Automated Truck Mounted Attenuator: Phase 2 Performance Measurement and Testing

December 2023 | Final Report

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16. Abstract

Truck-Mounted Attenuators (TMAs) are energy-absorbing devices added to heavy shadow vehicles to provide a mobile barrier that protects work crews from errant vehicles entering active work zones. In mobile and short-duration operations, drivers manually operate the TMA, keeping pace with the work zone as needed to function as a mobile barrier protecting work crews. While the TMA is designed to absorb and/or redirect the energy from a colliding vehicle, there is still significant risk of injury to the TMA driver when struck. TMA crashes are a serious problem in Virginia, where they have increased each year from 2011 (17 crashes) to 2014 (45 crashes), despite a decrease in the number of active construction sites between 2013 and 2014. Although various efforts have been made to improve TMA vehicle crashworthiness (e.g., by adding interior padding, harnesses, and supplemental head restraints), the most effective way to protect TMA drivers may be to remove them from the vehicle altogether. Recent advances in automated vehicle technologies—including advanced sensing, high-precision differential GPS, inertial sensing, advanced control algorithms, and machine learning—have enabled the development of automated systems capable of controlling TMA vehicles. Furthermore, the relatively low operating speeds and platoon-like operating movements of leader-follower TMA systems make an automated control concept feasible for a variety of mobile and short-duration TMA use cases without the cost or complexity of full autonomy. This project seeks to develop an automated control system for TMA vehicles using a short following distance, leader-follower control concept which will remove the driver from the at-risk TMA.

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Abstract

Truck-Mounted Attenuators (TMAs) are energy-absorbing devices added to heavy shadow vehicles to provide a mobile barrier that protects work crews from errant vehicles entering active work zones. In mobile and short-duration operations, drivers manually operate the TMA, keeping pace with the work zone as needed to function as a mobile barrier protecting work crews. While the TMA is designed to absorb and/or redirect the energy from a colliding vehicle, there is still significant risk of injury to the TMA driver when struck. TMA crashes are a serious problem in Virginia, where they have increased each year from 2011 (17 crashes) to 2014 (45 crashes), despite a decrease in the number of active construction sites between 2013 and 2014. Although various efforts have been made to improve TMA vehicle crashworthiness (e.g., by adding interior padding, harnesses, and supplemental head restraints), the most effective way to protect TMA drivers may be to remove them from the vehicle altogether. Recent advances in automated vehicle technologies—including advanced sensing, high-precision differential GPS, inertial sensing, advanced control algorithms, and machine learning—have enabled the development of automated systems capable of controlling TMA vehicles. Furthermore, the relatively low operating speeds and platoon-like operating movements of leader-follower TMA systems make an automated control concept feasible for a variety of mobile and short-duration TMA use cases without the cost or complexity of full autonomy. This project seeks to develop an automated control system for TMA vehicles using a short following distance, leader-follower control concept which will remove the driver from the at-risk TMA.

Acknowledgements

This project was funded by the Safety through Disruption (Safe-D) National University Transportation Center, a grant from the U.S. Department of Transportation – Office of the Assistant Secretary for Research and Technology, University Transportation Centers Program. The research team would like to acknowledge the support from the Virginia Department of Transportation and the Virginia Transportation Research Council, who assisted with their work zone expertise and supported live work zone testing. The project team would also like to thank Andy Petersen, Chief Engineer at VTTI for providing his subject-matter expertise throughout this program.

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Introduction

Truck Mounted Attenuators (TMAs) provide an added measure of safety to work zones by acting as a physical barrier between work crews and passing traffic or errant vehicles. However, even with energy-absorbing crash barriers and safety restraint protections, the human driver of the TMA-equipped vehicle is put at risk of injury when that vehicle is struck by a car or heavy truck. This is particularly true in mobile and short-duration work zone operations when the driver remains in the vehicle during the work activity.

The emerging field of vehicle automation offers a potential solution that would allow the TMA to be operated without a human driver occupying the vehicle, which eliminates the risk of injury should the TMA vehicle be hit. In May of 2019, a consortium was formed between the Virginia Tech Transportation Institute (VTTI), Transurban, the Virginia Department of Transportation (VDOT), and DBi Services (Now DeAngelo Contracting Services [DCS]) to design and develop a leader-follower automated TMA (ATMA) System (Phase 1).

At the conclusion of Phase 1 of this project, the VTTI team designed and built a leader-follower ATMA System that works under the following operational design domain (ODD) conditions:

- Speeds of 15 mph or less
- Dependable GPS signal
- Commanded following distances between 50 and 400 feet
- Commanded lateral offsets of +/- 12 feet
- Clear weather
- Night and day operations

The Phase 1 ATMA System also successfully monitored, detected, and responded to object intrusions in the safety zone (the area between the lead and follower vehicles) using the LIDAR-based system developed by VTTI. The team also designed and developed an internal human-machine (HMI) system that would allow an operator in the lead vehicle to control the lateral and longitudinal offsets of the follower vehicle, apply waypoint holds and releases, and provide situational awareness of the entire operation. The resulting HMI is intuitive and provides a means for the lead operator to safely drive and control the vehicle with minimal attentional demand. The ATMA System also has a remote operation feature that utilizes a joystick to control the following vehicle at a range of up to 500 meters.

This second phase of the project aimed to build upon the first by expanding the functional capabilities and ODD as well as migrating the ATMA System testing and performance evaluations from a closed course to public roadways in live work zones. The expanded ODD requirements are discussed in detail below.

GPS-denied environments. It is important that an ATMA can operate in GPS-denied environments, including under large overpasses, in tunnels, and in urban canyons, as they are a part of typical work zone operations. In Phase 1, progress was made towards implementing a

LIDAR-based simultaneous localization and mapping (SLAM) solution to support operation in a GPS-denied environment. The SLAM method uses point cloud returns from the LIDAR to map physical features near the roadway to provide landmarks for the ATMA to localize itself and navigate by. However, the type of LIDAR sensor originally specified for the ATMA was intended to be used more for forward object detection than LIDAR-based mapping. As such, the accuracy and range of the 16 beam LIDAR units used in the SLAM model were limited and ultimately the lateral tracking accuracy suffered. One option to resolve this issue was to specify a different class of LIDAR unit that would provide the resolution and range necessary for accurate roadside LIDAR mapping. However, higher performance LIDAR units were cost prohibitive for a commercially viable product. As such, VTTI explored the substitution of a camera-based perception system that can track lane lines and road edges as an alternative to the LIDAR-based SLAM approach. One LIDAR was still be retained on the ATMA design to support forward object detection but will no longer be used for mapping. Higher performance cameras were added to the ATMA and lead vehicle technology package to support accurate camera-based mapping. The resulting performance and economics of the approach will support operations in GPS-denied environments and provide a lower per-unit cost for the resulting ATMA System.

Improved Operation. One of Phase 2's primary focuses was to improve the ease of operation, stability of operation, and accuracy performance at speeds up to 35 mph over long distances and durations.

Reduced Cost and Footprint A technology refresh also leveraged new, more capable component products that entered the market after the onset of the original ATMA project, such as improved sensing, computing, and communication equipment. This enabled the team to reduce the amount of total computers from five to two, improve the range, capability, and reliability of the wireless link, and achieve more accurate GPS signal at a much lower cost.

