the Kratos leader kit. In the background in the blue follower truck, rented from Kratos.

Figure 3-7. Follower vehicle showing Scorpion impact-absorbing device extended to the rear

3.3.2 Tour of Follower Vehicle Technologies

The follower truck is guided by digital "crumbs," a series of GPS locations provided by the leader truck. Cameras on the follower vehicle provide visual feedback to the leader driver, who can also monitor aspects of the follower's performance on the operator control unit. However, the follower does not blindly follow; it is equipped with a variety of sensors to detect vehicles or other possible interferences. The sensors can cause the follower to stop in order to prevent a collision if, for example, a vehicle should enter the space between the leader and follower. The following images show the external devices attached to the follower vehicle, including external sensors, front-facing lidar and front-facing radar (Figure 3-8), and lateral-facing lidar (Figure 3-9)

- External control: emergency stop (E-stop) activator (Figure 3-10)
- Internal controls: steering actuator ring, steering tabs, and steering fingers (Figures 3-11 and 3-12); brake and accelerator cable system (Figure 3-13); and operator control unit (Figure 3-14)

The following pictures provide an overview of different components of leader and follower trucks.

Figure 3-8. Follower truck – External sensors: The forward-facing obstacle detection system is attached to the front bumper of the follower vehicle. (1) The large device in the white housing is an off-the-shelf lidar (SICK, Inc.) which has a 190° view. During autonomous operation, the lidar narrows its field of view to the leader vehicle so that during a turn or in a roundabout, the follower vehicle will not respond to objects that are in its line of sight but not in its path of motion. Otherwise, the follower vehicle would detect, for example, a street light on the opposite corner and execute an automatic stop (A-stop). (2) The rectangular black device below the white housing is a standard automotive radar (Delphi, Inc.). The radar can detect objects out to 150 ft. If the radar detects an object in the range of 100 ft to 150 ft, the follower truck will automatically slow to 7 mph. If the radar detects an object within 100 feet, the follower truck will execute an A-stop. (3) The lensed device above the white lidar housing is a legacy lidar. It is no longer used and will be not be included in future versions of the system.

Figure 3-9. Follower truck – External sensors: In the lower center of the image is the lateral-facing lidar. There is one on both sides of the follower truck. It has a field of view of 100° to 120°. If an object is detected, the person in the leader vehicle monitoring the follower vehicle is notified by through the user interface, but it will not cause an A-stop. The mount is readily adaptable to many vehicle types.

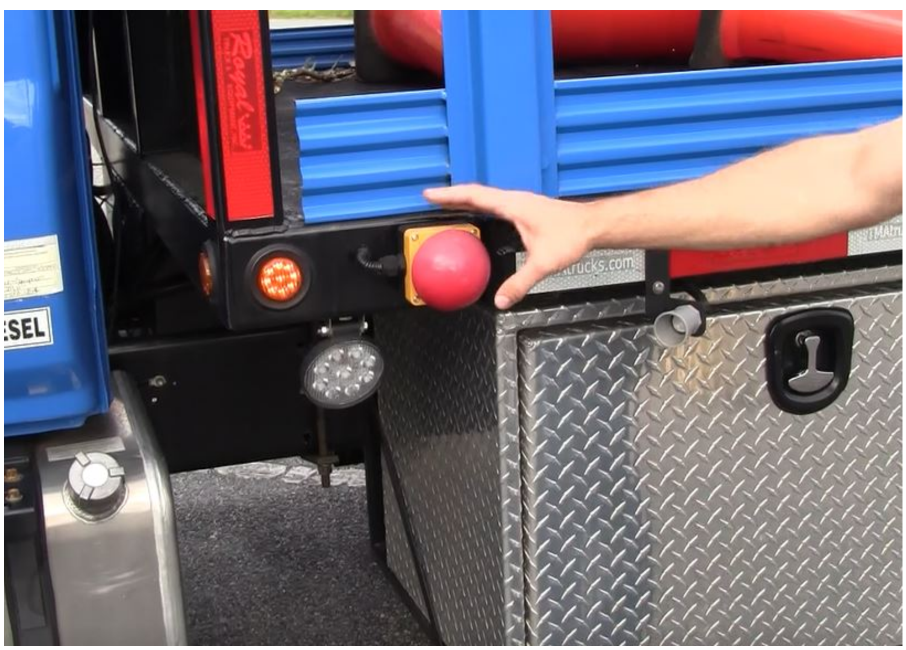


Figure 3-10. Follower truck – External controls: The big red button in the center of the image is the emergency stop (E-stop) activator. There is one on both sides of the follower truck. Pressing the E-stop activator both applies the follower truck's brakes and stops the engine.

Figure 3-11. Follower truck – Internal controls: Steering in the follower truck is controlled by an actuator ring, seen in the image as a heavy black ring on the steering column below the steering wheel. The silver tab sticking up from the actuator ring is a steering tab. There are two steering tabs on the steering actuator ring.

Figure 3-12. Follower truck – Internal controls (left): The steering actuator ring is linked to the steering wheel when the “steering fingers” are mounted on the two steering tabs. When the set screws are tightened, the steering fingers form a secure and tight connection between the steering actuator ring and the steering wheel. Internal controls (right): The steering actuator ring appears in the upper part of the image, with the servo housing at the right. Beneath the servo is the junction box and CAN bus that connects the steering controls to the follower vehicle’s on-board systems control unit (SCU).

Figure 3-13. Follower truck – Internal controls: The Kratos demonstrator points to the custom cable system that operates the brake and accelerator in the follower vehicle. There are two cable linkages to the brake pedal: one provides a range of motion for normal operations and A-stops; the other one provides full braking during an E-stop.

Figure 3-14. Follower truck – Internal controls: In the center of the dash is the follower truck version of the operator control unit (OCU). Near the right of the panel is the on/off switch which engages the OCU in preparation for autonomous operation. The light above the switch verifies that the system is on and operational. When the OCU is switched on, the system will attempt to locate GPS signals. When 6-7 satellite signals have been located, the GPS Lock light illuminates. When the system is powered on, initialized, and GPS lock is achieved, the Ready light lights up to show that the follower vehicle is ready for autonomous mode. The switch in the black rectangle switches the follower vehicle between idle mode and GO mode: in idle mode, the follower truck is ready for autonomous mode but still under manual steering, braking, and accelerating control; in GO mode, the follower truck is in autonomous mode and under control from the leader truck. When leader driver has completed the leader vehicle checklist, the follower driver will be instructed to enter "Go" mode, and the GO light illuminates. The follower driver will then exit the follower vehicle and enter the passenger seat in the leader vehicle to act as system monitor. The follower driver can return to the follower vehicle at any time it is stopped, switch to idle mode, and take manual control of the follower vehicle. The big red button on the OCU panel is an E-stop (only active when the OCU is on). An E-stop will be activated automatically if the follower vehicle loses contact with the leader.

Figure 3-15. Low on the dash are the controls that lower and raise the Scorpion tail and the arrow board on the rear of the follower truck. There is also a port on the Scorpion tail that allows it to be raised and lowered with a plug-in controller (not shown).

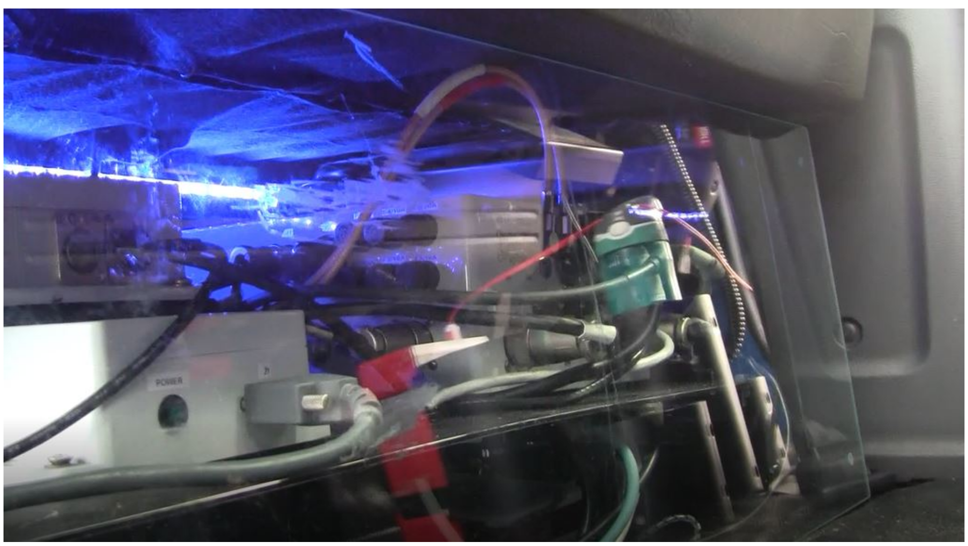


Figure 3-16. Follower truck – Internal controls: Hardware including RS232 hub, gyro, CAN bus hub, video amplifier, and wireless video link are located under the passenger seat. Communications are protected from hacking during operation with military-grade encryption.

3.3.3 Tour of Leader Truck Technologies

The retrofit included four components: a power link to the leader truck's battery (Figure 3-17); an antenna array (Figure 3-18); an OCU (Figures 3-19 and 3-20); and the system hardware (Figure 3-21), as shown in the following images.

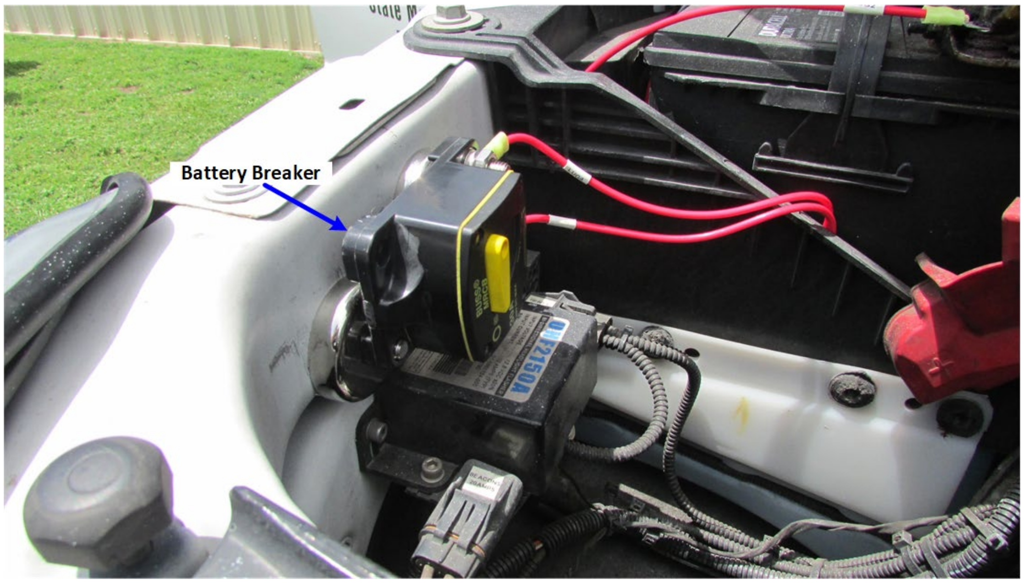


Figure 3-17. Leader truck – System tie-in: Under the hood of the leader truck, near the center of the image, is the magnetically mounted device that supplies power to the leader control systems from the leader truck's battery.

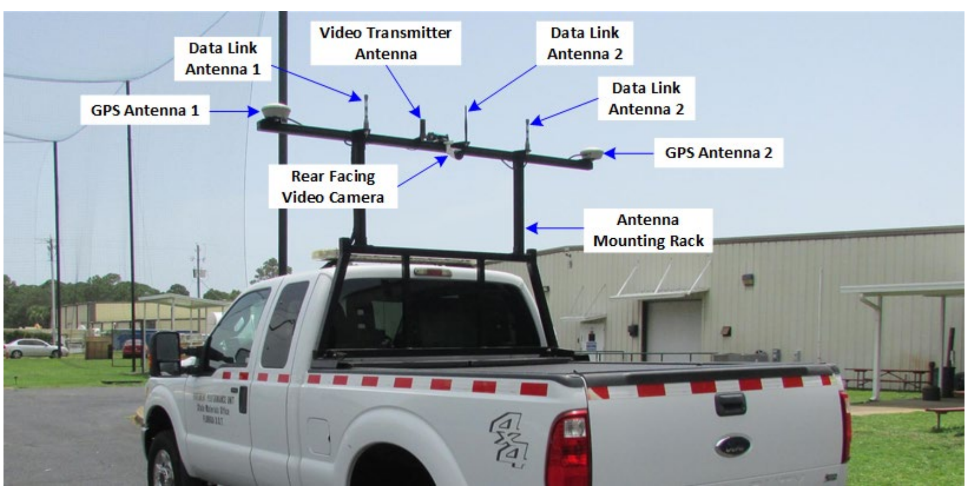


Figure 3-18. Leader truck antenna array: The leader truck and follower truck carry the same antenna array. On the outer reach of the array are two GPS receivers. Next in are the 2.4-GHz antennas, then the 915-GHz main radio link (taller spike near the middle), and the video link to the front-facing camera on the follower truck (shorter antenna near middle). In the center of the leader truck antenna array is a rear-facing camera.

Figure 3-19. The leader vehicle OCU includes a laptop computer screen that displays the control user interface, two control panels in front of the screen, and a viewer that displays the signal from the follower truck's front-facing camera. The OCU is held on a pivoting arm that is pulled out for a clearer view. Through the user interface, the follower truck operator can enable the system, view warnings, adjust offset and gap, and more.

Figure 3-20. The control panels are the same as the dashboard OCU panel in the follower truck. On the left is an E-stop activator. On the right are the on/off and idle/GO switches and the GPS Lock and Ready lights. The big yellow button is an A-stop.

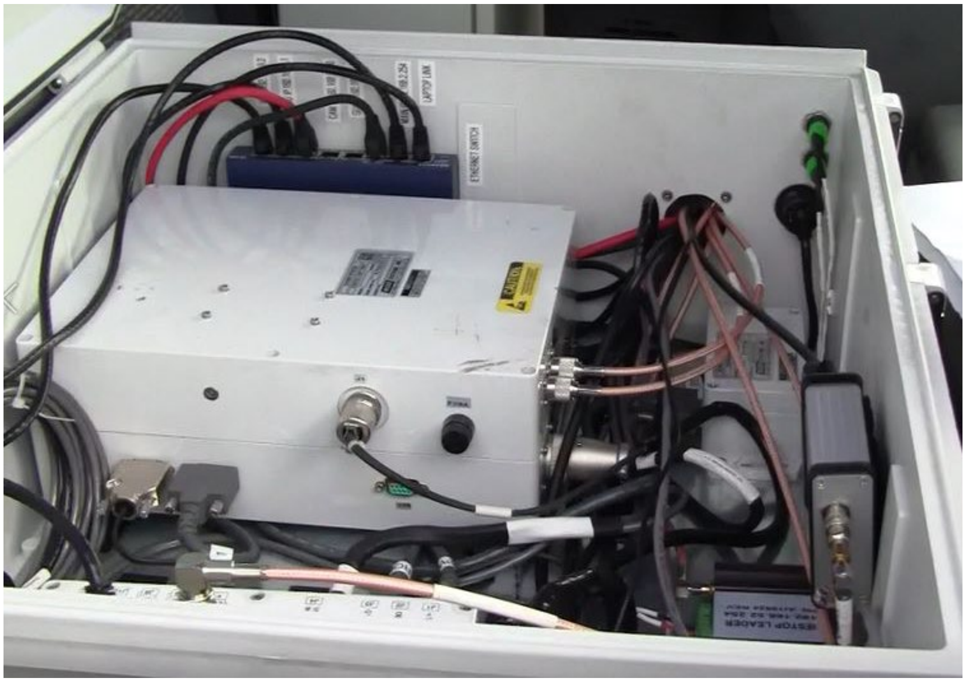


Figure 3-21. Leader vehicle: System hardware – "The brain of the system" is located behind the passenger seat. It draws power from battery as shown previously and includes the GPS receiver, interfaces to the OCU and I/O computer, the vehicle interface, radios, fiber optic gyro, and receiver for analog video.

3.4 Falling Weight Deflectometer and Maintenance of Traffic Requirements

This section provides an overview of the falling weight deflectometer and the different maintenance of traffic setups for the field work application.

Falling Weight Deflectometer

The falling weight deflectometer (FWD) testing is a mobile stop-and-go operation that requires intermittent stops at predetermined intervals to perform pavement testing. FDOT adopts MUTCD indexes 607 and 619 for two-lane and multi-lane operation (Figure 3-22).

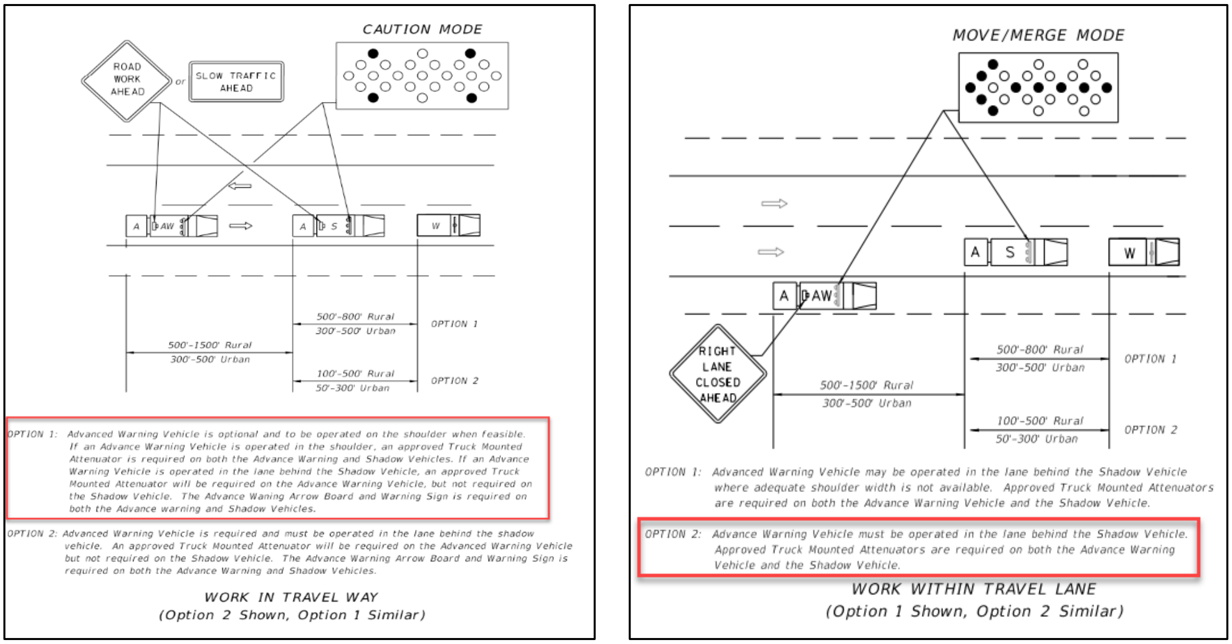


Figure 3-22. Index 607 for testing on two-lane roadways (left) and Index 619 for testing on multilane roadways (right)

The autonomous truck-mounted attenuator (ATMA), also known as autonomous impact protection vehicle (AIPV), was evaluated as a potential replacement to the advanced warning vehicle (AW). The Figure 3-23 shows the 3-vehicle operation on multilane roadways and 2-vehicle operation on 2-lane roadways.

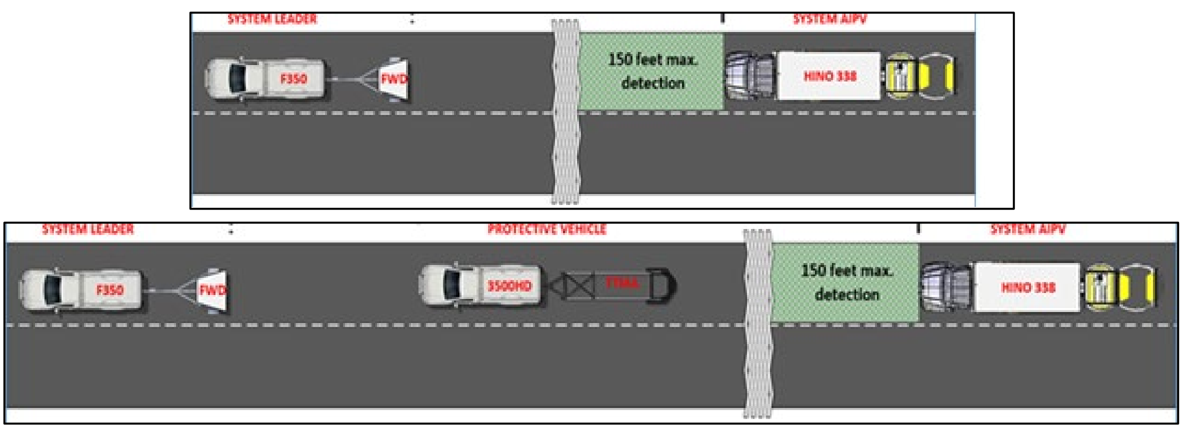


Figure 3-23. Two-vehicle setup (top) and three-vehicle setup (bottom) for multilane roadway operation (Image source: Kratos)

Chapter 4 – Site Selection and Testing Plan

The scope of this project included two main testing scenarios. The first scenario was in a closed loop setting where the operational and safety features could be tested along with trial runs. The second scenario was the open road test where we deployed the ATMA for an active work zone application. This chapter provides the details of the site selection and the testing scheme development.

UF coordinated with FDOT State Materials Office to select the sites for the live testing on public roadways. There were several factors that were considered, including facility type (vehicle mix, speed limit, number of lane, land use), maintenance of traffic (MOT) crew availability, typical operation of FWD, and safety considerations. The following sites and schedule were approved by the FDOT State Materials Office prior to the demonstration. For each site, this section provides an overview of the testing context, light condition when the testing was performed, the direction of testing conducted, and the number of vehicles in the work platoon.

4.1 Closed Loop (CL) Sites

There were two locations for closed loop tests: the FDOT Maintenance Office in Gainesville, FL, shown in Figure 4-1, and the Gainesville Regional Transit System (RTS) bus depot, shown in Figure 4-2 . Initially, the location outlined in yellow was selected for the closed loop tests at the FDOT maintenance office. However, the Kratos staff stated that the tree canopy (Figure 4-1 right) interfered with the GPS signal for the ATMA and that it was not able to operate in autonomous mode. After several unsuccessful attempts, the team then moved to the south leg of the yellow section where they were able to establish the GPS network required to operate the autonomous mode; however, when the ATMA negotiated the north side of the section, near the tree canopy, the ATMA lost signal, would throw an “e-crumb” error, and could not operate in autonomous mode. After further unsuccessful attempts, the team decided to move to the east section of the red highlighted zone in the picture where the unit operated without any issues. At the second location, which is an abandoned RTS warehouse (Figure 4-2), there was no issue with the GPS connectivity.

Figure 4-1. Location of FDOT Gainesville Maintenance Office aerial (left); street view showing the tree canopy (right)

Figure 4-2. Location of RTS bus depot located at 36-2 SE 10th Ave, Gainesville, FL

4.2 Field Test Sites

FT-1: US-441 (Paynes Prairie)

Context: Multilane, semi-urban high-speed environment with moderate traffic

Light condition: FWD test was conducted under daylight condition.

Direction: The FWD testing was performed in both NB and SB directions.

3-Vehicle operation: The offset distance between FWD truck and lead TMA was 50 feet, and between the TMA and ATMA, the gap was set at 300 feet.

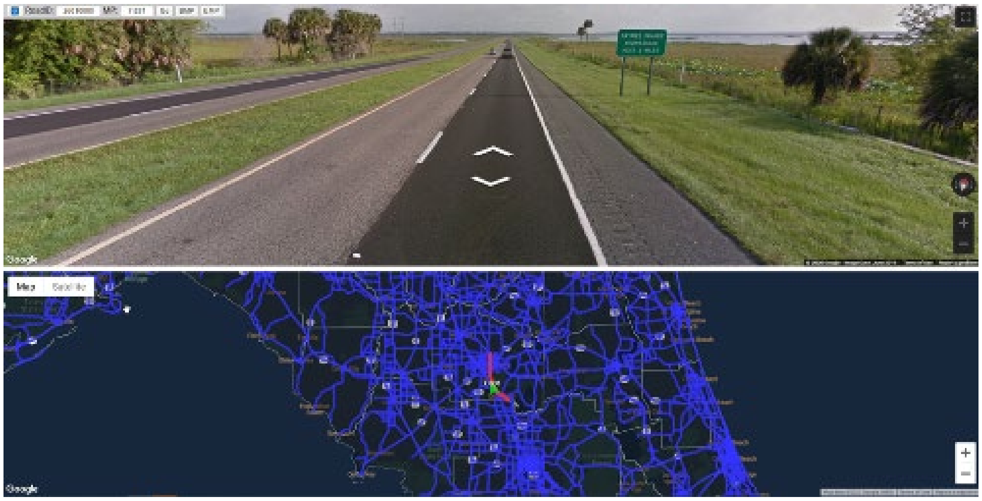


Figure 4-3. Location of Field Test Site 2 on US-441 in the Paynes Prairie area of Gainesville

FT-2: I-75

Context: Limited access, multilane, urban high-speed freeway with high traffic volume

Light condition: FWD test was conducted in non-daylight (night) condition.

Direction: The FWD testing was performed in both NB and SB directions.

3-Vehicle operation: The offset distance between the Leader (FWD) and TMA was 50 feet, and between the TMA and ATMA, the gap was set at 300 feet.

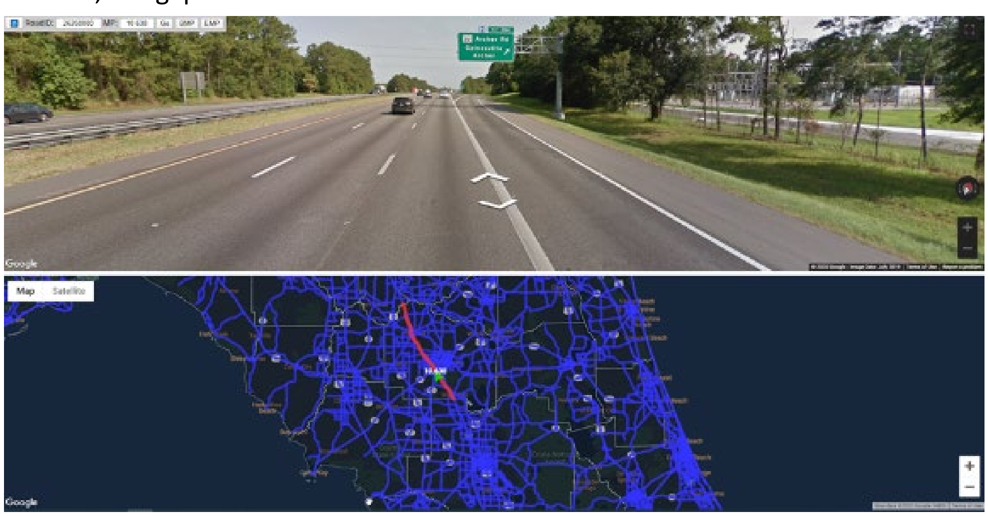


Figure 4-4. Location of Test Site 3 on I-75 in the Gainesville area

FT-3: SR-222

Context: Multilane, high traffic, low-speed urban environment with three signalized intersections and multiple access points on corridors

Light condition: The FWD test was conducted under daylight condition.

Direction: The FWD testing was performed in both EB and WB directions.

3-Vehicle operation: The offset distance between the leader (FWD) and TMA was 50 feet, and between the TMA and ATMA, the gap was set at 200 feet.

Figure 4-5. Location of Test Site 3 on SR-222 in the Gainesville area

FT-4: SR-26

Context: High speed, rural, two-lane roadway with high traffic volume

Light condition: The FWD test was conducted under daylight condition.

Direction: The testing was performed in EB direction only.

2-Vehicle operation: The offset distance between FWD Truck and TMA was 300 feet.

Figure 4-6. Location of Test Site 4 on SR-26, East of SMO in the Gainesville area

FT-5: SW 2nd Ave

Context: Low speed, urban, two-lane roadway with low traffic

Light condition: ATMA test was conducted under daylight condition.

No FWD testing: Only ATMA operation was performed through the loop.

2- Vehicle operation: The offset distance between FWD Truck and TMA was 50 feet.

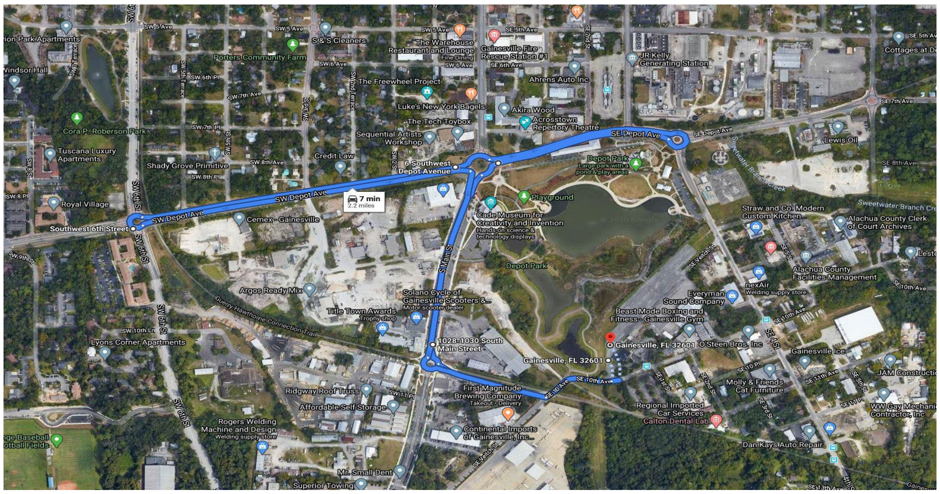


Figure 4-7. Location of Field Test Site 5

FT-6: NE Waldo Road

Context: High speed, semi-urban, multi-lane roadway with moderate traffic.

Light condition: Test was conducted under daylight condition.

No FWD testing: Only ATMA operation was performed in both directions.

3- Vehicle operation: The offset distance between FWD truck and lead TMA was 50 ft, and the gap between TMA and ATMA varied, starting with 300 ft, then stepped up to 500 ft, 750 ft, and 1,000 ft and then reduced stepwise to 750 ft, 500 ft, and 300 ft.

Notes: This segment was added to the list to accommodate multiple tests that were not accomplished in closed loop due to space constraints.

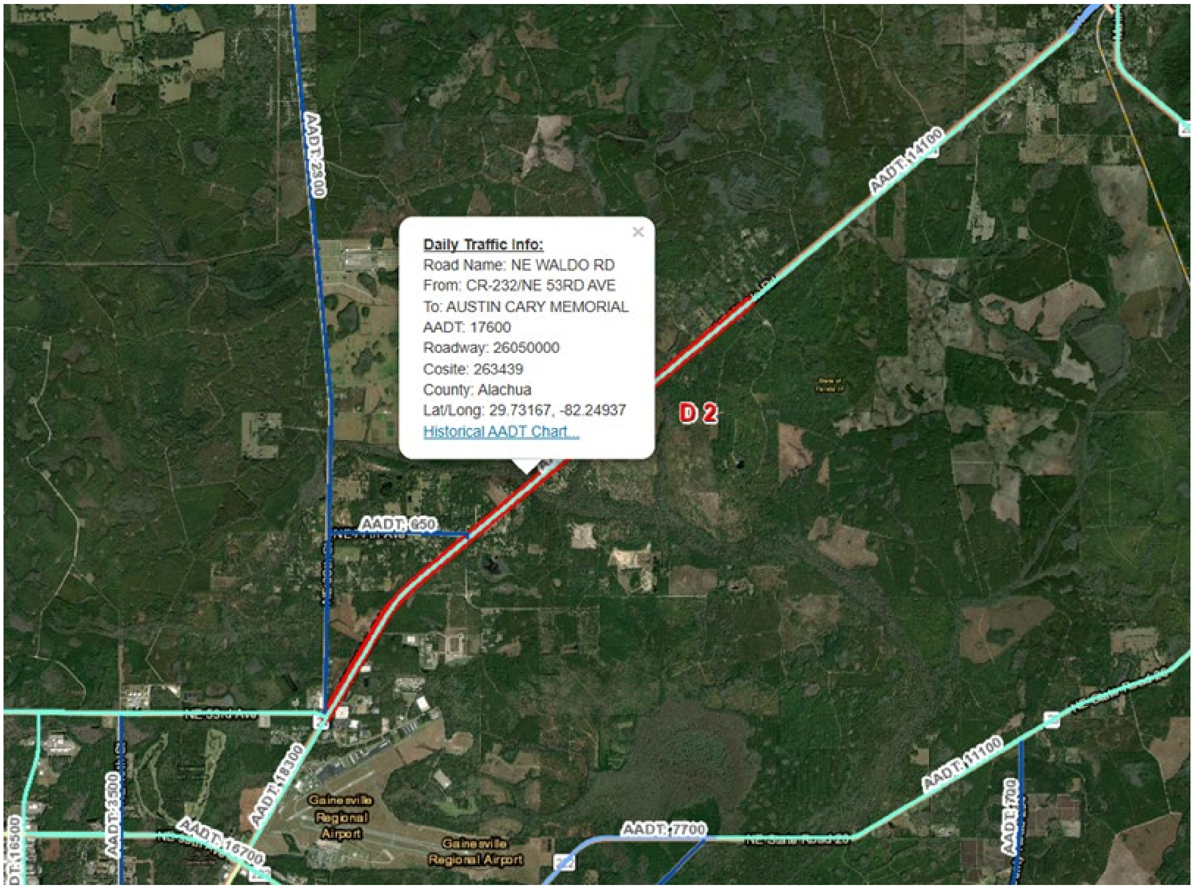


Figure 4-8. Location of Test Site 7 on SR-24

4.3 Summary of Test Sites

The test setups and corresponding sites described above are summarized in Table 4-1 below.

Table 4-1. Summary of test sections for the proposed ATMA evaluation

Test Set Up	ID	SR/Interstate	Roadway ID	Milepost	Annual Average Daily Traffic (AADT)[1]
1	CL	FDOT D-2 Gainesville Maintenance and RTS Depot			
2	FT-1	US-441	26010000	7.700 to 9.700	13,900
3	FT-2	I-75	26260000	10.500 to 12.500	73,203
4	FT-3	SR-222	26005000	6.500 to 8.000	22,914
5	FT-4	SR-26	26130000	6.400 to 8.000	10,788
6	FT-5	SW 2nd Ave			7,651
7	FT-6	SR-24 Waldo Rd			16,273

[1] Source: https://tdaappsprod.dot.state.fl.us/fto/

Schedule

Over 110 test runs were performed over a period of two weeks. These include 26 closed loop tests with an average of four runs each and an additional five field tests with multiple runs. The schedule of these tests is provided in Table 4-2, below.

Table 4-2. Test schedule

Day	Date	Weather		Start Time															
		HT/LT (°F)	Precipitation (mm)	8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00
Mon	7/13	91/72	0.00	Training		Practice Protocols			CL Test 1- 4			CL Test 7							
Tue	7/14	94/76	0.00	CL Test 7	CL Test 6		CL Test 8		CL Test 8		CL Test 9	CL Test 22							
Wed	7/15	93/72	27.43						CL Test 11 - 12						FT #3				
Thu	7/16	93/70	0.00				CL Test 15	CL Test 17	CL Test 19		CL Test 21	CL Test 16							
Mon	7/20	92/71	0.00	FT #2					FT #4		CL Test 10 & 13								
Tue	7/21	93/73	20.57	FT #5					FT #6										
Wed	7/22	91/72	0.76	FT/CL Test 5, 18, & 20 (Waldo					Two lane highway FWD										
Thu	7/23	89/73	0.00	CL 23- 26					Dissassemble Leader Kit & Data Inventory										
CL = Closed Loop @ FDOT SMO facility; FT = Field Test; HT = Average High Temperature; LT= Average Low Temperature																			

Chapter 5 – Data Collection

With the demonstration and testing scheme designed for a two-week period, it was critical for the team to develop a data collection plan. This chapter provides the details of data collected, their purpose, and the equipment used. As noted earlier, the primary objective was to quantify the operational and safety effectiveness of ATMA. For this purpose, we retrieved the high resolution log file data from the ATMA recorder, which captures all the vehicular characteristics and attributes of the leader and follower vehicle. For validation, the ground truth data were collected using dash camera videos, and in specific cases, external cameras, drone, and manual inspections were adopted.

The table below provides an overview of the data collected and its purpose.

Table 5-1. Data collection methods

Equipment or method	Data or purpose
Dashcam	Time stamp, Location of vehicle (latitude, longitude), velocity of the vehicle, video of front of vehicle
ATMA Log File	Variety of leader and follower vehicle attributes listed in the below section
Drone (for selected scenarios)	Traffic characteristics and driver behavior of other vehicles in the vicinity of the ATMA
Manual Inspection	Stopping distance, vehicle behavior (user experience for lead vehicle driver and as safety driver in ATMA), other vehicle behavior around ATMA, traffic characteristics

5.1 Dashcam

Figure 5-1 shows the screen capture of the GARMIN dash cam. At the bottom of the picture, the date, time stamp, latitude and longitude, and speed information can be seen. This was used as ground truth for validating the data retrieved from ATMA log files by developing a time-space diagram.

Figure 5-1. Screenshot from dashcam used for data collection

5.2 ATMA Log File Structure

The telematics system of the ATMA is capable of recording high resolution data, which include the event and the associated time stamps. The team retrieved the following data for every test run in CSV file format.

The CSV data file structure was as follows:

> UTC_TIMESTAMP, VEH, CRUMB, STAMP, LAT, LON, ALT, HEADING, HDG(Desired), VELOCITY, VEL(Desired), GAP, GAP(Desired), #SATS, VALID, CTE, ACCEL, STEER, STATE, COURSE, NEAREST_CRUMB, TOTAL_CRUMBS

where

UTC_TIMESTAMP = Time in UTC (HH:MM:SS.ms)

VEH = Vehicle (FLW = Follower; LDR = Leader)

CRUMB = e-crumb id (an integer value for identification)

STAMP = Timestamp integer value used by GPS

LAT = Latitude in degrees

LON = Longitude in degrees

ALT = Altitude in meters above sea level

HEADING = Vehicle heading in degrees

HDG (DESIRED) = Where the vehicle wants to go; heading in degrees

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

#SATS = Number of satellites acquired (count)

VALID = Position state value (1 = good; other values are 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 operator; ROLLOUT = beginning autonomous plan; RUN = autonomous mode; ASTOP = automatic stop)

COURSE = Track heading generated by GPS (not used)

NEAREST_CRUMB = Closest e-crumb id in list

TOTAL_CRUMBS = Total e-crumbs in list.

One of the important data categories reported in these log files is the cross track error (CTE). Upon consultation from the Kratos team, it was learned that CTE can be used as one of the performance measures. The cross track is the error from following the desired e-crumb path (Figure 5-2). The cross track error is calculated at 10 Hz, using the nearest e-crumb path segment. The e-crumbs are generated based on the follower's position and the vector position of the leader in relation to the follower. These vector positions are accurate at sub-centimeter accuracy in relation to the follower's GPS absolute position. The ATMA algorithm tries to match the path of the leader, and the aim is to close the cross track between the two paths. In the following closed loop evaluation sections, the minimum, maximum, and standard deviations of CTE are reported. It should be noted that if the ATMA is in manual mode, there is no e-crumb path, so there is no cross track error to calculate.

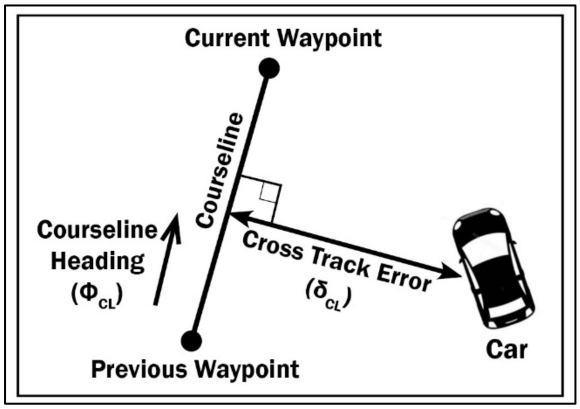


Figure 5-2. Cross track error (CTE)

5.3 Drone Data

For selected roadways, aerial video was captured using a drone to understand the effect of the ATMA on general traffic characteristics of the corridor by visual inspection. These data were helpful in visually reviewing several items, including lane-changing behavior of vehicles following the work platoon (Figure 5-3) and driver behavior in between leader and follower vehicle. The aerial video data were also helpful in proposing driver training techniques – for example, the effect of an ATMA stop in the vicinity of intersections.

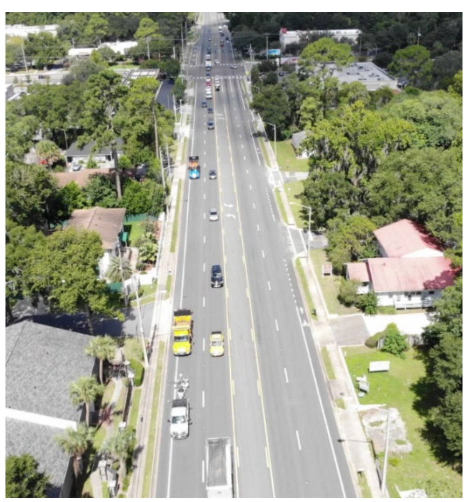


Figure 5-3. Screenshot of drone video data

5.4 Manual Inspections

For closed loop tests, a manual data collection and inspection process was adopted for specific scenarios. These included the following:

- Stopping distance in closed loop test
- Engine status
- Vehicle trajectory
- Driver and passenger experience in closed loop and open road tests
- Queue formation and aggressive driver behavior behind ATMA on two-lane roadways.

Figure 5-4. Manual data collection

5.5 Data Repository

All of the above were stored and catalogued by test number and titles. The quality control process included reviewing the data, eliminating, truncating, or filtering to retain only the useful data. This dataset is stored in an external hard disk to be submitted as a media deliverable (USB) along with the final report. These data are also available to download from UFTI-T2 website: https://techtransfer.ce.ufl.edu/florida-atma-demonstration-and-evalution/.

Chapter 6 – Data Analysis

This chapter details the data analysis undertaken for both closed loop tests and field tests. For each test, the test objective (title), testing procedure, equipment, staff, and expected results were documented. For closed loops, multiple runs were performed to replicate the testing under different condition (e.g., speed changes). For field tests, only one run was planned for each direction; however, in certain cases, testing was modified (delayed, terminated, or extended) based on field conditions.

For closed loop testing, 26 test cases were designed in seven focus areas: safety functions, following accuracy, lateral accuracy, turning requirements, obstacle detection, operational tests, and communication tests. Field testing was conducted on five roads in the Gainesville, FL, area, ranging from urban streets to state roads to an Interstate highway.

6.1 Closed Loop Testing

Table 6-1 lists all the tests undertaken for each of the seven focus areas during the demonstration and testing phase.