Background

The ATMA Phase 2 project addressed the following research questions:

1) Can a TMA be automated in a lead-follow configuration suited well enough for practical usage in live road work zone operations?

2) What will be the government and contractors' reaction to an ATMA system and what is the sentiment surrounding adoption in future operations?

Method

Task 1: Project Management

VTTI led the Project Management tasks throughout the project while keeping the other consortia members apprised of the project status. Status update meetings were held on a consistent basis via remote conferencing. VTTI also completed budget tracking on a monthly basis. As part of this task, the team members completed all activities, milestones, and deliverables according to the Milestones/Deliverables Schedule.

Technology Transfer activities at the conclusion of this project will also be completed under Task 1. A collaborative agreement was created to manage the control of the ATMA2 Technology Package that was generated by this project. DCS was given the first opportunity to commercialize the ATMA2 Technology Package, which they have indicated they intend to do. Negotiations have begun with VT's LICENSE intellectual property (IP) management group to negotiate a royalty-bearing license to use the ATMA2 Technology Package.

Near the end of the project, the team started an additional regular stakeholder meeting that included members of the funding consortia, VDOT, the Virginia State Police, the Virginia Department of Motor Vehicles, VTTI's Safety Committee, and members of the VDOT districts where early testing was proposed to be conducted. Through this stakeholder group, the VTTI team vetted its plans for conducting final test track validation testing, and plans for migrating the technology to public roads in scenarios, working with both contractor and VDOT operational crews.

Task 2: Integrate Vision-based Lateral Control System and Testing

VTTI evaluated vision-based path perception technologies for an ATMA lateral control engine that will allow operating in GPS-denied environments. These technologies are camera-based hardware and software systems which output road geometry for current and adjacent lanes, obstacle data, free-space detection, and path information, allowing the ATMA control engine algorithm to operate in both GPS and GPS-denied environments.

Under task 2, the VTTI team developed a vision-based navigation solution by first tracking lane lines and then tracking the distance from those visible lane lines to an artificial center line of the camera's field of view corresponding the centerline of the vehicle extended straight ahead. The lateral distances between that center line and those lane lines are then passed from the lead vehicle back to the ATMA or "follow vehicle" for it to use as a target when it eventually arrives at the spot where the lead vehicle collected those measurements. It determines the distance between the two vehicles using radar and vehicle odometry (pulling controller area network [CAN] speed data) to know what lateral position in the lane to mimic and when. For example, if the lead vehicle saw that it was perfectly in the center of the right most lane, and the ATMA was following at 150 ft, once the ATMA had traveled 150 ft, it would aim to align its centerline directly in the center of the right most lane. VTTI demonstrated the performance of this vision-based navigation solution in a proof-of-concept activity for VDOT, Virginia Transportation Research Council, and DCS and ultimately received a go-ahead decision to proceed to the successive tasks of Phase 2. Figure 1 shows the debugging lane perception frame from the vision-based application.

Figure 1. Vision-based lane perception.

Task 3: ATMA Technical System Upgrade

During Task 3, the VTTI team made many improvements to both hardware and software to increase the reliability, stability, and performance of the system.

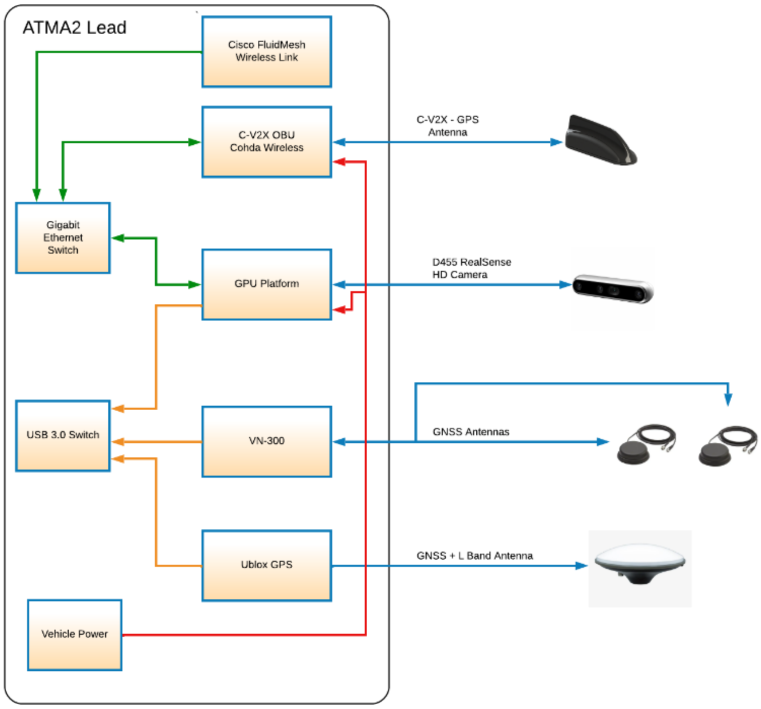


Figure 2. ATMA2 Lead high level system diagram.

The ATMA software modules, including Robotic Operating System (ROS) and Linux OS, were upgraded to the latest versions, Melodic and Ubuntu 18.04, respectively. Both the lead and follow computing packages were integrated to run the same master code on just one computer per vehicle. Boot up time from ignition on to automation ready was reduced to just 5 minutes by streamlining and cleaning code. Figure 2 shows the ATMA2 Lead high-level system diagram with the main components.

VTTI also removed three of the four Lidar units, leaving only one unit on the following vehicle for redundant safety zone monitoring/object detection within the ATMA's path of travel. This greatly reduced the overall bill of materials (BOM) cost. The differential GPS (DGPS) system was reduced from a Novatel GPS receiver and a Vantage DGPS corrections receiver to just one Ublox three band DGPS/GNSS unit receiving real time kinematic (RTK) corrections through L-band satellite transmission, also at lower cost than the previous configuration and with improved results. The old wireless communication link between the two vehicles was improved in stability, range, speed, bandwidth, and security by implementing Cisco's Ultra Reliable Wireless Backhaul (CURWB) system. An improved Teltonika RUTX11 industrial dual-sim cellular router was installed for improved remote operation and observation. As an additional safety measure recommended by VTTI's safety committee, a mechanical parking brake engagement failsafe solution was added, which meant that any time an emergency stop was triggered in software, the vehicle would command full braking, but also engage the parking brake; additionally, the parking brake would engage independently from the software if any emergency stop button was pressed, including the wireless e-stop, or if power was lost. Figure 3 shows the ATMA2 Follow high-level system diagram with the main components.

In anticipation of having a fully functional ATMA System that passed the closed-course performance testing in Task 4, VTTI engaged the stakeholder group early as the team sought to gather feedback throughout the refinement of the system to gain alignment on procedures and ensure practicality in real world application. Additionally, the group was formed to ensure compliance with laws and regulations and comply with any requests by the stakeholder group that would prevent operation on live roadways. This stakeholder group helped select the work zone projects to use for the on-road testing and set operational guidelines and requirements for how the testing could proceed. The group will be further engaged after the conclusion of Phase 2 to host further pilot tests and transition into Phase 3.

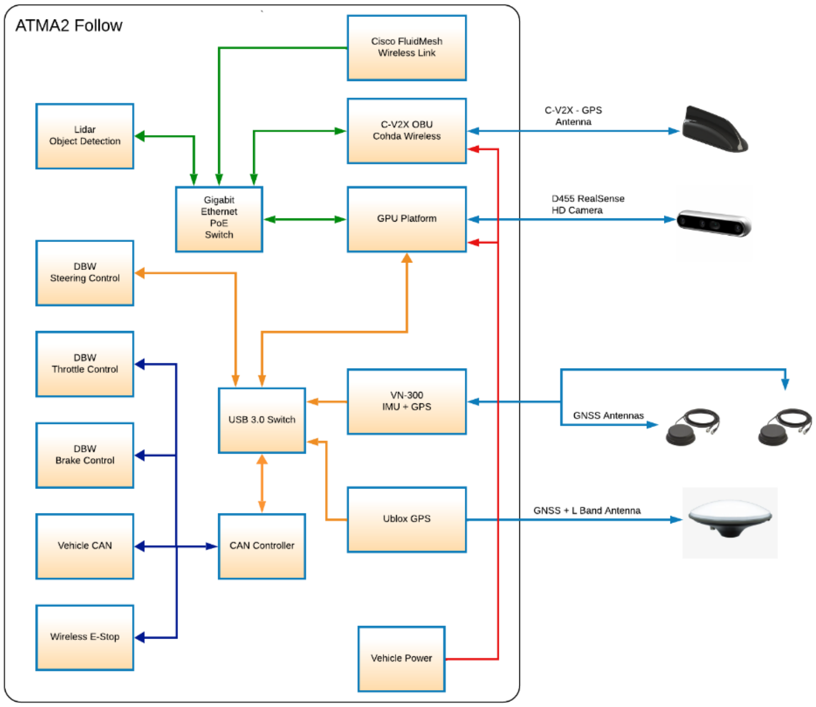


Figure 3. ATMA2 Follow high level system diagram.

Task 4: Final System Performance Measurement and Testing

At the conclusion of Task 3, most system development work had been completed and a test plan had been produced with feedback from the stakeholder group and VTTI's Safety Committee. This closed road test plan was part of the larger integration plan based off the initial integration plan from Phase 1 and was designed to report out performance metrics that would help the primary stakeholder make an informed decision about its readiness for a live road event. Prior to testing activities, the VTTI team presented the ATMA Test Plan to both the ATMA2 Consortium and the VTTI Smart Road Safety Committee for review and to gain approval to conduct testing. The VTTI team also conducted a hazard analysis including a Failure Mode, Effects, and Criticality Analysis and presented that to the VTTI Smart Road Safety Committee in addition to sharing it with the ATMA2 Consortium. All testing activities throughout Phase 2 still required a trained VTTI safety driver behind the wheel of the ATMA to monitor local vehicle functions and to intervene and take control of the ATMA if necessary during the testing activities. Multiple means to shut down and stop the ATMA from both on-board and remote systems were integrated with the system to help ensure safe operations during testing.

The closed road test plan consisted of three main categories of tests: stops, performance through varying roadway geometry, and HMI manipulation. The tests are listed below; all tests were conducted at 5, 15, and 25 mph with three trials each unless otherwise stated.

- Emergency Stop – Lead HMI Tablet
- Emergency Stop – Wireless Button

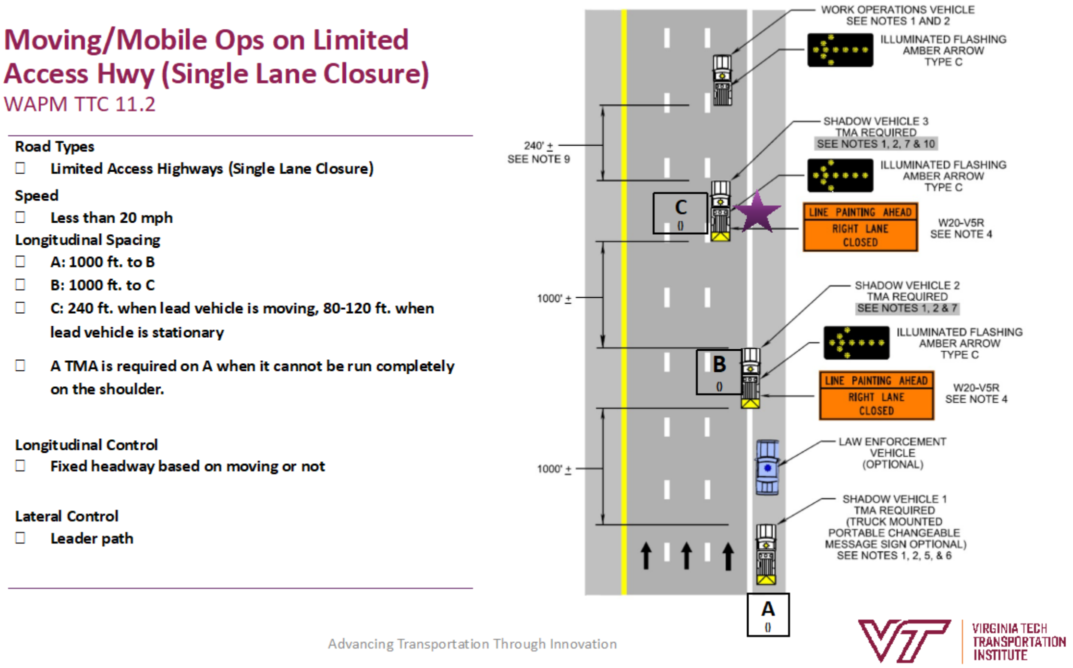
- Emergency Stop – External Mushroom Buttons (5 mph only)
- Lead Hold
- Static Obstacle Detection
- Highway Loop (Only one 5 mph trial)
- Curve T4
- Decline
- HMI Longitudinal Change Incline
- Emergency Stop – Front Bumper (Stationary)
- Follow Hold
- Dynamic Obstacle Detection
- Curve T1
- Incline
- HMI Lateral Change
- HMI Longitudinal Change Decline

The metrics collected and reported were dependent on the test category. In both the HMI manipulation and varying roadway performance categories, lateral and longitudinal accuracy was reported. In the “stops” categories, the deceleration profile and therefore stopping time and distance were reported. For each emergency stop and hold test, the team waited until the follow vehicle assumed the target test speed and then initiated the emergency stop. The deceleration profile was recorded automatically by the computer in a ROS bag. For the static and dynamic obstacle detection tests, a standard traffic drum was either placed in the ATMA’s path after the lead vehicle had passed or was pulled across its path on a dolly. For each roadway geometry test, the ATMA was operated for the entire length of the Virginia Smart Roads Highway Section, approximately 4.4 miles for one full loop. In that loop, there are relatively level straight sections, a steep incline and decline, as well as two tight turn arounds of 114 ft radius (T4) and 262 ft radius (T1). In each of these sections, the system performed slightly differently, so data was automatically collected as the test team operated the system for the full loops. The data was also reported parsed out between these sections as well as for the whole run to show performance under these roadway configurations and the maximum error expected. The full highway loops were additionally performed using the fallback vision-based navigation solution, excluding T1 and T4, as these radii are too tight for the vision system in its current configuration, which is suited for off/on ramps of limited access highways (500+ ft radii). These vision tests were run at 5 and 15 mph. The 25 mph test were not run, as re-paving on the Smart Roads Highway during our period of performance prevented any further testing.