Table 6-1. List of focus areas and closed loop test cases

Closed Loop Test Cases	
Focus area 1 – Safety	
TC-1	Automatic stop (A-stop) – Leader vehicle internal button (OCU)
TC-2	Emergency stop – ATMA internal button (OCU)
TC-3	Emergency stop – ATMA external button
TC-4	Emergency stop – Leader independent E-stop button (initiator)
Focus area 2 – Following Accuracy	
TC-5	Follow distance set by user interface (UI) panel
TC-6	Following accuracy on straight line (A&H)
TC-7	Following accuracy on slalom course (A&H)
Focus area 3 – Lateral Accuracy	
TC-8	Lane-changing accuracy (A&H)
TC-9	Lateral offset
Focus area 4 – Turning	
TC-10	Minimum turn radius
TC-11	Obstacle detection – Front
TC-12	Simple curve
TC-13	U-turns
Focus area 5 – Obstacle	
TC-14	Bump test
TC-15	Obstacle detection – Front
TC-16	Vehicle intrusion
TC-17	Object recognition

Table 6-1. List of focus areas and closed loop test cases (continued)

Focus area 6 – Operational tests	
TC-18	Speed test (A&H)
TC-19	Braking – Leader vehicle (A&H)
TC-20	ATMA human driver takeover (A&H)
TC-21	Leader reverse
TC-22	Acceleration/deceleration
Focus area 7 – Communication	
TC-23	Loss of sensor (radar, LIDAR)
TC-24	Loss of GPS
TC-25	Loss of communication (single V2V radio)
TC-26	Loss of communication (both V2V radios)

6.1.1 Focus Area 1 – Safety

The safety tests were designed to evaluate the functionality of various stop buttons on the leader and ATMA vehicles, including: leader vehicle A-stop button on the operator control unit (OCU) and the leader E-stop button (Figure 6-1); ATMA follower emergency stop (E-stop; Figure 6-2); and the ATMA follower external button (Figure 6-3).

Figure 6-1. Leader vehicle A-stop and E-stop

Figure 6-2. ATMA follower E-stop button

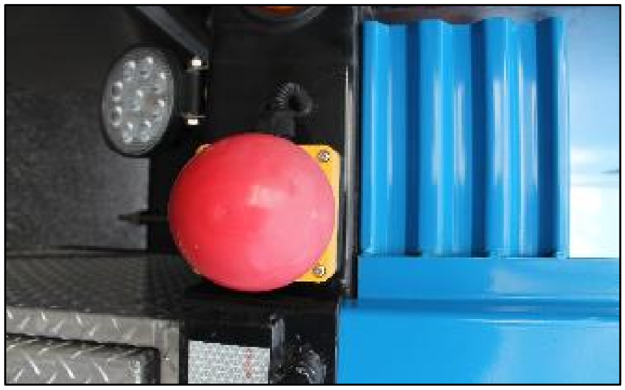


Figure 6-3. Emergency stop ATMA follower external button

The following four subsections explain the test scenarios for Test Cases 1 to 4 and the observed results. In Test Cases 1 through 4, cones were set up at 20-ft spacing, as shown in Figure 6-4. After the back of ATMA passed a marked cone, the stop command was executed. The time and distance it took for the ATMA to stop were recorded.

TC-1: A-stop – Leader Vehicle Internal Button (OCU)

TC-1 – Purpose

This test was designed to check the performance of the ATMA in case the leader activates the A-stop button. This test was implemented on the FDOT closed loop.

TC-1 – Operation Procedure

The test was executed with speeds of 10 and 15 mph, two times for each speed (total of four runs). The leader set the gap to 100 ft and traveled in a straight line until the gap stabilized. After the ATMA passed a marked point, the operator in the leader vehicle activated the A-stop button. Table 2 summarizes the operation procedure, data collection, and expected results.

Table 6-2. Test Case 1 operation procedure, data collection, and expected results

Operation Procedure	• Gap set to 100 feet • Activated leader and ATMA • The leader traveled in a straight line at 10 mph. • Activated A-stop button inside of the leader vehicle at a predetermined location • Repeated test at 15 mph • 2 runs for each speed
Data Collected	• The stopping distance of the ATMA once the A-stop button is activated • The stopping time of the ATMA once the A-stop button is activated • Status of the engine • Video data
Expected Result	ATMA should decelerate and stop
Team members	The leader vehicle driver, ATMA driver, a technician to activate the A-stop, and a technician to record data (external)
Supporting Equipment	Traffic cones and measurement equipment (time and distance)
Total Number of Runs	4

TC-1 – Schematics

Figure 6-4 shows the field setup for this test case. The cones were set at a 20-ft spacing to mark the A-stop activation location and establish a reference point for video reviews (Figure 6-5). The stopping distance was measured after the ATMA stopped, using a measuring wheel.

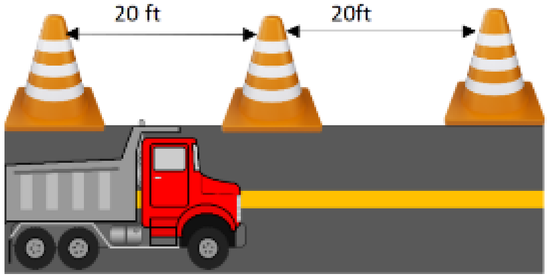


Figure 6-4. Reference points (traffic cones) for Test Case 1

TC-1 – Field Pictures

For this test (as well as the other tests), cameras were installed outside and inside the vehicle for data collection. For instance, Figure 6-5 and Figure 6-6, respectively, show the external camera and ATMA dashcam views.

Figure 6-5. Test Case 1 external camera view

Figure 6-6. Test Case 1, follower dashcam view

TC-1 – Data and Results

Table 6-3 summarizes the field observation for this test.

Table 6-3. Test Case 1 field observations

Run #	Test Speed (mph)	Did ATMA Stop? (Yes/No)	Time to Stop after A-stop Initiation (sec)	Distance Traversed after A-stop Initiation (ft)	Status of Engine after A-stop Initiation (on/off)
1	10	Y	3.12	36	On
2	10	Y	2.85	38	On
3	15	Y	3.26	55	On
4	15	Y	3.77	46	On

As expected, the ATMA stopped after the A-stop command was initiated. It should be noted that unlike E-stop, an A-stop does not turn off the engine because A-stop is activated when there is a less critical issue. The average stopping times for the speeds 10 and 15 mph were 2.99 and 3.52 seconds, respectively. The average stopping distances for the two speeds were 37 and 40.5 ft, respectively.

TC-1 – ATMA Log File Data

The leader truck shares the location information for the follower truck through e-crumbs, and this information becomes the reference guide or the desired location and speed of the follower truck. The log file records the speed and deviation of the follower truck from the leader truck. Figure 6-7 shows the ATMA log file output for Test Case 1. The top picture compares the velocity of the leader truck and the follower ATMA. The bottom picture shows the cross track error (CTE), which is the absolute deviation of the follower truck from its intended path. The velocity graphs are used here for visual review. The graph displays the activation of the A-stop as the graph dips vertically. The CTE statistics shown in Table 6-4 indicate that the follower deviated a maximum of 19.49 inches (Run 4) and an average standard deviation of 6.09 inches. Even though the ideal range for CTE is ±6 inches, in this case, the CTE is not critical because the safety feature that was the focus of interest was E-stop, and this is not sensitive to the lateral deviation because the tests were not performed under perfectly aligned straight lines and, as such, a larger deviation was expected.

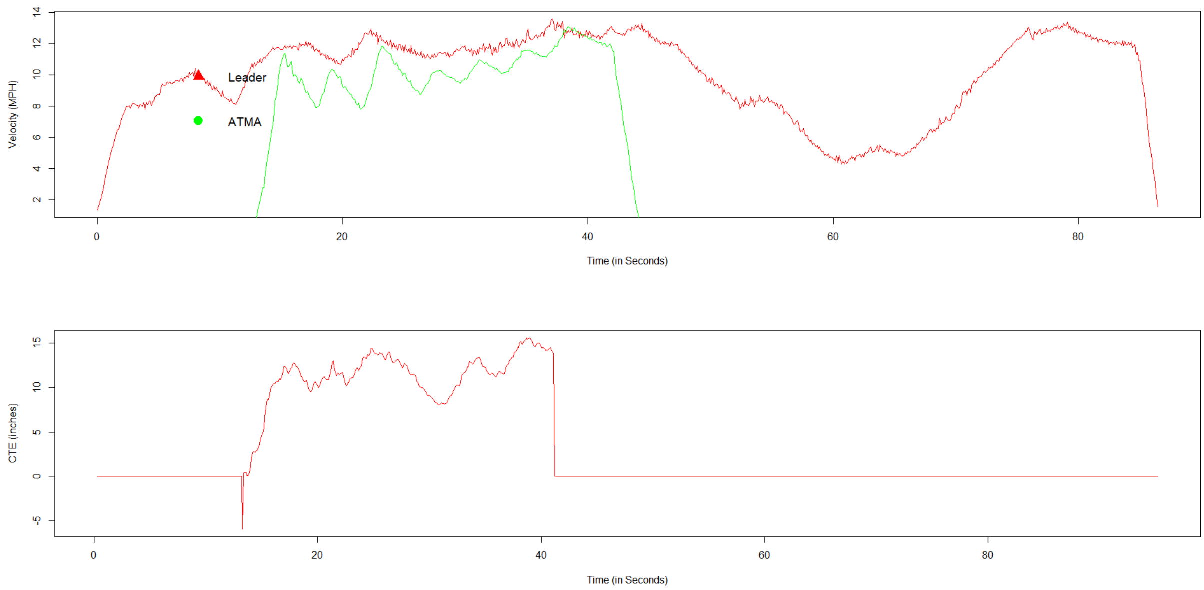


Figure 6-7. ATMA log file output for Test Case 1, Run 1: velocity graph (top); cross track error (CTE) (bottom)

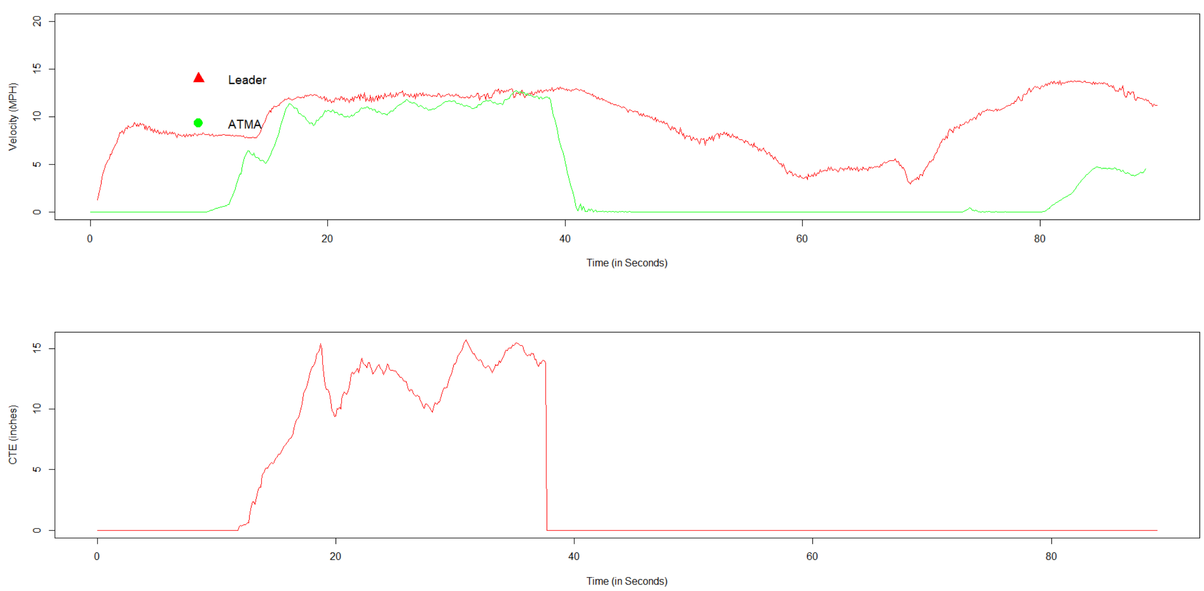


Figure 6-8. ATMA log file output for Test Case 1, Run 2: velocity graph (top); cross track error (CTE) (bottom)

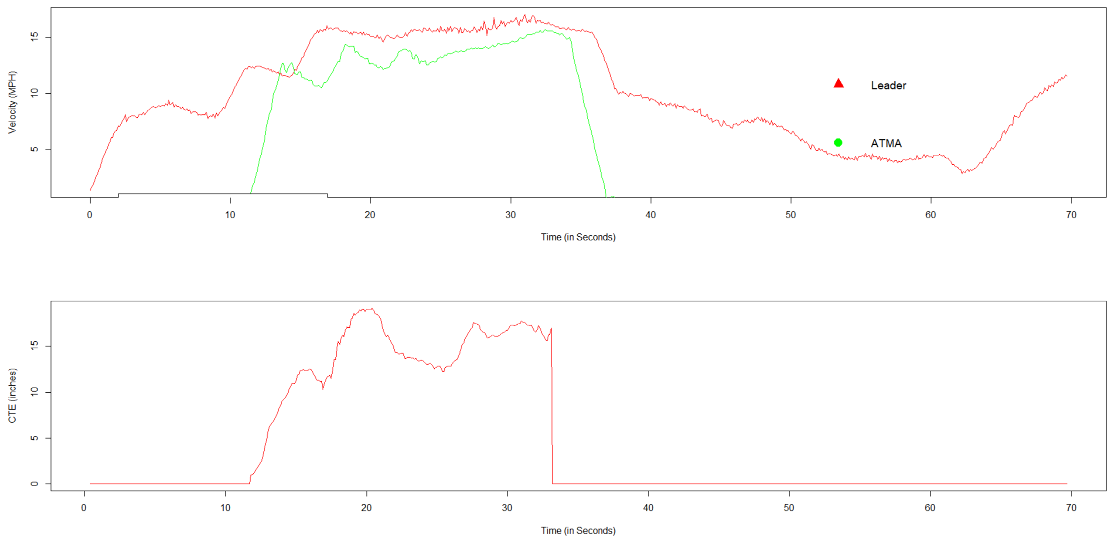


Figure 6-9. ATMA log file output for Test Case 1, Run 3: velocity graph (top); cross track error (CTE) (bottom)

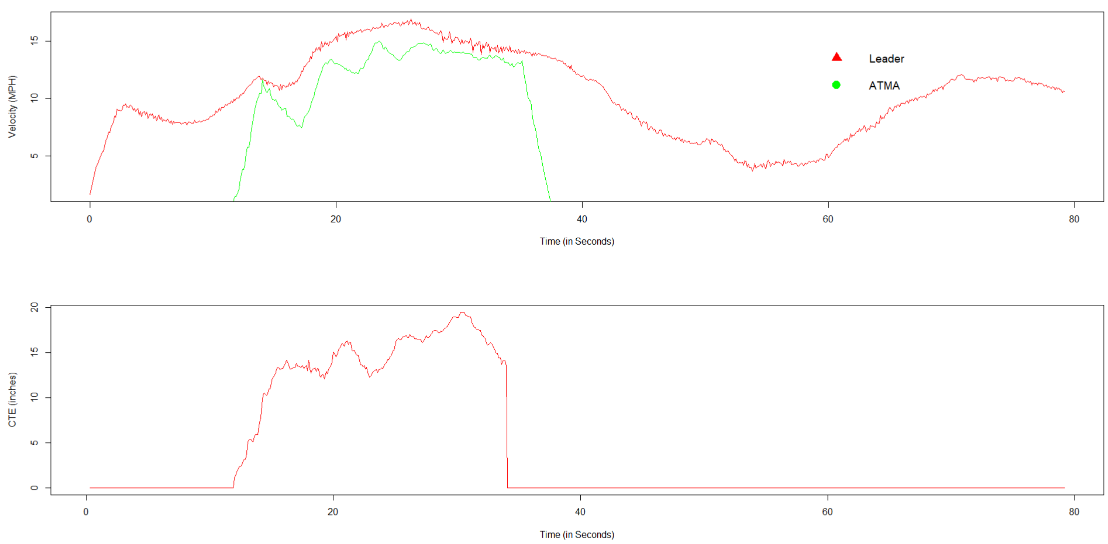


Figure 6-10. ATMA log file output for Test Case 1, Run 4: velocity graph (top); cross track error (CTE) (bottom)

Table 6-4. Test Case 1 ATMA log file analysis results – CTE (inches)

Test	Run #	Min	Max	Mean	Standard Deviation
1	1	-5.91	15.63	3.29	5.39
	2	0	15.75	3.29	5.54
	3	0	19.2	4.3	6.8
	4	0	19.49	3.92	6.63

TC-2 – E-stop: ATMA Internal Button (OCU)

This test was implemented on the FDOT closed loop with speeds of 10 and 15 mph. The test was executed two times for each speed (total of four runs). Note that with E-stop activation, it is expected a serious event has triggered the stop, and the expectation is that the ATMA stops and turns off the engine. Table 6-5 explains the operation procedure, data collection, and expected results.

Table 6-5. Test Case 2 operation procedure, data collection, and expected results

Operation Procedure	• Gap set to 100 ft • Activated leader and ATMA • Leader traveled in a straight line at 10 mph • Activated E-stop button inside of the ATMA vehicle at a predetermined location • Repeated test at 15 mph • 2 runs for each speed
Data Collected	• The stopping distance of the ATMA once the E-stop button is activated • The stopping time of the ATMA once the E-stop button is activated • ATMA log data after each run • Status of the engine • Video data
Expected Result	ATMA should decelerate and stop, and the engine should be shut off.
Team Members	The leader vehicle driver, ATMA driver, a technician to activate the E-stop, and a technician to record data (external)
Supporting Equipment	Traffic cones and measurement equipment (time and distance)
Total Number of Runs	4

TC-2 – Schematics

Figure 6-11 shows the field setup for this test case, which was similar to A-stop setup. The cones were set at a 20-ft spacing to mark E-stop locations and provide a reference point for video reviews. The stopping distance was measured after the ATMA stopped using a measuring wheel.

TC-2 – Field Pictures

Figure 6-11. External camera view

Figure 6-12. Follower dashcam view

Table 6-6 summarizes the field observation for this test. In all the runs, the ATMA stopped after the stop command, as expected. All E-stops, including the ATMA internal E-stop button, shut the engine off. The average stop times for the speeds 10 and 15 mph were 3.65 and 3.52 seconds, respectively. The average stopping distances for the two speeds were 41 and 58.5 ft, respectively.

Table 6-6. Test Case 2 field observations

Run #	Speed (mph)	ATMA Stopped	Time to Stop (sec)	Distance Traversed (ft)	Status of Engine (On/Off)
1	10	Y	3.34	40	Off
2	10	Y	3.96	42	Off
3	15	Y	3.63	56	Off
4	15	Y	3.4	61	Off

TC-2 – ATMA Log Files

No log files were required for this test case because the results were quantified with manual field data collection detailed above.

TC-3: E-stop: ATMA External Button

This test was performed on the FDOT closed loop at a speed of 5 mph. There are two E-stop buttons on the ATMA, one at each side (refer to Chapter 3 for system overview). The test was executed two times by pressing each button (total of four runs). Table 6-7 summarizes the operation procedure, data collection, and expected results.

Table 6-7. Test Case 3 operation procedure, data collection, and expected results

Operation Procedure	• Gap set to 100 ft • Activated leader and ATMA • Leader traveled in a straight line at 5 mph • Activated E-stop button located on the driver side of the ATMA (external) at a predetermined location • Repeated test for the passenger-side button • 2 runs each for both E-stop buttons
Data Collected	• The stopping distance of the ATMA once the E-stop button is activated • The stopping time of the ATMA once the E-stop button is activated • ATMA log data after each run • Status of the engine • Video data
Expected Result	ATMA should decelerate and stop, and the engine should be shut off.
Team members	The leader vehicle driver, ATMA driver, a technician to activate the E-stop, and a technician to record data (external)
Supporting Equipment	Traffic cones and measurement equipment (time and distance)
Total Number of Testing Runs	4

Similar to previous tests, the cones were set at a 20-ft spacing to mark the E-stop location and provide a reference point for video reviews. The stopping distance was measured after the ATMA stopped.

TC-3 – Field Pictures

Figure 6-13. External camera view

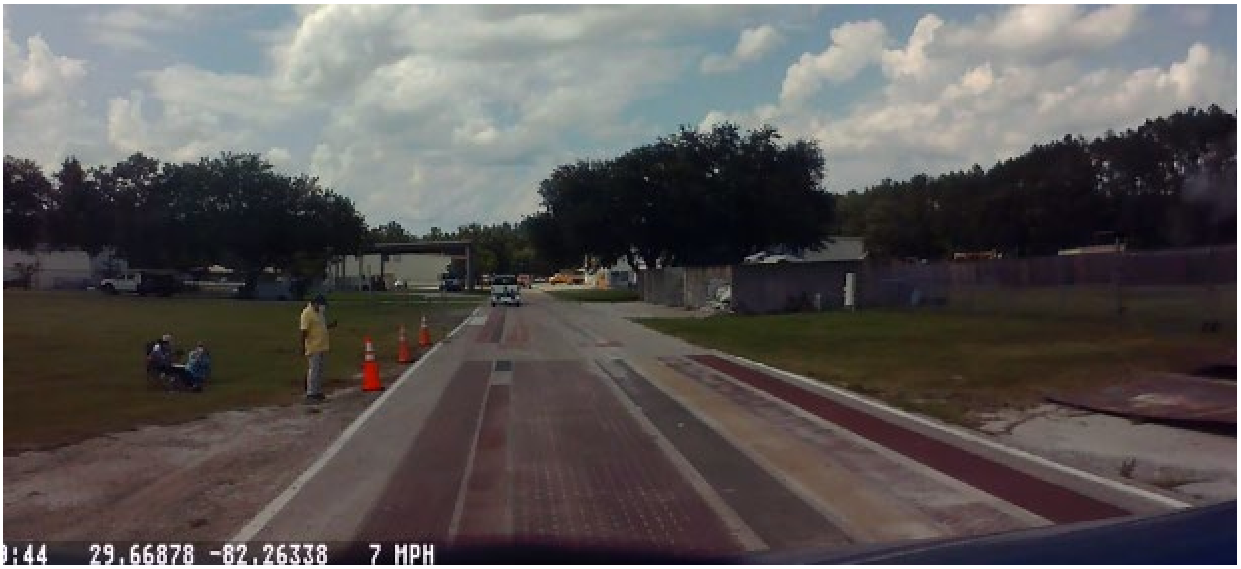


Figure 6-14. Test Case 3 field observations

Table 6-8. Test Case 3 field observations

Run #	Button	Speed (mph)	ATMA Stopped	Time to Stop (sec)	Distance Traversed (ft)	Status of Engine (On/Off)
1	Driver side	5	Y	3.5	23	Off
2	Driver side	5	Y	3.46	21	Off
3	Passenger side	5	Y	2.3	36	Off
4	Passenger side	5	Y	3.6	26	Off

TC-3 – ATMA Log Files

No log files were required for this test case since the results were quantified with field data collection detailed above.

TC-4: E-stop: Leader Internal E-stop Button

This test was implemented on the FDOT Closed Loop at speeds of 10 and 15 mph. The test was executed two times for each speed (total of four runs). Table 6-9 summarizes the operation procedure, data collection, and expected results.

Table 6-9. Test Case 4 operation procedure, data collection, and expected results

Operation Procedure	• Gap set to 100 ft • Activated leader and ATMA • The leader traveled in a straight line at 10 mph. • Activated E-stop button inside of the leader vehicle at a predetermined location • Repeated test at 15 mph • 2 runs for each speed
Data Collected	• The stopping distance of the ATMA once the E-stop button is activated • The stopping time of the ATMA once the E-stop button is activated • ATMA log data after each run • Status of the engine • Video data
Expected Result	ATMA should decelerate and stop, and the engine should be shut off.
Team Members	The leader vehicle driver, ATMA driver, a technician to activate the E-stop, and a technician to record data (external)
Supporting Equipment	Traffic cones and measurement equipment (time and distance)
Total Number of Testing Runs	4

Similar to previous tests, the cones were set at a 20-ft spacing to mark E-stop locations and provide a reference point for video reviews. The stopping distance was measured after the ATMA stopped.

TC-4 – Field Pictures

Figure 6-15. External camera view

Figure 6-16. Dashcam view

Table 6-10. Test Case 4 field observations

Run #	Speed (mph)	ATMA Stopped	Time to Stop (sec)	Stopping Distance (ft)	Status of Engine (on/off)
1	10	Y	4.22	41	Off
2	10	Y	4.52	50	Off
3	15	Y	3.55	61	Off
4	15	Y	3.56	55	Off

6.1.2 Focus Area-2 – Following Accuracy

Four tests were designed to quantify the following accuracy of the ATMA in straight travel line, on a slalom course, and during a lane change. Following accuracy refers to how accurately the ATMA follows the footprint of the leader vehicle as its intended path. The accuracy measure used in this study is cross track error (CTE) determined from Kratos output log files as well as visual observations in the field. In addition, test case TC-5 measured the time it takes for the ATMA to change its distance to the leader vehicle.

TC-5: Following Distance Set by User Interface (UI) Panel

The first test was executed on the FDOT closed loop (CL) in a circular path. There was not enough distance available to achieve the desired command gap within the closed loop. As an alternative, the test was implemented on an open road: Waldo Road in Gainesville, FL. This test focused on measuring the time that it takes for the ATMA to change its gap with the follower. The user interface inside the leader vehicle includes a gap command to set the distance between the leader vehicle and the ATMA.

Table 6-11 summarizes the operation procedure, data collection, and expected results. In the first run, the gap changed from 300 ft to 500 ft to 750 ft, to 1,000 ft, with a speed of 10 mph. In the second run, the gap was changed in reverse order, from 1,000 ft to 750 ft to 500 ft to 300 ft. These two runs were duplicated with a speed of 15 mph (runs 3 and 4). In the next runs, the gap changed directly from 300 ft to 1,000 ft and vice versa, with speeds of 10 and 15 mph.

Table 6-11. Test Case 5 operation procedure, data collection, and expected results

Operation Procedure	• Activated the leader and the ATMA. Command gap distance was set to 300 ft and drove in a straight line at 10 mph. • While traveling at a steady 10 mph, the command gap was set to 500 ft, and the actual gap was allowed to stabilize. • Changed the command gap to 750 ft and 1,000 ft, and the actual gap was allowed to stabilize. • Repeated the change in the command gap from 1,000 ft to 750 ft to 500 ft to 300 ft, allowing the actual gap to stabilize after each change • Repeated the tests with a speed of 15 mph • Repeated the tests from 300 ft directly to 1,000 ft and vice versa with a speed of 15 mph • Log data were pulled after each test • Repeated each test at least 2 times

Table 6 11. Test Case 5 operation procedure, data collection, and expected results (continued)

Data Collected	• The speed change during the process • The time is taken by ATMA to stabilize at the command gap • Stabilized follow distance accuracy
Expected Result	The ATMA can perform the actual gap distance changes via the leader user interface (UI)
Team Members	The leader vehicle driver, ATMA driver, a technician to activate the E-stop, and a technician to record data (external).
Supporting Equipment	Laptop, Ethernet cable to connect with vehicle, and cones
Total Number of Testing Runs	6

TC-5 – Schematics

The testing scheme developed was not successful within a closed loop. This test required a very long track (>1,000 ft) to achieve the command gap; therefore, it was conducted in the field (Waldo Rd).

TC-5 – Field Pictures

Figure 6-17. Insufficient test track in closed loop location for Test Case 5 (closed loop), external camera view

Figure 6-18. Test Case 5 (field test on Waldo Rd), external camera view

Figure 6-19. Test Case 5 (field test), dashcam view

Table 6-12 summarizes the field test results. Depending on the profile of the roadway, the time to stabilize varied. Generally, at a lower speed, the ATMA took longer to increase the command gap, and the opposite holds true to reduce the command gap at a higher speed. Overall, the system performed as expected. First, the ability to change the command gap while operating was validated, and second, to achieve the desired gap within a reasonable time was quantified.

Table 6-12. Test Case 5 field observations

Run #	Speed (mph)	Command Gap (ft)	Time to Stabilize (mm:ss)	Stabilized Accuracy (ft)
1a	10	300 → 500	04:03	±15
1b	10	500 → 750	04:17	±15
1c	10	750 → 1,000	04:44	±15
2a	10	1,000 → 750	03:51	±15
2b	10	750 → 500	03:25	± 15
2c	10	500 → 300	03:15	± 15
3a	15	300 → 500	00:29	±15
3b	15	500 → 750	01:33	±15
3c	15	750 → 1,000	02:51	±15
4a	15	1,000 → 750	02:21	±15
4b	15	750 → 500	03:22	±15
4c	15	500 → 300	02:57	± 15
5	15	300 → 1,000	05:50	± 15
6	15	1,000 → 300	04:35	±15

TC-5 – ATMA Log File Data

Figure 6-20 below shows the processed data from ATMA log file. In Figure 6-20, the speed profile red for the leader vehicle and green for the ATMA. The speed profiles changed over time with the desired command gap. The ATMA speeds exceeded the leader vehicle's when the command gap was reduced so in order to narrow the gap between the leader and follower, the follower increased its speed to achieve the desired gap. A UF team member visually confirmed when each command gap was attained using the interface in the ATMA. It is noted that during the test, four A-stops occurred due to vehicle intrusion during Run 1, three A-stops during Run 2 and Run 3.

NB Run 1 Command gap sequence: 300, 500, 750,1000, 750, 500, 300

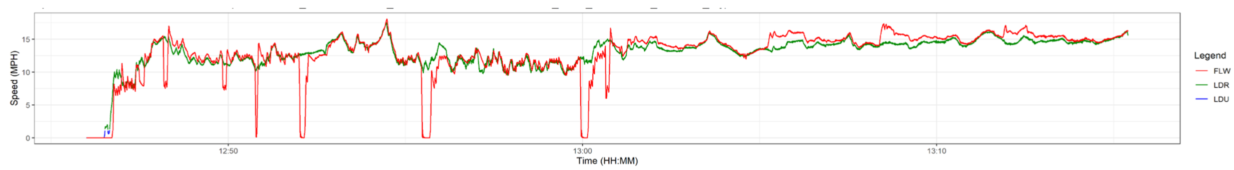


Figure 6-20. Northbound, Run 1: Speed profiles of leader and follower

SB Run 1 Command gap sequence: 300, 500, 750, 1000, 750, 500, 300

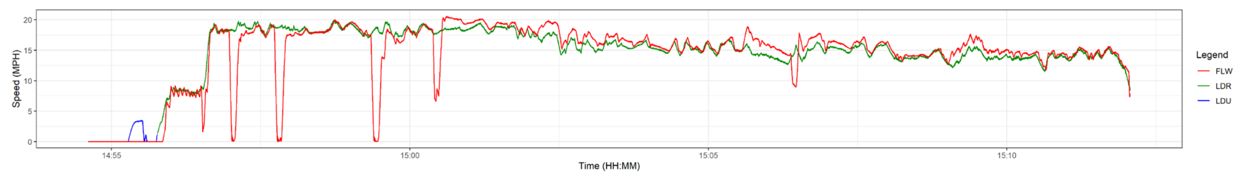


Figure 6-21. Southbound, Run 1: Speed profiles of leader and follower

The figures below show the distance vs. time plot developed to review the headway distance and headway time through the testing. Figures below show the plot for each run as the command gap was changed to different distance. The vertical distance between the two lines is the headway, which corresponds to the command gap input by the leader operator. For each test, the command gap was achieved as expected. In the each graph below, one can visually inspect that the follower achieved the headway and maintained consistent distance throughout the test.

SB Run 1 Command gap sequence: 300, 1000, 300

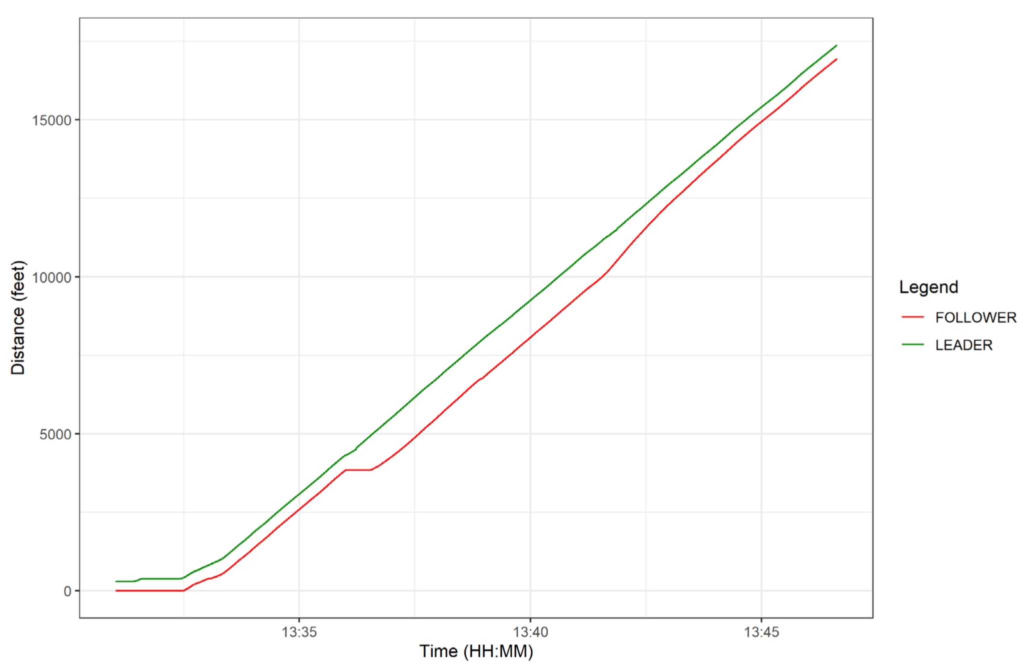


Figure 6-22. Southbound Run 1: Distance vs. time plot

The figure below shows the comparison of the desired gap of ATMA versus the gap set forth by the leader. In each case, when the command gap was changed, the follower ATMA accelerated or decelerated to achieve the desired gap.

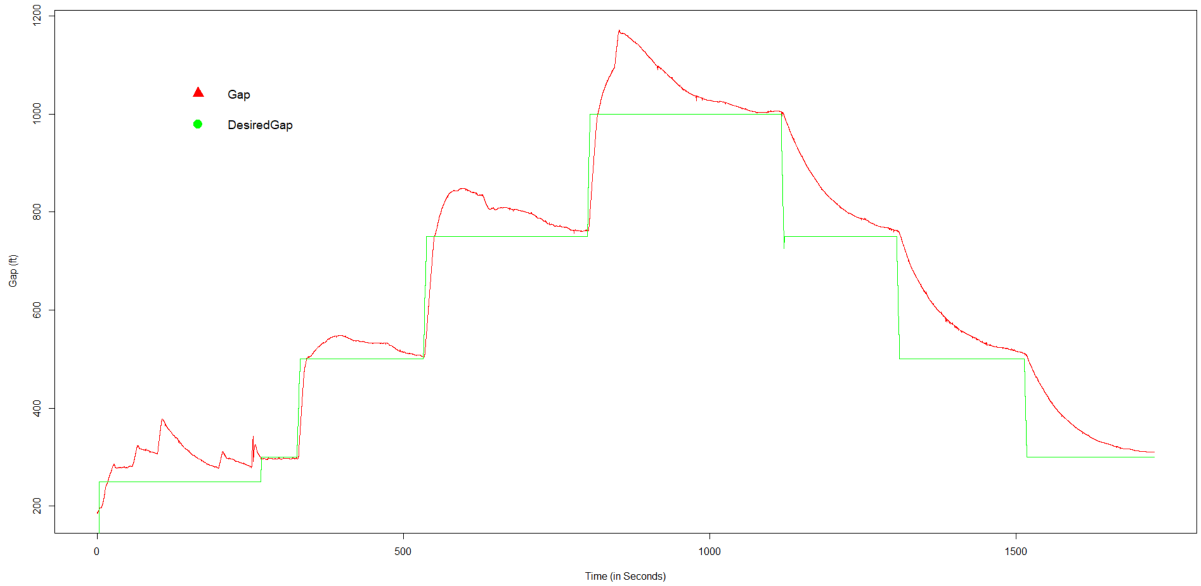


Figure 6-23. Test Case 5, Run 1: follower truck gap response to changes in the command gap

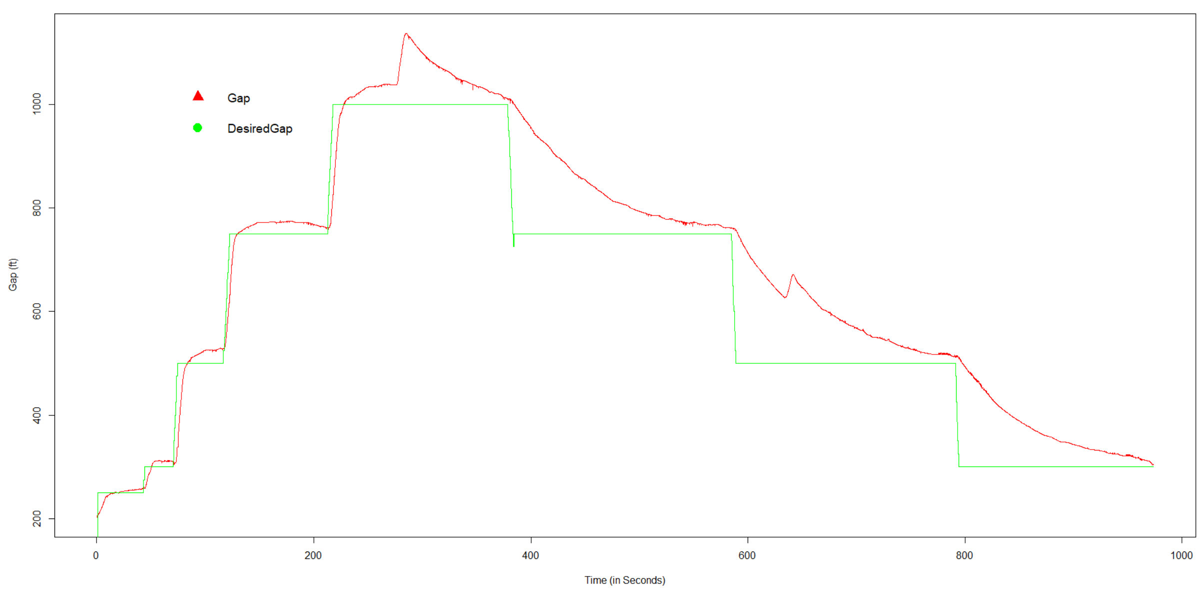


Figure 6-24. Test Case 5, Run 2: follower truck gap response to changes in command gap

Table 6-13. Test Case 5 ATMA log file analysis results – CTE (inches)

Test	Run #	Min	Max	Mean	Standard Deviation
5	1	-6.1	5.91	-2.34	1.32
	2	-9.69	5.91	-3.93	2.35
	3	-13.74	5.91	-5.91	1.87

TC-6: Following Accuracy on Straight Line (Human Driver)

This test was designed to measure the accuracy of the ATMA following the leader vehicle footprint on a straight path. The accuracy measure is CTE. This test was implemented on a closed loop with speeds of 10 and 15 mph. Table 6-14 summarizes the operation procedure, data collection, and expected results.

Table 6-14. Test Case 6 operation procedure, data collection, and expected results

Operation Procedure	• Activated leader and ATMA. Command gap distance was set to 100 ft and drove in a straight line at 10 mph. • Repeated the test with a speed of 15 mph • Log data were pulled after each test. • Repeated each test at least 2 times
Data Collected	Worst-case lane accuracy on a straight line
Expected Result	The ATMA maintains the lateral accuracy of ±6 inches from the leader's path.
Team Members	The leader vehicle driver, ATMA driver, and technician to set up system and export data
Supporting Equipment	Laptop, Ethernet cable to connect with vehicle, and cones
Total Number of Testing Runs	4

TC-6 – Schematics

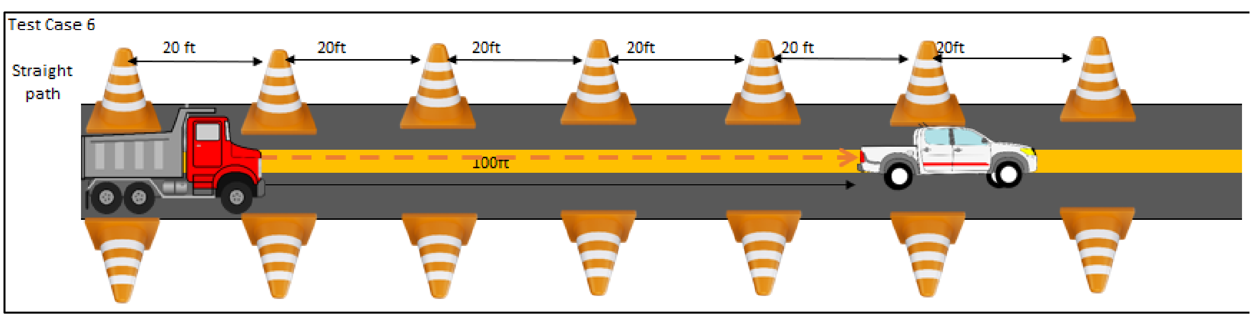


Figure 6-25. Closed loop test setup

TC-6 – Field Pictures

Figure 6-26. External camera view

Figure 6-27. Dashcam view

Table 6-15 includes the test case results for Test 6 on lane accuracy. Field observations included visual inspection while the leader vehicle and ATMA complete the course. In addition, cameras were set up on cones to capture the trajectory of both vehicles. Based on the visual inspection, the ATMA maintained a straight line and lateral accuracy.

Table 6-15. Test Case 6 field observations

Run #	Speed (mph)	Mode of Operation (Autonomous/Human)	Straight Line Accuracy Maintained	Lateral Accuracy Maintained
1	10	A	Y	Y
2	10	A	Y	Y
3	15	A	Y	Y
4	15	A	Y	Y

TC-6 – ATMA Log File Data

In addition to the visual inspection, log files were evaluated to compare the cross track error (Figure 6-28–Figure 31) for all runs. With an average deviation of 1.075 inches for all four runs, the ATMA maintained the lateral accuracy as expected. A visual inspection of the velocity graphs also indicates a synchronized operation for the following speed. The CTE graphs also indicate a maximum deviation of 4.25 inches, which is less than the 6 inches threshold established.