To ensure unbiased feedback and to identify potential shortcomings of the startup procedure and operation that may not be as intuitive to those not familiar with the system, all tests were completed by a team within VTTI that did not include ATMA developers. Any incidents of system error, required vehicle take-over, or emergency stops etc. were also recorded and reported to the consortium and the VTTI safety committee. The highlights of these results are presented in the following Results section of this document.

After presenting test results to the ATMA consortium and VTTI’s Safety Committee to both group’s satisfaction and approval, the VTTI team reached out to contacts at VDOT to arrange a meeting with local traffic operations engineers and maintenance personnel to develop a live road test scenario. The group decided to close the outside lane of US-460 (65 mph limited access highway) in Montgomery County, VA near VTTI using Work Area Protection Manual (WAPM)

Temporary Traffic Control (TTC) configuration 11.2: *Moving/Mobile Operations on Limited Access Highway (Single Lane Closure)* with the lead vehicle being the "work operations vehicle" and the ATMA being TMA C (see Figure 4).



Moving/Mobile Ops on Limited Access Hwy (Single Lane Closure)

WAPM TTC 11.2

Road Types

☐ Limited Access Highways (Single Lane Closure)

Speed

☐ Less than 20 mph

Longitudinal Spacing

☐ A: 1000 ft. to B

☐ B: 1000 ft. to C

☐ C: 240 ft. when lead vehicle is moving, 80-120 ft. when lead vehicle is stationary

☐ A TMA is required on A when it cannot be run completely on the shoulder.

Longitudinal Control

☐ Fixed headway based on moving or not

Lateral Control

☐ Leader path

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Figure 4. Single lane closure template.

The test event comprised two parts: an introduction to the system and a live road test. In the morning, the VDOT crew were given an introduction and crash course on the ATMA system. Then, roles were assigned, and the crews were given the operations manual to practice on VTTI's Smart Road Highway before moving on to the live road test in the afternoon. The live road test consisted of two VTTI personnel, four VDOT personnel, and one observer in the lead vehicle, with live video being streamed back to the rest of the event attendees. The VTTI personnel acted only to advise on the use of the system and as safety drivers; the VDOT crew operated the system out on the road while providing valuable guidance regarding safe operation on a busy high-speed roadway. To begin automation, the lead and following vehicle were navigated to the shoulder of the highway on-ramp, and the team waited until the ramp was relatively clear, then engaged automation and closed the right most lane just as instructed by the VDOT crew. The test was conducted at 15 mph between the Industrial Park Road exit and the Tom's Creek Road exit, first heading westbound, and then heading back eastbound, approximately 6 miles between exits. Between those two exits are three overpasses, under which the system lost GPS and reverted to its fallback vision-based navigation. ROS bags containing all sensor data including additional forward and rear video were automatically collected.

A subjective questionnaire was designed to gather worker opinions of the ATMA and was administered to ATMA operators, work crew members, and work zone managers. The questionnaire was sent out after conclusion of the live road test to those who were present or remotely involved in its conception and execution. The questionnaire can be found in Appendix C.

Results

The following sections present the results of executing the testing plan that was developed with the stakeholder group.

Closed road performance metrics

Following Accuracy

Figure 5 shows the lateral error calculated on the Follow vehicle using GPS as path following source at different speeds.

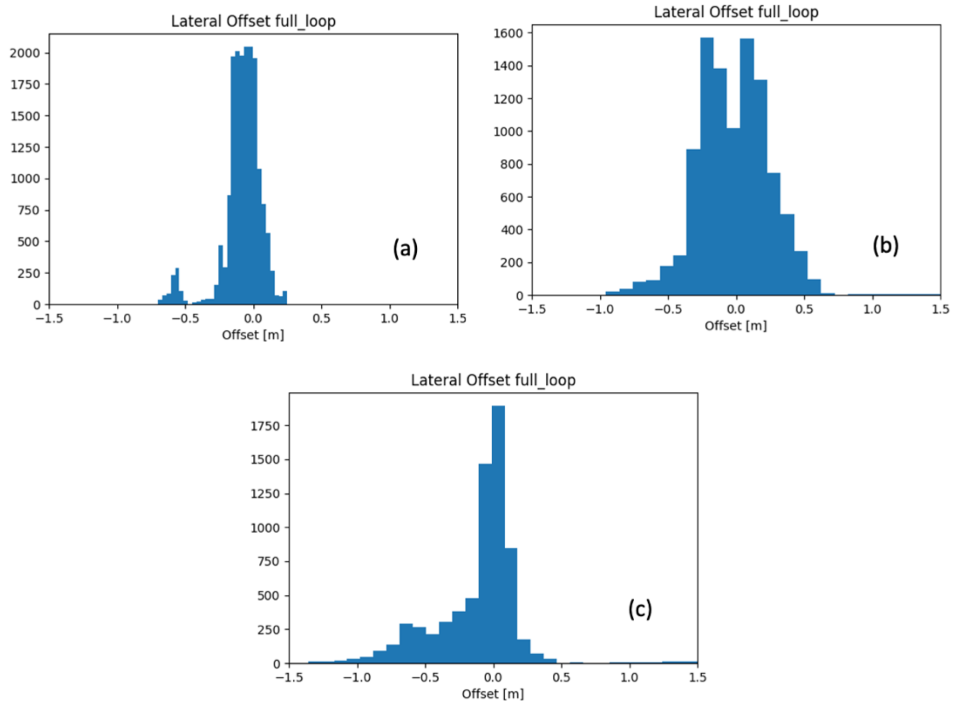


Figure 5. Lateral error with GPS as source at (a) 5 mph, (b) 15 mph, and (c) 25 mph.

Figure 6 shows the lateral error calculated on the Follow vehicle using vision as the navigation source at different speeds.

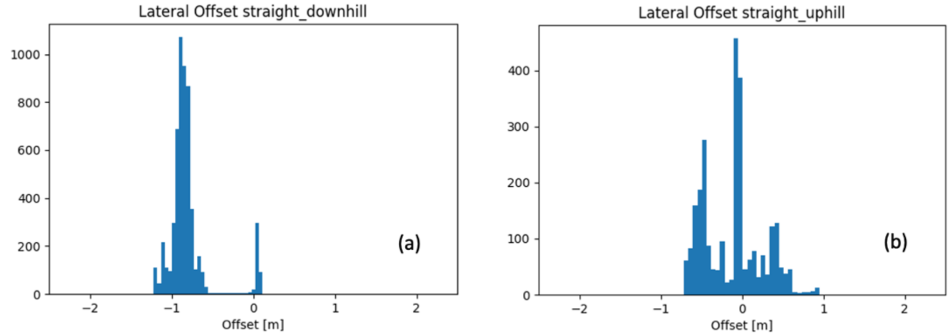


Figure 6. Lateral error with vision as source at (a) 5 mph and (b) 15 mph.

Figure 7 shows the longitudinal error calculated on the follow vehicle using GPS as the navigation source at different speeds.

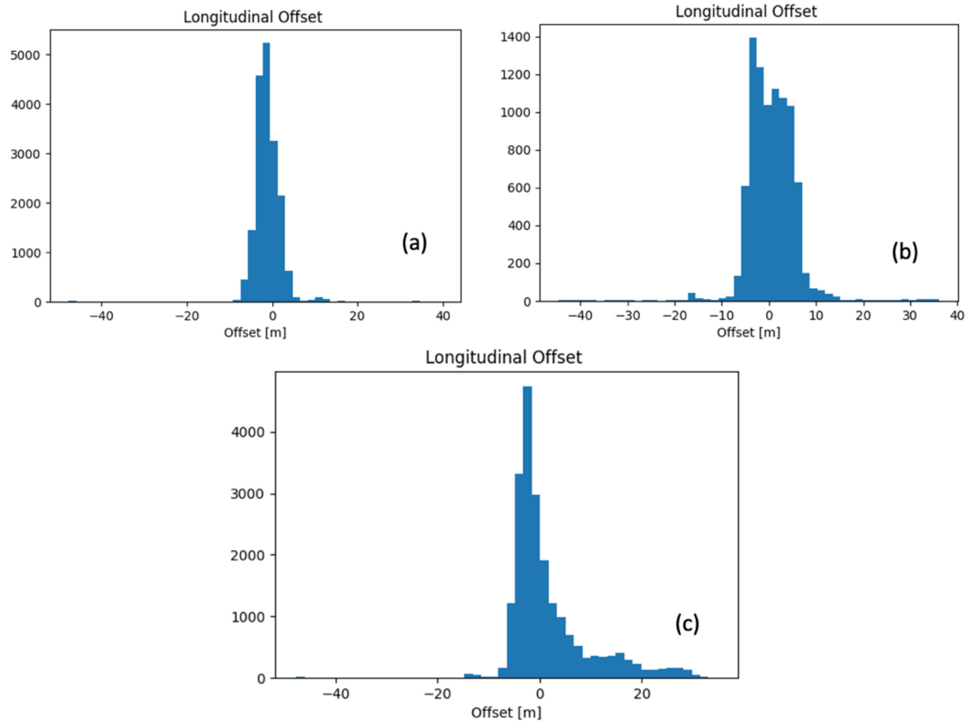


Figure 7. Longitudinal Error with GPS as source at (a) 5 mph, (b) 15 mph, and (c) 25 mph.

Figure 8 shows the longitudinal error calculated on the follow vehicle using vision as the navigation source at different speeds.

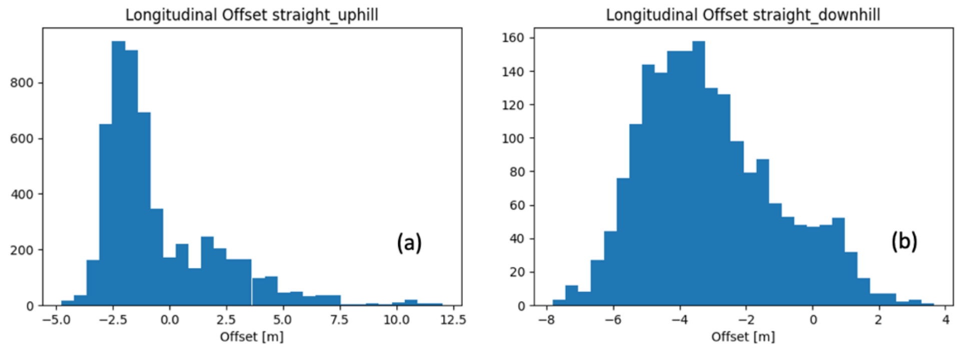
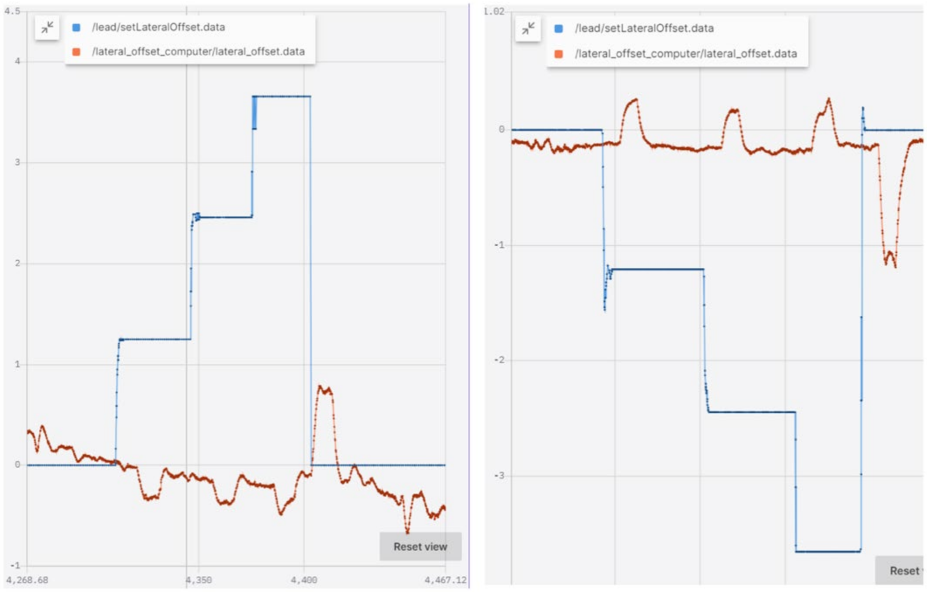


Figure 8. Longitudinal error with vision as the source at (a) 5 mph and (b) 15 mph.

Lateral Offset

Figure 9 shows the commanded lateral offset ranging from 0 to 12 ft for the left and right.



(a)

(b)

Figure 9. Commanded offset left 4, 8, 12, back to 0 – 4-5 seconds from command to offset assumption for (a) left and (b) right.

Longitudinal Offset

Figure 10 shows the commanded longitudinal offset changing from 200 ft (61 m) to 150 ft (46 m) when travelling uphill, taking approximately 15 seconds. The blue line shows the commanded offset while the yellow line is the actual; this actual measurement can be noisy and the large deviations can be assumed as sensor error.

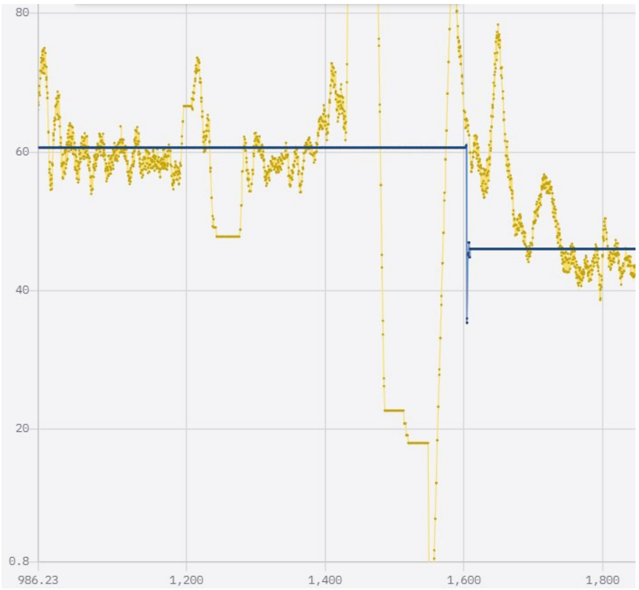


Figure 10. Commanded longitudinal offset.