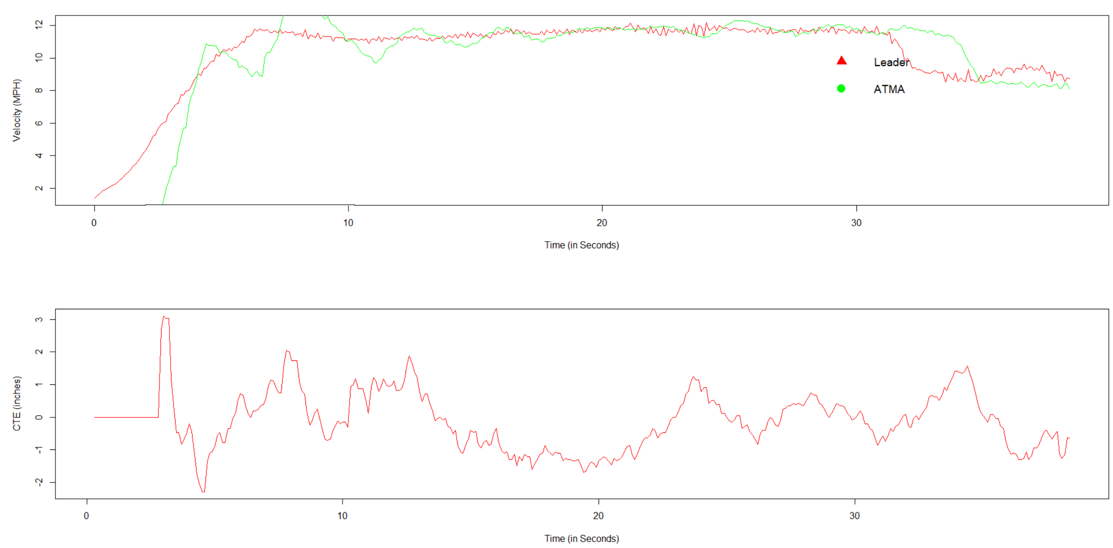


Figure 6-28. Test Case 6, Run 1: follower truck velocity (top); cross track error (CTE) (bottom)

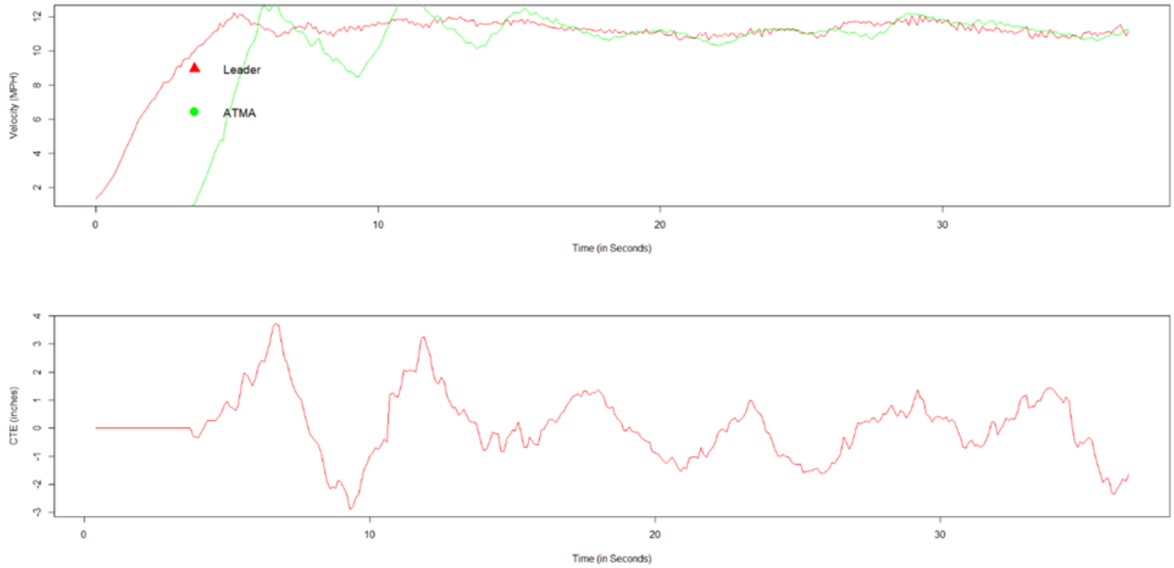


Figure 6-29. Test Case 6, Run 2: follower truck velocity (top); cross track error (CTE) (bottom)

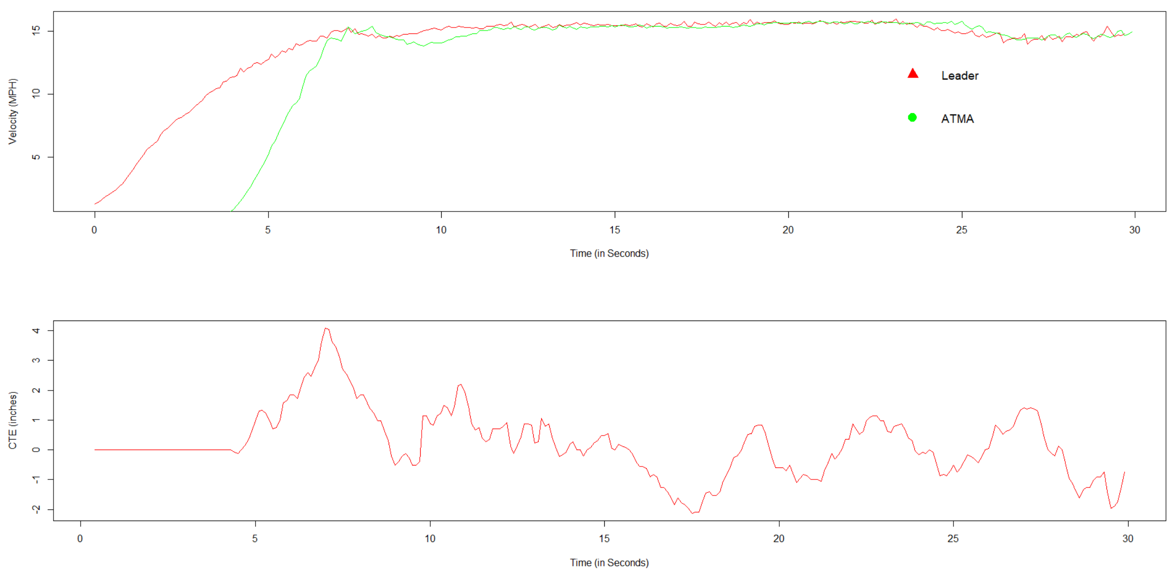


Figure 6-30. Test Case 6, Run 3: follower truck velocity (top); cross track error (CTE) (bottom)

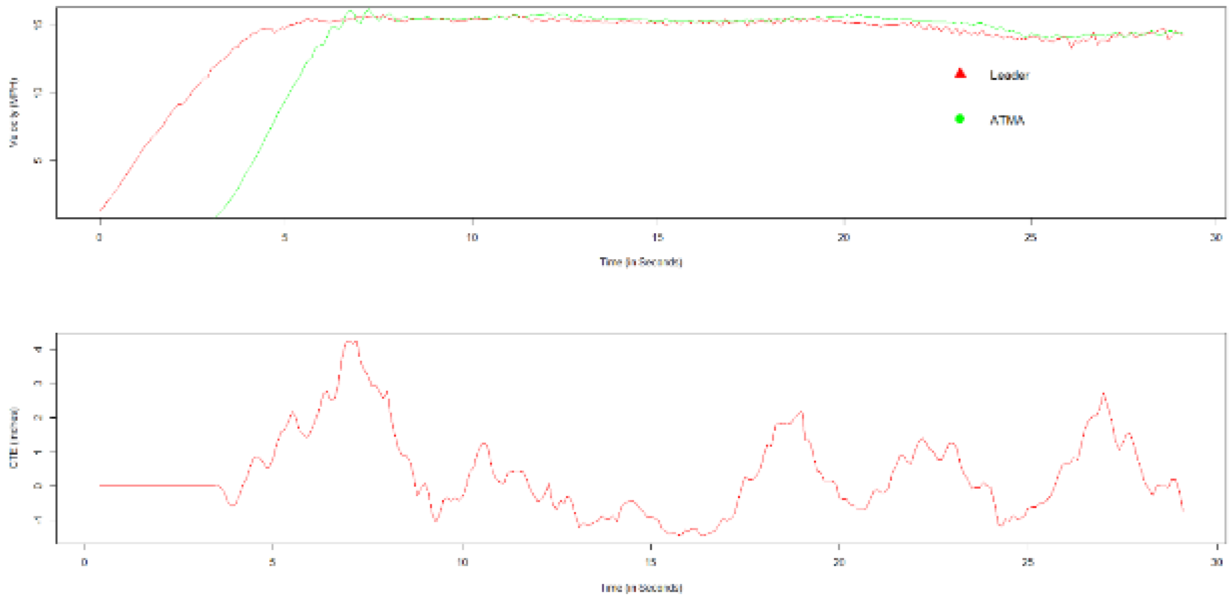


Figure 6-31. Test Case 6, Run 4: follower truck velocity (top); cross track error (CTE) (bottom)

Table 6-16. Test Case 6 ATMA log file analysis results – CTE (inches)

Test	Run #	Min	Max	Mean	Standard Deviation
6	1	-2.28	3.11	-0.11	0.88
	2	-2.87	3.74	0.07	1.15
	3	-2.13	4.09	0.21	1.09
	4	-1.46	4.25	0.34	1.18

TC-7: Following Accuracy on Slalom Course

This test was designed to measure the accuracy of the ATMA following the leader vehicle footprint on a slalom course. CTE was used as a performance measure for this test. This test was implemented on a closed loop with speeds of 10 and 15 mph. Table 6-17 summarizes the operation procedure, data collection, and expected results.

Table 6-17. Test Case 7 operation procedure, data collection, and expected results

Operation Procedure	• Slalom course lane was developed by setting up cones 100 ft apart (minimum of 5 cones) • Activated leader and ATMA drove on slalom course at 10 mph • Repeated the test with a speed of 15 mph • Log data were pulled after each test. • Repeated each test at least 4 times
Data Collected	Cross track error and speed
Expected Result	Ensure the ability of ATMA to maintain lane accuracy in curves

Table 6-17. Test Case 7 operation procedure, data collection, and expected results (continued)

Team Members	The leader vehicle driver, ATMA driver, and technician to set up the system and export data
Supporting Equipment	Laptop, Ethernet cable to connect with vehicle, and cones
Total Number of Testing Runs	16

TC-7 – Schematics

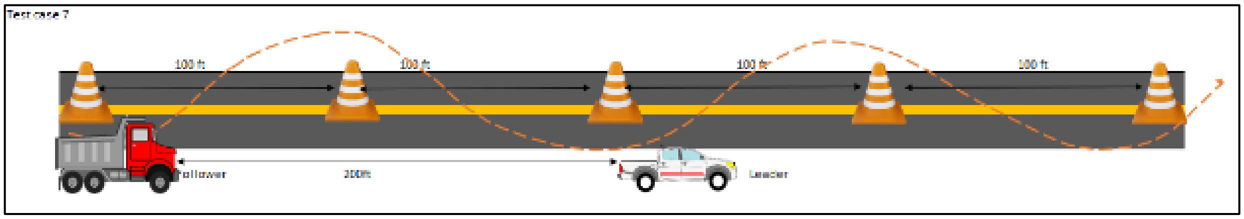


Figure 6-32. Closed loop slalom test setup

TC-7 – Field Pictures

Figure 6-33. External camera view of the slalom course

Figure 6-34. Dashcam view of the slalom course

Table 6-18 shows the autonomous and human driver results for Test Case 7. As can be seen that ATMA maintained lane accuracy in all scenarios. In one of the runs, when a human driver was negotiating the slalom course, one of the cones was struck which indicated the deviation from the assigned course.

Table 6-18. Test Case 7 field observations

Run #	Speed (mph)	Autonomous/Human Driver	Lane Accuracy Maintained (Autonomous)
1	10	A	Y
2	10	A	Y
3	10	A	Y
4	10	A	Y
5	15	A	Y
6	15	A	Y
7	15	A	Y
8	15	A	Y
9	10	H	Y
10	10	H	Y
11	10	H	Y
12	10	H	Y
13	15	H	Y
14	15	H	Y
15	15	H	N (Cone was hit)
16	15	H	Y

TC-7 – ATMA Log File Data

In addition to the visual inspection and field data collected, the ATMA log files were analyzed. Figure 6-35 shows the overlay of the leader vehicle trajectory (in orange) with the follower ATMA (in green). As can be seen, the follower ATMA maintained a consistent path based on the GPS trajectory data. Figures

6-36 through 6-43 show the velocity plots and the CTE plots for Test Case 7, Runs 1 through 8, and Table 6-19 shows the statistics of the CTE analysis. The CTE statistics indicate a maximum deviation of 24.72 inches with an average maximum of 15.85 inches and an average minimum of -14.24 inches which is higher than the established 6-inch threshold. The average of CTEs was 0.49 in with a standard deviation is 6.3 inches.

Figure 6-35. Path of the follower vehicle on the slalom course

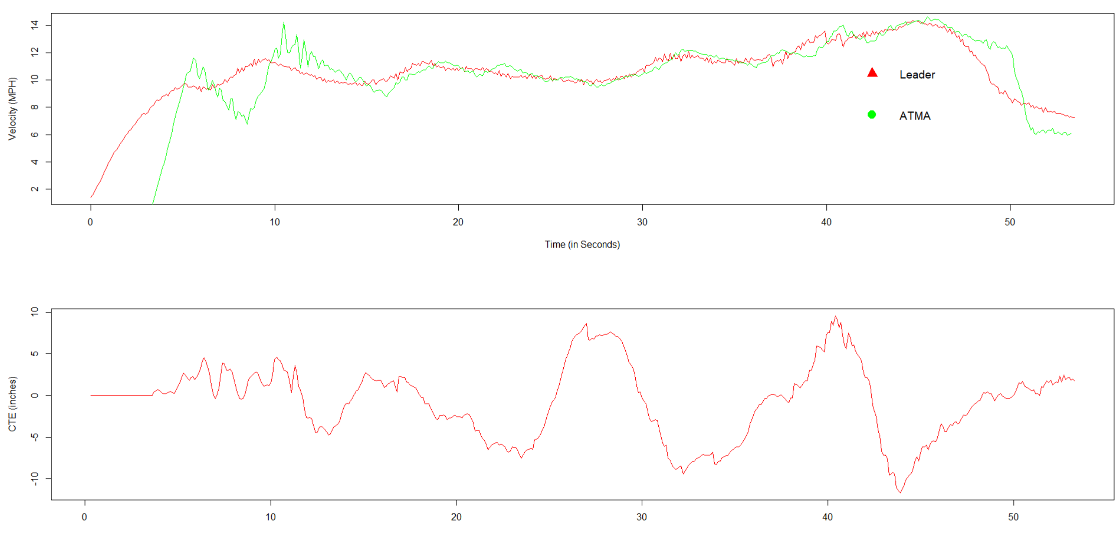


Figure 6-36. Test Case 7, Run 1: follower truck velocity (top); cross track error (CTE) (bottom)

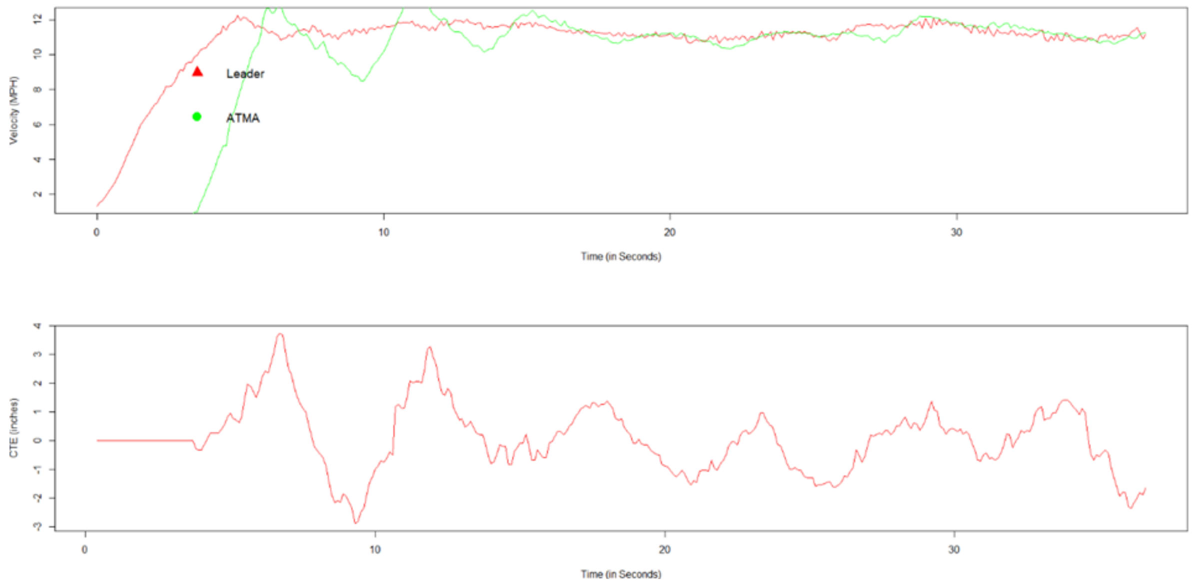


Figure 6-37. Test Case 7, Run 2: follower truck velocity (top); cross track error (CTE) (bottom)

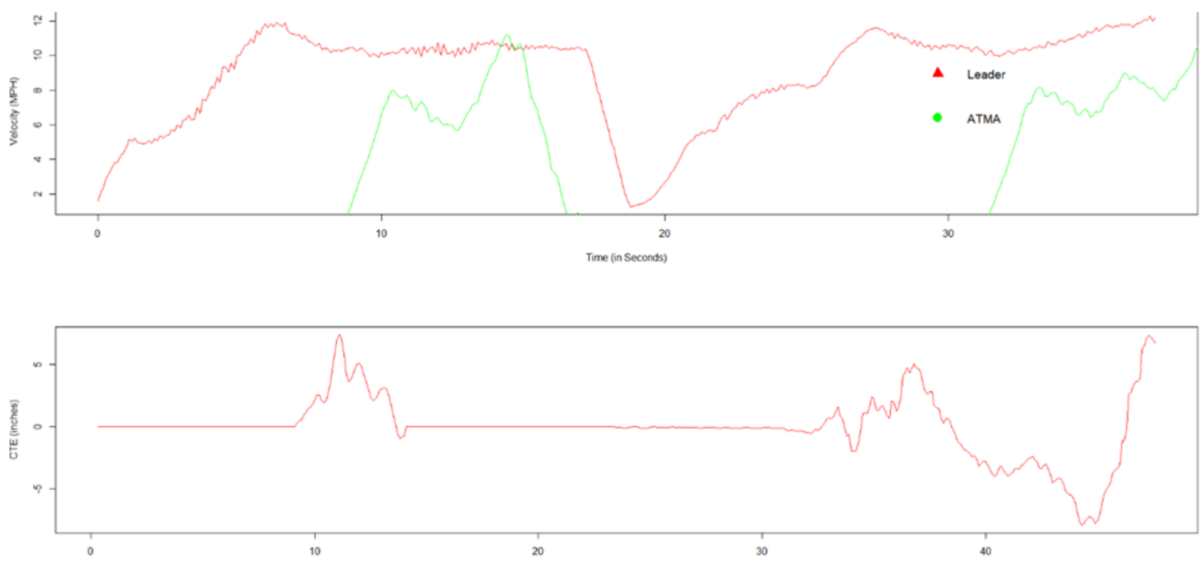


Figure 6-38. Test Case 7, Run 3: follower truck velocity (top); cross track error (CTE) (bottom)

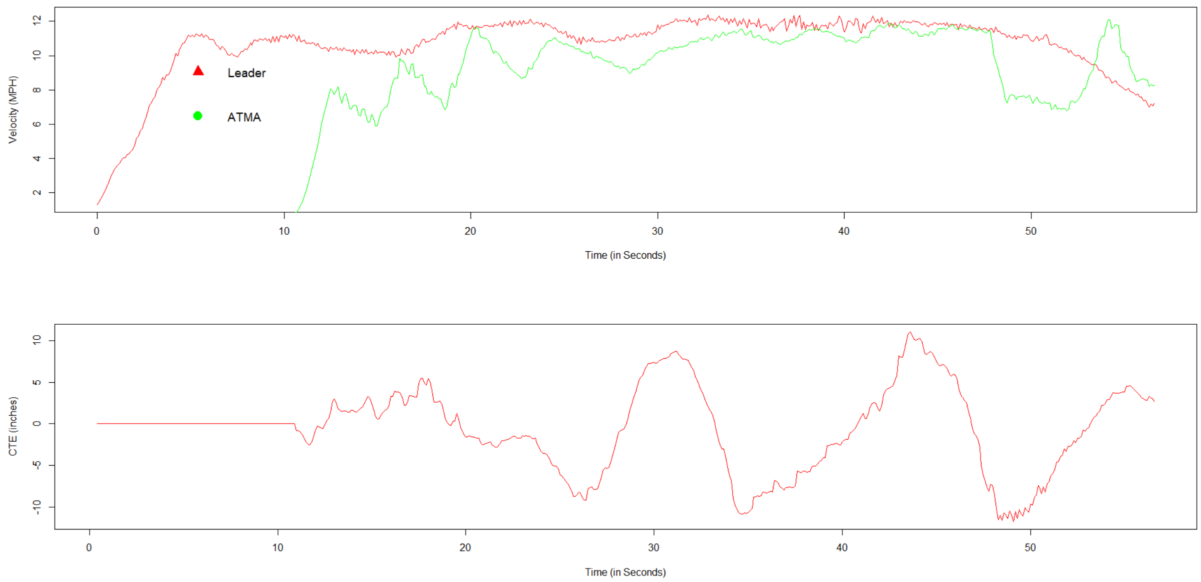


Figure 6-39. Test Case 7, Run 4: follower truck velocity (top); cross track error (CTE) (bottom)

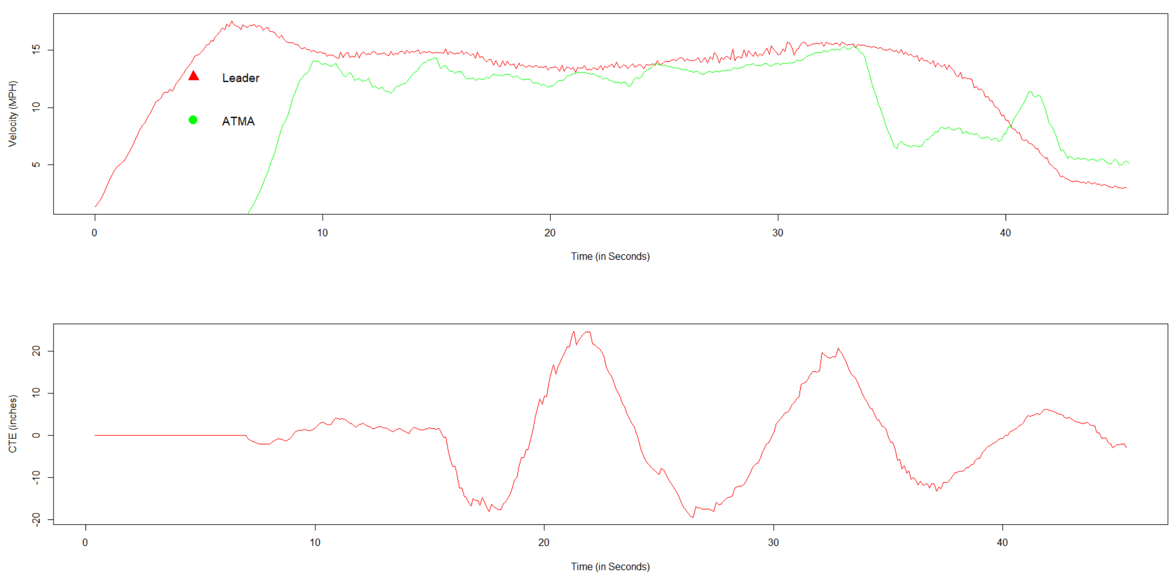


Figure 6-40. Test Case 7, Run 5: follower truck velocity (top); cross track error (CTE) (bottom)

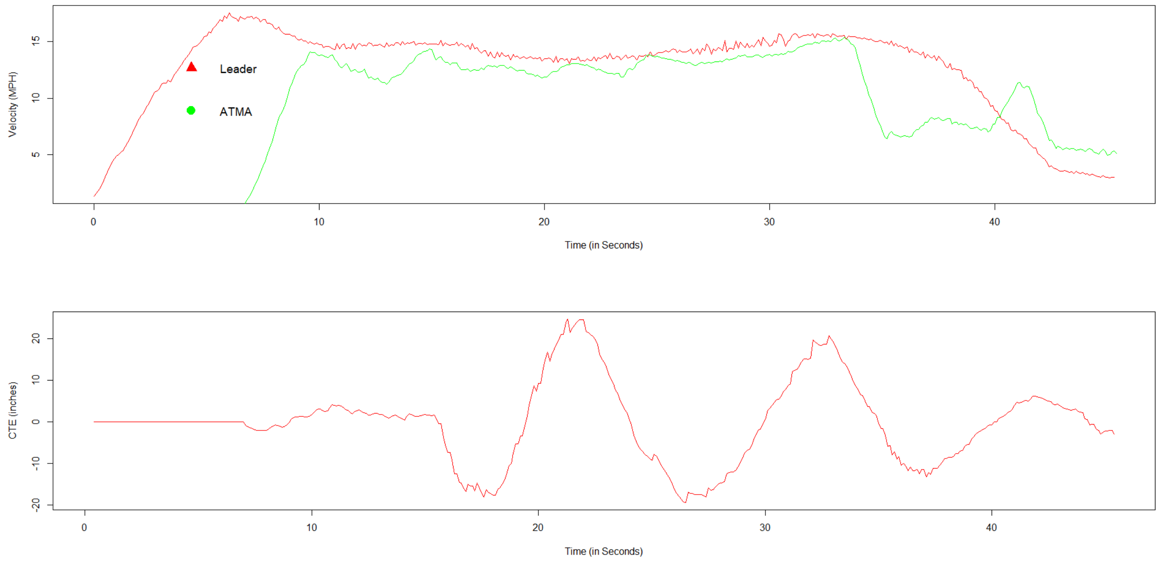


Figure 6-41. Test Case 7, Run 6: follower truck velocity (top); cross track error (CTE) (bottom)

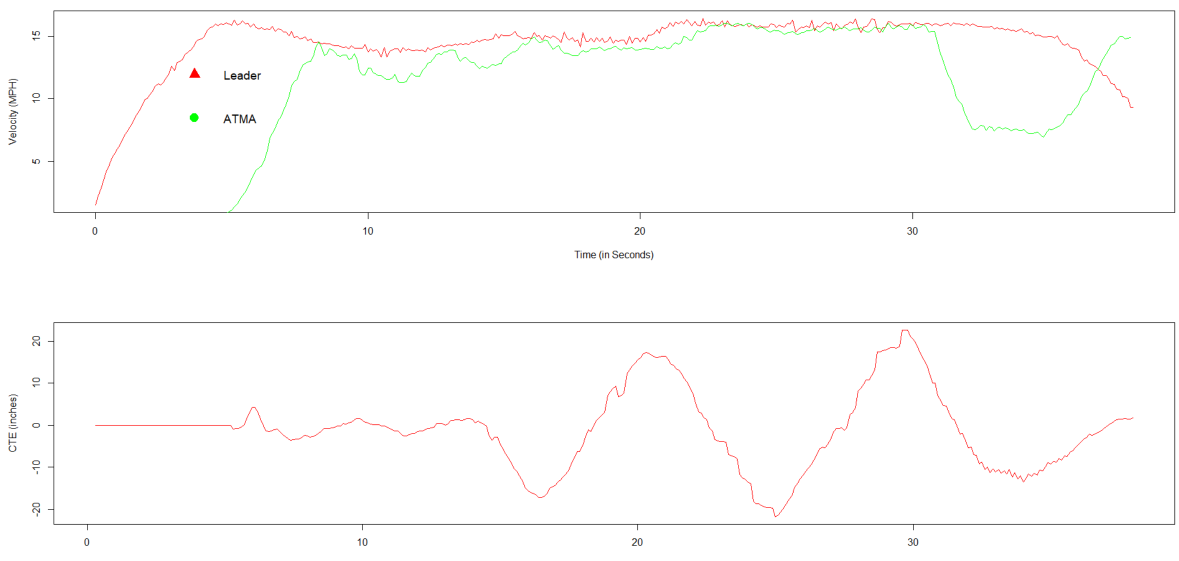


Figure 6-42. Test Case 7, Run 7: follower truck velocity (top); cross track error (CTE) (bottom)

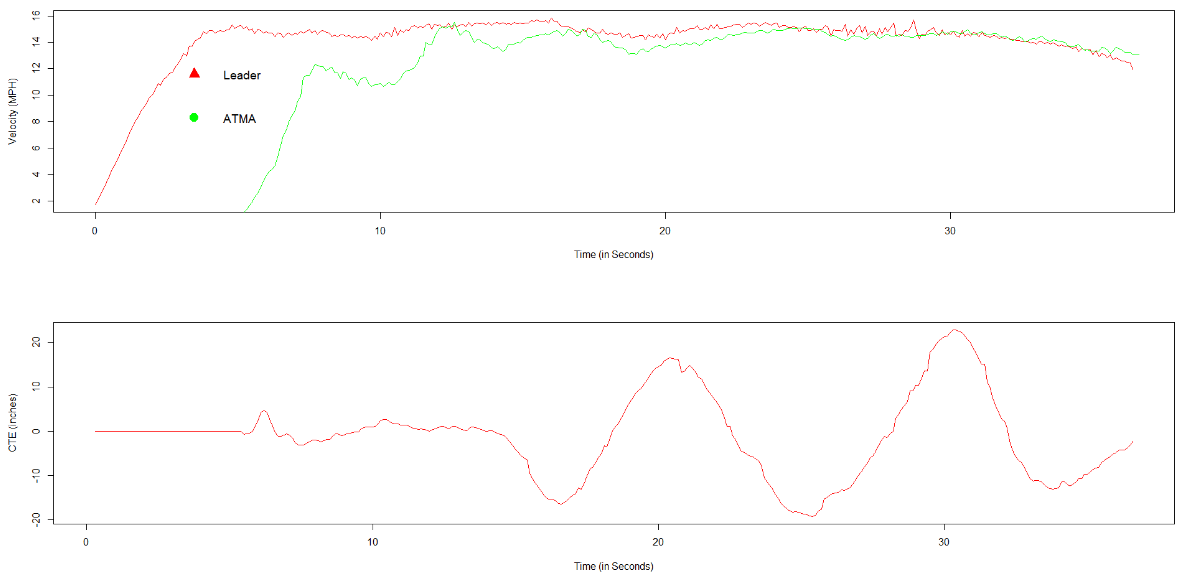


Figure 6-43. Test Case 7, Run 8: follower truck velocity (top); cross track error (CTE) (bottom)

Table 6-19. Test Case 7 ATMA log file analysis results – CTE (inches)

Test	Run #	Min	Max	Mean	Standard Deviation
7	1	-11.65	9.57	-0.72	4.38
	2	-2.87	3.74	0.07	1.15
	3	-7.91	7.44	-0.04	2.42
	4	-11.69	11.06	-0.58	4.96
	5	-19.41	24.72	-0.17	9.55
	6	-19.41	24.72	-0.17	9.55
	7	-21.77	22.64	-1.17	9
	8	-19.25	22.91	-1.11	9.33

6.1.3 Focus Area 3 – Lateral Accuracy

TC-8: Lane Change

This test was designed to measure the accuracy of the ATMA following the leader vehicle footprint during a lane change. The accuracy measure is CTE. This test was implemented on a closed loop with speeds of 10 and 15 mph. Table 6-20 summarizes the operation procedure, data collection, and expected results. Lane changes were conducted both to a lane to the right of the ATMA (lane change to right) and then repeated with lane changes to a lane to the left of the ATMA (lane change to left).

Table 6-20. Test Case 8 operation procedure, data collection, and expected results

Operation Procedure	• Two adjacent lanes, 12 ft wide and 600 ft long, were set up with cones at a spacing of 10 ft. • Removed the cones between the two lanes for 200 ft; ensured that there is enough space to complete the lane change • Activated leader and ATMA and tested the lane change at speeds of 10 and 15 mph • Repeated the test with left-side lane closed • GPS data were pulled from systems. • Log data were pulled after each test. • Repeated each test at least 2 times
Data Collected	• Cross track error and speed • Drone
Expected Result	ATMA to maintain lane accuracy during lane change process
Team members	Leader vehicle driver, ATMA driver, and technician to set up system and export data
Supporting Equipment	Laptop, Ethernet cable to connect with vehicle, and cones
Total Number of Testing Runs	8

TC-8 – Schematics

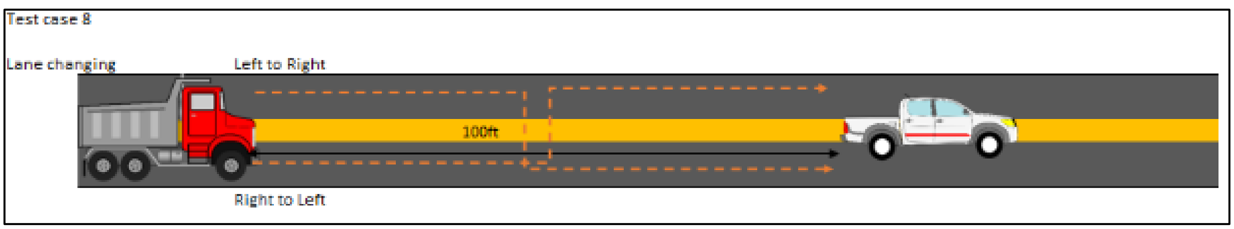


Figure 6-44. Closed loop lane-change test setup

TC-8 – Field Pictures

Figure 6-45. External camera view of lane change test

Figure 6-46. Dashcam view of lane change test

Table 6-21 shows Test Case 8 field observations. Based on the field observation, the follower vehicle was able to maintain the desired path in following the leader vehicle in all scenarios (left to right and right to left lane change).

Table 6-21. Test Case 8 field observations

Run #	Speed (mph)	Direction of Lane Change	Lane Accuracy Maintained
1	10	LR	Y
2	10	LR	Y
3	15	LR	Y
4	15	LR	Y
5	10	RL	Y
6	10	RL	Y
7	15	RL	Y
8	15	RL	Y

TC-8 – ATMA Log File Data

The velocity distribution show a consistent pattern in ATMA following the speeds of the leader. The CTE graphs (Figures 6-47 to 6-54) and results presented in Table 6-22 indicate that the ATMA had a maximum cross track error of 4.37 inches and -12.2 inches in all tests with an average standard deviation of 2.38 inches.

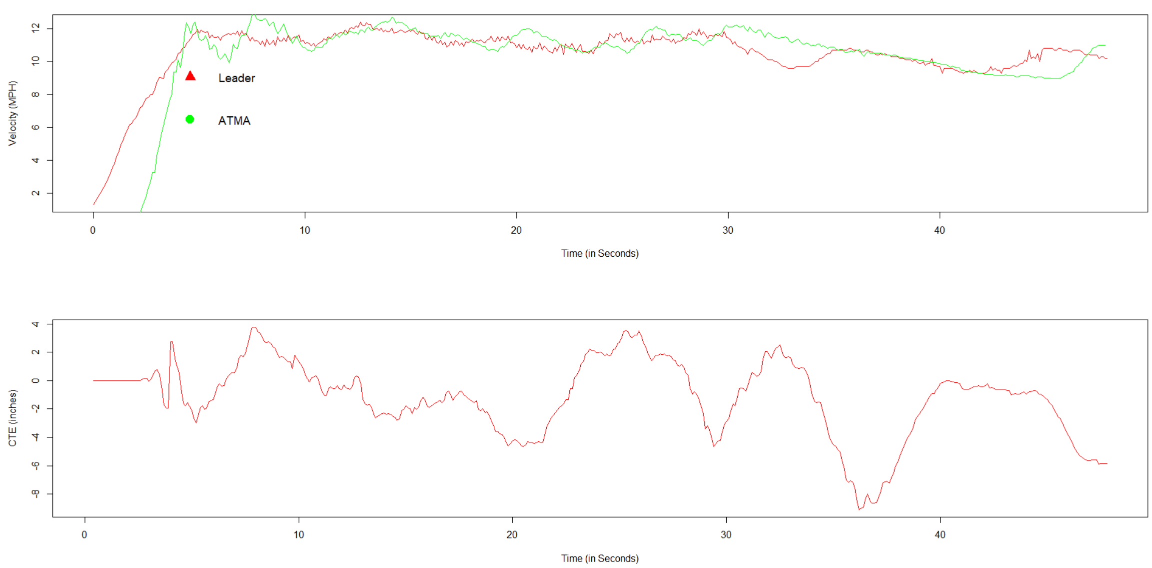


Figure 6-47. Test Case 8, Run 1 at 10 mph (lane change to right): follower truck velocity (top); cross track error (CTE) (bottom)

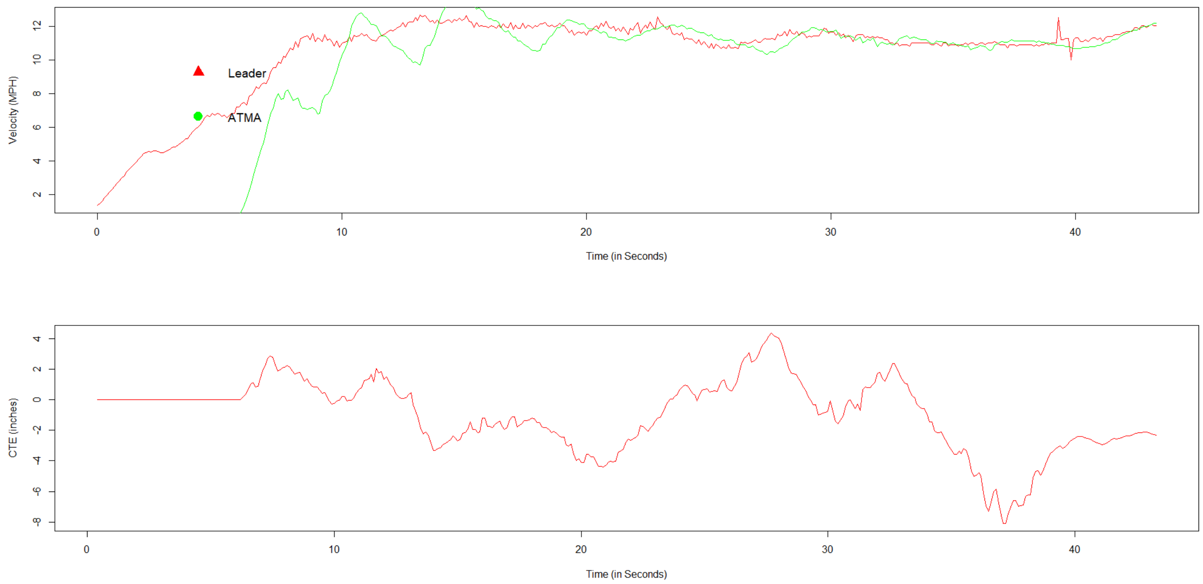


Figure 6-48. Test Case 8, Run 2 at 10 mph (lane change to right): follower truck velocity (top); cross track error (CTE) (bottom)

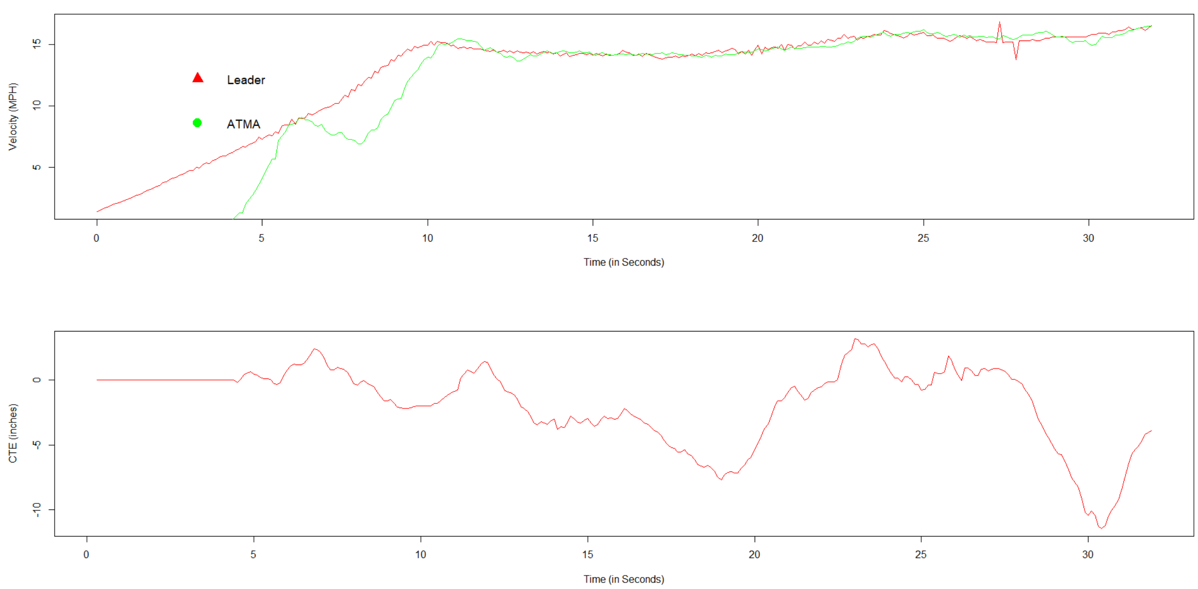


Figure 6-49. Test Case 8, Run 3 at 15 mph (lane change to right): follower truck velocity (top); cross track error (CTE) (bottom)

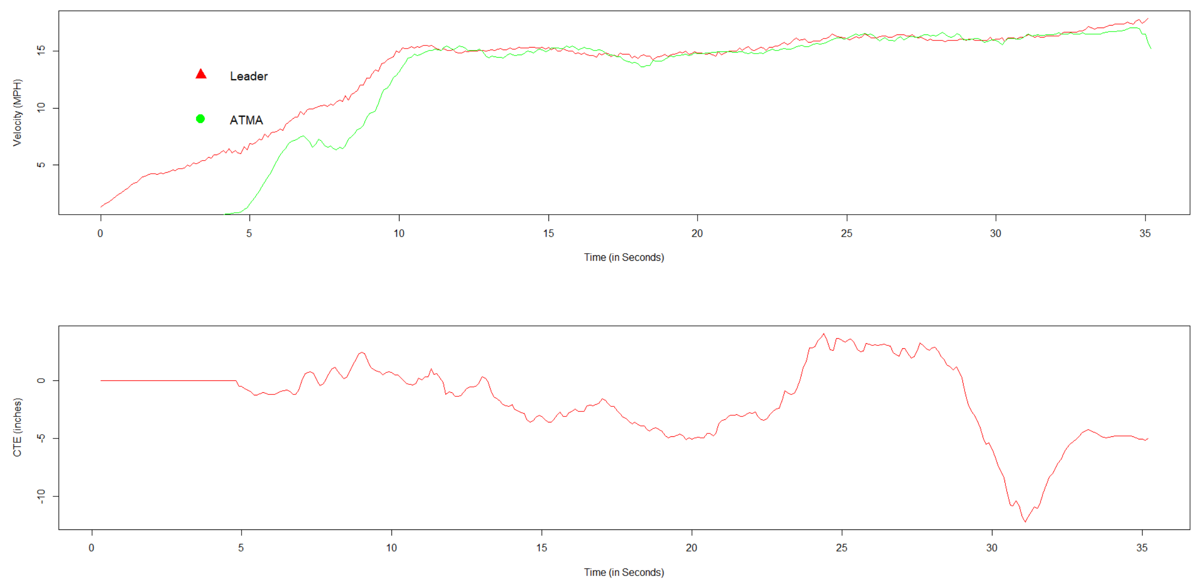


Figure 6-50. Test Case 8, Run 4 at 15 mph (lane change to right): follower truck velocity (top); cross track error (CTE) (bottom)