Stopping

Figure 11 shows the emergency stop braking profile, which was executed under the following conditions: fully loaded ATMA (just under 20 k lbs) stopping from 25 mph via wireless e-stop with a slight incline on dry pavement. Thee time from intial button press to 0 mph was appoximately 3 seconds, during which time the ATMA traveled approximately 50 ft.

When stopping to mimic hard braking from 25 mph behind the lead vehicle without the use of an emergency stop (graph not shown), the ATMA stopped just slightly slower than the lead vehicle, gaining around 30 feet on the lead vehicle's position on dry pavement with a slight incline.

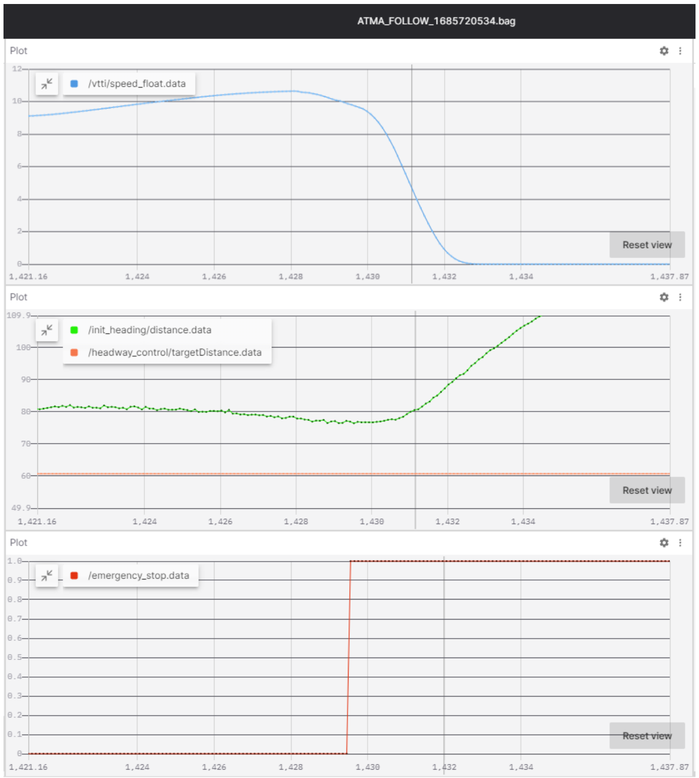


Figure 11. Emergency stop braking profile.

Object Detection

The ATMA was put through a variety of tests to determine the effectiveness and reliability of its obstacle detection and emergency braking capabilities. The first test was a stationary traffic drum placed in the path of the ATMA in the center of its lane. In all trials at 5 and 15 mph, the ATMA properly detected the cone and brought the vehicle to a halt prior to contact with the cone; however, it only succeeded in 33% of trials at 25 mph. Additional tests were conducted to test lane edge object detection. For a traffic barrel on the inside edge of right and left lane lines, the system stopped at 5 and 15 mph in all trials but did not stop in time at 25 mph; the ATMA contacted the traffic drum and the front bumper sensor triggered an emergency stop. For a traffic barrel on outside edge of the right and left lane lines, the system did not stop at 5 mph in all trials, stopped at 15 mph in 33% of trials, and did not stop at 25 mph in all trials. For the dyanmic tests, where the traffic barrel was pulled from one lane edge to the other in front of the ATMA, the vehicle stopped at 5 and 15 mph in all trials. The 25 mph dynamic obstable detection tests were not run due to the failed static tests at that speed.

Transition to Vision-based navigation

The last closed road test was ensuring proper transition from GPS navigation to vision-based navigation. This was accomplished by pulling the GPS antenna from the lead vehicle computer and then reconnecting. In all trials, the ATMA fell back to vision localization and continued navigating. However, in some trials, there was an error when the GPS was reconnected; this issue was resolved with an update to the code and retesting was a full success.

Live Road Testing

Below is a written transcript of the closed road test event. Videos and ROS bags of the event will be provided to SAFE-D.

As stated in the Methods section, the closed road testing group decided to close one lane of US-460 (65 mph limited access highway) in Montgomery County, VA near VTTI using a Work Area Protection Manual (WAPM) Temporary Traffic Control (TTC) configuration 11.2: *Moving/Mobile Operations on Limited Access Highway (Single Lane Closure)* shown in Figure 4 with the lead vehicle being the "work operations vehicle" and the ATMA being TMA C. The test was conducted on Monday, 11 September 2023, in the afternoon, with fair weather. The route on US-460 between the Industrial Park Rd and Tom's Creek Road can be seen below highlighted by the orange arrowed line in Figure 12. Operations were conducted at 15 mph with a 100 ft following distance.

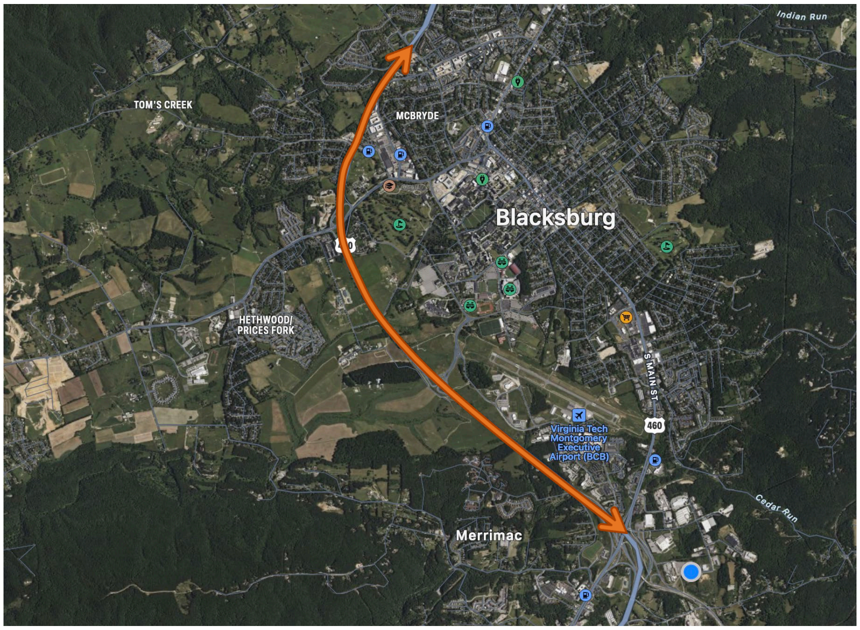


Figure 12. Live testing route.

The lead vehicle and the three participating TMAs migrated from the Automation Hub facility at VTTI (Blue dot in Figure 12) to the onramp of US-460 at Industrial Park Drive, where the convoy pulled over to the shoulder to stage, as would be the case in a normal operation. The three TMAs deployed their crash cushions and illuminated their signboards and the ATMA vehicles engaged automation, taking less than 1 minute. The ATMA did not noticeably affect the lane closing operation starting procedures. The convoy proceeded down the ramp where the ATMA and lead vehicle rode the shoulder until TMA B (as indicated in Figure 4) straddled the shoulder line, at which point the ATMA and the lead vehicle took the entire right lane.

The convoy proceeded at 15mph underneath the Southgate Road overpass and to the Prices Fork Road bridge, underneath which a sensor error was triggered, and the vehicle came to a halt in its lane. After the ATMA came to a full stop, the safety driver took over and navigated the truck off of US-460, where the convoy circled around and started from the Southgate on-ramp. The convoy once again pulled over to the shoulder, engaged automation, and closed the right most lane. However, the system once again errored out underneath the Prices Fork Road overpass, which prompted the convoy to pull over and investigate the issue. The error discovered was the result of a hard drive in the ATMA computer becoming completely full and preventing the proper operation of the vision-based navigation system. So, when the GPS signal (covariance value) dropped below the set threshold, the system looked to its vision source. Because the vision source was not running properly, the health check process ceased automated navigation and brought the vehicle to a full hard stop, which was the desired behavior during system malfunction.

Once the issue was discovered, the convoy proceeded westbound to the Tom's Creek Road exit, where it circled around to head eastbound. With the hard drive capacity issue resolved, the team engaged automation on the shoulder, closed the right most lane, and proceeded the 6 miles from Toms Creek Road to Industrial Park Drive, successfully switching between GPS and vision-based navigation when traversing under bridges. The only other anomalies observed during the test were several false object detections for overhanging trees, lampposts, and bridge features. Post-test data review revealed the cause for most of these issues, which will be resolved through a filtering process in future iterations of the system.

The crews who participated in the demonstration and on-road testing were skeptical at first, but were ultimately impressed with the technology and performance. Crew members made several comments about the significant need for this technology and the desire to see it implemented in their operations. The crews will be further testing the ATMA in their own districts and operations in the coming months under a different funding opportunity.

Discussion

Throughout the multi-meeting stakeholder workshop series, no concrete standards/goals for driving accuracy and performance were contrived; the general consensus was that the ATMA should perform about as well as its human counterpart. This was generally phrased in terms of "do not leave the intended lane of travel" and follow "about as well as the typical operator can estimate their following distance," but this was not as critical as keeping lateral following accuracy. Additionally, the vehicle would need to operate for at least 30 minutes without interruption and should be able to remain stationary for extended periods of time. There was also unanimous agreement that the ATMA vehicle should not run into any object, stationary or moving.

Closed Road Test Analysis

Following Accuracy

Looking at the lateral accuracy graphs for the full highway loops, it is clear that the system performs best at lower speeds, with the bulk of error at 5 mph being under 1 ft, while the majority of error at 15 and 25 mph remained under 2 ft. Maximum error was observed in tight curves where the system biases towards the inside. This error around T1 and T4 was separated out from the straight sections where it can be more clearly seen; those charts can be found in Appendix B. As for the vision based lateral accuracy, at 5 mph, the error was centered around -1 but mostly grouped within a +/- 0.5 ft error, while the 15 mph graph shows the grouping centered around 0 with +/- 2 ft accuracy. This is because the 15 mph test was conducted first, and it is most likely that the camera became misaligned before the 5 mph test and therefore biased the ATMA to following left of the lead centerline. This will be fixed in the future by having a more rigid camera mount for both vehicles and including a process for verifying calibration prior to operation.

HMI Manipulation

All HMI manipulation tests were performed successfully, and it was demonstrated that lateral offset command changes were assumed in approximately 4–5 seconds with little to no overshoot regardless of the magnitude of the change. This was satisfactory to the stakeholders in that the vehicle reacted promptly but not too quickly, and the vehicle would not offset too far and perhaps cross into an unintended lane. Feedback from the non-developer test crew suggested two changes to the HMI. The first suggestion was to report either error from set commanded offsets or the absolute value the HMI is tracking, but to make the method of lateral reporting match the longitudinal. Currently, the HMI reports out error from the commanded lateral offset but reports out the absolute value for the following distance (longitudinal). Secondly, the crew expressed that buttons that would increase the commanded offsets by fixed intervals or buttons for preset offsets would be easier to use while driving rather than the continuous sliders on the HMI now in use, which are shown in Figure 8.

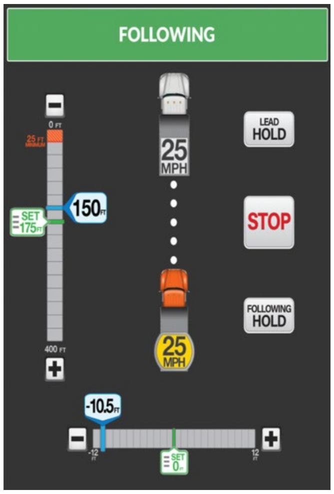


Figure 13. HMI display example.

Stopping

All emergency stop and hold tests were run successfully to the satisfaction of the stakeholders. There were no suggestions offered for additional emergency stop capabilities.

Object Detection

From the results of the static and dynamic obstacle detection, the team was confident that under 15 mph, the vehicle could operate on the live road with minimal false detections, but more importantly, experienced no missed object detection. However, at 25 mph, the ATMA was essentially "overdriving" the range of its LIDAR, meaning that since the LIDAR could only reliably detect the traffic barrel at 20 m and the ATMA had a stopping distance of 20 m at 25 mph, the system would just barely detect the traffic barrel in time to stop under perfect conditions. Accordingly, the VTTI team suggested to the stakeholders that live road operations target speeds of 15 mph or lower. The current LIDAR, which was satisfactory for Phase 1, is simply not suited for a higher speed with longer stopping distance. However, since this limitation is hardware based, a simple upgrade to the LIDAR would allow for higher speed operation with successful emergency braking, opening the possibility for operation at higher speeds.

Live Road Test Feedback from Operators and Industry

Both VTTI and the stakeholders were happy with the ATMA's successful integration into a live road TTC-11.2 on US-460. The vehicle performed to the stakeholders' expectations, keeping a good visual following distance, maintaining its lane, and starting up/engaging automation as soon as the vehicles were in position and ready to enter the highway. The only major improvement that the VDOT crew suggested was a button to command the ATMA to take the lane adjacent to the lead vehicle and remain centered in that lane as the lead vehicle then takes the lane afterwards. This was accomplished through the use of the lateral offset command, but using the HMI slider for the width of the lane and bringing the offset back to 0 as the lead changed lanes proved challenging. Feedback was nearly entirely positive, with most individuals who attended having high hopes for the future of the product and its broader deployment.

Additional bugs and operating procedures, such as hard drive space checks, will be discovered and implemented as the system is migrated from a research platform to a commercial product; more on these procedures are provided in Appendix A.

Bill of Materials

A goal of this phase of development was to reduce the cost of the BOM required to deliver the leader and follower systems. The result of completing Phase 2 development was to reduce the overall BOM for the leader package by 30% while making it more compact and easier to deploy. The BOM for the follower package was reduced by 50% while making the ATMA more accurate in its lateral following accuracy and adding a robust vision-based tracking fallback option.

Conclusions and Recommendations

The goals of the Phase 2 project were (1) to add a robust lateral tracking capability when a reliable GPS signal is lost, making the system functionality align with typical operations at speeds up to 30 mph, and (2) to reduce the cost of the system, making it more attainable for DOTs. The results of both the final test track and on-road testing suggest that sufficient lateral tracking in typical freeway and highway operations was achieved. Using GPS as the primary source of tracking and supplementing it with a machine-vision based fallback proved to be an adequate means to make the system more robust and able to handle GPS denied environments such as areas under bridges and in tunnels, etc. The ATMA lateral control system is now able to gracefully handle situations when GPS is lost and re-attained during normal operations. Longitudinal tracking remained adequate to support typical operations on freeways and highways.