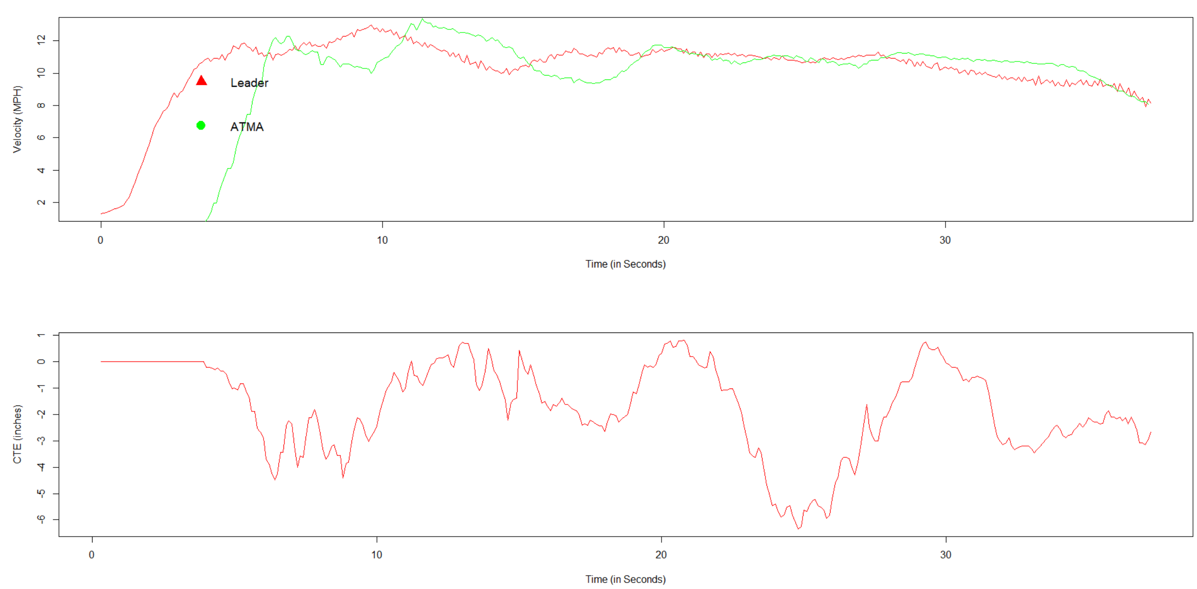


Figure 6-51. Test Case 8, Run 5 at 10 mph (lane change to right): follower truck velocity (top); cross track error (CTE) (bottom)

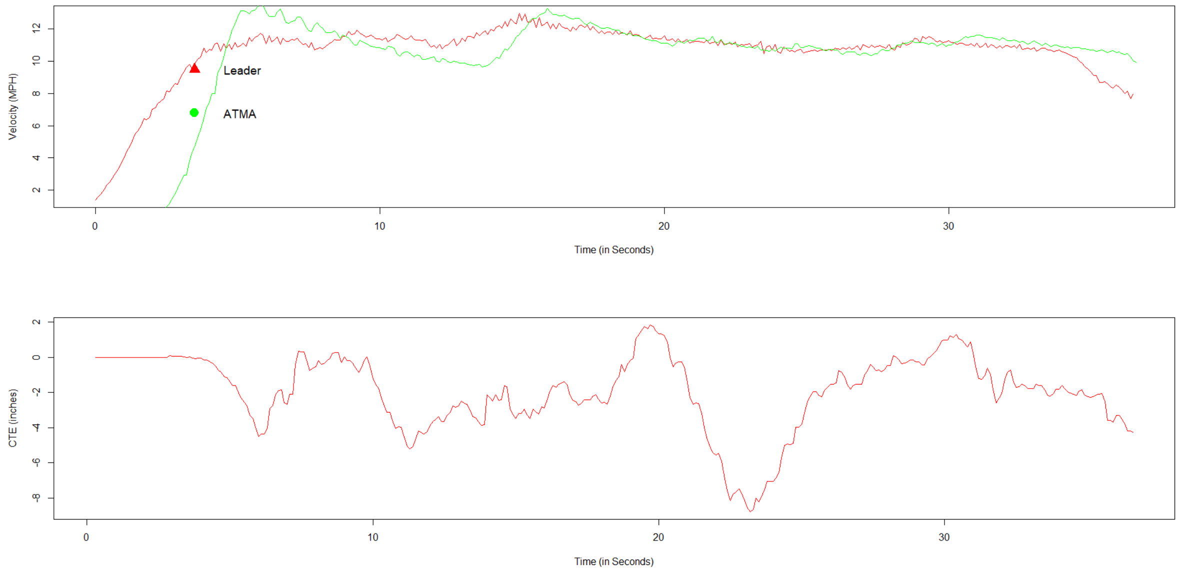


Figure 6-52. Test Case 8, Run 6 at 10 mph (lane change to left): follower truck velocity (top); cross track error (CTE) (bottom)

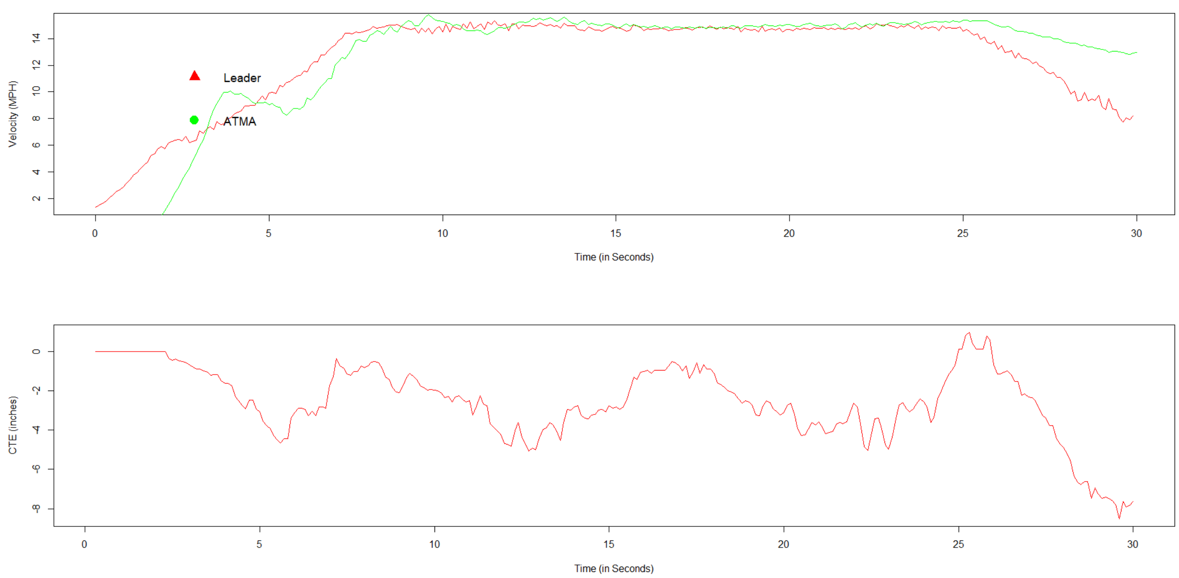


Figure 6-53. Test Case 8, Run 7 at 15 mph (lane change to left): follower truck velocity (top); cross track error (CTE) (bottom)

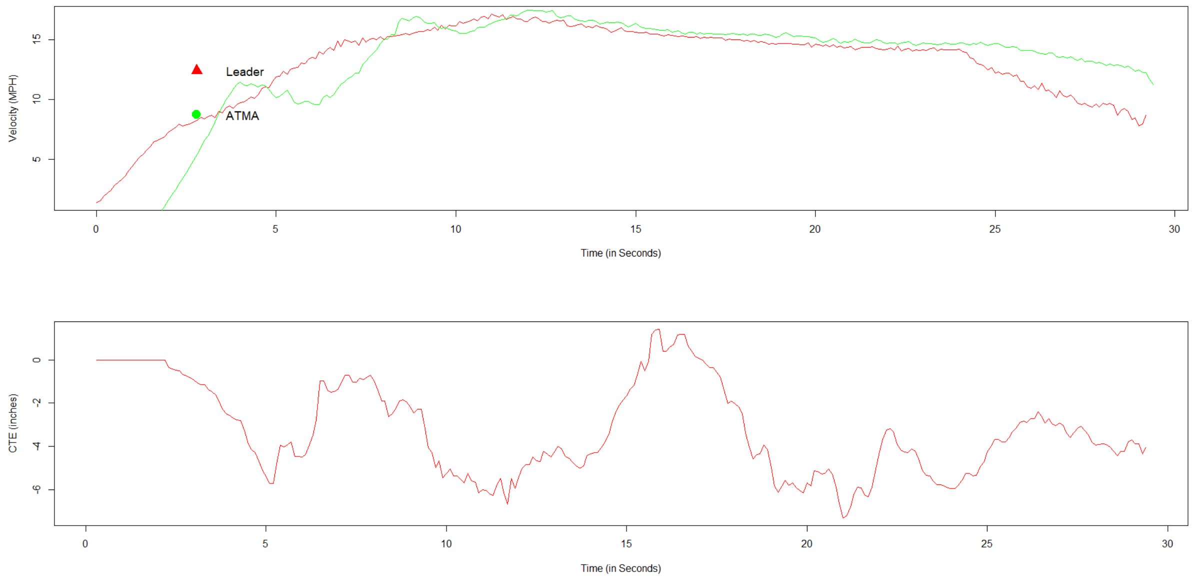


Figure 6-54. Test Case 8, Run 8 at 15 mph (lane change to left): follower truck velocity (top); cross track error (CTE) (bottom)

Table 6-22. Test Case 8 ATMA log file analysis results – CTE (inches)

Test	Run #	Min	Max	Mean	Standard Deviation
8	1	-9.09	3.78	-1.2	2.65
	2	-8.07	4.37	-0.98	2.33
	3	-11.42	3.19	-1.79	3.04
	4	-12.2	4.09	-1.66	3.25
	5	-6.34	0.83	-1.71	1.69
	6	-8.78	1.85	-1.93	2.12
	7	-8.5	0.98	-2.54	1.88
	8	-7.28	1.42	-3.24	2.1

TC-8 – Lateral Offset

This is one of the new features added to the ATMA where the ATMA can operate at a fixed lateral offset from the leader vehicle. This offers a variety of applications for maintenance operation and the following tests were performed to quantify the feasibility and performance of ATMA in achieving and maintaining a pre-determined fixed offset.

TC-9: Lateral Offsets of 1, 5, and 12 ft

After rolling out and stabilizing the gap of 100 ft, the operator in the leader vehicle changed the command offset. After reaching the offset, the field team took measurements to check the accuracy.

This test was executed for three runs with offsets of 1 ft, 5 ft, and 12 ft. Table 6-23 shows the operation procedure, data collection, and expected results.

Table 6-23. Test Case 9 operation procedure, data collection, and expected results

Operation Procedure	• Activated the leader and ATMA; command gap was set to 100 ft and drove in a straight line at 10 mph. • While traveling at steady speed of 10 mph, command lateral offset was set to 1 ft then changed it to 5 ft and then to 12 ft by allowing the offset to stabilize. • Recorded the change in the lateral offset • Log data were pulled after each test • Repeated each test at least 2 times
Data Collected	• Offset measurements • CTE analysis
Expected Result	The ATMA can perform the actual lateral offset changes via the leader user interface (UI)
Team Members	Leader vehicle driver, ATMA driver, a technician to activate the E-stop, and a technician to record data (external).
Supporting Equipment	Laptop, Ethernet cable to connect with vehicle, cones, measuring equipment.
Total Number of Testing Runs	3

TC-9 – Schematics

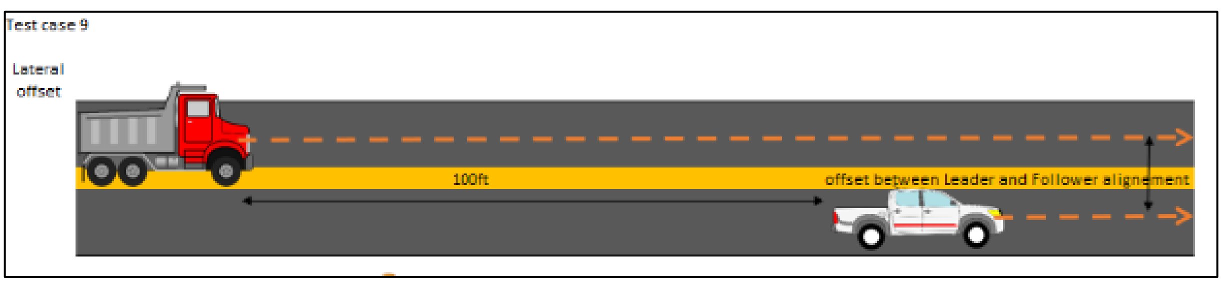


Figure 6-55. Closed loop test setup for lateral offset test

TC-9 – Field Pictures

Figure 6-56. User interface view of lateral offset test showing 1-ft offset towards left

Figure 6-57. External camera view of lateral offset test

Figure 6-58. Dashcam view of lateral offset test

Table 6-24. Test Case 9 field observations

Run #	Speed (mph)	Lateral Offset (ft)	Actual Lateral Offset Measured (ft)
1	10	1	1
2	10	5	4.7
3	10	12	11.7

TC-9 – ATMA Log File Data

The ATMA log files were analyzed to validate the lateral offset through the CTE data. The research team verified and validated the 1-ft, 5-ft, and 12-ft lateral offsets by visual inspection in the field as well as geospatially by using the trajectory data. The time for ATMA to achieve an offset of 12 feet (from 0 feet initial) is about 7.5 seconds.

Figure 6-59. Image of recorded video of 5-ft offset test

6.1.4 Focus Area 4 – Turning

TC-10: Minimum Turn Radius

This test was undertaken to identify a minimum turn radius for ATMA. For this purpose, the cones were set up in a U-turn shape. The internal radius was selected as 25 ft. With initial tests, it was found that the radius was insufficient for the ATMA to negotiate the curve, and the radius was increased incrementally by 5 ft. Finally, the minimum radius for ATMA was found to be 45 ft (internal radius with 12-ft lane width). The test with a 45-ft radius was executed four times. The schematic is shown in Figure 6-60, Test Case 10 field implementation. The ATMA negotiated the curve appropriately three times, but during the last run, it hit one traffic cone. As the setup was the same as the U-turn, the results of this test were considered for Test Case 13, U-turns. Table 6-25 shows the operation procedure, data collection, and expected results.

Table 6-25. Test Case 10 operation procedure, data collection, and expected results

Operation Procedure	• A 90° corner was set up with cones spaced at an interval of 50 ft and an internal turn radius of 45 ft. • Navigated leader vehicle around the turn at 5 mph or less • Repeated with both left turns and right turns • Log data were pulled after each test . • Repeated each test at least 2 times
Data Collected	Cross track error
Expected Result	ATMA to maintain lane accuracy around turns
Team Members	Leader vehicle driver, ATMA driver, and technician to set up system and export data
Supporting Equipment	Laptop, Ethernet cable to connect with vehicle, and cones
Total Number of Testing Runs	4

TC-10 – Schematics

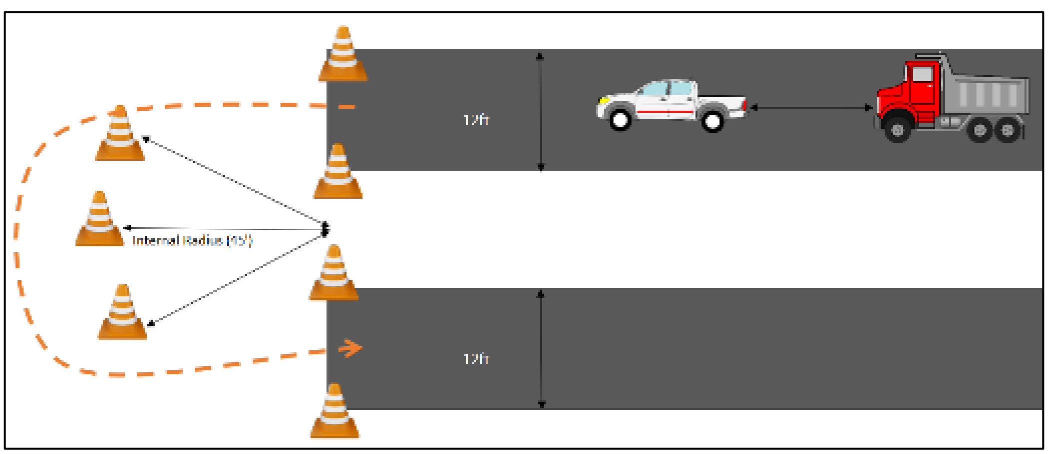


Figure 6-60. Test Case 10 field implementation

TC-10 – Field Pictures

Figure 6-61. External camera view of the minimum radius turning test

Figure 6-62. Dashcam view of the minimum radius turning test

Table 6-26 shows the field observations for Test Case 10. For three out of four runs ATMA successfully negotiated the curve with the internal radius of 45 ft and lane width of 12 ft.

Table 6-26. Test Case 10 field observations

Run #	Speed (mph)	Turning Radius (ft)	Able to Turn (Yes/No)
1	< 5	45	N
2	< 5	45	Y
3	< 5	45	Y
4	< 5	45	Y

TC-10 – ATMA Log File Data

Figure 6-63. Trajectory from log file results that shows two of the successful turns with radius of 45 ft

TC-11: Simple Curve (FT also)

This test was executed on a closed loop. The purpose of this test was to measure CTE on a simple curve. The curve radius was set as 250 ft, with lane width of 12 ft. The test was executed one time with the speed of 5 mph, two times with speed of 10 mph, and two successful times with speed of 15 mph. Table 6-27 shows the operation procedure, data collection, and expected results.

Table 6-27. Test Case 11 operation procedure, data collection, and expected results

Operation Procedure	• Two adjacent lanes, 12 ft wide and 600 ft long, were set up using cones spaced at 50 ft at both end of the designed curve. • The cones were placed at 10-ft spacing distances for curve radius of "2Radii". • Activated leader and ATMA and tested the lane accuracy while negotiating at speed of 5, 10, and 15 mph. Test was executed once with 5 mph and twice each with 10 and 15 mph. • GPS data were pulled from systems. • Log data were pulled after each test. • Repeated each test at least 2 times
Data Collected	• Cross tract error and speed
Expected Result	ATMA to maintain lane accuracy in curves.
Team Members	Leader Vehicle driver, ATMA driver, and technician to set up system and export data
Supporting Equipment	Laptop, Ethernet cable to connect with M-PAK® components, and traffic cones
Total Number of Testing Runs	5

TC-11 – Field Pictures

Figure 6-64. External camera view of simple curve test. The follower vehicle hits a cone.

Figure 6-65. External camera view of follower truck turning. The follower vehicle unexpectedly leaves its course.

Figure 6-66. Dashcam view of simple curve test

Table 6-28 summarizes the field observations for Test Case 11. The ATMA was able to successfully negotiate the curve at 5 mph. In the two tests with 10 mph, ATMA hit a cone in its first run. Even though the ATMA was able to maintain its lane accuracy with respect to the leader track, it hit the cone due to lack of driver training. Because there is a difference in leader and ATMA vehicle sizes, the driver needs to be conscious of the path that ATMA would need in order for the ATMA to successfully navigate. In addition to the driver issue, there was a terrain issue and a user issue. For this test, the beginning section had a bump where the vehicle leaves the pavement and enters the grass. When the ATMA encountered the bump, it unexpectedly left its path (Figure 6-67). In addition to the bump, the Kratos staff explained that the system was not restarted between the tests and that potentially caused some issues with the e-crumb data. The test was executed two more times with 15 mph, with the ATMA successfully negotiating the curve. Table 6-28 summarizes the field observations for this test.

Table 6-28. Test Case 11 field observations

Run #	Speed (mph)	Lane accuracy maintained (Yes/No)	Able to turn (Yes/No)
1	5	Y	Y
2	10	Y	Y
3	10	N (A cone was hit)	Y
4	15	N (Abrupt deviation from lane)	Y
4-a	15	Y	Y
5	15	Y	Y

TC-11 – ATMA Log File Data

Figure 6-67. The trajectory of the vehicle from the pavement to the grass for Test Case 11

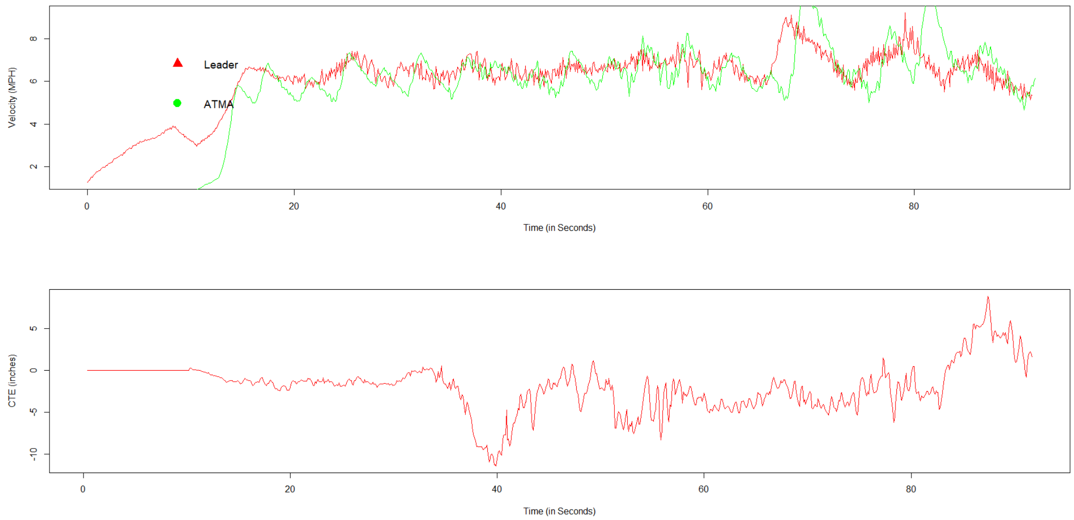


Figure 6-68. Test Case 11, Run 1 at 5 mph: follower truck velocity (top); cross track error (CTE) (bottom)

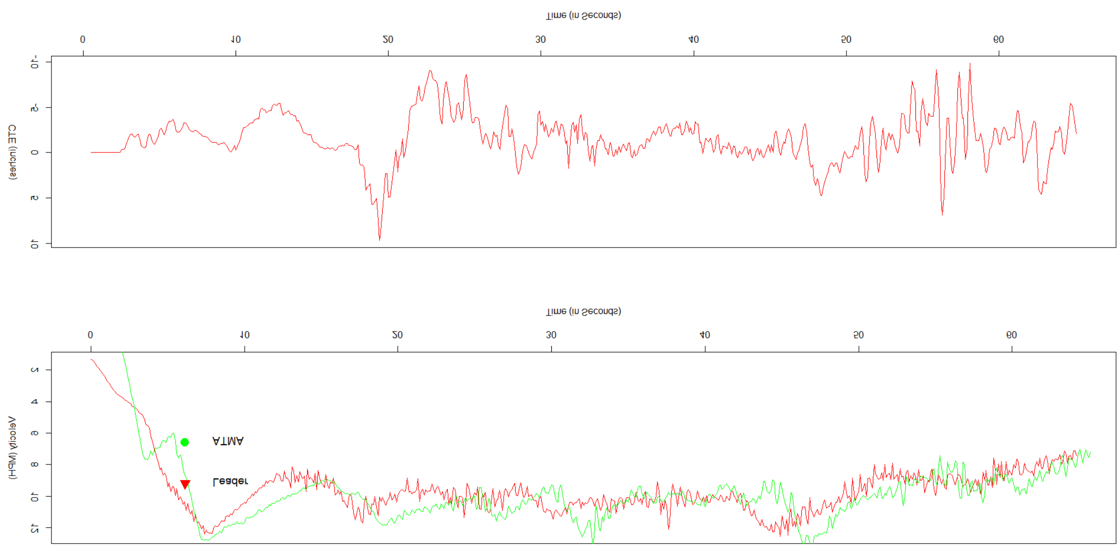


Figure 6-69. Test Case 11, Run 2 at 10 mph: follower truck velocity (top); cross track error (CTE) (bottom)

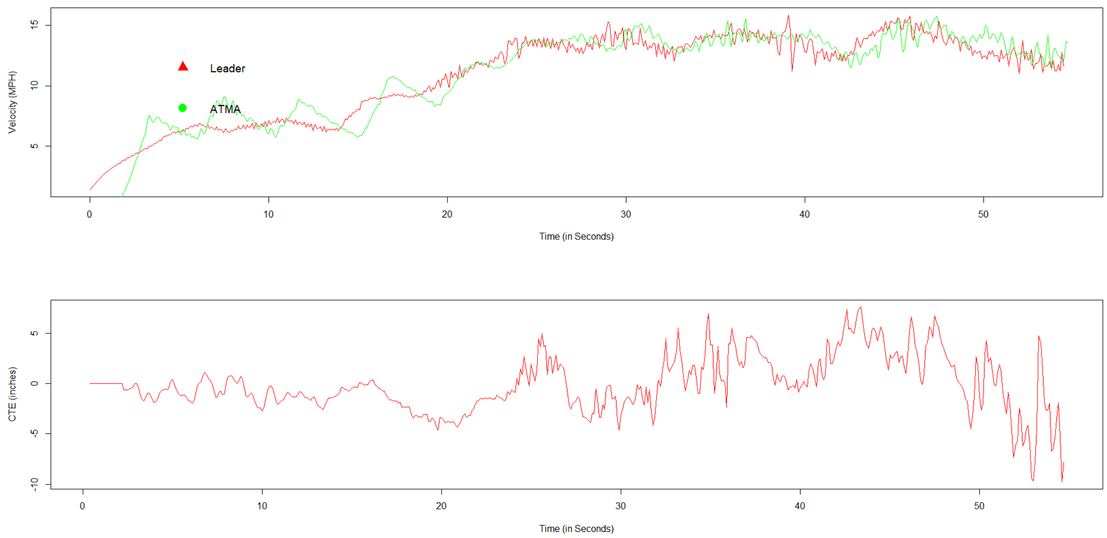


Figure 6-70. Test Case 11, Run 4a at 15 mph: follower truck velocity (top); cross track error (CTE) (bottom)

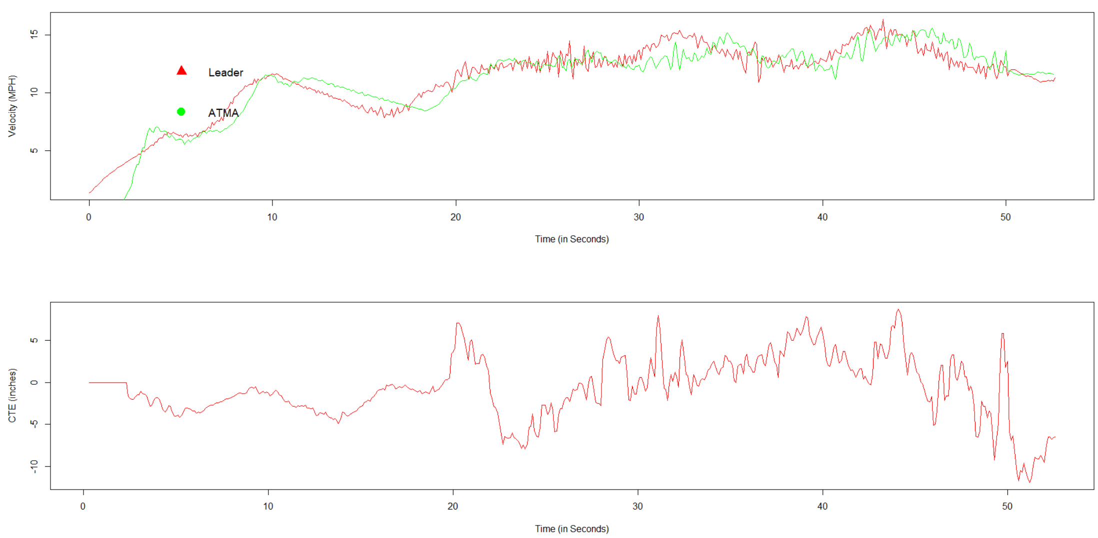


Figure 6-71. Test Case 11, Run 5: follower truck velocity (top); cross track error (CTE) (bottom)

Table 6-29. Test Case 11 ATMA log file analysis results – CTE (inches)

Test	Run #	Min	Max	Mean	Standard Deviation
Test Case 11	1	-11.42	8.86	-1.92	2.85
	2	-9.84	9.72	-1.52	2.6
	4a	-9.76	7.64	-0.09	2.78
	5	-11.93	8.78	-0.64	3.77

TC-12: Roundabouts

This test was designed to evaluate the performance of ATMA to negotiate a roundabout, along with the minimum radius required for ATMA. The roundabout was set with internal radius of 65 ft and lane width of 12 ft. Table 6-30 shows the operation procedure, data collection, and expected results. Initial tests were unsuccessful because the ATMA knocked the traffic cones with its bumper or attenuator at various locations on the roundabout. The lane width was increased by 2-ft increments by changing the location of cones that marked the outer boundary of roundabout. This process was continued to the lane width of 18 ft, where the ATMA could negotiate the roundabout two consecutive times without any issue. The internal radius of the roundabout was 65 ft, and the external radius was 83 ft. The center footprint of vehicles (retrieved from log files) showed the radius of 74 ft (148.7-ft diameter) in the two consecutive successful runs (Figure 6-75).

Table 6-30. Test Case 12 operation procedure, data collection, and expected results

Operation Procedure	• Two adjacent lanes were set up using cones: 12 ft wide, 600 ft long, and cone spacing of 50 ft at both end of designed curve. • Cones placed at 10-ft spacing distances for curve radius of 65 ft • Activated leader and ATMA and tested the lane accuracy while negotiating the roundabout at a speed of 5 mph. • When the test run was not successful, the lane width was increased by moving the outer cones of the roundabout. • GPS data were pulled from systems. • Log data were pulled after each test. • Repeated each successful test at least 2 times.
Data Collected	• Cross track error and speed
Expected Result	ATMA to maintain lane accuracy in curves.
Team Members	Leader vehicle driver, ATMA driver, and technician to set up system and export data.
Supporting Equipment	Laptop, Ethernet cable to connect with M-PAK® components, traffic cones.
Total Number of Testing Runs	2

TC-12 –Field Pictures

Figure 6-72. External camera view

Figure 6-73. External camera view

Figure 6-74. Dashcam view

Table 6-31 shows the field observations for successful runs of Test Case 12.

Table 6-31. Test Case 12 field observations

Successful Run #	Speed (mph)	Lane accuracy maintained (Yes/No)	Able to turn (Yes/No)
1	5	Y	Y
2	5	Y	Y

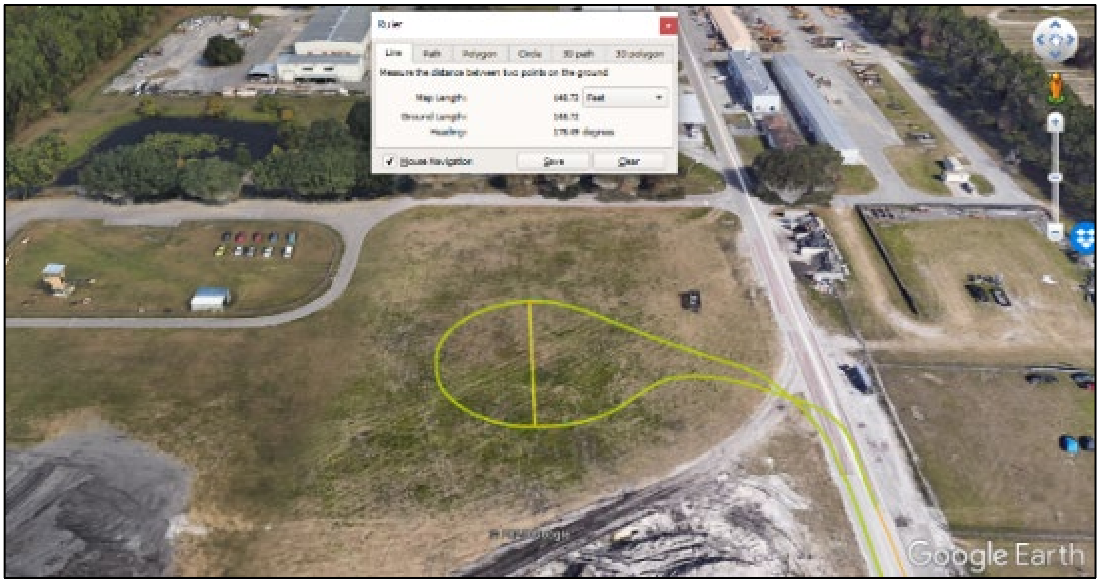


Figure 6-75. Leader and ATMA follower footprint of roundabout test (diameter of 148.7 ft).

TC-12 – ATMA Log File Data

The velocity graphs and CTE distributions are shown below. The ATMA followed the leader closely in maintaining the speed profile. Table 6-32 shows the CTE distribution, which indicates that the ATMA followed the leader's path with a deviation between -15.98 inches to 15.83 inches which is greater than the 6-inch threshold.

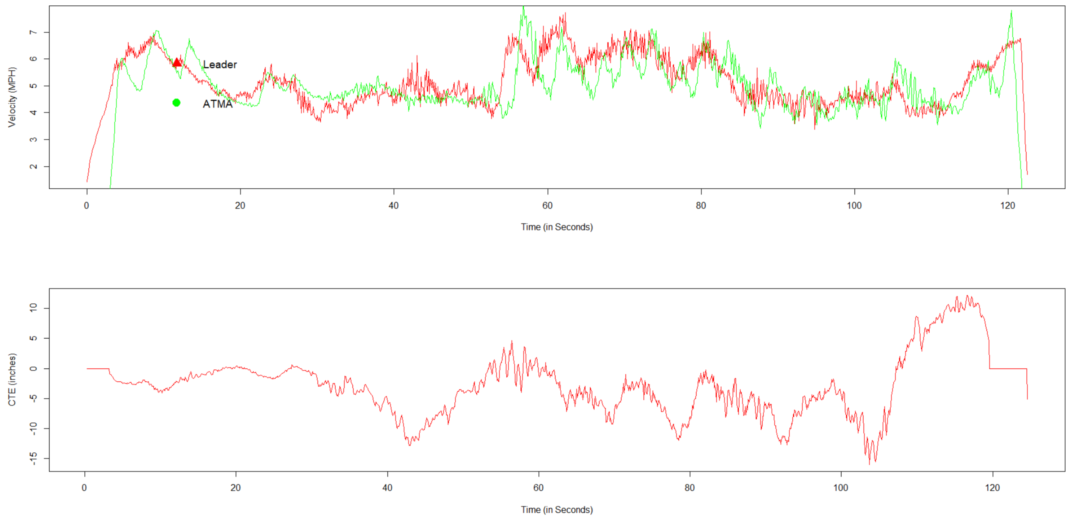


Figure 6-76. Test Case 12, Run 1 at 5 mph: follower truck velocity (top); cross track error (CTE) (bottom)

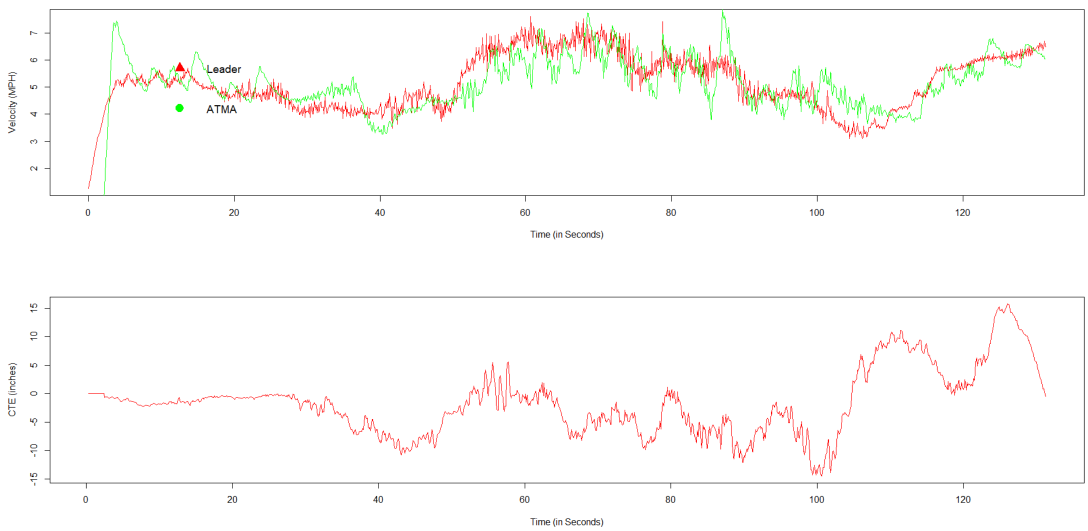


Figure 6-77. Test Case 12, Run 2 at 5 mph: follower truck velocity (top); cross track error (CTE) (bottom)

Table 6-32. Test Case 12 ATMA log file analysis results – CTE (inches)

Test	Run	Min	Max	Mean	Standard Deviation
12	1	-15.98	12.20	-2.82	4.97
	2	-14.49	15.83	-1.64	5.72

TC-13: U-turns

This test was executed in the same setup as Test Case 10 (minimum radius). The purpose of this test was to check if a U-turn maneuver was possible on various geometries. The results were the same as minimum radius test of turning. For a U-turn, there is a minimum turn radius of 45 ft for a 12-ft lane width. For most facility types, there is not enough space for such a U-turn (unless it is a 6-lane highway). It is suggested that the U-turn be performed in manual mode by a human driver in idle mode.

6.1.5 Focus Area 5 – Obstacle

This set of tests was designed to quantify the performance of the ATMA system when various objects on the roadway and adjacent to the roadway are detected.

TC-14: Bump Test

This test was not specifically conducted because the response to the behavior to bumps was observed in other closed loop tests. The transition from the grassy area to the pavement in the FDOT maintenance area was abrupt and provided many bump scenarios during other tests. The only issue regarding bumps is covered under Test Case 11.

TC-15: Obstacle Detection

This test aimed to quantify the ATMA performance when there is an obstacle on the roadway. In this test, two different obstacles were tested. The first obstacle's dimensions were 2'7" wide and 4'5" high (as shown in Figure 6-78). The second obstacle was a regular traffic barrel (Figure 6-82) with dimensions of 1'8" diameter and 3' height. The obstacle was located on the adjacent lane and was pulled into the ATMA lane by a rope, after the leader passed the obstacle location. Table 33 shows the operation procedure, data collection, and expected results.

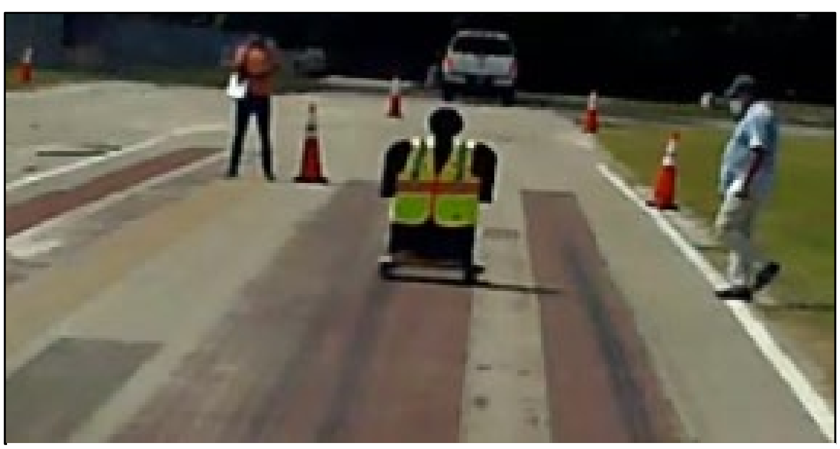


Figure 6-78. Dashcam view of the first obstacle

Table 6-33. Test Case 15 operation procedure, data collection, and expected results

Operation Procedure	• Activated leader and ATMA and drove in a straight line at 10 mph with the gap set to 200 ft (300 ft for speed of 20). • Barrel was set to mark the start of the gap. • Once the rear of the leader passed the marker barrel, the traffic barrel was pulled into the path of the ATMA in the center of the lane using a rope. • Log data were pulled after each test. • Repeated test at least 2 times. • Speeds 5, 10, 15, and 20 mph
Data Collected	• Distance at which ATMA detects the traffic barrel • Distance between front of the ATMA and traffic barrel after ATMA stops
Expected Result	ATMA detects the traffic barrel and executes an A-stop.
Team members	Leader vehicle driver, ATMA driver, and technician moving the barrel and recording data.
Supporting Equipment	Traffic cones, measurement equipment (time and distance), Traffic barrel or other obstacle
Total runs	10

TC-15 – Schematics

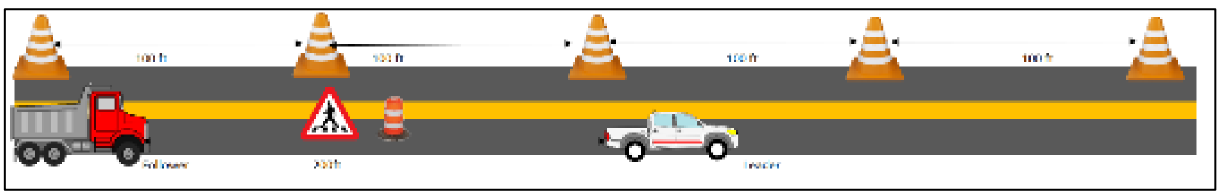


Figure 6-79. Test Case 15 scheme

TC-15 – Field Pictures

Figure 6-80. External camera view

Figure 6-81. External camera view

Figure 6-82. External camera view when traffic barrel was struck

Figure 6-83. Dashcam view when the obstacle was almost hit

The test with this obstacle was executed two times for each speed of 5, 10, 15, and 20 mph. Table 6-34 shows the field observations of Test Case 15. For the speeds of 5, 10, and 15 mph, the ATMA recognized the obstacle and stopped. At a speed of 20 mph, in both runs, the obstacle was detected, and the ATMA applied brakes. In Run 7, the ATMA stopped, but in Run 8, the safety operator in ATMA (driver) applied brakes to avoid hitting the obstacle because there was not enough stopping distance available.

In Run 9, with speed of 15 mph, a traffic barrel of 1’8” diameter and 3’ height was used in a vertical position as the obstacle. The ATMA recognized the obstacle and stopped appropriately. In runs 1 through 9, the obstacle was recognized in a range between 72 and 96 ft.

In the last run, the same barrel was used in a horizontal position (3’ width and 1’8” height). The safety officer in the ATMA had to manually apply the brake to avoid hitting the barrel. The object was recognized by the ATMA lidar at a distance of 3.6 ft. This test indicated that the sensor location and configuration are critical in recognizing obstacles with a height of less than 1 ft.

Table 6-34. Test Case 15 field observations

Run #	Speed (mph)	ATMA detects the obstacle (Yes/No)	Final distance to obstacle (ft)	Distance at first detection (ft)	Angle of detection (-90° to +90°)	Time to stop after detecting the obstacle (sec)
1	5	Y	≈50	84.9	-1.75	5.72
2	5	Y	≈50	96.1	-2.25	3.56
3	10	Y	≈50	82.1	-2.5	6.13
4	10	Y	≈50	94.5	-1.7	6.79
5	15	Y	21	73.7	-2.5	8.9
6	15	Y	39	81.2	-3	9.72
7	20	Y	3	72.2	-1.25	7.52
8	20	N	—	76.7	-2.5	8.42
9	15	Y	56	72.3	-1	N/A
10	15	N	—	3.6	-27.25	16.84

TC-15 – ATMA Log File Data

No log file analysis was required for this test case.

TC-16 – Vehicle Intrusion

This test was performed to evaluate the ATMA performance in the event a vehicle intrudes between the leader and follower vehicles. It is expected that the ATMA would stop. The test was executed on a closed loop. For this test, the leader and ATMA operated at 10 and 15 mph, with a 300-ft gap. Another passenger vehicle (black sedan) operated beside the ATMA on adjacent lane. After a marked point, the vehicle in the adjacent lane changed its lane to cut the ATMA's path and then left the lane (to replicate a last-minute exit maneuver) (Figure 6-85). Table 35 includes the operation procedure, data collection, and expected results.

Table 6-35. Test Case 16 operation procedure, data collection, and expected results

Operation Procedure	• Activated leader and ATMA and drove in a straight line at 10 or 15 mph with the GAP set to 300 ft. • An external vehicle was driven between the leader and ATMA. • Log data were pulled after each test. • Repeated test at least 2 times.
Data Collected	• The stopping distance of ATMA • The stopping time of ATMA • Status of engine
Expected Result	ATMA detects vehicle and executes an E-stop.
Team Members	Leader vehicle driver, ATMA driver, intruder vehicle driver and technician riding in ATMA to record data
Supporting Equipment	Laptop, Ethernet cable to connect with vehicle, cones, and an external vehicle
Total Number of Testing Runs	4

TC-16 – Schematics

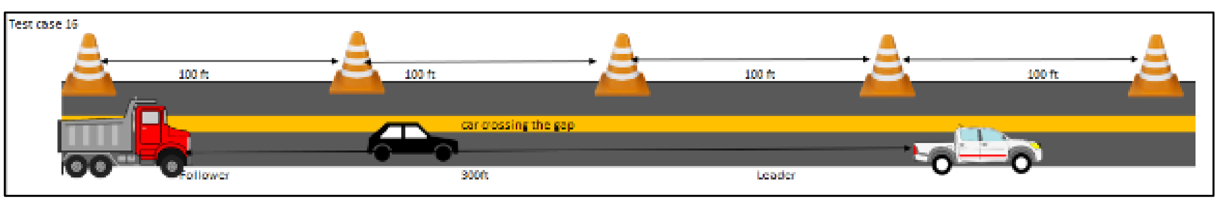


Figure 6-84. Closed loop test setup

TC-16 – Field Pictures

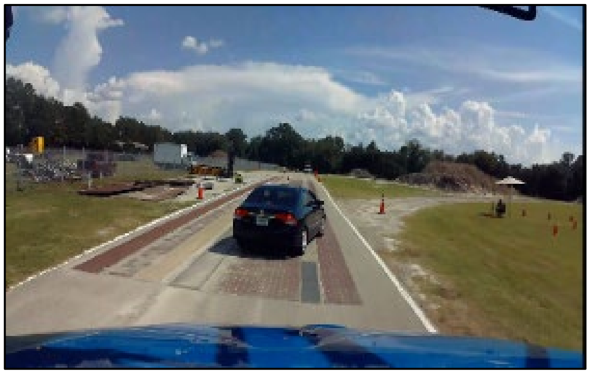


Figure 6-85. Dashcam view(left) and external cam view (right) of vehicle intrusion test

Table 6-36 shows the field observations for Test Case 16. ATMA successfully stopped in all test runs after the vehicle intruded into its lane. The engine status was on after the stop.

Table 6-36. Test Case 16 field observations

Run #	Speed (mph)	ATMA detects the vehicle (Lidar/ Radar)	Time to stop after detecting the obstacle (sec)	Status of Engine
1	10	Lidar	4.89	On
2	10	Lidar	4.54	On
3	15	Lidar	3.12	On
4	15	Lidar	4.76	On

TC-16 – ATMA Log File Data

The following figures show the velocity plots of the leader and ATMA. It can be seen that the velocity of the follower vehicle drops to zero, indicating a stop due to vehicle intrusion. In each case, the ATMA was able to stop immediately and then resume after an override from the safety operator.

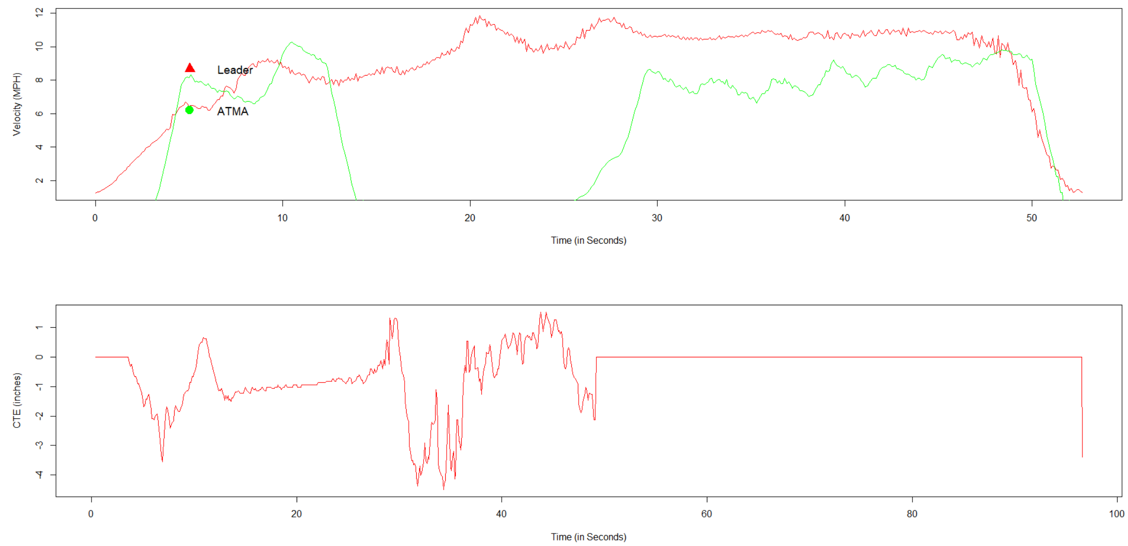


Figure 6-86. Follower truck velocity (top); cross track error (CTE) (bottom)

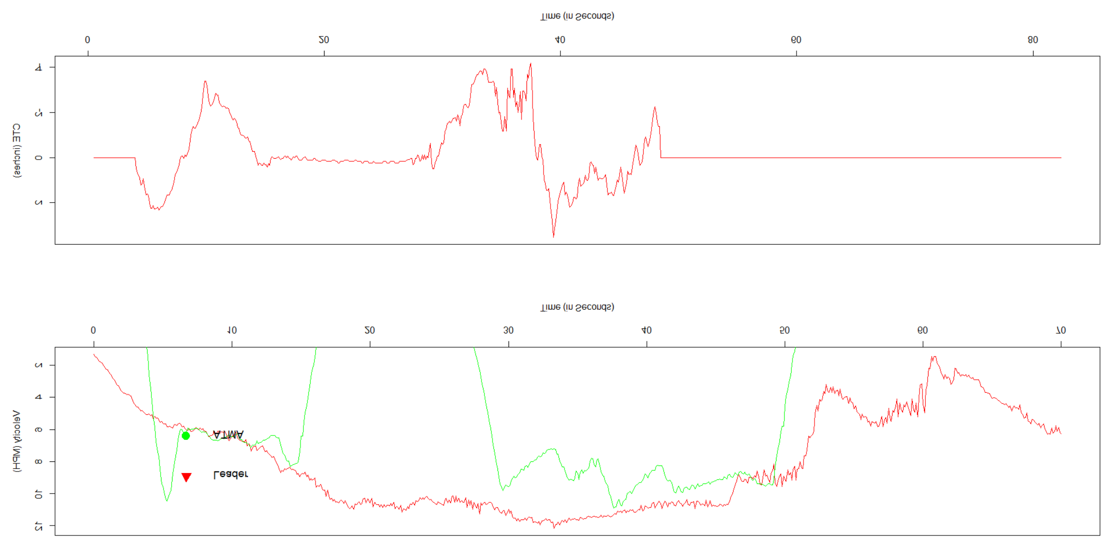


Figure 6-87. Follower truck velocity (top); cross track error (CTE) (bottom)

TC-17: Object Recognition

This test was designed to figure out if the ATMA recognizes the vehicles and objects in adjacent lane. Table 6-37 includes the operation procedure, data collection, and expected results. A vehicle parked in the adjacent lane (one side at a time). Leader and ATMA drove though their lane, and the recognition of an object in adjacent lane by the ATMA system was recorded.

Table 6-37. Test Case 17 operation procedure, data collection, and expected results

Operation Procedure	• Activated leader and ATMA and drove in a straight line at 10 mph with the GAP set to 175 ft. • Parked a vehicle in the adjacent lane on the left side of the ATMA. As the ATMA passed the parked vehicle, the GUI was observed for an indication of side collision detection. • Repeated the same test on right side. • Repeated test at least 2 times.
Data Collected	Object recognition on the user interface.
Expected Result	The object is displayed in the user interface.
Team members	Leader vehicle driver, ATMA safety driver/rider, and technician riding in ATMA to record data.
Supporting Equipment	Parked vehicle, traffic cones
Total number of testing runs	4

TC-17 – Schematics

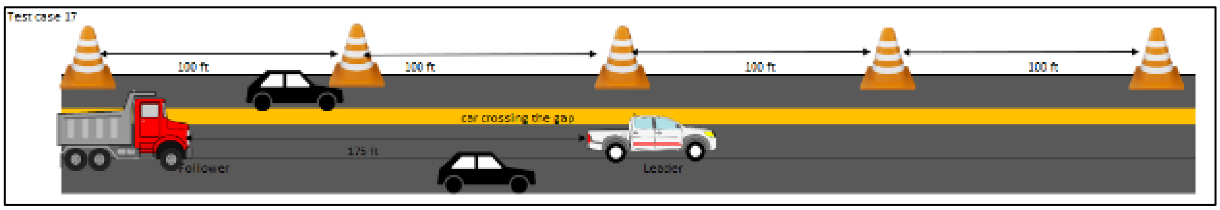


Figure 6-88. Closed loop test setup

TC-17 – Field Pictures

Figure 6-89. External camera view

Figure 6-90. User interface view showing the warning as it recognized the object

Figure 6-91. Dashcam view

In each case, the system was successful in recognizing the object.

Table 6-38. Test Case 17 field observations

Run #	Speed (mph)	Object Recognized on UI (Yes/No)
1	10	Yes
2	10	Yes
3	10	Yes
4	10	Yes

TC-17 – ATMA Log File Data

No log file analysis was required for this test case.

6.1.6 Focus Area 6 – Operational Tests

TC-18: Speed Test

Test Case 18 was executed on Waldo Road in Gainesville, FL. This test aimed to quantify the performance of the ATMA when it was required to reduce the gap after a commanded pause. The process began with setting the initial gap to 300 ft. Upon stabilizing at 300 ft, the operator in the leader vehicle commanded a pause for the ATMA which increased the gap because the leader is in motion and the follower ATMA is stopped. When the gap reached 1,000 ft, the operator released the ATMA. The expected result was that the ATMA would catch up and attain the established gap of 300 ft without exceeding 20 mph. Table 6-39 summarizes the operation procedure, data collection, and expected results.

Table 6-39. Test Case 18 operation procedure, data collection, and expected results

Operation Procedure	• Gap set to 300 ft • Activated leader and ATMA and drove in a straight line at 10 or 15 mph. • Initiated a pause command on UI system to bring the ATMA to a temporary stop. • Continued to drive the leader vehicle at the same speed up to a gap distance of 1,000 ft (not exceeding the maximum gap distance). • Released the ATMA to catch up to the leader vehicle and stabilize at 100 ft. • Log data were pulled after each test. • Repeated test at least 2 times.
Data Collected	• Maximum speed during catch-up • Final stabilized gap distance
Expected Result	ATMA catches up to leader vehicle to the set gap distance. Catch-up speed not to exceed 20 mph.
Team Members	Leader vehicle driver, ATMA driver, and technician to set up system and export data.
Total Number of Testing Runs	4

TC-18 – Field Pictures

Figure 6-92. External camera view

Table 6-40 shows the field observations for Test Case 18. The ATMA was able to reach the established gap of 300 ft after the pause of 253 seconds in the first run, 240 seconds in the second run, 301 seconds in the third run, and 250 seconds in the last run, with an overall average of 261 seconds.

Figure 6-93. Dashcam view

Table 6-40. Test Case 18 field observations

Run #	Speed (mph)	Command Gap (ft)	Time to stabilize back to 300 ft. (mm:ss)	Stabilized accuracy (ft)	Maximum speed during catch-up (mph)
1	10	300-Pause-1000-300	04:13	± 15	≤ 20
2	10	300-Pause-1000-300	04:00	±15	≤ 20
3	15	300-Pause-1000-300	05:01	±15	≤20
4	15	300-Pause-1000-300	04:10	± 15	≤ 20

TC-18 – ATMA Log File Data

The velocity plots below show the ATMA vehicle velocity profile in green and leader vehicle profile in red. When the follower was catching up after the pause (horizontal line), the velocity was higher than the leader to catch up, which can be seen in the following graphs. However, it did exceed the 20-mph threshold as shown in following graphs.

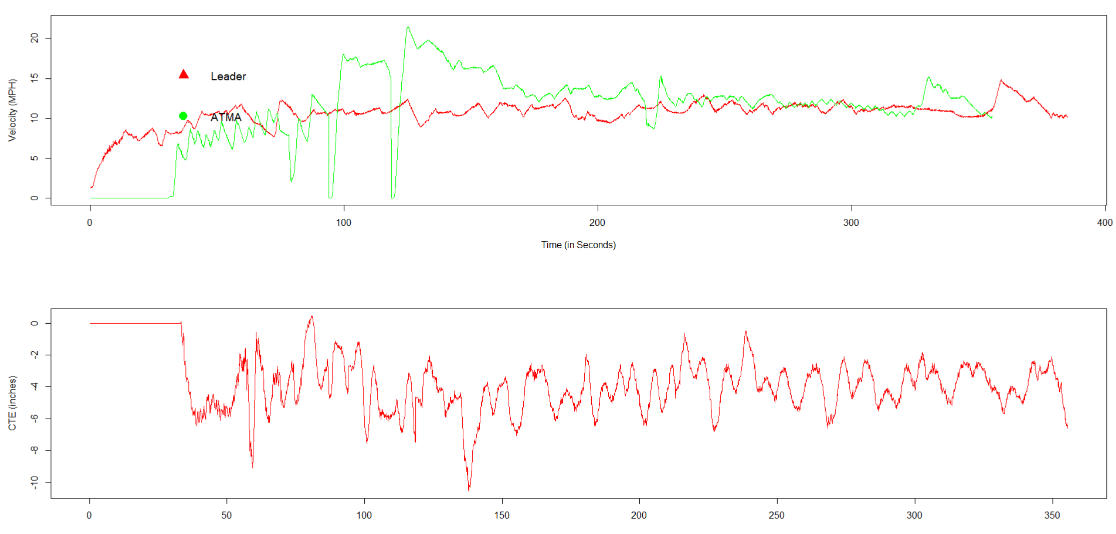


Figure 6-94. TC-18, Run 1: Follower truck velocity (top); cross track error (CTE) (bottom)

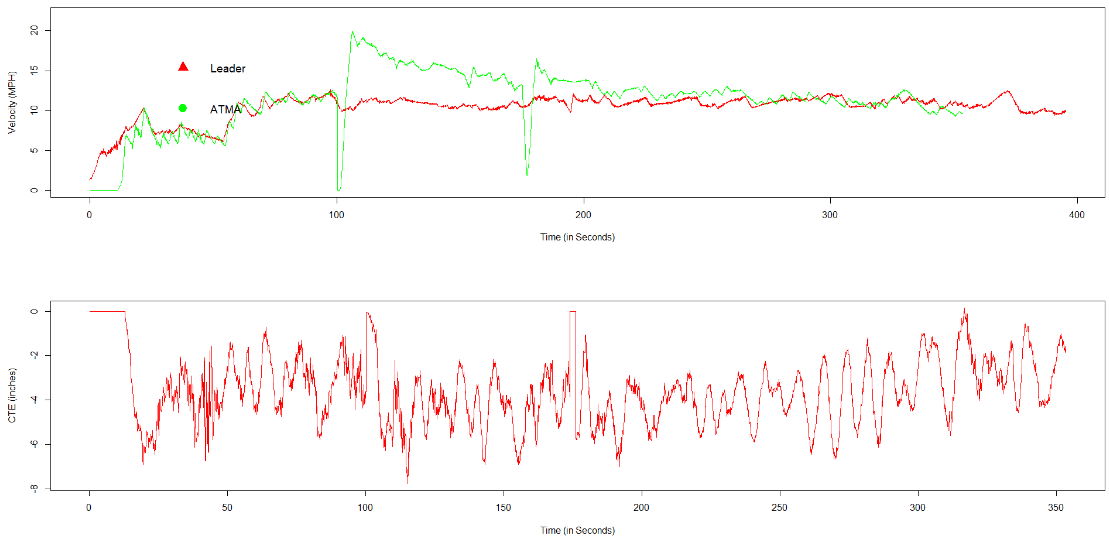


Figure 6-95. TC-18, Run 2: Follower truck velocity (top); cross track error (CTE) (bottom)

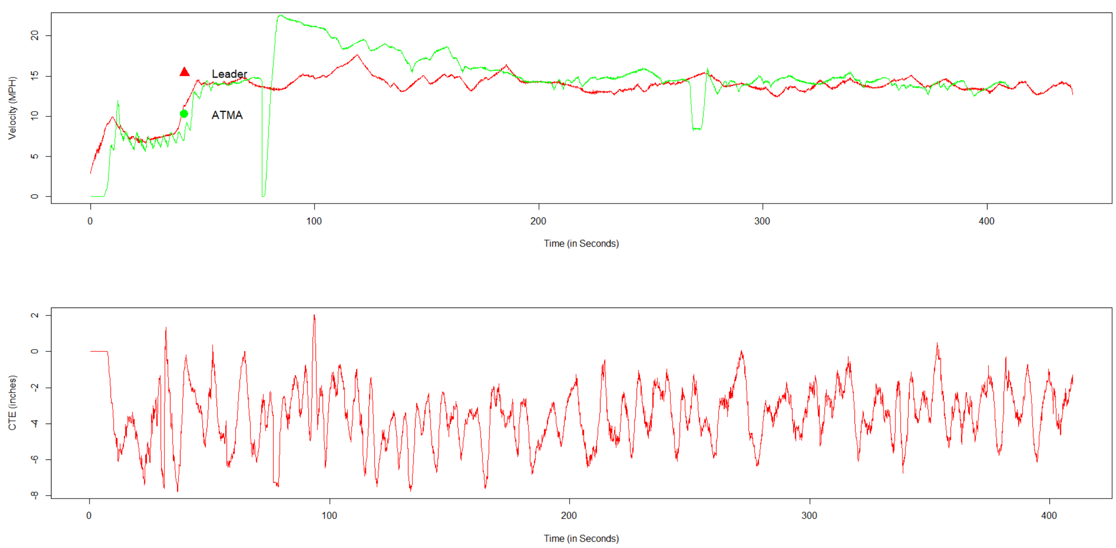


Figure 6-96. TC-18, Run 3 at 15 mph: Follower truck velocity (top); cross track error (CTE) (bottom)

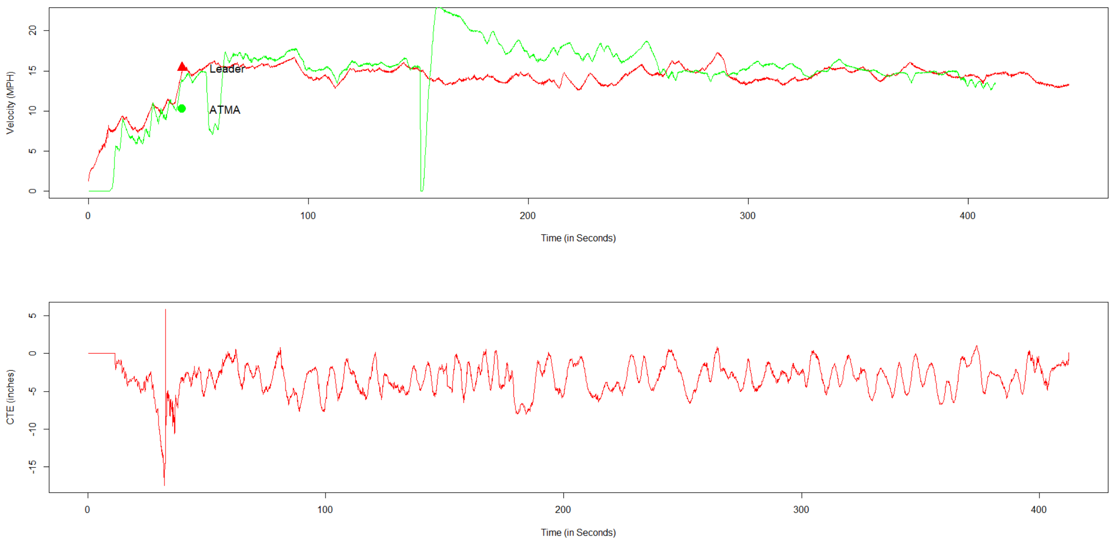


Figure 6-97. TC-18, Run 4: Follower truck velocity (top); cross track error (CTE) (bottom)

Figure 6-98. Velocity distribution showing Runs 1, 3, and 4 exceeding 20 mph in order to catch up to the leader vehicle. (Note: Run 2 did not exceed 20 mph.)

From Figure 6-98, it can be seen that on Run 3, the ATMA speed exceeded 20 mph for about 24.5 seconds, and on Run 4, the ATMA speed exceeded 20 mph for 20.1 seconds.

Table 6-41 shows the CTE results which indicate a range of -17.48 inches to 5.91 inches deviation in CTE for all runs.

Table 6-41. Test Case 16 ATMA log file analysis results – CTE (inches)

Test	Run #	Min	Max	Mean	Standard Deviation
18	1	-10.55	0.47	-3.7	1.85
	2	-7.76	0.16	-3.54	1.55
	3	-7.76	2.05	-3.48	1.64
	4	-17.48	5.91	-3.2	2.07

TC-19: Braking – Leader Vehicle

Test Case 19 was executed on Waldo Road in Gainesville, FL. This test was intended to validate the performance of the ATMA when the leader brakes hard and stops the vehicle. The expected result was that the ATMA would also stop immediately. The test was executed at speeds of 10 and 15 mph. This test also compared the human driver performance with autonomous mode. Table 6-42 summarizes the operation procedure, data collection, and expected results.

Table 6-42. Test Case 19 operation procedure, data collection, and expected results

Operation Procedure	• Gap set to 100 ft. • Drove the leader vehicle at a constant speed (10 or 15 mph). Once the gap was stabilized, recorded actual gap as reported by UI. • Once the leader vehicle passed a predetermined limit line (cone), the driver engaged the brake instantly. • With both vehicles stopped, recorded the updated actual gap. • Care should be taken to ensure that a safe gap is used in performing this test. • Repeated test at least 2 times.
Data Collected	Leader and ATMA log files
Expected Result	The ATMA should deaccelerate and stop.
Team Members	Leader vehicle driver, ATMA driver, and technician to set up system and export data
Supporting Equipment	Laptop, cables to connect with vehicle, traffic cones
Total Number of Testing Runs	4 × 2

TC-19 – Schematics

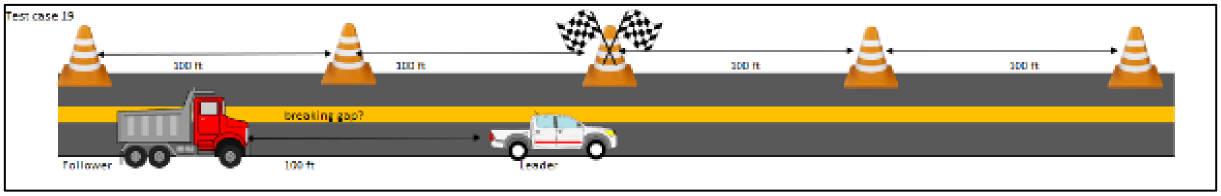


Figure 6-99. Closed loop setup

TC-19 – Field Pictures

Figure 6-100. External camera view

Figure 6-101. External camera view

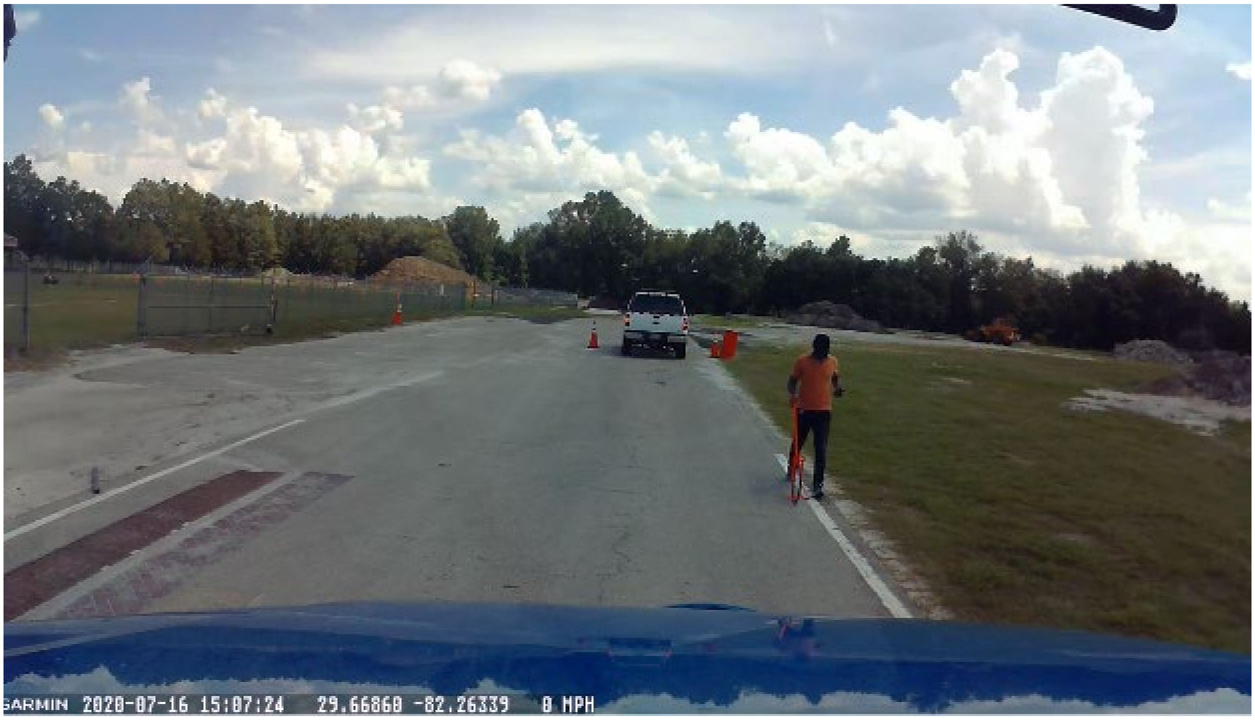


Figure 6-102. Dashcam view

Table 6-43 shows the field observations for Test Case 19. In all the runs, the ATMA stopped safely. The stop time for the ATMA ranged between 1.5 to 3.91 seconds, with an average of 2.92 seconds. This is while the human driver stopping time ranged between 1.72 to 3.56 seconds, with an average of 2.57 seconds. The gap measured after the complete stop ranged between 81 and 97 ft. The CTE analysis shows that the vehicle was within the established threshold of ±6 inches (Table 6-44).

Table 6-43. Test Case 19 field observations

Run #	Speed (mph)	Mode of Operation (Autonomous/Human)	Time to stop (sec)	Gap Measured after Stop (ft)
1	10	A	1.5	90
2	10	A	2.7	97
3	10	H	1.79	77
4	10	H	1.72	86
5	15	A	3.91	92
6	15	A	3.57	81
7	15	H	3.2	116
8	15	H	3.56	98

Table 6-44. Test Case 19 ATMA log file analysis results – CTE (inches)

Test	Run #	Min	Max	Mean	Standard Deviation
19	1	-4.65	5.91	-1.6	0.85
	2	-3.62	2.13	-0.98	1.05
	3	-5.55	3.07	-0.7	1.39
	4	-6.14	2.36	-2.17	1.34

TC-20: ATMA Human Driver Takeover (Human Driver)

The purpose of this test was to check if the human driver can take over the ATMA while operating. In various tests, the driver in the ATMA was able to successfully take over the ATMA many times. So, this test was not executed separately.

TC-21: Leader Reverse

Test Case 21 aimed to check the operation of the ATMA in case the leader backs up toward the follower. The expected result was an E-stop for the ATMA. Table 6-45 explains the procedure for this test. The ATMA did not execute an E-stop in both runs. Instead, the ATMA started to move forward toward the leader truck. The safety driver manually stopped the ATMA from moving forward. According to Kratos representatives, the system is not designed for such scenario, and this will be considered for future enhancements.

Table 6-45. Test Case 21 operation procedure, data collection, and expected results

Operation Procedure	• Activated leader and ATMA and drove leader on reverse with the gap set to 100 ft. • Repeated test at least 2 times.
Data Collected	Performance of ATMA
Expected Result	ATMA executes E-stop
Personnel Needed	Leader vehicle driver, ATMA driver and observer
Total number of runs	2

TC-21 – Schematics

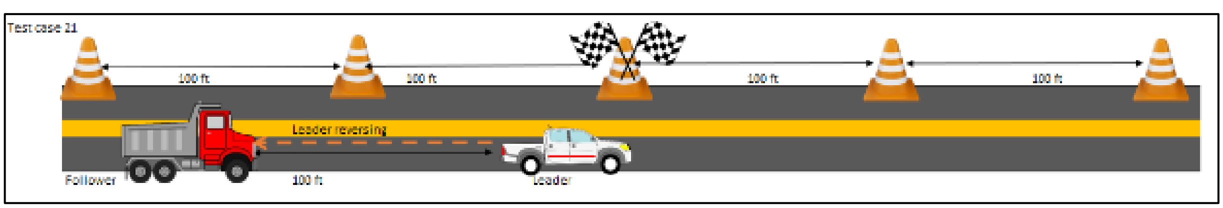


Figure 6-103. Closed loop test setup

TC-21 – Field Pictures

Figure 6-104. User interface view

Figure 6-105. External camera view

Figure 6-106. Dashcam view

TC-21 – ATMA Log File Data

No log file analysis was required for this test case.

TC-22: Acceleration/Deceleration

Test Case 22 measured the time it takes to accelerate from 5 to 15 mph and decelerate from 15 to 5 mph. Table 6-46 explains the procedure of executing this test. The acceleration process on Runs 1 and 2 took 7.77 and 9.19 seconds, respectively, to fully stabilize according to the UI. In Runs 3 and 4, the deceleration took 10.27 and 7.92 seconds, respectively (Table 6-47), to fully stabilize according to the UI.

Table 6-46. Test Case 22 operation procedure, data collection, and expected results

Operation Procedure	• Activated leader and ATMA. Drove leader in a straight lane with the gap set to 100 ft. • Drove with steady 5 mph and accelerated to 15 mph to stabilize, and vice versa. • Repeated test at least 2 times.
Data Collected	Time taken by ATMA to stabilize
Expected Result	ATMA maintains command gap while accelerating and deaccelerating.
Personnel Needed	Leader vehicle driver, ATMA driver and observer
Total Number of Runs	4

TC-22 – Schematics

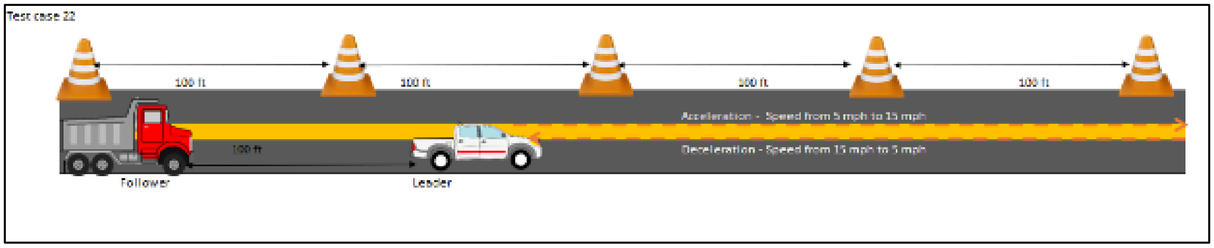


Figure 6-107. Closed loop test setup

TC-22 – Field Pictures

Figure 6-108. External camera view

Figure 6-109. Dashcam view

Table 6-47. Test Case 22 field observations

Run #	Speed (mph)	Time taken to stabilize (sec)
1	5 to 15	7.77
2	5 to 15	9.19
3	15 to 5	10.27
4	15 to 5	7.92

TC-22 – ATMA Log File Data

The log files indicated that the leader vehicle accelerated from 5 to 15 mph in about 2 seconds. From the beginning of the leader acceleration in time, it took the ATMA follower about 5 seconds to reach 15 mph. Note that the actual acceleration took only 3 seconds; however, the time it took to process the e-crumb data and react to attain the desired speed was about 5 seconds.

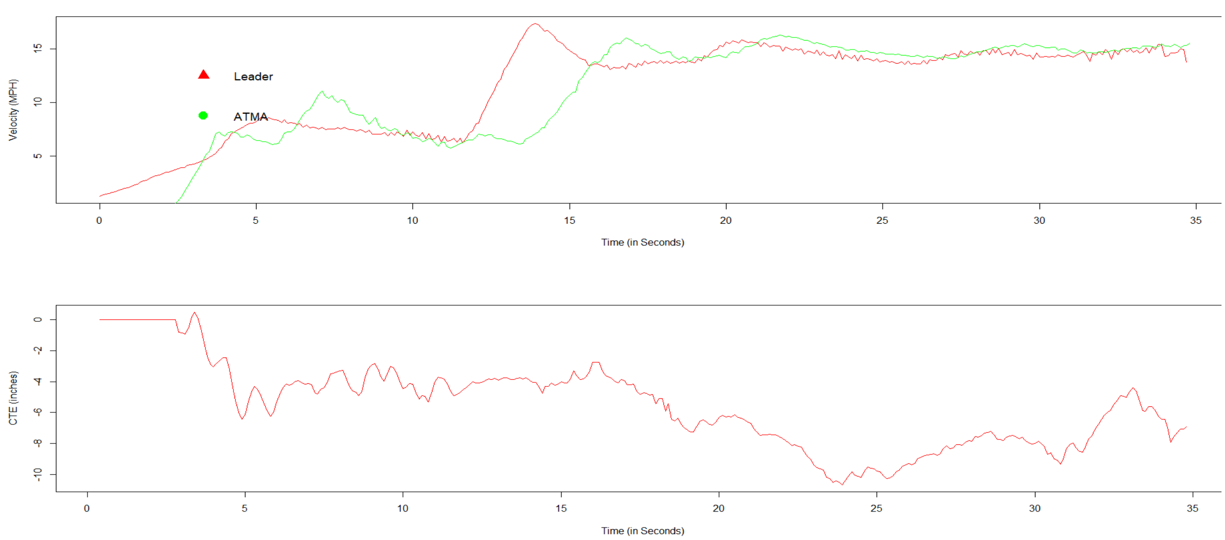


Figure 6-110. Test Case 22, Run 1: Leader-follower truck velocity graph (top); cross track error (CTE) (bottom)

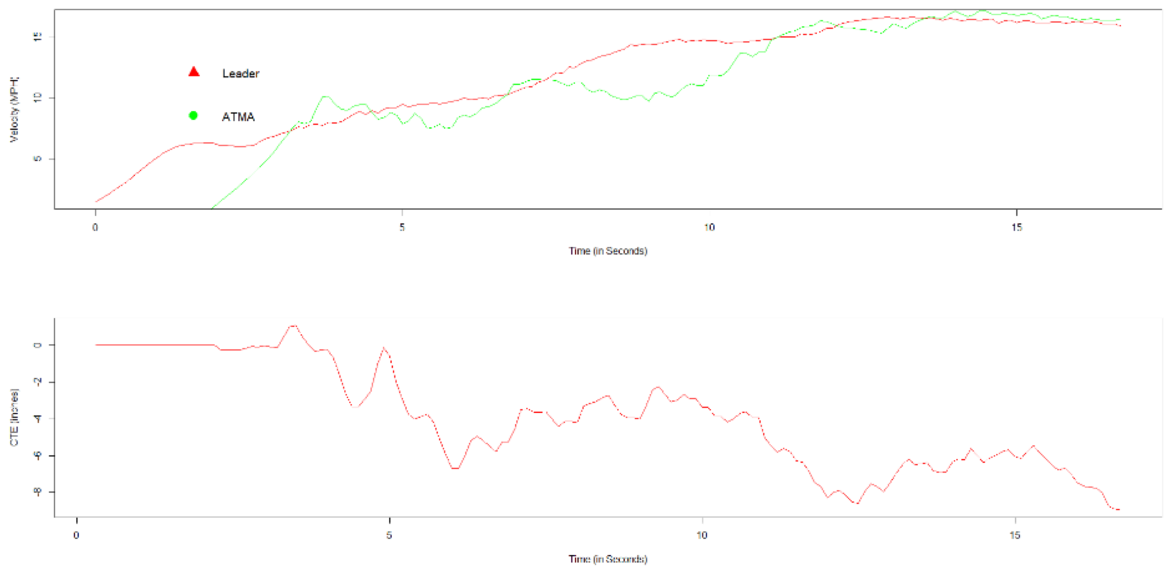


Figure 6-111. Test Case 22, Run 2: Leader-follower truck velocity graph (top); cross track error (CTE) (bottom). The stabilized speed of 5 mph is not obvious in this speed plot. The time for the ATMA to accelerate was about 9 seconds.

Table 6-48. Test Case 22 ATMA log file analysis results – CTE (inches)

Test	Run #	Min	Max	Mean	Standard Deviation
22	1	-10.67	0.51	-5.5	2.73
	2	-8.94	1.06	-3.93	2.78
	3	NA	NA	NA	NA
	4	-14.92	0	-7.5	4.18

6.1.7 Focus Area 7 – Communication Tests

This section is focused on analyzing the ATMA behavior in case of any communication loss of sensors, GPS, and vehicle-to-vehicle (V2V) radio communication. For the communication tests, no log file analysis was required.

TC-23: Loss of Sensor (Radar and LIDAR)

This test was designed to evaluate the ATMA performance in case of communication loss by radar, lidar, or front-facing ultrasonic. The Kratos representative explained that the ultrasonic sensors are no longer required with the advancement of the lidar sensor. So, the test only focused on radar and lidar output. Table 6-49 explains the procedure of executing this test. The expected result was an A-stop for ATMA.

Table 6-49. Test Case 23 operation procedure, data collection, and expected results

Operation Procedure	• Activated leader and ATMA, and drove in a straight line at 10 mph with the gap set to 100 ft. • Disconnected the radar, lidar, and front-facing ultrasonic sensors one at a time. • Log data were pulled after each test. • Repeated test at least 2 times.
Data Collected	• Time to stop after sensor was disconnected
Expected Result	The ATMA initiates an A-stop (throttle released, brake fully applied, transmission in neutral).
Team members	Leader vehicle driver, ATMA driver, and technician to set up system and export data
Supporting Equipment	Laptop, cables to connect with vehicle, traffic cones
Total number of testing runs	6

TC-23 – Field Pictures

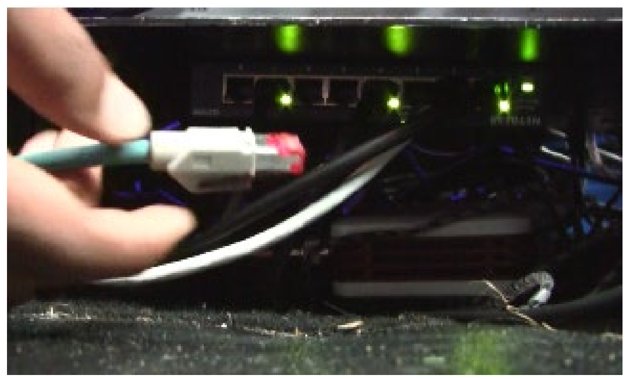


Figure 6-112. Unplugging radar cable (left) and lidar cable (right) for Test Case 23

Table 6-50 shows the field observations for Test Case 23. In all runs, the ATMA stopped between 7 and 9 seconds.

Table 6-50. Test Case 23 field observations

Run #	Radar/ Lidar	Speed (mph)	A-stop (Yes/No)	Time taken to stop (sec)	UI indicates the Loss of sensor (Yes/No)	UI Message
1	R	10	Y	8	Y	Not receiving radar
2	R	10	Y	9	Y	Not receiving radar
3	L	10	Y	6	Y	Not receiving lidar
4	L	10	Y	7	Y	Not receiving lidar

TC-23 – ATMA Log File Data

The ATMA log files was not analyzed since the field data was sufficient for validation of this test.

TC- 24: GPS Loss (GPS-Denied Environment)

This test was designed to evaluate the ATMA performance in case of GPS loss. Table 6-51 explains the procedure of executing this test. The GPS communication can be disconnected by system control unit inside the leader or ATMA. The expected result is for ATMA to keep its accuracy and perform an A-stop in less than one minute.

Table 6-51. Test Case 24 operation procedure, data collection, and expected results

Operation Procedure	• Gap set to 200 ft. • Activated leader and ATMA, and drove in a straight line at 10 mph. • Disconnected GPS signal of ATMA (primary antenna). • Log data were pulled after each test. • Repeated test on leader vehicle GPS. • Repeated each test at least 2 times
Data Collected	• The time ATMA maintained its lane accuracy (±6”). • The time without GPS before the ATMA initiated an A-stop
Expected Result	• The ATMA maintains lane accuracy for a minimum of 45 seconds after GPS is lost. • The ATMA initiates an A-stop in under 1 minute.
Team Members	Leader vehicle driver, ATMA driver, and technician to set up system and export data
Supporting Equipment	Laptop, cables to connect with vehicle, traffic cones
Total Number of Testing Runs	4

Table 6-52 shows the field observations for Test Case 24. In all the four runs, the ATMA stopped, and the time it took ranged between 10 and 43 seconds.

Table 6-52. Test Case 24 field observations

Run #	GPS Cable Disconnected (ATMA/Leader)	Speed (mph)	A-stop Initiated and Stopped (Yes/No)	Time Taken to Stop (Sec)	UI Indicates the Loss of Navigation (Yes/No)	UI Message
1	ATMA	5	Y	10	Y	No navigation sent from leader
2	ATMA	5	Y	35	Y	No navigation sent from leader
3	Leader	5	Y	42	Y	Not receiving GPS data accurately
4	Leader	5	Y	43	Y	Not receiving GPS data accurately

TC- 25: Loss of Communication (Single V2V Radio)

This test was designed to evaluate the ATMA performance in case of one of V2V communication was lost. Note that there are two radios: the main radio and the redundant radio. Table 6-53 explains the procedure of executing this test. The expected result is for ATMA is to continue its defined path accurately.

Table 6-53. Test Case 25 operation procedure, data collection, and expected results

Operation Procedure	• Gap set to 100 ft. • Activated leader and ATMA; drove in a straight line at 10 mph. • Disconnected communications link between leader and ATMA (one V2V radio). • Log data were pulled after each test. • Repeated test at least 2 times.
Data Collected	• Worst-case lane accuracy in loss of a single communications channel event • UI indication of loss of communications channel event
Expected Result	The ATMA continues to follow the path of the leader without interruption and notifies the user of the bad communication channel.
Team Members	Leader vehicle driver, ATMA driver, and technician to set up system and export data
Supporting Equipment	Laptop, cables to connect with vehicle, and traffic cones
Total Number of Testing Runs	2

Table 6-54 shows the field observations for Test Case 25. In both runs, the ATMA continued following the leader path, and the leader UI showed message showing primary or redundant V2V communication is disconnected.

Table 6-54. Test Case 25 field observations

Run #	Speed (mph)	Communication Cable Pulled	UI indicates the Loss of Communications channel (Yes/No)
1	5	Primary	Y
2	5	Secondary	Y

TC-25 – ATMA Log Files Data

The ATMA log files were not analyzed because the field data were sufficient for validation of this test.

TC-26: Loss of Communication (Both V2V Radios)

With ATMA unmanned, it is critical to maintain constant and reliable communication at all times. This test was design to replicate the main and redundant V2V communication loss with ATMA and observe the outcomes. Table 6-55 explains the procedure of executing this test. The expected result is for ATMA is to execute an A-stop. In both cases the ATMA A-stopped after the communication loss (Table 6-56).

Figure 6-113 below shows the status of follower link: first, when both indicators were active; then both communication links were disconnected, which was confirmed in the UI as shown in the figure. For the second test, only one of the communication links was disconnected (confirmed in the UI).

Table 6-55. Test Case 26 operation procedure, data collection, and expected results

Operation Procedure	• Gap set to 100 ft. • Activated leader and ATMA; drove in a straight line at 10 mph. • Disconnected communications link between leader and ATMA (both V2V radios). • Log data were pulled after each test. • Repeated test at least 2 times.
Data Collected	• Time from loss of communications until A-stop initiated • Distance from point of communication loss until ATMA stopped • UI indication of loss of communications
Expected Result	The ATMA stops after the communication is lost.
Team members	Leader vehicle driver, ATMA driver, and technician to set up system and export data
Supporting Equipment	Laptop, cables to connect with vehicle, traffic cones
Total number of testing runs	2

Table 6-56. Test Case 26 closed loop data

Run #	Speed (mph)	Radios Disconnected	UI indicates the Loss of Communications channel (Yes/No)	ATMA A-STOP
1	10	Y	Y	Y
2	10	Y	Y	Y

TC-26 – ATMA Log Files Data

ATMA log file analysis was not required for this test because this was manually validated by the field team.

Both Follower Link

Both Follower Link

One Follower Link Active

Figure 6-113. User interface showing status of communication link during loss of communication test

6.2 Field Tests

The mobile work zone (ATMA) was tested on five various facilities in Gainesville, Florida: SR-222, I-75, US-441, SR-26, and SW 2nd Ave. In the first four field tests the falling weight deflectometer (FWD) was used. In the SW 2nd Ave field test, ATMA performance in roundabouts was examined.

6.2.1 Field Test 1 – SR-222

Figure 6-114 below shows an aerial view of the Field Test 1 (FT-1) test section on SR-222, a multilane, high traffic (average AADT of 22,914), low-speed (speed limit: 45mph) urban environment with three signalized intersections and multiple access points on corridors. Historical AADT is provided in Table 6-57. The testing was conducted under daylight conditions on both EB and WB directions. This was a three-vehicle operation with the offset distance between the leader (FWD) and TMA being 50 feet, and between the TMA and ATMA follower vehicle, the gap was set at 200 feet. The overall testing took about 4 hours. The FWD made stops every 375 feet for a couple of minutes and moved to the following test location. Overall, the testing was performed as expected with one issue as documented below.

Table 6-57. Test Site 3 testing section and historical AADT

Roadway	Coordinates		Section		AADT				
	Begin	End	From	To	2015	2016	2017	2018	2019
SR-222 (39th Ave)	29.688597, −82.341491	29.688326, −82.316601	NW 21st Dr	US-441/ SR-25/ NW 13th St	27,000	27,500	26,000	27,000	27,500
			US-441/ SR-25/ NW 13th St	SR-20/ NW 6th St	22,000	20,500	21,000	22,000	21,500
			SR-20/ NW 6th St	CR- 329/ N Main St	25,000	23,500	24,500	25,500	24,000
			CR-329/ N Main St	NE 11th Ter	18,600	18,800	18,900	18,900	18,700

AADT source: https://tdaappsprod.dot.state.fl.us/fto/

Figure 6-114. Location of Test Site 3 on SR-222 in the Gainesville area

FT-1 – Personnel Feedback

The FDOT leader vehicle operator (FDOT staff) did not report any significant safety issue during the testing; however, there were several operational issues where the leader vehicle had to clear A-stops due to vehicle intrusion in front of ATMA. The staff member indicated that he felt safe throughout the testing period. There was no issue with the radio communication with the safety officer and no interruption during FWD testing. The staff member mentioned that the testing went as it would have with manual TMA operation.

The middle TMA vehicle operator did not report any significant event. He was required to maintain 50 feet or less from the leader, which was not difficult. No issues were reported with the communication with either leader or the ATMA follower vehicle.

The safety operator (Kratos staff) in the ATMA reported the following events:

- The rollout distance had to be adjusted to 200 ft because of the middle TMA vehicle.
- Several A-stops occurred due to vehicle intrusion in front of ATMA.

The UF observer, a passenger in the ATMA, reported the following:

- The testing started at 10:46 am.
- There were initial difficulties when the leader began; however, the ATMA follower was not configured due to the middle TMA vehicle distance issue. The command gap was set to 300 ft, which solved the issue.
- Generally, the ATMA follower has a rocking feel with instant acceleration and deceleration.
- Very often, the ATMA follower path was cut by traffic, and an A-stop was triggered several times (Figure 6-115).
- One vehicle deviated from the outside lane towards the inside lane in front of the ATMA follower vehicle.
- Overall, weaving was a common issue, and the traffic did not see the three vehicles as a work platoon with a leader and follower unit.

- The camera in the leader unit could not differentiate the signal light color due to sun glare.
- In one instance, the ATMA follower drifted towards the outside lane, and the control was overridden by the Kratos safety officer. The cause could not be determined.
- At 11:48 AM, the system operated on Idle because it did not receive the leader message.
- At 12:03 PM, due to a hard break, the system misreported a collision, and the safety operator (Kratos staff) was required to change to Idle mode.
- At intersections, driver training is critical to understand the implications of ATMA operation, for example, stop the work platoon downstream of the intersection to avoid a traffic bottleneck at the intersection (Figure 6-117).

Figure 6-115. Multiple vehicle intrusions in front of ATMA that caused frequent A-stops

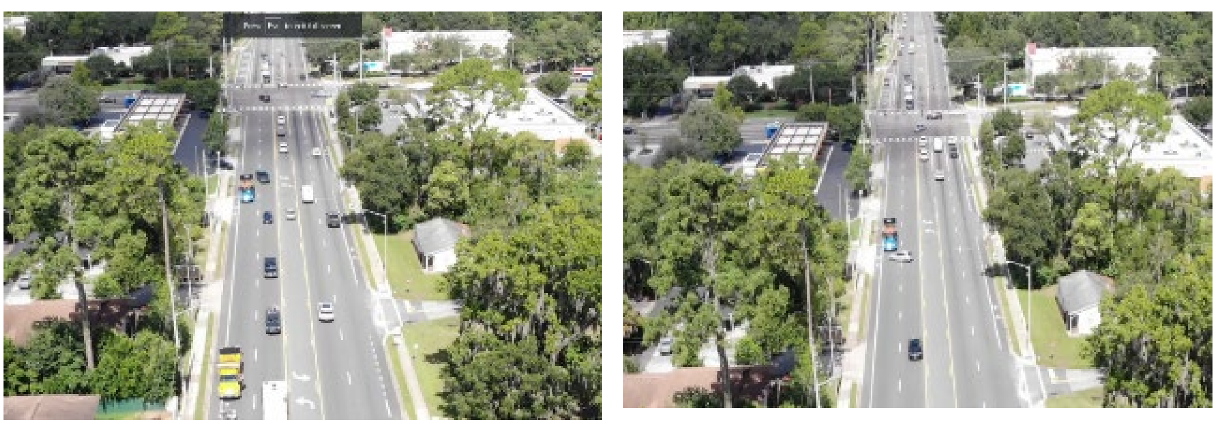


Figure 6-116. ATMA stop near driveways causes issue for ATMA as well as for public access

Figure 6-117. ATMA stop too close to intersection caused traffic backup for left-turning traffic at intersection

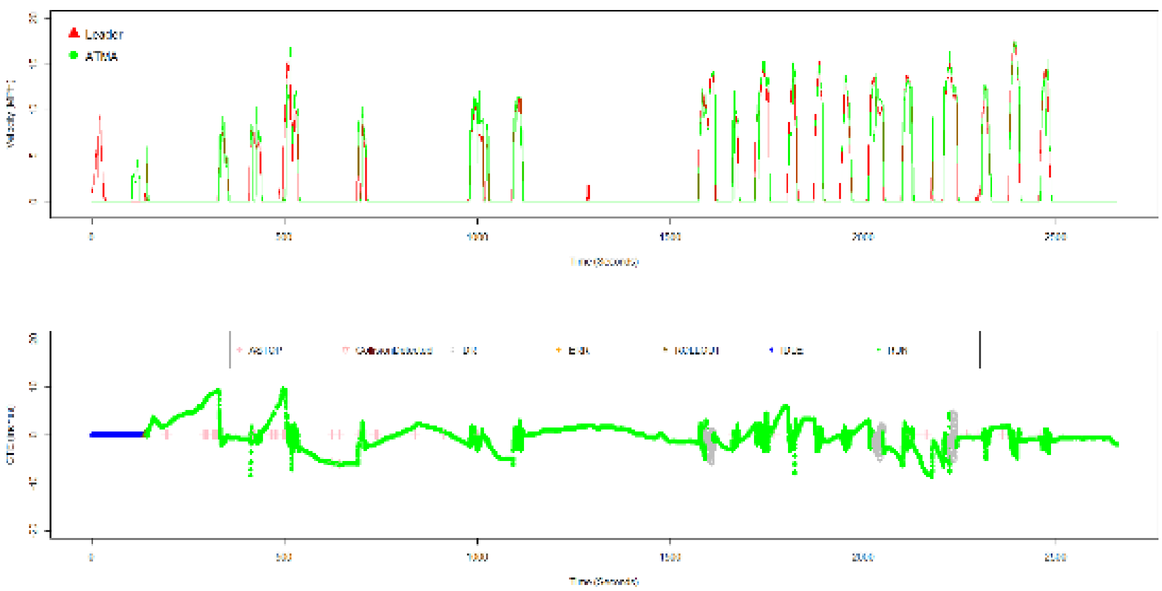
FT-1 – ATMA Log File Data

This section summarizes the results from ATMA log file analysis for the field test on SR-222. Figure 6-118 shows the velocity and cross track error (CTE) of this field test on westbound (WB) and eastbound (EB). The test on EB took 2,640 seconds, while the WB test took about 1,341 seconds. Visual inspection of speed plots indicates that the follower was able to keep up with the leader vehicle profiles closely. The CTE plots show the various states of the ATMA follower. The duration and percentage of these states are shown in Table 6-58. On WB, the ATMA detected a possible crash and stopped. The percentage of A-stop durations on EB and WB were 3.7% and 1.8%, respectively. On WB, in 1.8% of durations, an error occurred. In addition to the initial rollout on WB, the ATMA had to perform the rollout process two more times due to error and collision detection. The A-stop plots are shown in Figure 6-119. The ATMA follower experienced a total of 29 A-stops on EB and 11 on WB.

The CTE statistics were as follows:

- EB: Minimum value of −8.90 in, maximum of 9.56 in, mean of −0.36 in, with a standard deviation of 2.57 in;
- WB: Minimum value of −19.17 in, maximum of 5.91 in, mean of −5.50 in, with a standard deviation of 3.92 in.

EB



WB

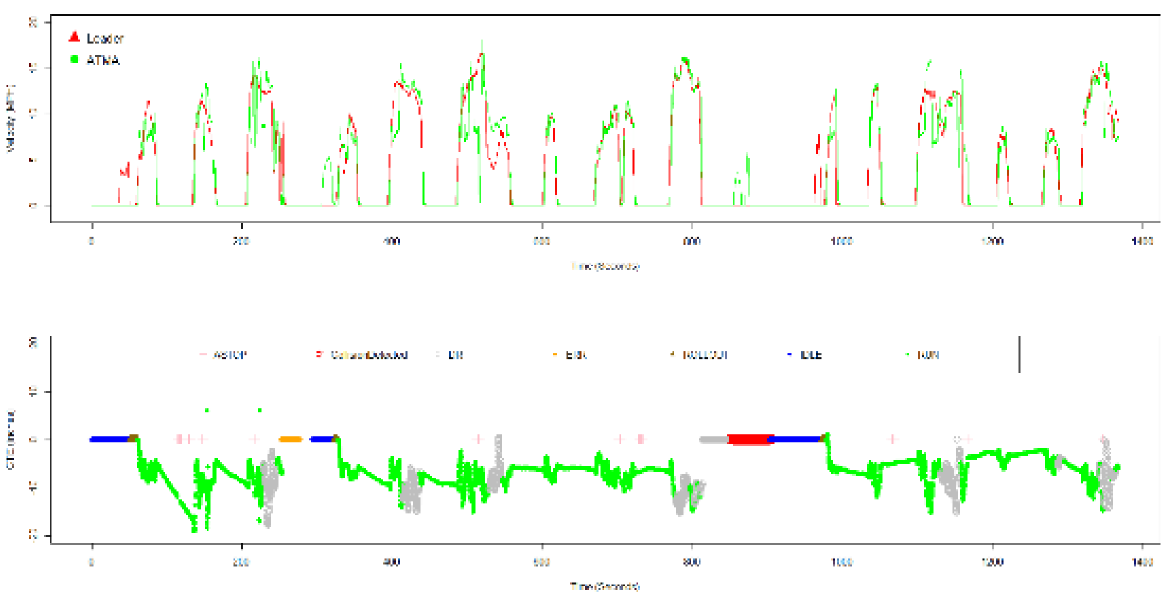
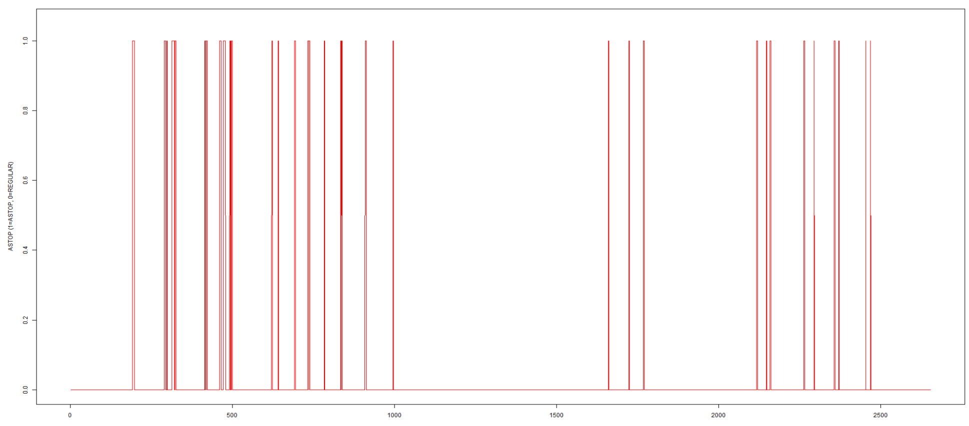


Figure 6-118. Velocity and cross track error of SR-222 field test

Table 6-58. Percentage of various states of ATMA for SR-222 field test

State	NB		SB	
	Seconds	Percentage	Seconds	Percentage
ASTOP	96.8	3.7	23.7	1.8
Collision Detected	0	0	48.8	3.6
DEADRECKONING	54.5	2.1	176.8	13.2
ERROR	0	0	23.6	1.8
IDLE	136.4	5.2	150.1	11.2
Rollout	4.1	0.2	15.4	1.1
Run	2,348.4	88.9	902.2	67.3
Sum	2,640.2	100	1,340.6	100

EB



WB

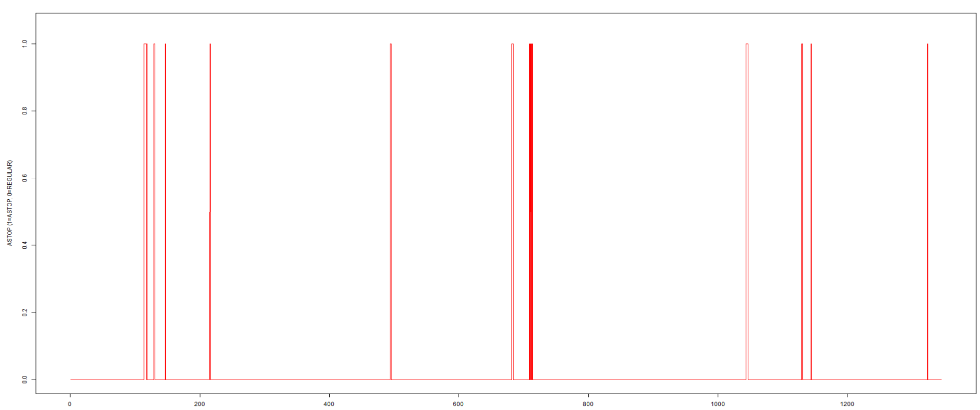


Figure 6-119. A-stop plot of SR-222 field test (FT-1)

6.2.2 Field Test 2 – I-75

Figure 6-120 shows the Field Test 2 (FT-2) test section on I-75, which is a limited access, urban high-speed freeway with an average AADT of 73,203. Table 6-59 provides the historical AADT at this site. The test was conducted at night between 10:30 p.m. and 1 a.m. The test was scheduled to start at 9 p.m.; however, with heavy rain, the FWD was unable to operate, and due to safety concerns, the test was delayed. The FWD test was performed in both NB and SB directions, starting at 10 p.m. This was a three-vehicle operation along with a sheriff department police escort. The offset distance between the leader (FWD) and TMA was 50 feet, and between the TMA and ATMA, the gap was set at 300 ft. The FWD made stops every 375 ft for a couple of minutes and moved to the following test location. Overall, the testing was performed as expected with a couple of issues as documented below.

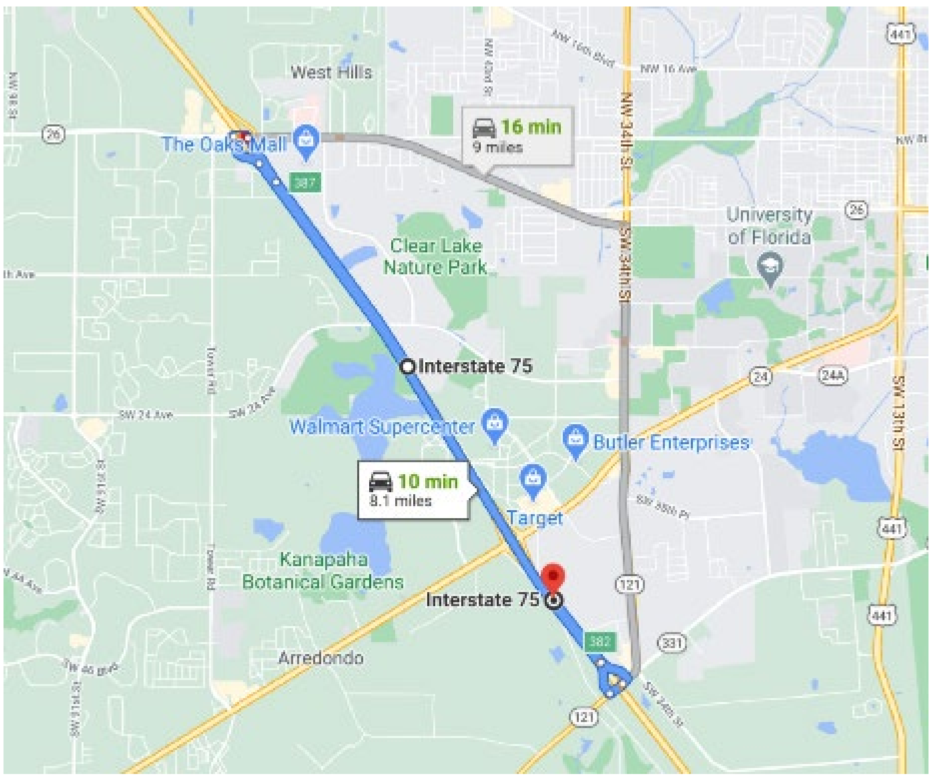


Figure 6-120. Location of Test Site 2 on I-75 in the Gainesville area

Table 6-59. Test Site 2 testing section and historical AADT

Road-way	Coordinates		Section		AADT				
	Begin	End	From	To	2015	2016	2017	2018	2019
I-75	29.611106, −82.381182	29.635589, −82.398786	Bridge No. 260061	Bridge No. 260063	NA	NA	57,000	64,500	67,500
			Bridge No. 260063	Bridge No. 260054	67,000	63,500	73,500	79,000	83,500
			Bridge No. 260054	Bridge No. 260057	78,000	84,000	78,500	90,500	89,000

FT-2 – Personnel Feedback

The FDOT leader vehicle operator (FDOT staff) did not report any significant safety issue during the testing; however, there was one operational issue. When the ATMA went into dead reckoning (DR) mode, the leader could not make the stop to conduct the FWD testing, and as a result, one data point was not collected because of the DR issue. The staff member indicated that he felt safe throughout the testing period. There was no issue with the radio communication with the safety officer and no interruption during the FWD testing. He mentioned that the testing went on as it would have with manual TMA operation.

The middle TMA vehicle operator did not report any significant event. He was required to maintain 50 ft or less from the leader, which was not difficult. No issues were reported with the communication with either leader or the follower ATMA.

The safety operator (Kratos staff) in the ATMA follower reported the following events:

- The steering fingers were installed when entering the testing site before entering autonomous mode.
- The rollout distance had to be adjusted to 190 ft because of FWD trailer. The max rollout is 200 ft. The ATMA follower would identify obstacles within 150 ft and was detecting the trailer as an obstacle. Adjustments were made to the gap distance.

The UF observer, a passenger in the ATMA, reported the following:

- The steering fingers were installed when entering the testing site before entering autonomous mode.
- The rollout distance had to be adjusted to 190 ft because of FWD trailer. The max rollout was 200 ft. The ATMA would identify obstacles within 150 ft and was detecting the trailer as an obstacle. Adjustments were made to the gap distance.
- The system went into DR near the Archer Road exit.
- The lidar on top of the ATMA was facing upward and forward to detect overhead obstacles that would cause the GPS-RTK signal to lose satellite connection. The system is designed to go into DR immediately upon detecting an overhead obstruction that could block any satellite “lock.” The DR early detection is an added precaution, and the Kratos team discussed adding a feature to the user interface to disable the overhead lidar detection to reduce the number of stops and restarts.
- On I-75, we did not have any stops and restarts and only had one data point planned in an area that was not able to be collected because of the DR mode of the leader/follower. The point was skipped to avoid a restart during field testing.
- During other tests, we experienced the challenge of DR mode and the need for the UI enable/disable of the overhead lidar.

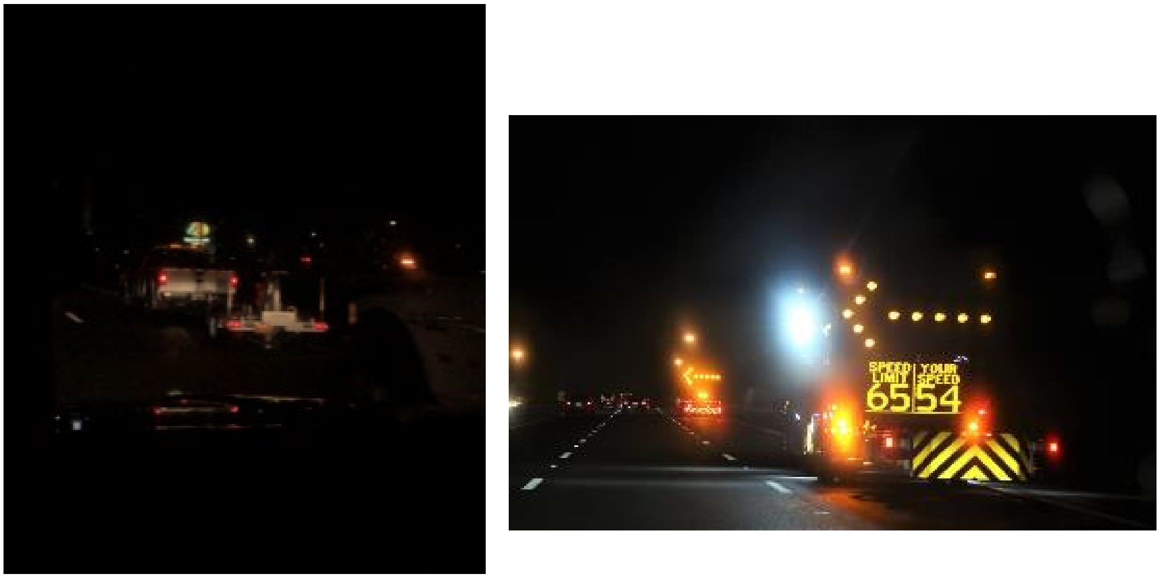


Figure 6-121. Leader vehicle (FDOT FWD) testing on I-75 (left); TMA followed by ATMA (right)

FT-2 – ATMA Log File Data

This section summarizes the results from ATMA log file analysis for the field test on I-75. Figure 6-122 shows the velocity and cross track error (CTE) of this field test on northbound (NB) and southbound (SB). The test on NB took 2,385 seconds, while the SB test took about 2,687 seconds. Visual inspection of the speed plots shows that the ATMA followed the leader accurately. The CTE plots show the various states of the ATMA. On NB, the ATMA was in dead reckoning (DR) mode between 1,500 to 1,528 seconds. Due to this, an e-crumb error occurred. After the stop, the ATMA was in the rollout process until 1,722 seconds. At 1,722 seconds, another error occurred, and the rollout process needed to be redone. The ATMA went on dead reckoning mode 6 and 2 times, respectively, on NB and SB.

The duration and percentage of these states are shown in Table 6-60. On NB, there were no A-stops or collision detection. On SB, there was one A-stop, with the duration percentage of 1.2%, and there was no collision detection. There was no A-stop on NB and only one on SB.

The CTE statistics were as follows:

- NB: Minimum value of −9.72 in, maximum of 12.87 in, mean of −2.09 in with a standard deviation of 2.09 in;
- WB: Minimum value of −23.82 in, maximum of 8.94 in, mean of −1.76 in with a standard deviation of 2.49 in.

NB

SB

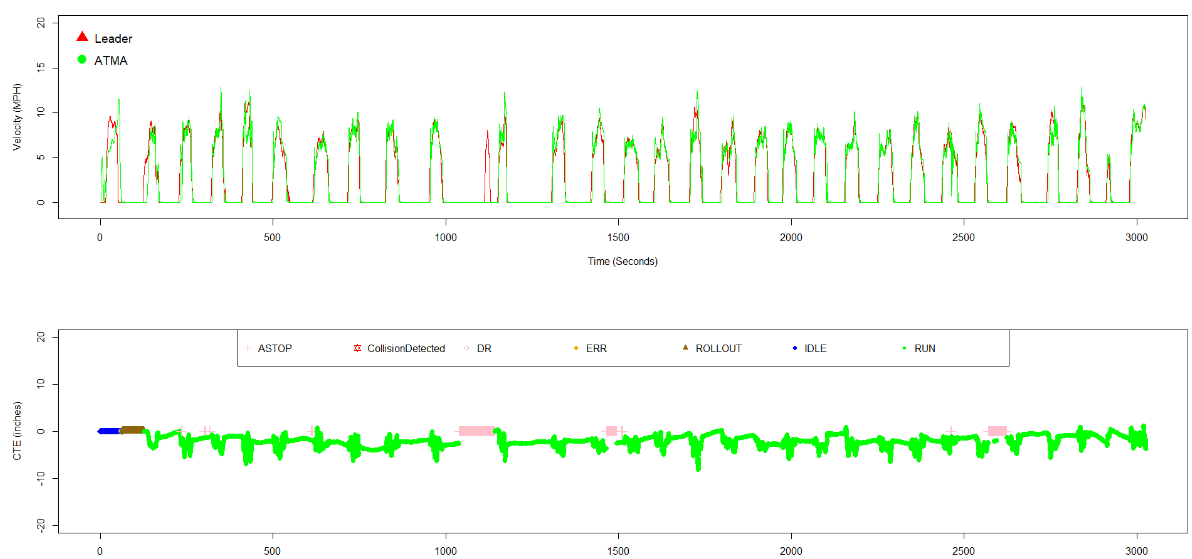


Figure 6-122. Velocity and cross track error of I-75 field test

Table 6-60. Percentage of various states of ATMA for I-75 field test

	NB		SB	
State	Seconds	Percentage	Seconds	Percentage
ASTOP	0	0	32.2	1.2
Collision Detected	0	0	0	0
DEADRECKONING	65.2	2.7	49.8	1.9
ERROR	28	1.2	0	0
IDLE	207.8	8.7	402.9	15
Rollout	87.8	3.7	71.8	2.7
Run	1,995.9	83.7	2,130.6	79.3
Sum	2,384.7	100	2,687.3	100

6.2.3 Field Test 3 – US-441 at Paynes Prairie

Figure 6-123 shows the Field Test 3 test section on US-441, which is a four-lane, semi-urban, high-speed (65 mph speed limit) roadway with grass median. The roadway carries moderate traffic with AADT shown in Table 6-61 below. The FWD testing was performed in both NB and SB directions. Figure 6-126 shows the aerial views of the offset distance between FWD truck and lead TMA (50 feet), and between the TMA and ATMA, the gap was set at 300 ft. The staging was done in the grass shoulder where the attenuators were positioned, and safety checks were performed for all vehicles. After radio checks, the rollout was initiated until the command gap was achieved. Initially, the ATMA detected the middle TMA vehicle as an obstacle, but after minor adjustment in the gap from the TMA vehicle (closer to leader), the ATMA follower went into autonomous mode. The total testing duration was about 4 hours. The FWD made stops every 375 feet for a couple of minutes and moved to the following test location. Overall, the testing was performed as expected without any significant issues to report.

FT3 – Personnel Feedback

The FDOT leader vehicle operator (FDOT staff) did not report any significant event during the testing. The staff member indicated that he felt safe throughout the testing period. There was no issue with the radio communication with the safety officer and no interruption during the FWD testing. He mentioned that the testing went on as it would have with manual TMA operation.

The middle AW vehicle operator (FDOT staff) did not report any significant event. He was required to maintain 50 ft or less from the leader, which was not difficult. No issues were reported with the communication with either leader or the follower ATMA.

The safety operator (Kratos staff) at the ATMA reported the following events:

- In one instance, a vehicle in the opposite direction performing a U-turn cut the ATMA off, which caused the A-stop to occur (Figure 6-129).
- Initial rollout required multiple runs because the middle TMA vehicle was reported as an obstacle.
- Once started, the overall testing period went successfully.

The UF observer, a passenger in the ATMA follower, reported the following:

- Similar observations as the safety operator with respect to a vehicle cutting ATMA path while performing a U-turn
- The system did not report DR mode, which means that the GPS signal was strong and consistent throughout.
- The traffic approaching the ATMA from the back changed lanes ahead of time so there were no last minute conflicts or lane changes in this test section.

Table 6-61. Test Site 3 testing section and historical AADT

Roadway	Coordinates		Section		AADT				
	Begin	End	From	To	2015	2016	2017	2018	2019
US-441 Paynes Prairie	29.587389, −82.338585	29.559037, −82.331176	SE 132 LN	SW 63 AVE	12,100	13,600	15,000	14,400	14,600

AADT source: https://tdaappsprod.dot.state.fl.us/fto/

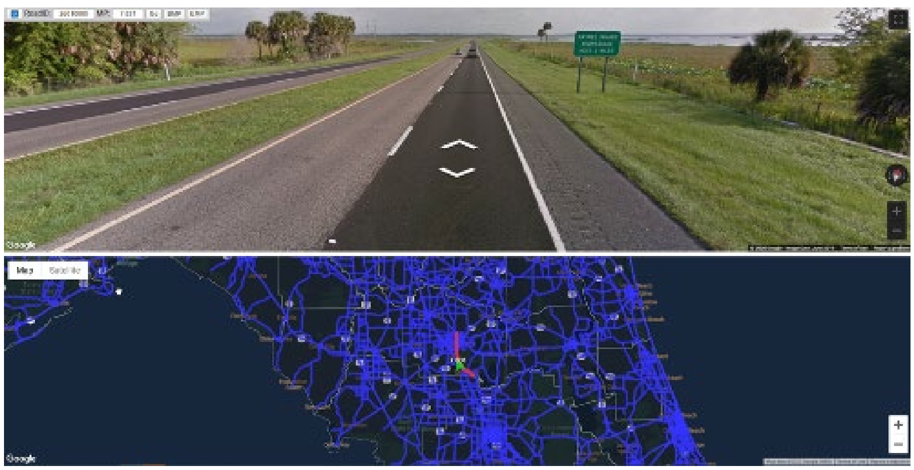


Figure 6-123. Location of Field Test Site 3 on US-441 in the Paynes Prairie area of Gainesville

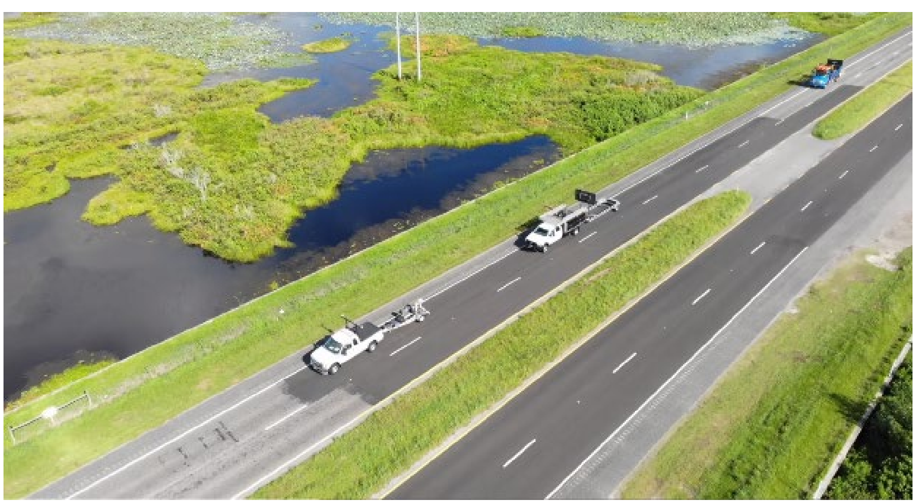


Figure 6-124. US-441 section – Leader: FDOT F350 FWD, middle TMA with attenuator; ATMA follower vehicle

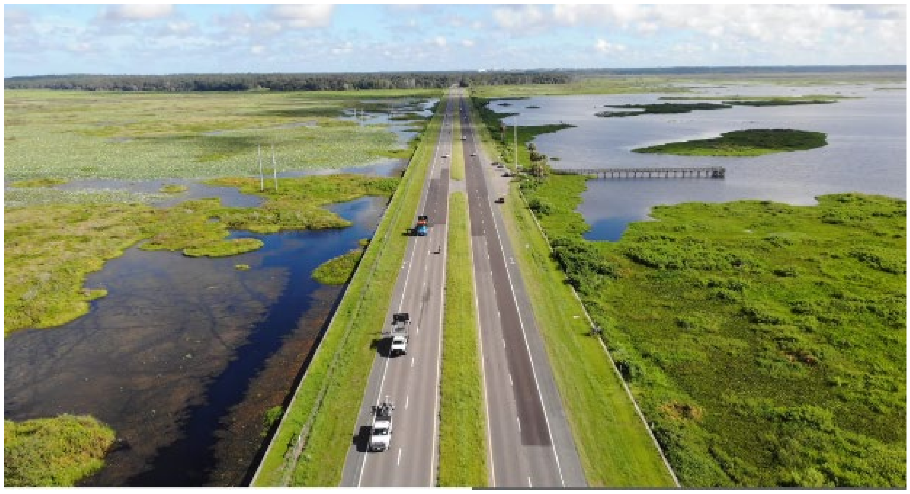


Figure 6-125. Front view showing upstream vehicles changing lanes before approaching the work platoon section

Figure 6-126. View from the back of the work platoon

FT-3 – ATMA Log File Data

This section explains the results from ATMA log files analysis for field test on US-441. Figure 6-127 shows the velocity and cross track error (CTE) of this field test on northbound (NB) and southbound (SB). The test on NB took 2,956 seconds, while the SB test took about 3,011 seconds. The visual inspection of speed plots shows that the ATMA follows the leader accurately. The CTE plots show the various states of ATMA. The duration and percentage of these states are shown in Table 6-62. There were 12 and 10 A-stops on NB and SB, respectively. As shown in Figure 6-128, most of these A-stops were due to vehicle intrusions. These A-stops took 3.3% and 6.7% of the total run duration on NB and SB, respectively. There was no interruption that led to stop and rerun (rollout) on either direction.

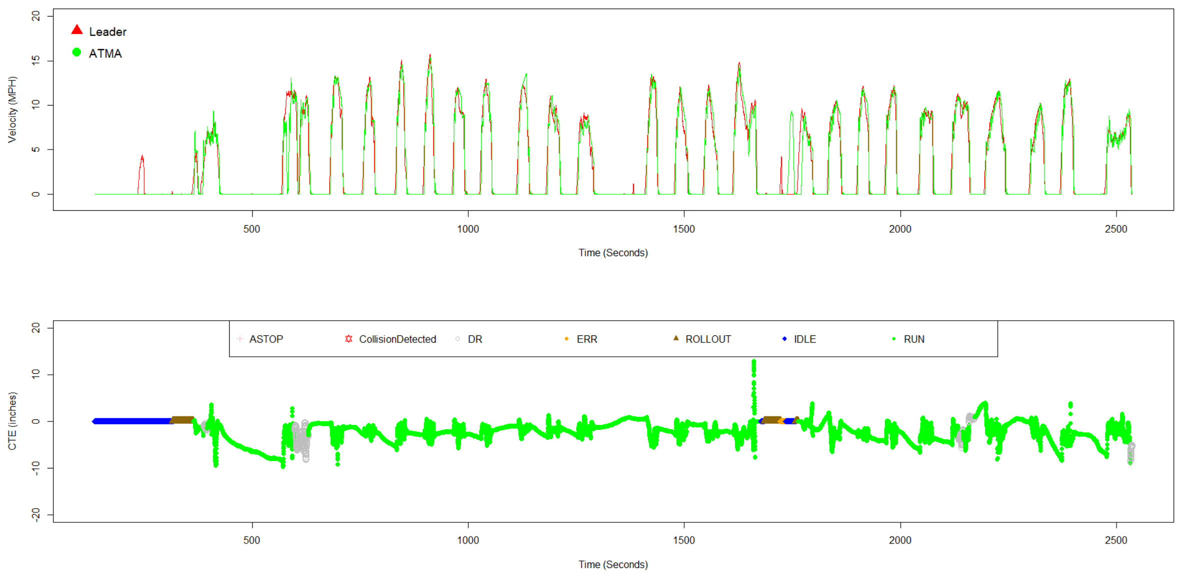
The CTE statistics were as follows:

- NB: Minimum value of −12.83 in, maximum of 0.11 in, mean of −3.30 in with a standard deviation of 1.77 in;
- WB: Minimum value of −8.19 in, maximum of 1.10 in, mean of −1.89 in with a standard deviation of 1.27 in.

Table 6-62. Percentage of various states of ATMA for US-441 field test

	NB		SB	
State	Seconds	Percentage	Seconds	Percentage
ASTOP	98.1	3.3	200.6	6.7
Collision Detected	0	0	0	0
DEADRECKONING	0	0	1.8	0.1
ERROR	0	0	0	0
IDLE	29.9	1	62	2.1
Rollout	6.7	0.2	60.4	2
Run	2,821.6	95.4	2,685.9	89.2
Sum	2,956.3	100	3,010.7	100

NB



SB

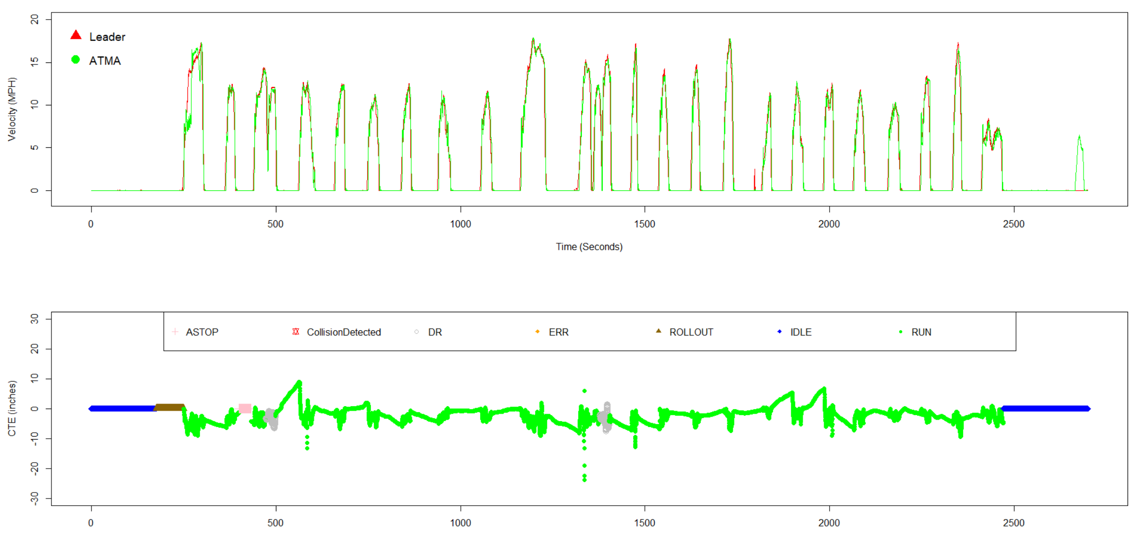
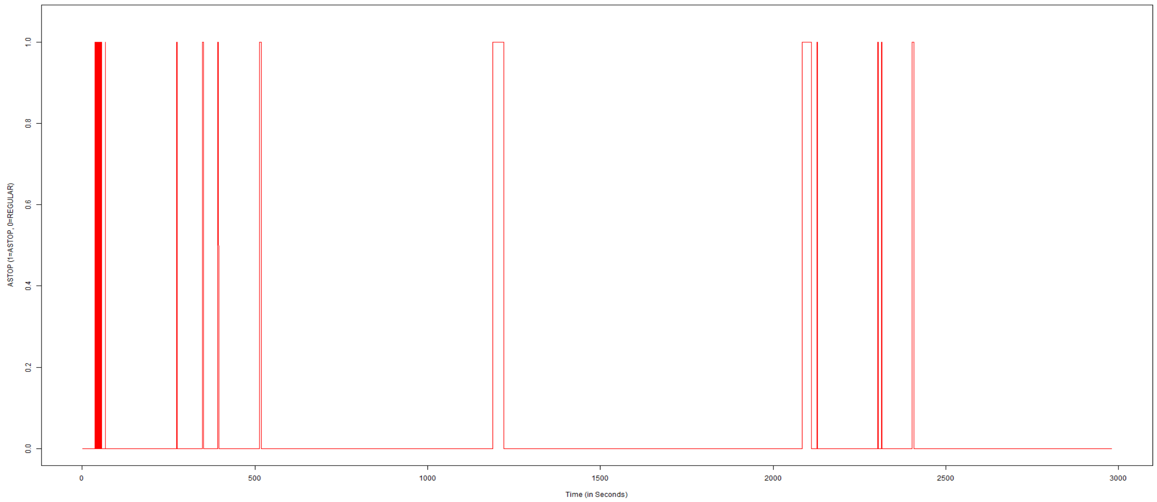


Figure 6-127. Velocity and cross track error of US-441 field test

NB



SB

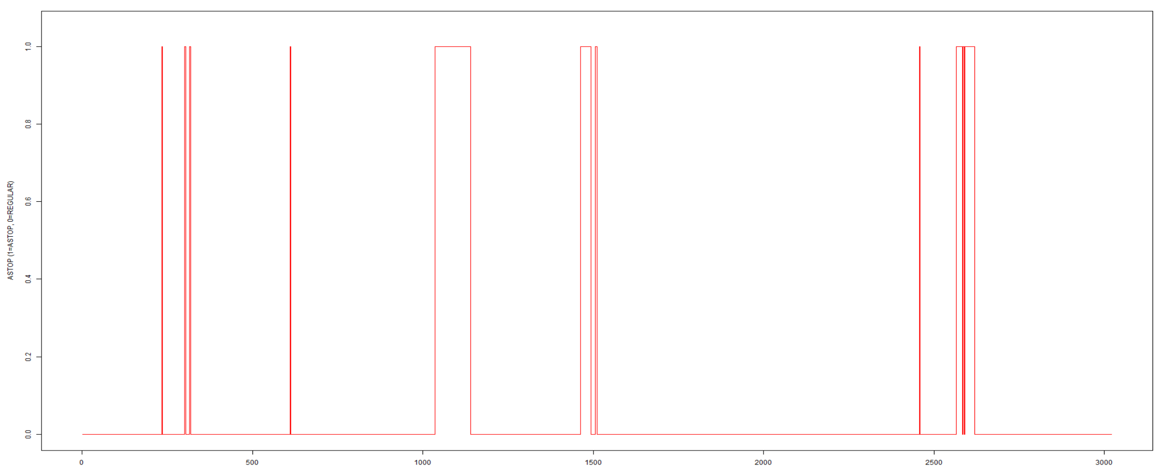


Figure 6-128. A-stop plot of US-441 field test

Figure 6-129. Vehicle making a U-turn and cutting the path of ATMA follower vehicle

6.2.4 Field Test 4 – SR-26

SR-26 is a high speed, rural, two-lane roadway with high traffic volume (Table 6-63). The FWD testing was conducted under daylight conditions. The testing was performed in the EB direction only; however, it was terminated early due to increased traffic and safety reasons. This was a two-vehicle operation. The offset distance between FWD leader and ATMA follower was 300 ft.

Table 6-63. Test Site 4 testing section and historical AADT

Roadway	Coordinates		Section		AADT				
	Begin	End	From	To	2015	2016	2017	2018	2019
SR-26	29.690411, −82.199105	29.702228, −82.176250	SR-222	NE 70th Pl	10,100	10,300	11,300	11,200	11,100

Figure 6-130. Location of Test Site 4 on SR-26, east of SMO in the Gainesville area

FT-4 – Personnel Feedback

The FDOT leader vehicle operator (FDOT staff) reported concerns on increased traffic, which caused impatient drivers to overtake with limited spacing. In addition, the ATMA follower went into DR mode a couple of times, which did not help with the testing. The FDOT staff member did not feel safe conducting this test under the given traffic conditions. The staff member, however, mentioned that this was the similar case with a manual TMA as well and that it was not different under ATMA operation.

The UF observer in the ATMA follower as a passenger reported the following:

- Similar observations as the leader vehicle operator, with increased traffic causing safety concerns
- Figure below shows the traffic backing up behind the ATMA follower. With the ATMA follower being a large vehicle, it obstructs the passing sight distance of the vehicle behind, which caused an unsafe condition in the field.
- When the ATMA follower went into DR mode, the platoon had to pull over in order to clear the traffic behind.
- The team decided to terminate the test due to safety concerns.

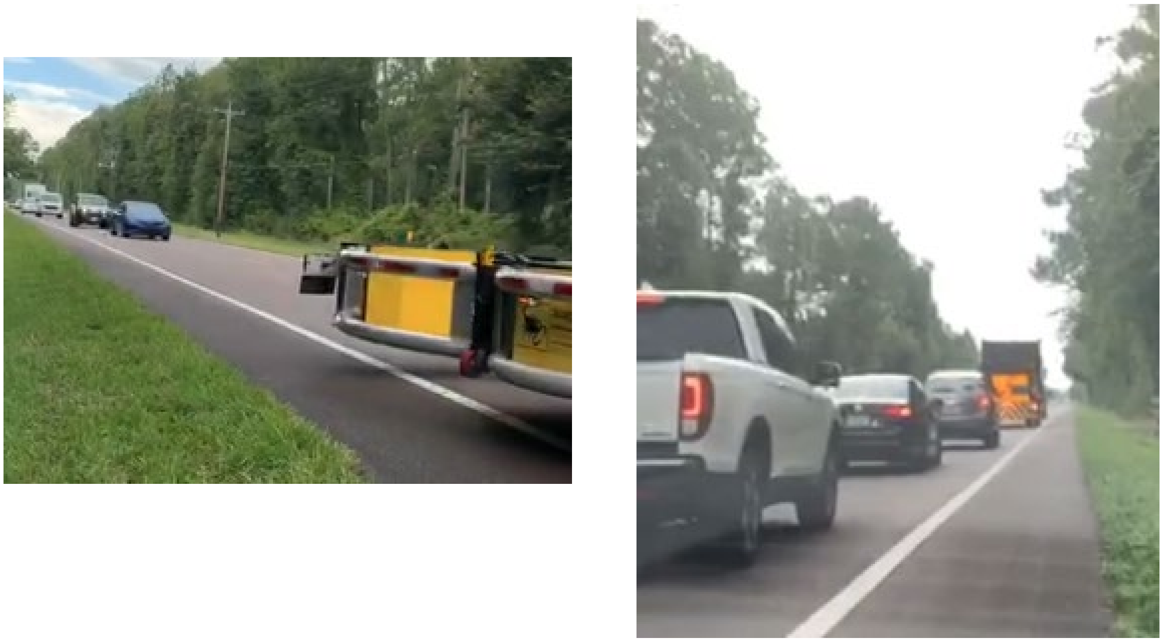


Figure 6-131. Traffic backed up due to slow moving operation on two-lane roadway

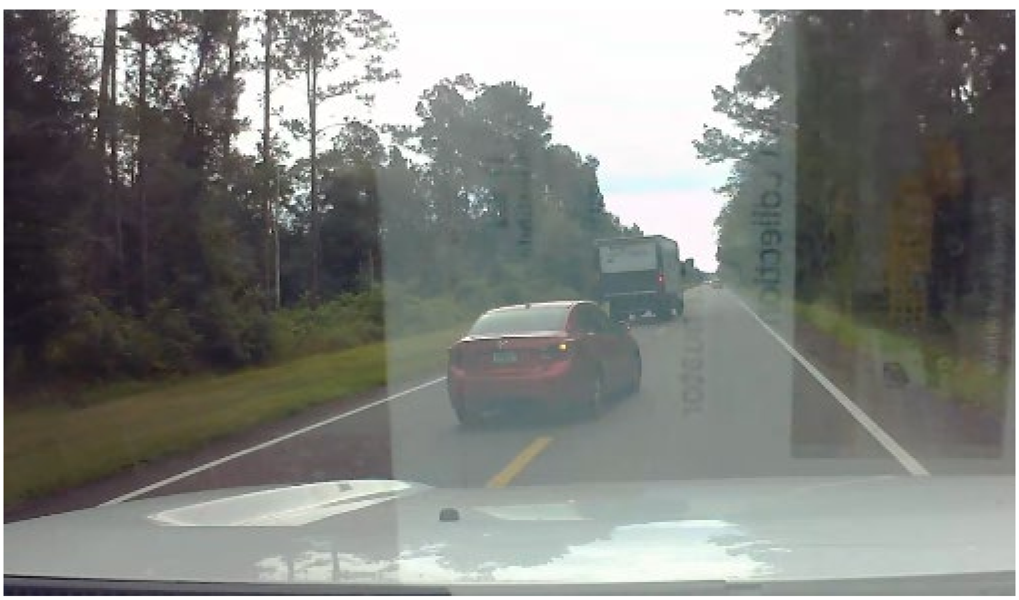


Figure 6-132. Traffic overtaking the work platoon

FT-4 – ATMA Log File Data

This section explains the results from ATMA log files analysis for the field test on EB SR-26. This section of SR-26 is a two-way two-lane road. Due to the low speed of the operation, a large queue was forming behind the mobile work zone. As explained in the previous section, the work zone vehicles had to pull over to give the queue the opportunity to clear. Due to the safety concerns, the test was terminated after 1,669 seconds. Figure 6-133 shows the velocity and cross track error (CTE) of this field test. The visual inspection of speed plots shows that the ATMA follower vehicle followed the leader accurately. As shown in Figure 6-132, there are tall trees on both sides of the road. This led the ATMA follower to work under dead reckoning mode. When the ATMA works under dead reckoning mode for 45 consecutive seconds, it applies an A-stop. The dead reckoning A-stop occurred seven times during the SR-26 field test: during intervals 476-483, 548, 570-575, 596-597, 603-604,1,046-1,056, and 1,274-1,279 seconds. After each of these A-stops, a rollout process was required. There was another A-stop that was due to vehicle intrusion.

The duration and percentage of various ATMA states are shown in Table 6-64. For 4.5% of the duration, the ATMA was in dead reckoning mode. The CTE statistics were as follows: minimum value of −28.70 in, maximum of 20.31 in, mean of −1.76 in with a standard deviation of 3.55 in.

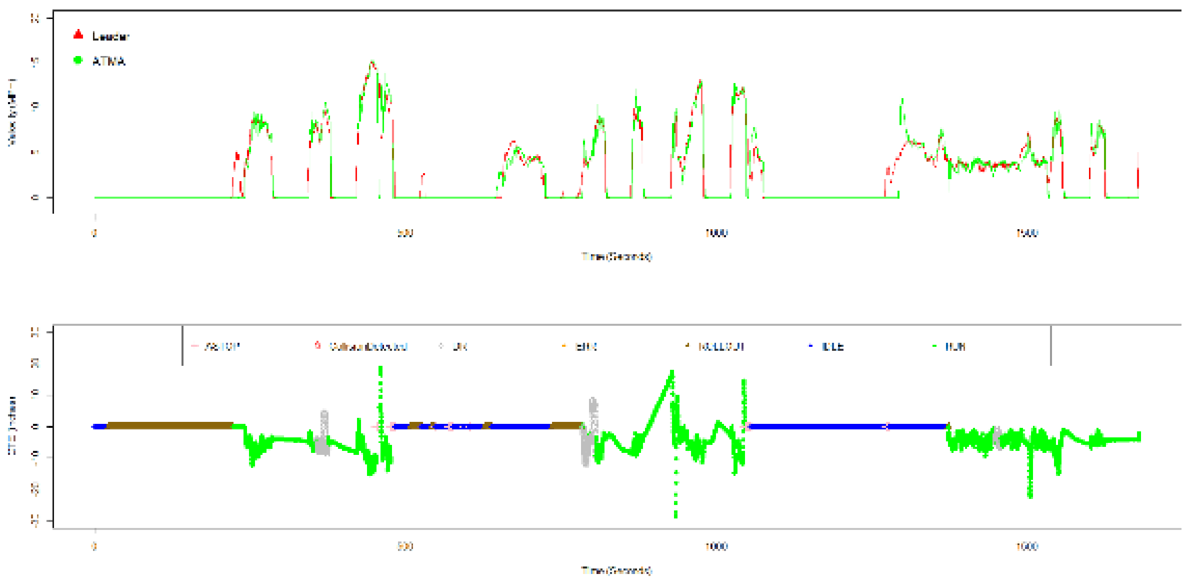


Figure 6-133. Velocity and cross track error of SR-26 field test (EB)

Table 6-64. Percentage of various states of ATMA for SR-26 field test

	EB	
State	Seconds	Percentage
ASTOP	4.1	0.2
Collision Detected	0	0
DEADRECKONING	74.3	4.5
ERROR	0.1	0
IDLE	543.8	32.6
Rollout	275.5	16.5
Run	770.8	46.2
Sum	1,668.6	100

6.2.5 Field Test 5 – SW 2nd Avenue

SW 2nd Ave is a low speed, urban, two-lane roadway with low traffic (Table 6-65). No FWD testing was performed. Only leader-follower capabilities were tested in this scenario. This was a two-vehicle operation: The offset distance between FWD leader vehicle and ATMA follower on the first run was 250 ft. It was observed that with this spacing, it is not possible to find an appropriate traffic gap in the roundabouts. In the second run, the spacing was set to 50 feet to increase the chance of finding an appropriate gap.

Table 6-65. Test Site 5 testing section and historical AADT

Roadway	Section		AADT				
	From	To	2015	2016	2017	2018	2019
SW 2nd Ave	US-441/SW 12th St	SW 6th St	5,400	5,600	5,800	5,900	6,000
	SW 16th St	SW 2nd Ave	8,500	7,200	9,600	7,000	10,400
	US-441 /SR-24/ SW 13th	SR-331/SE 11th St	4,900	6,400	7,000	7,200	8,300
	Depot Ave	SR-24/SR-26/ University Ave	12,100	13,100	12,600	14,700	12,100
	SW 6th St	SR-311/ Williston Rd	4,200	4,400	4,600	4,700	4,800

AADT source: https://tdaappsprod.dot.state.fl.us/fto/

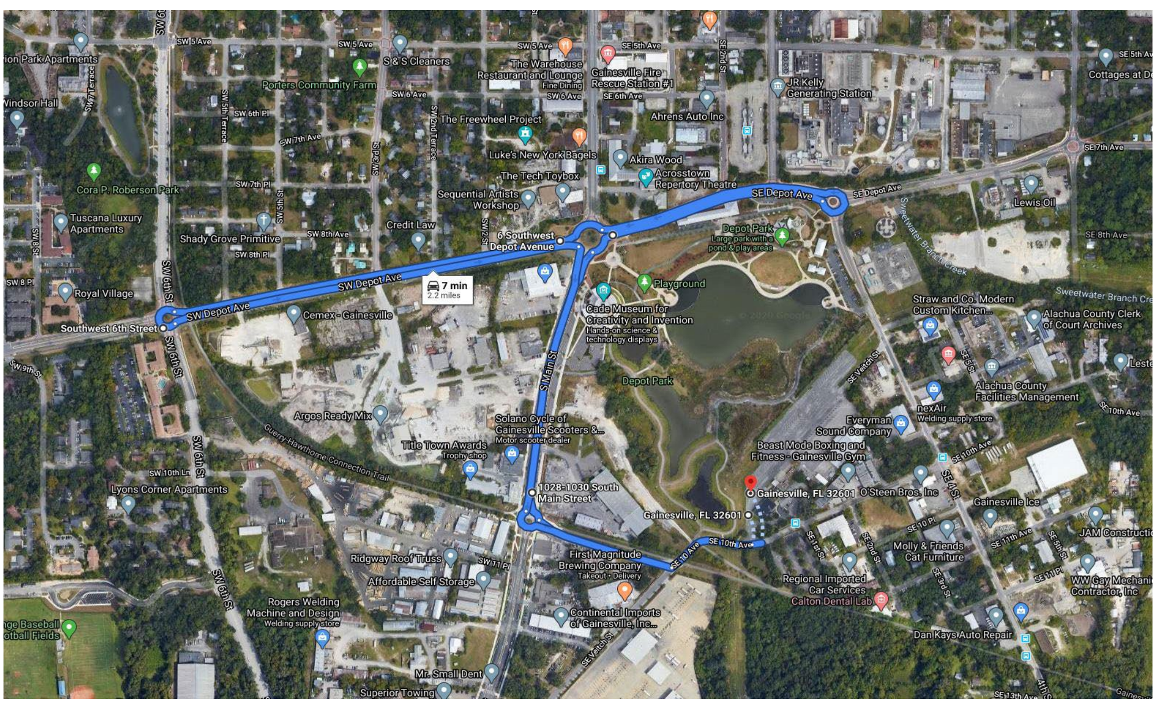


Figure 6-134. Location of Field Test Site 5

The primary objective was to negotiate different sizes of roundabouts in the field. In most cases, the ATMA was not able to negotiate them completely and appropriately. It is recommended that the system be operated in idle/manual when negotiating small roundabout (diameter less than 65 feet).

FT-3 – ATMA Log File Data

This section explains the results from ATMA log files analysis for field test on SW 2nd Avenue. Figure 6-135 shows the velocity and cross track error (CTE) of this field test for first and second field tests. The test on NB took 3,345 seconds, while the SB test took about 1,290 seconds. The visual inspection of speed plots shows that the ATMA follower vehicle followed the leader accurately. The CTE plots show the various states of the ATMA follower. The duration and percentage of these states are shown in Table 66. There were 12 and zero A-stops in Runs 1 and 2, respectively.

Most A-stops were due to the ATMA follower not being able to negotiate the roundabout, and some were due to vehicle intrusions. These A-stops in Run 1 took 2.9% of the total run duration. In the second run, the ATMA follower was in dead reckoning mode three times that took 6.7% of the duration. In this run, the system had to redo the rollout process three times during the field test.

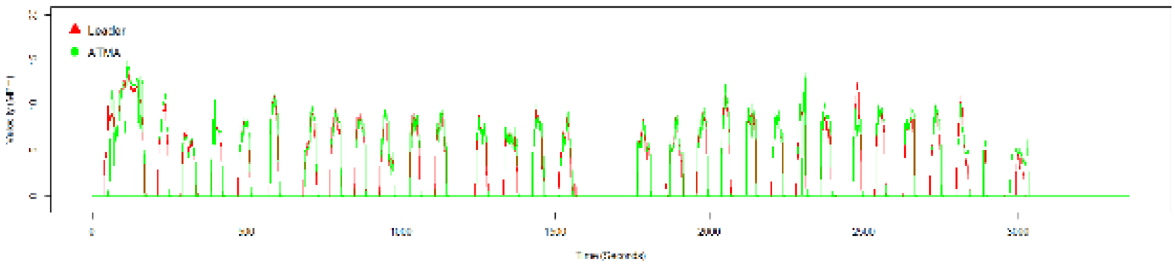
The CTE statistics were as follows:

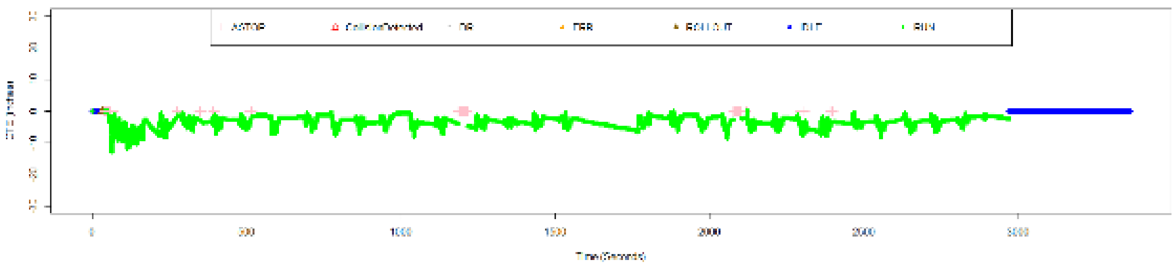
- Run 1: Minimum value of −12.83 in, maximum of 0.12 in, mean of −2.92 in with a standard deviation of 1.97 in;
- Run 2: Minimum value of −17.95 in, maximum of 15.39 in, mean of −2.23 in with a standard deviation of 3.66 in.

Table 6-66. Percentage of various states of ATMA follower for SW 2nd Avenue field test

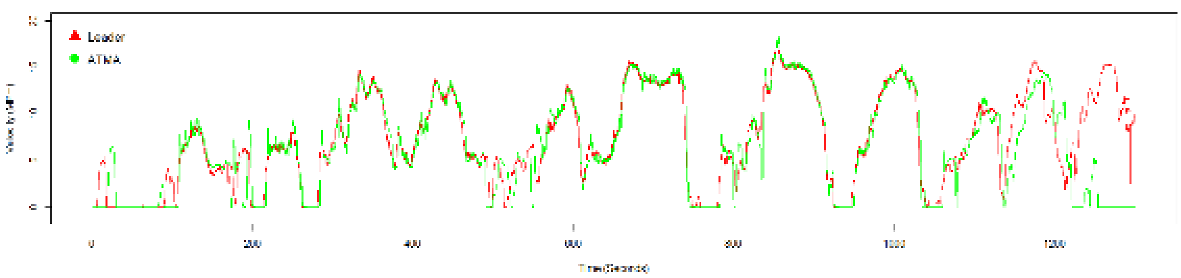
	Run 1		Run 2	
State	Seconds	Percentage	Seconds	Percentage
ASTOP	98.1	2.9	0	0
Collision Detected	0	0	0	0
DEADRECKONING	0	0	87.5	6.7
ERROR	0	0	4.1	0.3
IDLE	418.5	12.5	408.7	31.7
Rollout	6.7	0.2	6.2	0.5
Run	2,821.7	84.4	783.9	60.7
Sum	3,345.1	100	1,290.4	100

Run 1





Run 2



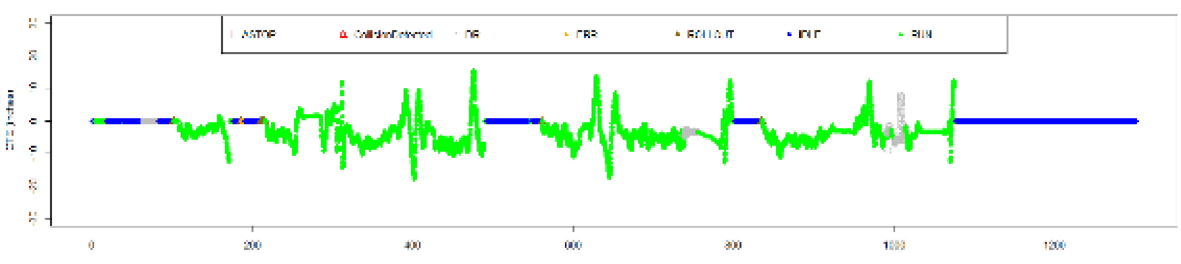
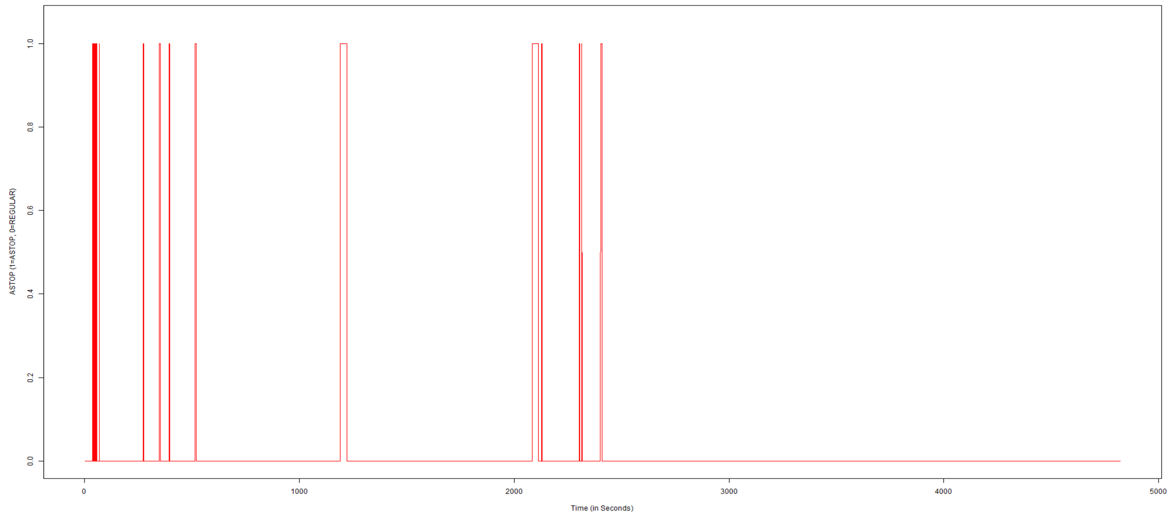


Figure 6-135. Velocity and cross track error of SW 2nd Avenue field test

Run 1



Run 1

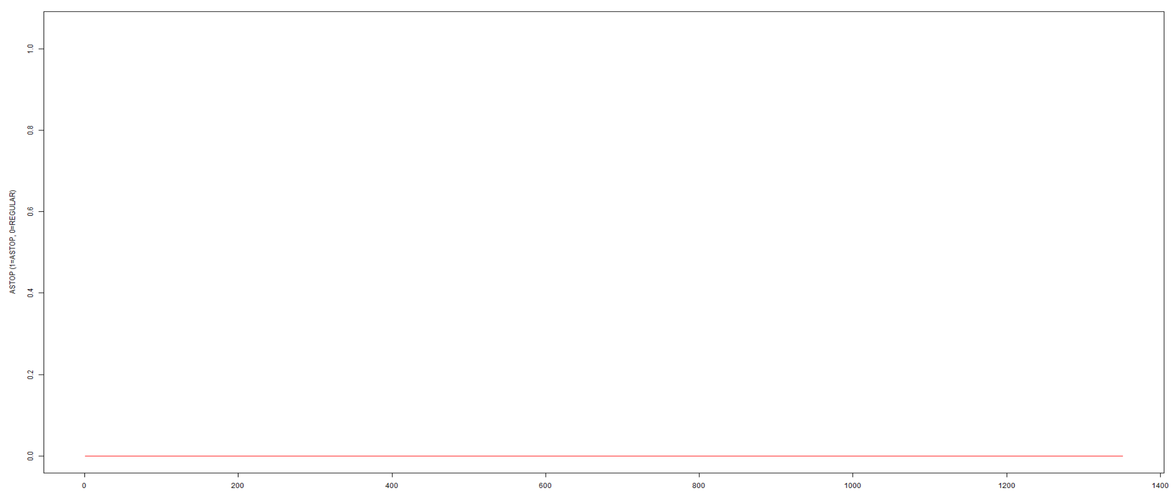


Figure 6-136. A-stop plot of SW 2nd Avenue test

Chapter 7 – Benefit-Cost Analysis Tool

This section's focus is on developing a methodology to find the monetary value of ATMA benefits and costs. This robust methodology was implemented in a user-friendly spreadsheet-based tool. The next four sections are statistics of TMA-related crashes (Missouri), benefit calculations, cost calculations, and benefit-cost analysis.

7.1 TMA-related Crash Statistics

There are a number of studies and statistics on work-zone-related crashes in the literature. However, there is not enough information about crashes in moving work zones and, more specifically, TMA-involved crashes. Feng [16] published informative statistics on TMA-related crashes in Missouri. Between the years of 2012 and 2017, 144 TMA-related crashes occurred in Missouri, including one fatal crash. In the same period, Missouri experienced 12,699 work-zone-related crashes. These two numbers show that 1.134% ($= \frac{144}{12,699}$) of work zone crashes were TMA related.

Between 2011 and 2016, there were 117 TMA-related crashes in Missouri [16]. As shown in Figure 7-1, in 19.658% ($= \frac{11+12}{117}$) of crashes, MoDOT (Missouri Department of Transportation) workers were injured. The purpose of the ATMA is to remove the driver from the TMA truck. By using ATMAs instead of TMAs, the agency workers will be safer and ideally, there will be no worker injury in TMA-related crashes.

Crash Severity	Detailed Crash Severity	Frequency	Percentage (%)	Total Frequency	Total Percentage (%)
PDO		74	63.25	74	63.25
Total Injury	Only MODOT Worker	11	9.4	42	35.9
	Only Third-Party Injury	19	16.24		
	Both Injury	12	10.26		
Fatality	MODOT Worker Fatality	0	0	1	0.85
	Third Party Fatality	1	0.85		
Total		**117**	**100**	**117**	**100**

Figure 7-1. TMA-related crashed by crash severity classification (Table 5-1 from Feng [16])

7.2 Benefit Calculations

The first step in calculating the benefits is to find the crash types that can be mitigated by ATMA. In this study, these crashes were considered as TMA-related crashes in which a DOT worker was injured or killed. Based on the statistics in the previous section, these crashes can be found using the following formulas. The user needs to input the average yearly number of work-zone-related crashes associated with their agency (AYWZ crashes).

$$TMA\ crashes\ =\ AYWZ\ Crashes \times 1.134\%$$

$$TMA\ injury\ crashes\ involved\ DOT\ workers\ =\ TMA\ crashes \times 19.658\%$$

The developed tool calculates the benefit and cost of adding one ATMA to an agency's set of equipment. To find the number of crashes that could be mitigated per one TMA, the TMA fatal injury crashes involved DOT workers should be divided into the number of TMA vehicles in the network.

$$Mitigatable\ crashes\ per\ TMA = \frac{TMA\ fatal\ injury\ crashes\ involved\ DOT\ workers}{N+1}$$

$$Mitigatable\ crashes\ per\ TMA = \frac{AYWZ\ Crashes \times 1.134\% * 19.658\%}{N+1}$$

where N is the number of TMAs in the agency. The +1 in the formula is for adding one ATMA into the network.

The next step is finding the benefits by multiplying the unit crash cost by the crashes that will be mitigated. The average crash cost for fatal and injury crashes was extracted or calculated from the Florida Department of Transportation's (FDOT) *Design Manual* [17]. Table 122.6.2 of the *FDOT Design Manual*, shown in Figure 7-2, includes the crash cost based on the severity. Table 122.6.4 of the same manual (Figure 7-3) includes the portion of each crash severity on various Florida's facility types.

Table 122.6.2 FDOT KABCO Crash Costs

Crash Severity	Comprehensive Crash Cost
Fatal (K)	$10,670,000
Severe Injury (A)	$872,612
Moderate Injury (B)	$174,018
Minor Injury (C)	$106,215
Property Damage Only (O)	$7,700

Note:
(1) Source: Florida Department of Transportation State Safety Office's Crash Analysis Reporting (CAR) System, analysis years 2012 through 2016.

Figure 7-2. Estimates of comprehensive crash costs for classes to crash severity (from Florida Department of Transportation Design Manual [17]

Table 122.6.4 HSM Crash Distribution for Florida

Type Facility		Abbreviation	K	A	B	C	O
Rural Roadways	2-lane Undivided	R2U	0.028	0.094	0.181	0.187	0.509
	4-lane Undivided	R4U	0.033	0.093	0.164	0.186	0.524
	4-lane Divided	R4D	0.028	0.090	0.187	0.196	0.499
Urban & Suburban Arterials	2-lane Undivided	U2U	0.009	0.050	0.150	0.224	0.567
	3-lane TWLTL	U32LT			N/A		
	4-lane Undivided	U4U	0.004	0.031	0.110	0.204	0.650
	4-lane Divided	U4D	0.008	0.046	0.142	0.234	0.571
	5-lane TWLTL	U52LT			N/A		
Freeways	Rural		0.017	0.065	0.143	0.163	0.612
	Urban		0.006	0.035	0.113	0.206	0.641
	Ramps		0.004	0.032	0.107	0.210	0.647
All	All Roadways and Ramps		0.007	0.041	0.124	0.217	0.611

Notes: K – Fatality; A - Incapacitating Injury; B - Non-incapacitating Injury; C - Possible (or minor) Injury; O - Property Damage Only

Figure 7-3. *Highway Safety Manual* Crash Distribution for Florida (from *FDOT Design Manual* [17])

This study assumed that ATMAs are going to be used on all facility types. So, the severity portions in the last row of Table 122.6.4 were used. The weighted average fatal and injury (WAFI) crash cost is as follows:

$$WAFI\ crash\ cost = \frac{\$10{,}670{,}000 \times 0.007 + \$872{,}612 \times 0.041 + \$174{,}018 \times 0.124 + \$106{,}215 \times 0.217}{0.007 + 0.041 + 0.124 + 0.217}$$

$$WAFI\ crash\ cost = \$398{,}699.2$$

The benefit of adding one ATMA to the set of agency's set of TMAs is equal to:

$$ATMA\ benefit\ per\ vehicle = Mitigatable\ crashes\ per\ TMA \times WAFI\ crash\ cost$$

$$ATMA\ benefit\ per\ vehicle = \frac{AYWZ\ Crashes * 1.134\% * 19.658\%}{N+1} \times \$398{,}699$$

The benefit is calculated based on yearly mitigated crashes. To convert the yearly benefits to present value, the annuity factor must be used. By considering a discount rate of 4%, the present value of benefits is as follows:

$$Present\ value\ of\ benefits = ATMA\ benefit\ per\ vehicle \times \frac{1-(1+0.04)^{-(Life\ Cicle)}}{0.04}$$

7.3 Cost Calculations

The ATMA system includes a leader and a follower truck. The assumption of the study is that FDOT retrofits the leader kit in their existing truck and purchases only the following ATMA. However, the user can fill in any other value. As a guidance, cost to procure the ATMA technology is $250,000, and the deployment cost is $40,000 and $5,000 for yearly cost of maintenance. These are numbers suggested by the vendor (Kratos). However, the user can input other values.

The yearly cost should be converted to the present value using the annuity factor. The user chooses the life cycle of technology. The default value is 5 years.

7.4 Benefit-Cost Analysis

The tool calculates the present value of benefit and cost, and then benefit-to-cost ratio as output. In an example with 50 TMAs (N=50), the average yearly number of Florida work zone crashes (AYWZ crash = 3,520), and using the default values, the benefit-to-cost ratio was calculated as 0.93 (not acceptable). This example is shown in the Figure 7-4.

FDOT TWO BDV31-977-133

ATMA BC TOOL

Input	
Work Zone Crashes	
Annual average work zone related crashes in your agency	3520
Agency size	
Number of TMAs in your agency	50
Tool considers Cell F11 as the percentage of projects ATMA will be involved in. If you want to use another value, enter value in Cell C12. Otherwise, enter "0" in C12.	0.00%
System cost and characteristics	
TMA life cycle	5
Leader truck cost	$0
Follower truck cost	$0
Technology procurement cost	$250,000
Deployment cost	$40,000
Yearly maintenance cost	$1,000
System benefit	
Fatal/injury crash cost	$398,699

Output	
Predicted crashes	
Predicted # of TMA related crashes	39.91
Number of fatal/injury TMA crashes involved agency's workers	7.85
Crash per vehicle	
Percent crashes per TMA	1.96%
Fatal/injury TMA crashes per TMA	0.1539
Cost	
Annuity factor	4.452
Present value of cost	$295,000
System benefit	
Present value of benefits	$273,080
Benefit to cost ratio	**0.9257**

Header
User Input
Output

Figure 7-4. Example of benefit-cost analysis for FDOT

Chapter 8 – Results and Lessons Learned

This chapter provides the results from the data analysis completed in the closed loop and the field tests. The objective of this project was to gain firsthand awareness of ATMA functions, operations, and limitations as well as testing the system under various scenarios. The table below summarizes test results, and the subsequent section focuses on the limitation and the opportunities for system enhancements.

8.1 Closed Loop Test Results

A total of 26 testing scenarios were completed, with multiple runs for each test. Among the 26 tests, the ATMA performed as expected in 23 scenarios. In two tests, there were exceptions, and in one scenario, there was a critical error as summarized below.

Table 8-1. Overview of closed loop test results

Test Cases		
ID	Scenario	Performed as Expected?
TC-1	Automatic stop (A-stop) – leader vehicle internal button (OCU)	Yes
TC-2	Emergency stop – ATMA internal button (OCU)	Yes
TC-3	Emergency stop – ATMA external button	Yes
TC-4	Emergency stop – Leader independent E-stop button (initiator)	Yes
TC-5	Follow distance set by user interface (UI) panel	Yes
TC-6	Following accuracy on straight line (A&H)	Yes
TC-7	Following accuracy on slalom course (A&H)	Yes
TC-8	Lane changing accuracy (A&H)	Yes
TC-9	Lateral offset	Yes
TC-10	Minimum turn radius	Exception
TC-11	Simple curve (A&H)	Yes with critical error
TC-12	Roundabouts	Exception
TC-13	U-turns	Yes
TC-14	Bump test	Yes
TC-15	Obstacle detection – Front	No
TC-16	Vehicle intrusion	Yes
TC-17	Object recognition	Yes
TC-18	Speed test (A&H)	Yes
TC-19	Braking – Leader vehicle (A&H)	Yes
TC-20	ATMA human driver takeover (A&H)	Yes
TC-21	Leader reverse	Exception

Table 8 1. Overview of closed loop test results (continued)

Test Cases		
ID	Scenario	Performed as Expected?
TC-22	Acceleration/deceleration	Yes
TC-23	Loss of sensor (radar, lidar)	Yes
TC-24	Loss of GPS	Yes
TC-25	Loss of communication (single V2V radio)	Yes
TC-26	Loss of communication (both V2V radios)	Yes

8.1.1 Exceptions

Three scenarios had exceptions: TC-10, the minimum turn radius test, TC-12, the roundabout negotiating test, and TC-21, the leader reverse test. For TC-10, initially the minimum turn radius was set at 25 feet, which the ATMA follower could not negotiate. Further experiments revealed that the system was able to negotiate a turn with a radius of 45 ft. However, the ATMA follower was successful in 3 of the 4 runs at 45 feet.

For the roundabout scenario (TC-12), the test was unsuccessful with multiple attempts. It was noted that the system was designed to negotiate a roundabout with minimum internal diameter of 130 ft or a radius of 65 ft, which could not be simulated in the testing area. This scenario is reported as an exception because the scenario could not be validated. Supplemental efforts were made to negotiate roundabouts in an open road scenario; however, the roundabouts that the ATMA navigated had an inner diameter of less than 65 feet, and hence, it was unable to negotiate successfully. Based on several tests and attempts, it was concluded that system enhancements needs to be made in order for ATMA follower to negotiate a roundabout successfully.

For TC-21, when the leader vehicle reversed its course towards ATMA follower, the expectation was that the ATMA follower would make an emergency stop. However, it did not, and to the contrary, the ATMA follower moved forward towards the leader vehicle. It is acknowledged that this scenario is atypical, and that the system was not designed to negotiate such scenarios.

8.1.2 Critical Error

There were two critical errors observed during the two-week testing period. The first observation was failure to make an emergency stop even after the sensor detected an obstacle in a closed loop testing. The second observation was abrupt deviation of the ATMA follower from the intended path – both in closed loop testing and open road field test.

Failure to Stop after Detecting an Obstacle

Test Case 15 tested the vehicle's ability to detect an obstacle in its path and make an emergency stop. After seven successful attempts, the ATMA failed to identify the object in run 8. The safety operator in the ATMA follower (driver) applied brakes to avoid hitting the obstacle because there was not enough stopping distance available. The team then re-tested the last run by placing the same barrel in a horizontal position (3' width and 1'8" height). The safety officer in the ATMA follower had to manually apply brakes to avoid hitting the barrel. The object was recognized by the ATMA lidar at a 3.6-ft distance. This test indicated that the sensor location and configuration is critical in recognizing obstacles with height of less than 1 ft. System enhancement or user guidance needs to be made in order for the sensor to detect and for the system to react appropriately.

Abrupt Deviation from Paths

Two events were recorded where the ATMA follower abruptly deviated from its path. The first occurrence was during the closed loop test. In this case, the ATMA follower traveled from the paved road onto to a grassy area over a bump. When it encountered the bump, the ATMA follower deviated from its path, and the safety driver manually overrode the system to a stop. The second was during the field test at SR-222 as explained below.

8.2 Field Tests

Table 8.2 provides a summary of field test results. Three tests completed as expected; however, there were exceptions in three others.

Table 8-2. Overview of field test results

Test ID	SR/Interstate	AADT	Performed as Expected?
FT-1	US-441	13,900	Y
FT-2	I-75	73,203	Y
FT-3	SR-222	22,914	Exception & Critical
FT-4	SR-26	10,788	Exception
FT-5	SW 2nd Ave	7,651	Exception
FT-6	SR-24 Waldo Rd	16,273	Y

8.2.1 Exceptions and Critical Errors during Field Tests

Field Test 3 – SR-222

- The ATMA follower drifted off the intended path. In one instance, the ATMA follower drifted toward the outside lane, and the control was overridden by the Kratos safety officer. Even though the exact cause was not be determined, it was suspected that it may have been due to improper engagement of the steering lock.
- At 12:03 PM, due to a hard break, the system misreported a collision, and the safety operator (Kratos staff) was required to change to Idle mode. Kratos staff mentioned that this can be eliminated by system upgrades or enhancements.
- At intersections, driver training is critical to understand the implications of ATMA operation, e.g., the FWD test was being performed downstream of the intersection, and the work platoon blocked the left-turning traffic. This may cause a traffic bottleneck at the intersection (Figure 6-133) and, in some cases, safety concerns.

Field Test 4 – SR-26

The testing was performed in the EB direction only; however, it was terminated early due to increased traffic and safety reasons. This was a two-vehicle operation. This exception was not due to system limitation exclusively because two-lane operations are challenging even with traditional manual TMA operations. However, the ability to quickly move onto the shoulder to let traffic pass and then swiftly return to testing is something that the ATMA is lacking currently. This may improve with system enhancements and operator experience.

Field Test 5 – SW 2nd Avenue

This section was selected due to the presence of multiple roundabouts. The roundabout had a small inner diameter, and as such, the ATMA was unable to negotiate any of the roundabouts. It was observed that any turning movement less than a 65-ft radius was a challenge for the ATMA follower.

8.3 Lessons Learned

1. Operator training is essential and critical.

The lead vehicle driver essentially paves the path for the follower ATMA. As such, every decision the lead vehicle driver makes affects the operational and safety performance of the ATMA and the traveling public around the work platoon. The lead vehicle driver must be trained in several aspects, including conducting a route survey before the planned work in order to:

- Check GPS connectivity
- Scout start location for pre-checks
- Check for available distance for initial rollout
- Test obstacle detection and calibrate
- Check and plan for intersections along the routes
- Check and prepare for overhead signs and other structures for potential loss of connectivity
- Check potential bumps or road condition issues
- Check roadway alignments
- Check weather conditions
- Check traffic conditions.

2. Review FHWA STSDM guidelines; and DOT may potentially consider ATMA specific guidelines for TTC.

Short-term mobile operations have unique characteristics, and with ATMA evolving and finding new applications, DOT may consider developing guidelines specifically for ATMA operation. For instance, Table 8-3 is taken from ATSSA's STSDM guide [18] and modified based on the testing experience of the ATMA. The table describes some common work site characteristics that often create challenges and could require field adjustments and possible mitigation strategies to address them. Since the conditions and strategies may not be applicable for every work site characteristic, some guidance on how to alleviate safety challenges and suit field conditions is helpful.

Table 8-3. Strategies for mitigating the challenges to ATMA operation in specific work sites

WORK SITE CHARACTERISTICS	CONDITIONS REQUIRING REVISIONS TO STANDARD TA AND/OR FIELD ADJUSTMENT	POSSIBLE MITIGATION STRATEGIES	Star rating for ATMA operation based on the data collected and experience of testing completed
High-speed traffic	Increased potential for errant vehicles and/or higher-speed collisions	Temporary rumble strips	*
		Shadow vehicle(s) with warning devices	*****
		Dominant devices	****
		Arrow panel	*****
		Provide law enforcement officers/vehicles	*****
High-traffic volumes	Increased potential for errant vehicles and/or formation of queues	Consider staging	***
		Off-peak period work	*****
		Shadow vehicle(s)	*****
		Portable changeable message sign	*****
		Arrow board	*****
		Provide alternate routes/diversions	**
Roadway includes significant horizontal and/or vertical curvature	Reduces sight distance or may impact vehicle stopping distance	Use dominant devices, such as arrowboards, PCMS, etc.	*****
		Position shadow vehicles with arrow board for visibility	*****
Roadway includes high frequency of intersections and/or driveways	Vehicles entering/exiting the traffic stream from additional access point	Shadow vehicle(s)	*****
		Restrict turns	**
		Provide alternate access	***
Roadway includes significant pedestrian and/or bicycle traffic	Pedestrian and bicycle intrusion	Pedestrian detour signs	***
		ADA ramps	N/A or No data
		Pedestrian barriers	N/A or No data
Work expected to be performed during peak period	Peak period congestion	Detour or diversion	***
		Advance notification	*****
Two-lane roadway	Operation along roadway with significant horizontal and vertical curvature	Maintain flagger stations at end of tangents approaching work zone rather than following work crew at fixed distance	**

In addition, it is recommended that standard plans and guidance for ATMA operations would ensure consistency and enhance safety for DOT staff and contractors.

3. Avoid roundabout or untraditional intersection designs.

The testing revealed that the current system configuration has challenges to navigate a roundabout or make U-turns. Any intersection design such as roundabout, median U-turn (RCUT), etc. should be avoided until further testing to successfully navigate such a pathway is documented.

4. System enhancements for stop-and-go operation.

Currently, the ATMA system aims to achieve the desired fixed gap as long as there is enough time and space for the leader and follower to travel. However, in some instances, such as stop-and-go operation or even a stop-controlled intersection, this constant gap distance may hinder the operation. If the system has capability to reduce the gap when the leader is stopped to achieve a new gap and then resume the following pattern, that would be helpful in several scenarios. In addition, steps to mitigate atypical scenarios such as leader vehicle in reverse (Test Case 21) can be addressed.

5. Leverage the lateral offset feature in ATMA.

One of the latest enhancements of the ATMA system is the ability to maintain a lateral offset of up to 12 feet. The users must be trained to leverage this feature and function in field operation when applicable.

6. Test with no safety operator in ATMA.

All the testing was performed with a safety operator in the ATMA follower vehicle. While the intent of the ATMA is to eliminate the injuries and fatalities of TMA drivers, testing needs to be performed for ATMA without a safety operator in ATMA follower. It is acknowledged that this testing was conducted beyond the standard system design in that the leader kit was retrofitted in the FDOT truck. It is recommended that further calibration and testing be conducted without a safety officer for more data points to quantify the feasibility of ATMA in open road operation.

7. Longitudinal testing and data repository

Since ATMA is a new technology, having a clearinghouse and data repository would be beneficial for DOT and other agencies to track and quantify the performance over time. A list of performance measures can be identified for longitudinal analysis.

Chapter 9 – Conclusions

The expectation of the transportation industry for the ATMA technology is set very high. ATMA has the potential to transform the planning, design, and operations of mobile work zones. In order for the technology to penetrate the market, agencies across the country must become familiar with the capabilities as well as limitations to support existing operations and also identify future applications.

To assist the Florida Department of Transportation (FDOT) in the effort to become familiar with the ATMA technology, assess the feasibility of ATMA application to existing work, and test the system under different scenarios, this project identified an ATMA vendor, documented the ATMA's functions and features, and evaluated the ATMA system in a closed loop as well as with a live work zone application. The study reviewed available literature on ATMA and contacted other state agencies and researchers to learn from their experience. To date, only a handful of agencies have procured the system; however, there is a strong interest from several departments of transportation across the country with several pilot testing projects underway. While few states have considered the application of ATMA for maintenance operations such as striping and placing of cones, this project was the first of its kind in retrofitting an FDOT truck with the ATMA leader kit and using the ATMA follower to protect a falling weight deflectometer (FWD) operation. This was challenging on two fronts. First, it was challenging to retrofit a vehicle that contained other electronic equipment related to FWD with the ATMA leader kit. The second challenge was the presence of the FWD trailer attached to the leader truck. This, in theory, would trigger the front sensor of the ATMA as an obstruction, so the system was customized to meet this application need.

Before physical operations were undertaken, this study scheduled a virtual training webinar for all involved personnel to go over the functions and features of the ATMA. It was initially envisioned to be in-person; however, due to the COVID pandemic, a two-part training was implemented. The webinar was followed up with an in-person hands-on training during the demonstration day. The webinar was one hour in duration, and the in-person training was over an hour of instruction, with an open window of two hours for hands-on review and driver training. A survey to evaluate the training was performed, and the feedback overall was positive. The initial runs during the demonstration were hindered due to the lack of GPS signals, primarily due to obstructions from the trees. This was resolved when the demonstration location was moved to an open area for clear GPS reception.

The closed loop test locations and dates were finalized in coordination with all stakeholders. Over 100 test runs were designed and performed in the two-week period. For each run, a testing scheme was conceptualized and implemented. Various data were collected, including video recordings, high resolution log files from the ATMA, and manual field recordings on the test time and distance. The project also performed field validation of ATMA application while performing FWD testing on open roads. Five different facility types were selected to test the feasibility.

The results from the field observation and the data analysis suggest that the ATMA is designed for specific roadway conditions and for specific types of work.

Roadway condition — Based on the tests and data analysis, the study team observed that the ATMA system is ideally designed for multilane roadways, both rural and urban, which offer good GPS reception in the area. These facility types pose the highest risk in terms of speeding vehicles. Current STSDM application for these facility types could greatly benefit with added guidance to operators and field experience of the lead driver or technician. Conversely, the data also indicate that the system is not recommended for two-lane roadway operation. Currently, even manual operation of STSDM in two-lane operation causes congestion and is not preferred during peak hours; however, manual operation has the flexibility to pull over quickly to allow queued vehicles to pass by and then resume operation. Data from the field experiment indicate that this was not feasible. The data also indicate that the ATMA system is designed for tangent operation, and as such, roundabout or untraditional or innovative intersection designs must be avoided. The ATMA has the ability to negotiate occasional curves that are non-severe (>65-ft radius).

Operator training — TTC on any facility where STSDM operation takes place usually has limited planning time and therefore requires access to standard plans that the field personnel can quickly modify and implement. ATMA is relatively new for technicians around the nation, and field personnel must be trained to recognize a variety of safety issues posed by and to the ATMA system and methods of alleviating them to maintain a safe work zone. As detailed in the results and recommendations chapter, there needs to be guidance on route surveys, checklists, and training on how to identify issues in the field and prepare a plan for deployment of ATMA in work zones.

Extended testing — The two-week testing period provided the opportunity to become familiar with the system, test the operation and safety performance, and conduct pilot tests with a safety operator in ATMA. The goal is to take the safety operator out of the ATMA follower. The next phase of testing recommended includes testing without a safety operator in closed loop and open roads. In addition, having a data repository is critical to track the performance of the system and document the lessons learned with time.

High resolution data — This study developed a benefit-cost analysis tool. However, as noted in chapter 7, currently, the data for quantification of the benefit and cost are lacking. There is a need to collect higher resolution of data in work zones, data specifically related to workers involved in crashes in work zones. In addition, data on the number of TMAs and lead trucks and amount of work zone operation (mileage) is necessary for a sound analysis. Currently, the tool provides the structure for the analyst to input custom data and does the calculations; however, it is recommended that the DOT collect and make the data available within the tool.

Benefits of the ATMA deployment — The data indicate that there is potential for increased safety for workers, potential for cost reductions, and capability for work zone optimization. However, this requires more deployments and further validations. Before large-scale deployment can occur, the extended testing stated above is crucial for multiple stakeholders to recognize the benefit.

ATMA has the potential to assist FDOT with its “Vision Zero” or “Target Zero” initiative [2]; however, this would require further engagement with the ATMA vendor, extended testing, data repository or clearinghouse, guidance or standard plan development, operator trainings, and field personnel experience. With this pilot testing, FDOT staff has become more informed on the benefits and limitations of the system. With further system enhancements, ATMA has the potential to become a crucial contributor to safer and more efficient work zones in Florida.

References

1. National Institute for Occupational Safety and Health (NIOSH). (2019). Highway Work Zone Safety (webpage). Centers for Disease Control and Prevention, Atlanta, GA. https://www.cdc.gov/niosh/topics/highwayworkzones/

2. Florida Department of Transportation. (2020). *FY 2020 Highway Safety Plan*. FDOT, Tallahassee, FL. https://fdotwww.blob.core.windows.net/sitefinity/docs/default-source/safety/3-grants/forms/2020-florida-highway-safety-plan.pdf?sfvrsn=186bfcb9_0

3. Federal Highway Administration (FHWA). (). Part 6, "Temporary Traffic Control," in *Manual on Uniform Traffic Control Devices for Streets and Highways* (MUTCD). FHWA, Washington, D.C. https://mutcd.fhwa.dot.gov/pdfs/2009/part6.pdf

4. American Traffic Safety Services Association (ATSSA). (2012). *Field Guide for the Use and Placement of Shadow Vehicles in Work Zones*. Federal Highway Administration, Washington, D.C. https://www.workzonesafety.org/files/documents/training/fhwa_wz_grant/shad_veh_final.pdf

5. Transportation Research Board (TRB). (2020). TRID database. https://trid.trb.org/ accessed June 14, 2020.

6. Colorado Department of Transportation (CDOT). (2017). "CDOT and Partners Drive Safety With World's First Self-Driving Work Zone Vehicle" (webpage, posted August 18, 2017). CDOT, Denver, CO. https://www.codot.gov/news/2017-news/august/cdot-and-partners-drive-safety-with-world2019s-first-self-driving-work-zone-vehicle, accessed June 15, 2020 , accessed June 28, 2020.

7. Autonomous Media, LLC. (2019). "From War Zone To Work Zone" (webpage; posted July 23, 2019). https://insideunmannedsystems.com/from-war-zone-to-work-zone/, accessed June 28, 2020.

8. Huang, Ziye. (2019). Feasibility Study of Driverless Maintenance in Highway Construction Zones (master's thesis). Delft University of Technology, Delft, The Netherlands. Referencing link: https://www.workzonesafety.org/publication/feasibility-study-of-driverless-maintenance-in-highway-construction-zones/, accessed June 28, 2020. Permanent link: https://repository.tudelft.nl/islandora/object/uuid:b8545f7a-6eb5-45b6-963b-1fd907130f73.

9. Center for Sustainable and Intelligent Transportation Systems (CSITS). "Autonomous TMA Truck (ATMA): CDOT Evaluation and Performance Verification" (webpage). Colorado State University, Fort Collins, CO. http://www.csits.colostate.edu/autonomous-maintenance-technology.html , accessed June 28, 2020.

10. Transportation Research Board (TRB). (). "Leader-Follower TMA System," Research in Progress (RIP) webpage for Missouri Department of Transportation project. https://rip.trb.org/View/1511448 , accessed June 28, 2020.

11. Tang, Q., Cheng, Y., Hu, X., Chen, C., and Song, Y. (2020). "Field Testing and Evaluation of Leader-1 Follower Autonomous Truck Mounted Attenuator Vehicle System for Work Zone Maintenance." Transportation Research Board, Washington, D.C. https://www.researchgate.net/publication/337315905_Field_Testing_and_Evaluation_of_Leader-

Follower Autonomous Truck Mounted Attenuator Vehicle System for Work Zone Maintenance accessed June 28, 2020.

12. Development of ATMA/AIPV Deployment Guidelines Considering Traffic and Safety Impacts. https://rip.trb.org/view/1685038, accessed June 28, 2020.

13. MoDOT Autonomous Leader-Follower TMA System: Development of Autonomous Trucks Operation Guidelines and Driver Training Process. https://rip.trb.org/view/1581013, accessed June 28, 2020.

14. Automated Truck Mounted Attenuator. https://trid.trb.org/View/1591977, accessed June 28, 2020.

15. Autonomous Truck Mounted Attenuator (TMA) Pilot (TDOT). https://royaltruckandequipment.com/autonomous/, accessed June 28, 2020.

16. Feng, Huang. "TMA (track mounted attenuators) involved work zones safety analysis and modeling, using machine learning to predict crash severity and crash frequency in the state of Missouri." PhD diss., University of Missouri--Columbia, 2018.

17. Florida Department of Transportation (FDOT). (2020). *2020 FDOT Design Manual*. FODT, Tallahassee, FL.

18. Wayne State University Transportation Research Group. (2016). *A Guide to Short-Term Stationary, Short-Duration, and Mobile Work Zone Traffic Control*. Federal Highway Administration (FHWA), Washington, D.C. https://www.workzonesafety.org/files/documents/training/fhwa_wz_grant/wsu_STSDM_guide.pdf.

Appendix A – ATMA Training Materials

ATMA - AIPV
Operator Training Course

Discussion Topics

- AIPV System Overview
- Leader Vehicle Component Familiarization
- AIPV Component Familiarization
- Key Operating Parameters
- AIPV Safety Information
- A-Stop and E-Stop Information
- Operating Procedure Familiarization

Hands-on Training

FDOT UF UNIVERSITY of FLORIDA

- Demonstration and Practice Sessions
  - Pre-Start Inspection
  - AIPV Manned Operations
  - A-Stop / E-Stop During AIPV operations
  - AIPV System Start-up and Shut-down
  - AIPV Basic Maneuvers
    - Straight line, bends, and curves
    - Cornering, U-turns, Rollout, and 360-degree turns
- AIPV Basic Troubleshooting

2

KRATOS UNMANNED SYSTEMS DIVISION | Royal TRUCK & EQUIPMENT INC. | ATMA | AIPV

NASDAQ: KTOS
DEFENSE & SECURITY SOLUTIONS
REVISION DATE: 26/9/19

System Overview

FDOT UF UNIVERSITY of FLORIDA

- The AIPV retrofit autonomous kit converts Impact Protection Vehicle (IPV) into a AIPV Leader / Follower system
  - AIPV system increases worker safety by eliminating the need for a human driver in an IPV
  - During operations, the AIPV follows the path of the Leader Vehicle while maintaining a user-defined, safe distance
  - Leader Vehicle and AIPV maintain constant communication with each other over two redundant Vehicle-to-Vehicle (V2V) communication links
  - **Safety Features**
    - Redundancy in object detection and V2V links
    - Rear looking camera
    - A-Stop, E-Stop, Independent E-Stop
    - Human in the Loop

3

KRATOS UNMANNED SYSTEMS DIVISION | Royal TRUCK & EQUIPMENT INC. | ATMA | AIPV

NASDAQ: KTOS
DEFENSE & SECURITY SOLUTIONS
REVISION DATE: 26/9/19

Leader Vehicle Overview

Leader Vehicle Components

Circled Components are the only ones the user has to touch

Leader Vehicle Components

- Battery Breaker – Powers and protects AIPV components and systems
  - Connected directly to vehicle's battery
  - Typically mounted near the battery
  - Leader Vehicle components are connected to the battery breaker
  - Design prevents accidental discharge of the vehicle's battery when not in use
  - Switch must be turned to ON position before operating AIPV system components
  - Turn switch to OFF when system is not in use
  - Do not switch to OFF while system is on GO

Leader Vehicle Components

Custom OCU Model Indicators / Controls		
1 - ON Indicator	Red Light	When light is illuminated, indicates SCU is powered on.
2 - A-Stop Control	Automatic Stop	Depressing the A-Stop Control stops the AIPV. Turning the A-Stop Control clockwise causes the A-Stop Control to reset to its original position.
3 - Ready Indicator	Green Light	When light is on and not flashing, indicates SCU is completely initialized.
4 - GO Indicator	Green Light	When light is illuminated, indicates Leader Vehicle SCU is in the GO mode and starts transmitting GPS positioning and velocity data to AIPV SCU.
5 - ON / OFF Power	Toggle Switch	Used to power on or off the Leader system.
6 - GPS Lock Indicator	Green Light	When light is illuminated and not flashing, indicates that the GPS has acquired a signal to support AIPV operations.
7 - IDLE Indicator	Yellow Light	When light is illuminated, indicates Leader Vehicle SCU is in the IDLE mode; sends a status message to AIPV SCU that it is in the IDLE mode.
8 - GO / IDLE Control	Toggle Switch	Placing SCU in the GO mode transitions AIPV system into AIPV operations; placing AIPV SCU in IDLE position releases steering, brake, and accelerator controls to the operator.

KRATOS UNMANNED SYSTEMS DIVISION
Royal TRUCK & EQUIPMENT INC.
ATMA
AIPV
NASDAQ: KTOS
DEFENSE & SECURITY SOLUTIONS
REVISION DATE: 26/9/19

Leader Vehicle Components

Independent E-Stop Indicators / Controls		
1 - E-Stop Control	Emergency Stop	Depressing the E-Stop Control stops the AIPV and kills the AIPV engine. Turning the E-Stop Control clockwise causes the E-stop Control to reset to its original position.
2 - Status Light	Green / Red Light	When green light is illuminated, indicates that system is ON and operational. When red light is illuminated, that means an Emergency Stop was initiated and is active.

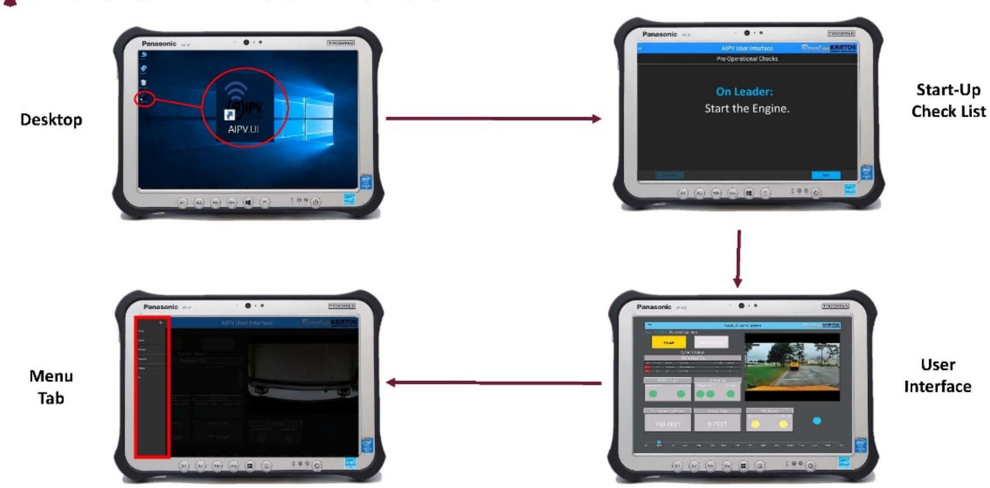
Hands On Section

- Break for On Truck review:
  - Battery Breaker location and operation
  - Leader OCU location and operation

Leader Vehicle Components

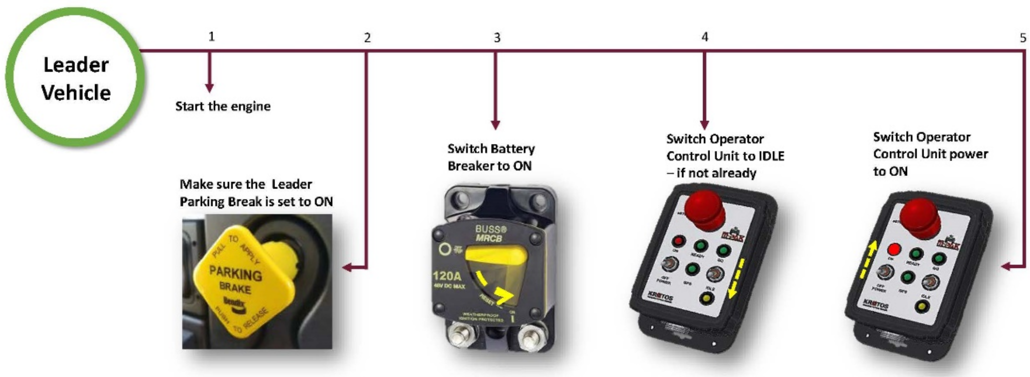
- User Interface – Enables user to conduct and monitor AIPV operations
  - Must be installed / powered to start AIPV operations
  - Enables Gap Control
  - Displays system warnings and cautions
  - Provides user with video feed for Leader rear looking camera

User Interface



User Interface – Check List

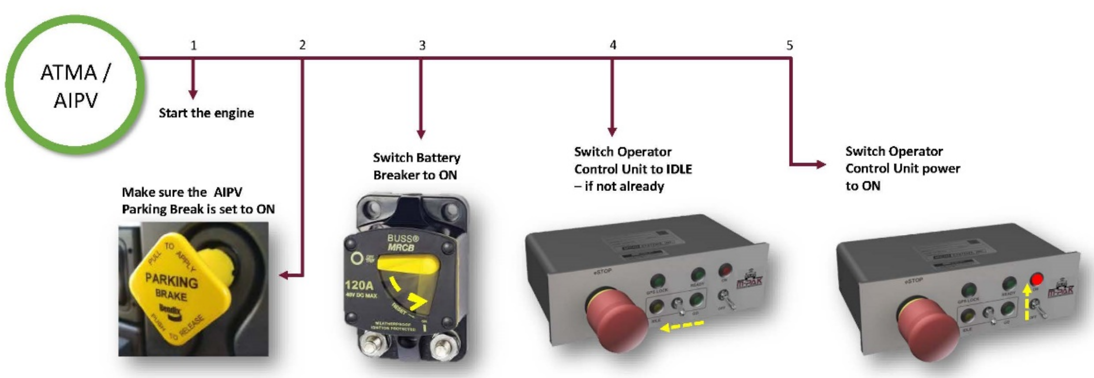
- User Interface Checklist gives the user a detailed procedure of how to start AIPV operations
  - System will not be able to operate until the checklist is complete



KRATOS UNMANNED SYSTEMS DIVISION | Royal TRUCK & EQUIPMENT INC. | ATMA | AIPV

NASDAQ: KTOS
DEFENSE & SECURITY SOLUTIONS
REVISION DATE: 26/9/19

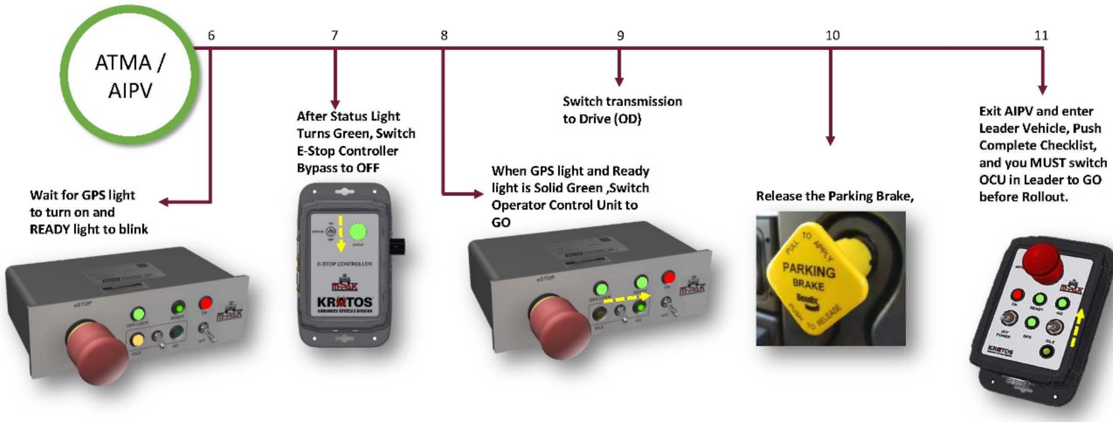
User Interface – Check List



KRATOS UNMANNED SYSTEMS DIVISION | Royal TRUCK & EQUIPMENT INC. | ATMA | AIPV

NASDAQ: KTOS
DEFENSE & SECURITY SOLUTIONS
REVISION DATE: 26/9/19

User Interface – Check List



KRATOS UNMANNED SYSTEMS DIVISION · Royal TRUCK & EQUIPMENT INC. · ATMA · AIPV

NASDAQ: KTOS
DEFENSE & SECURITY SOLUTIONS
REVISION DATE: 26/9/19

User Interface – Title Bar

Title Bar

KRATOS UNMANNED SYSTEMS DIVISION · Royal TRUCK & EQUIPMENT INC. · ATMA · AIPV

NASDAQ: KTOS
DEFENSE & SECURITY SOLUTIONS
REVISION DATE: 26/9/19

User Interface – Title / Status Bar

- Give the user overall status of operations

NextGen AIPV System

Normal operations will indicate a blue Status Bar with "NextGen AIPV System"

Follower Paused

When the system is Paused, you will see a yellow Status Bar with "Follower Paused"

Follower A-Stop

When the system initiates an A-Stop, you will see an orange Status Bar with "Follower A-Stop"

E-Stop

When the E-Stop button is pressed, you will see a red Status Bar with "E-Stop"

Collision Detected

In case of a collision to the AIPV, the G Sensor will trigger a stop to the vehicle, you will see a red Status Bar with "Collision Detected"

Error (Follower)

In case of a follower system error, you will see a red Status Bar with "Error (Follower)"

User Interface – Pause Button

Pause Button

User Interface – Pause

- The Pause button is orange and displays “Pause” as the text under normal operations
- If the vehicle is paused, then the text changes to “Clear Pause”
- If the vehicle is in A-Stop or an error state, then the Pause button is disabled
- Pause will stop AIPV and will keep track of the E-Crumbs for up to 1,500 feet
- When the pause is cleared, AIPV will follow the E-Crumbs that it collected to catch up slowly to the commanded gap
- Not recommended to use the Pause function for more than 1,500 feet and / or for a very long time

User Interface – Clear A-Stop

Clear A-Stop Button

This button is used to clear an A-Stop once the obstacle is no longer in the path of the AIPV. Once cleared, AIPV operations can resume.

User Interface – A-Stop

FDOT UF UNIVERSITY of FLORIDA

Follower A-Stop

This status bar indicates if an A-Stop has occurred. The warning dialog box will tell you the cause of the A-Stop.

Warning Dialog Box

The warning dialog box will list all system warnings.

User Interface – GPS / Radio Status

FDOT UF UNIVERSITY of FLORIDA

Radio Status

When V2V links are green, links are good. A link turns red when it is bad.

GPS Status

When GPS status is green, GPS signal is good. A status turns red when it is bad.

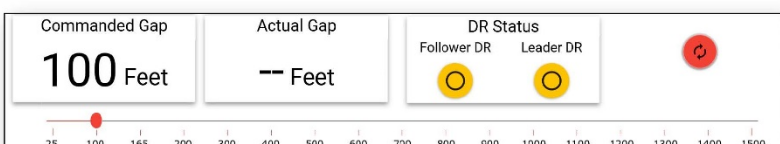
User Interface – Gap Control

GAP Control Section

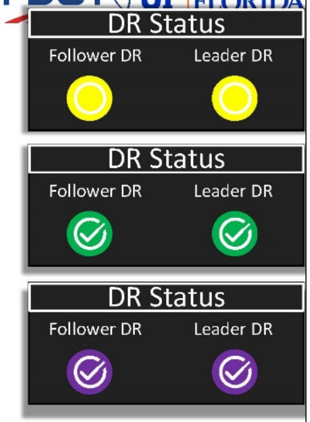
See next Slide for details

User Interface – Gap Control

- Command Gap is the set distance between the Leader and AIPV as adjusted by the user
- Actual Gap is the current distance from the rear of the Leader Vehicle to front of AIPV
- Gap Slider allows the user to choose the Commanded Gap from 25 to 1,500 feet
- Slider also works like a repeat button. By tapping on the Slider to the right or left of the thumb selector, the Gap will increment or decrement respectively



User Interface – DR Status



DR Navigation

DR Status

- When yellow, GPS denied navigation not available
- When Green, GPS denied navigation available
- When Purple, GPS denied navigation taking place
- Note DR Status will turn green when system is on GO

User Interface – Video

Rear Looking Video

This displays the video looking backwards from the leader

Video Refresh

This restarts the video camera

Hands On Section

- Break for On Truck review:
  - Leader User Interface

KRATOS UNMANNED SYSTEMS DIVISION · Royal TRUCK & EQUIPMENT INC. · ATMA · AIPV

NASDAQ: KTOS
DEFENSE & SECURITY SOLUTIONS
REVISION DATE: 26/9/19

Follower / AIPV Overview

KRATOS UNMANNED SYSTEMS DIVISION · Royal TRUCK & EQUIPMENT INC. · ATMA · AIPV

NASDAQ: KTOS
DEFENSE & SECURITY SOLUTIONS
REVISION DATE: 26/9/19

Follower/AIPV Vehicle Components

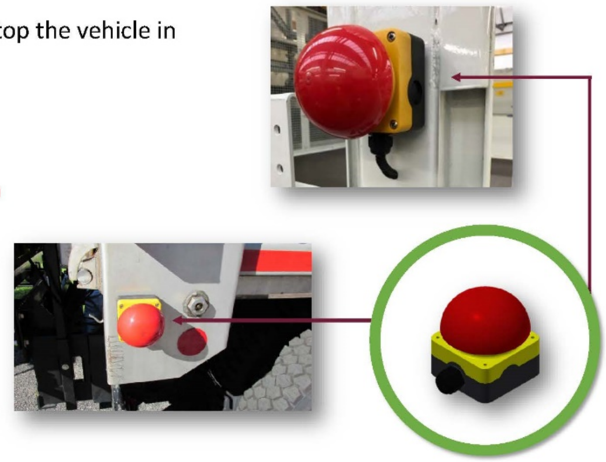
Circled Components are the only ones the user has to touch

Follower Vehicle Components

- Battery Breaker – Powers and protects AIPV components and systems
  - Connected directly to vehicle's battery
  - Typically mounted near the battery
  - AIPV SCU connected to the battery breaker
  - Design prevents accidental discharge of the vehicle's battery when not in use
  - Switch must be turned to ON position before operating AIPV system components
  - Turn switch to OFF when system is not in use
  - Do not switch to OFF while system is on GO

Follower Vehicle Components

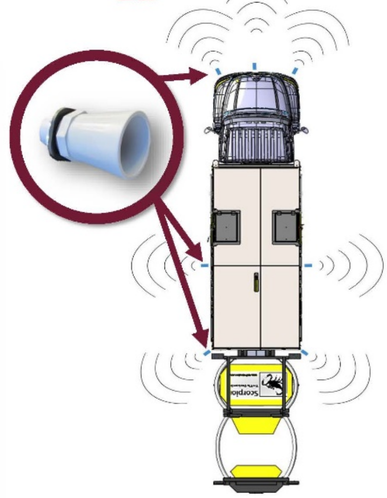
- External E-Stop Buttons – Allows workers to stop the vehicle in emergency situations
  - Installed outside of AIPV vehicle cab
  - Depressing an E-Stop button will bring AIPV to a controlled stop and shut down AIPV engine
  - Pulling the E-Stop button out resets the E-Stop button
  - Note, Rollout Process has to be repeated to start AIPV operations



Obstacle Detection

- Front View Obstacle Detection and Avoidance – Object detection and avoidance system
  - Radar – Detects objects in lane up to 150 feet, can cause A-Stops
  - LIDAR – Detects objects in lane up to 150 feet, can cause A-Stops
  - Ultrasonic Sensors – Detects and warns user of objects in front of vehicle up to 30 feet
- Side View Obstacle Detection Warnings – To detect and warn the user if there is an object on the side of AIPV
  - 4 Ultrasonic Sensors
  - If triggered, the system will warn the user of the Leader Vehicle

Obstacle Detection



Follower Vehicle Components

- Steering Actuator – Drives the steering wheel to make turns
  - Serves as controlling mechanism for AIPV's steering wheel
  - A pair of captive fastener thumbscrews are used to secure the fingers and allow easy removal to enable AIPV manned operations

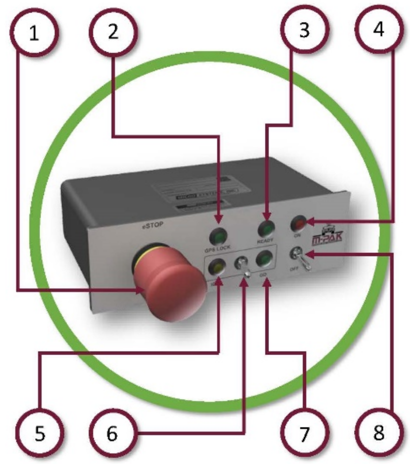
Cautionary Note

- Fingers must be re-attached before conducting AIPV operations
- Fingers must be off when not driving AIPV operations

Follower Vehicle Components

- OCU Indicators and Controls

In-Dash OCU Model Indicators / Controls		
1 - E-Stop Control	Emergency Stop	Depressing the E-Stop Control stops the AIPV. Turning the E-Stop Control clockwise causes the E-Stop Control to reset to its original position.
2 - GPS Lock Indicator	Green Light	When green light is illuminated, indicates that GPS has acquired a signal to support AIPV operations.
3 - Ready Indicator	Green Light	When green light is illuminated and not blinking, the AIPV is completely initialized.
4 - ON Indicator	Red Light	When red light is illuminated, the system is turned on.
5 - IDLE Indicator	Yellow Light	When yellow light is illuminated, the system is in the IDLE mode.
6 - GO / IDLE Control	Toggle Switch	Placing SCU in the GO mode transitions AIPV system into AIPV operations; placing AIPV SCU in IDLE position releases steering, brake, and accelerator controls to the operator.
7 - GO Indicator	Green Light	When green light is illuminated, indicates Leader Vehicle SCU is in the GO mode and starts transmitting GPS positioning and velocity data to AIPV.
8 - ON / OFF Power	Toggle Switch	Used to power on or off the system.



34

KRATOS UNMANNED SYSTEMS DIVISION

Royal TRUCK & EQUIPMENT INC.

ATMA

AIPV

NASDAQ: KTOS
DEFENSE & SECURITY SOLUTIONS
REVISION DATE: 26/9/19

Follower Vehicle Components

- E-Stop Indicator and Controls

Indicators / Controls		
1 - ON / OFF Bypass	Toggle Switch	Used to put the Independent E-Stop Controller in Bypass mode.
2 - Status Indicator	Green / Red Light	When green light is illuminated, that means the system is ON and operational. When red light is illuminated, that means the system is a "no-go" due to E-Stop button engaged or no V2V communication.

*this table is contained in Section 5 of AIPV User Manual

35

KRATOS UNMANNED SYSTEMS DIVISION

Royal TRUCK & EQUIPMENT INC.

ATMA

AIPV

NASDAQ: KTOS
DEFENSE & SECURITY SOLUTIONS
REVISION DATE: 26/9/19

Hands On Section

- Break for On Truck review:
  - Follower Vehicle Components

Operating Parameters

- GPS Navigation Functionality – Primary Navigation System
  - AIPV system uses electronic breadcrumbs (E-Crumbs) that enable Leader / Follower autonomous vehicle operations

- GPS Denied Navigation Functionality
  - Occurs when GPS satellite signals are blocked due to obstructions
  - AIPV system switches into GPS denied navigation when GPS is blocked
  - If GPS signal is not re-established in less than 45 seconds, safety software triggers an A-Stop

KRATOS UNMANNED SYSTEMS DIVISION
Royal TRUCK & EQUIPMENT INC.
ATMA
AIPV
NASDAQ: KTOS
DEFENSE & SECURITY SOLUTIONS
REVISION DATE: 26/9/19

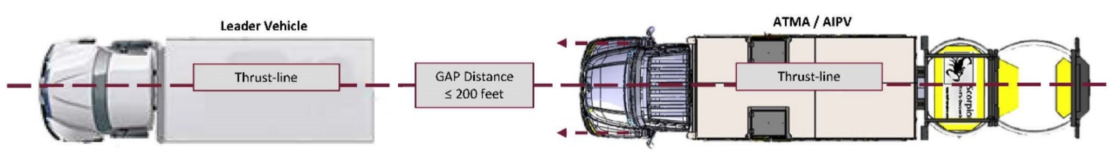
Operating Parameters

- AIPV Rollout
  - Rollout is the distance the AIPV travels at startup until it reaches the position the leader started from
    - Leader Vehicle must not roll out faster than 4 to 8 MPH
  - Rollout is a **critical** procedure for AIPV navigation
  - Rollout must be repeated after all E-Stop actions

- Do not go in REVERSE while in unmanned mode. System must be in OFF or IDLE for Leader Vehicle to go in reverse, if E-STOP is pressed and the AIPV is stopped and engine off then you may reverse
- Not recommended to stop in middle of rollout

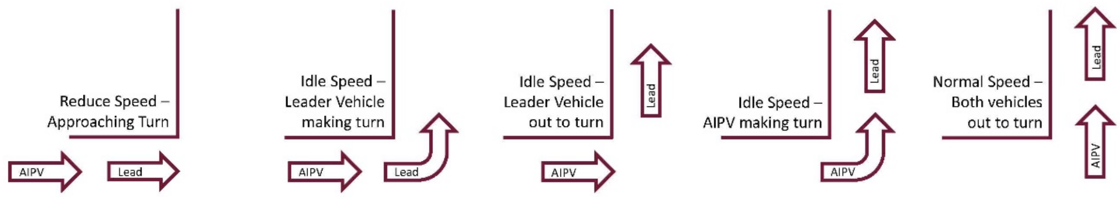
Operating Parameters

- Vehicle Alignment before Rollout
  - Vehicle alignment is a **critical** step in the Rollout process
  - Vehicle alignment must take place before powering on the Autonomous System
  - Vehicle alignment includes:
    - Align AIPV's front and rear axle in line to the Leader Vehicle's thrust-line
    - Ensuring the front tires on AIPV are pointed straight ahead



Operating Parameters

- Navigating Around Corners
  - Making safe turns require Leader Vehicle to reduce its speed
  - Best practice requires Leader Vehicle operator to maintain an idle speed (-5 MPH) **after** making the turn (may vary up or down hill)
    - Allows AIPV to make the turn at a safe speed
  - Visualize AIPV as a trailer with a long electronic hitch (E-Crumbs) on its rear bumper
  - Do not make sharp turns (65 foot minimum turn radius)



40

NASDAQ: KTOS
DEFENSE & SECURITY SOLUTIONS
REVISION DATE: 26/9/19

A-Stop and E-Stop Safety

- **AIPV system supports an emergency stop counter measure for unsafe conditions**
  - A-Stop functionality brings AIPV to a controlled stop
    - Releases Throttle
    - Applies Full Brake (operational brake actuator)
    - Leaves Engine Running
    - Can be cleared from the Leader Vehicle to resume operations
  - E-Stop functionality brings AIPV to a controlled stop
    - Releases Throttle
    - Applies Full Brake (emergency brake actuator)
    - Shuts Engine off
    - Cannot be cleared from the Leader Vehicle
    - Users will have to re-line up the vehicles for a new rollout

41

NASDAQ: KTOS
DEFENSE & SECURITY SOLUTIONS
REVISION DATE: 26/9/19

A-Stop and E-Stop Safety

- **AIPV system supports an emergency stop counter measure for unsafe conditions**
  - Independent E-Stop is a backup safety system
    - Capable of operating during a complete system failure if battery power is available
    - Overrides other system components in the event of an emergency
      - Releases Throttle
      - Applies Full Brake (emergency brake actuator)
      - Shuts Engine off
      - Cannot be cleared from the Leader Vehicle
      - Users will have to re-line up the vehicles for a new rollout

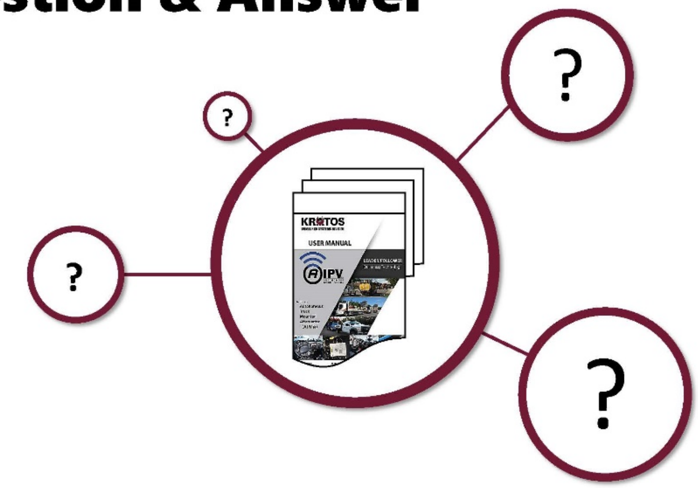
Safety Information

- It is important to follow all safety guidance in AIPV User Manual
  - AIPV operations require additional safety precautions to prevent consequences such as injury, loss of life, or damage to property

- KRATOS cannot anticipate every possible circumstance that might involve a potential hazard
  - Safety guidance in AIPV User Manual is not all inclusive
  - Be sure to review safety guidance in the vehicle's Operation and Maintenance Manual being used for AIPV operations

NASDAQ: KTOS
DEFENSE & SECURITY SOLUTIONS
REVISION DATE: 26/9/19

Question & Answer



NASDAQ: KTOS
DEFENSE & SECURITY SOLUTIONS
REVISION DATE: 26/9/19

Hands On Section

- Break for On Truck review:
  - Leader/Follower hands on operation

NASDAQ: KTOS
DEFENSE & SECURITY SOLUTIONS
REVISION DATE: 26/9/19