The VTTI team set a goal to support operations at speeds of up to 35 mph, as some striping and other operations may achieve that speed. While the system was successfully tested on the test track at 40 mph, object detection and response were limited by the LiDAR sensor, which did not have enough forward range to stop the ATMA in time should an obstacle be detected. This is a function of the capabilities of the LiDAR sensor that was used for the object detection task and could be fairly easily remedied by specifying a LiDAR with longer range and a narrower focus of its beams in the forward direction. The VTTI team will seek to make this adjust to the vehicle platform in future iterations. Testing crews did suggest a new function, which would set lateral tracking based on lane position rather than a simple lateral offset distance. The VTTI team will add this to a list of desired functionality that we will address during future iterations. All other operational functions were adequate to be able to take the ATMA into testing operations on public roadways.

Finally, with careful selection of components and right-sizing the computing and communications capabilities on the vehicle, significant reductions in the basic BOM were achieved. The ultimate price for a commercialized ATMA product will, of course, be set by the commercialization entity. However, the 30–50% reductions in our Phase 1 solution will make it possible for DOTs to begin using this technology to save lives in their operations in the near term.

Potential improvements

Upgrading the Lidar sensor will provide longer object detection range and faster full stop braking for scenarios where the following speed is higher than 15 mph. The team also tested a new IMU+GNSS-RTK device that can be integrated into the lead/follow vehicles with improved accuracy and minimal calibration. We also believe a feature that allows operators to set the lateral position based on lane position rather than just a straight offset distance would also be a useful function and could be enabled by the visual lane tracking capabilities.

Future Plans for the Platform

VTTI is still pursuing commercialization opportunities with the DCS consortia member. An intellectual property disclosure that defines the results of this phase of development has been filed with VT's LICENSE team and will be the subject of commercialization negotiations.

Additional Products

Link to project page on Safe-D website:

https://safed.vtti.vt.edu/projects/5190-2/

Education and Workforce Development Products

The project team completed the following education and workforce development activities during the course of the project.

Training Document

The VTTI team created training materials for both operators of the ATMA and for managers to understand how best to work an ATMA into their typical operations. The training materials can be found in the Appendix. These materials were delivered in a classroom setting with the stakeholders and operators who participated in the deployment demonstration and transition to on-road testing meetings.

ATMA2 Testing Plan

The ATMA2 project resulted in an updated testing plan that can be used as an example for other developers of an automated system as to the level of testing desired prior to migrating to on-road operations for a limited ODD.

Technology Transfer Products

An invention disclosure has been filed with Virginia Tech's LICENSE IP management group. The disclosure is the basis of negotiations with an external organization for creating a royalty-bearing license that will support commercialization. VTTI has demonstrated the ATMA to multiple VTTI visitors during special events. The technology was also featured during presentations and demonstrations at the DCS Maintenance Symposium, VDOT Rodeo event, and Intelligent Transportation Systems' VA Annual Conference.

Data Products

The dataset uploaded to Dataverse contains raw sensor data that was aggregated to inform the autonomous system control for both lead and following vehicles during live testing on US-460. The dataset includes a set of ROS topics in bag file form, each of which contains the following types of data: Lidar, IMU, GPS, vision, and vehicle speed. The dataset can be found on VTTI's Dataverse here:
https://dataverse.vtti.vt.edu/dataset.xhtml?persistentId=doi:10.15787/VTT1/A1FNMW

Appendix A: Operating Procedure Manual ATMA

ATMA2 User Manual

Rev: 2.0

Before Start up

1. Wireless e-stop must be on or the e-stop override switch must be flipped for the vehicle to move the ATMA
2. Navigate the vehicle out to the testing area
3. Shut down both vehicles, the lead vehicle computer comes on with ignition (no breakers) so you will have to wait for it to shut down (can watch internal display to see when computer is off) before start up procedure

Start up

There are two computers in the ATMA systems, a GPU in the lead vehicle and another GPU in the follow vehicle. Controlling the startup order of these devices helps ensure the system is completely connected prior to automation engagement. The start order is Lead GPU and then Follow GPU.

First Step

1. Flip the power switch for the ATMA in-cabin hardware located against the bench seat, illuminated red (image 9)

2. Wait for the wireless modem (silver box on the dash with antenna) to boot up (it will flash for about a minute or two until it will have 4G illuminated and a signal strength indicated)

Lead

1. Connect the USB power adapter to the vehicle cigarette lighter port.

2. Start/Turn on the Lead Vehicle (Tahoe)
3. Turn on lead tablet HMI
   a. Hold power button on side of tablet.
   b. Press *continue* when it asks about the charger.
4. Swipe up to log in. Password=das
5. Open ATMA GUI, bottom most tile on home screen
6. Turn on Wireless ESTOP (image 5) by holding the black button beside the antenna for a few seconds, red light should come on in the center of the red mushroom button
   a. Keep close by as this is for ESTOP events to the Follow Vehicle.
7. Ensure that the GPU display is showing the forward camera view

Follow

1. Make sure all 4 breakers are closed. Image 3, Image 4

2. Plug in both USB Power adapters into cigarette lighters for Tablet HMI and GPU Display
3. Turn on Follow Vehicle (ATMA-Truck)
    a. Turn key to ignition
    b. Wait for the "ignition heat" light to go off (1-5 seconds)
    c. Crank engine
4. Ensure both automation keys are turned on. (They should be on and can be left on after shutdown) Image 6
    a. Far Right key is for automation mode
    b. Far Left Key is to apply power to our system
5. Turn on tablet HMI same as the lead and open ATMA GUI
6. When ready, make sure all mushroom buttons, Wireless ESTOP (image 5), in-cab disable automation button (Image 6), and 4 outside ESTOPS on bed (image 8) are all depressed (not pressed) by twisting them to ensure release.
7. Ensure that the GPU display is showing the forward camera view
8. Once completing these steps both vehicles should be powered on and the systems ready to go.

Operation

1. Drive vehicles for at least 5 minutes (incorporating turns and/or lane changes if possible) after start-up in non-automated mode to acquire GPS signal and calibrate IMUs. The tablet GUI should display "non-automated" at the top after the 5 minutes, if this is not the case, shut down both vehicles and restart the start-up sequence.
2. Align both vehicles such that their headings are nearly identical and come to a stop with 75-125 ft in between the two vehicles.
3. *All of the following operations in reference to the GUI should be carried out by the lead vehicle, the follow vehicle should never touch their tablet GUI, it is for awareness only.*
    a. Click "begin initialization"
    b. Click "engage automation"
4. At this point, "automation ready" should be displayed on the top of both tablets and the safety driver can release control of the follow vehicle, it will hold itself stationary
5. The lead vehicle should drive forward a couple feet and then click "start follow", then immediately begin driving slowly forward along the intended path. The tablet should show the following distance increasing until the set distance when a blue border with "following" up top should appear. Once the set distance is achieved, the follow vehicle should start moving to keep that following distance, it will initially play catch up as the following distance is usually overshot to begin.

Image 3: Battery Breakers(2)

Image 4: 2 breakers underneath on bottom shelf in cabinet

Image 5: Wireless ESTOP

Image 6: Automation keys and Emergency Stop

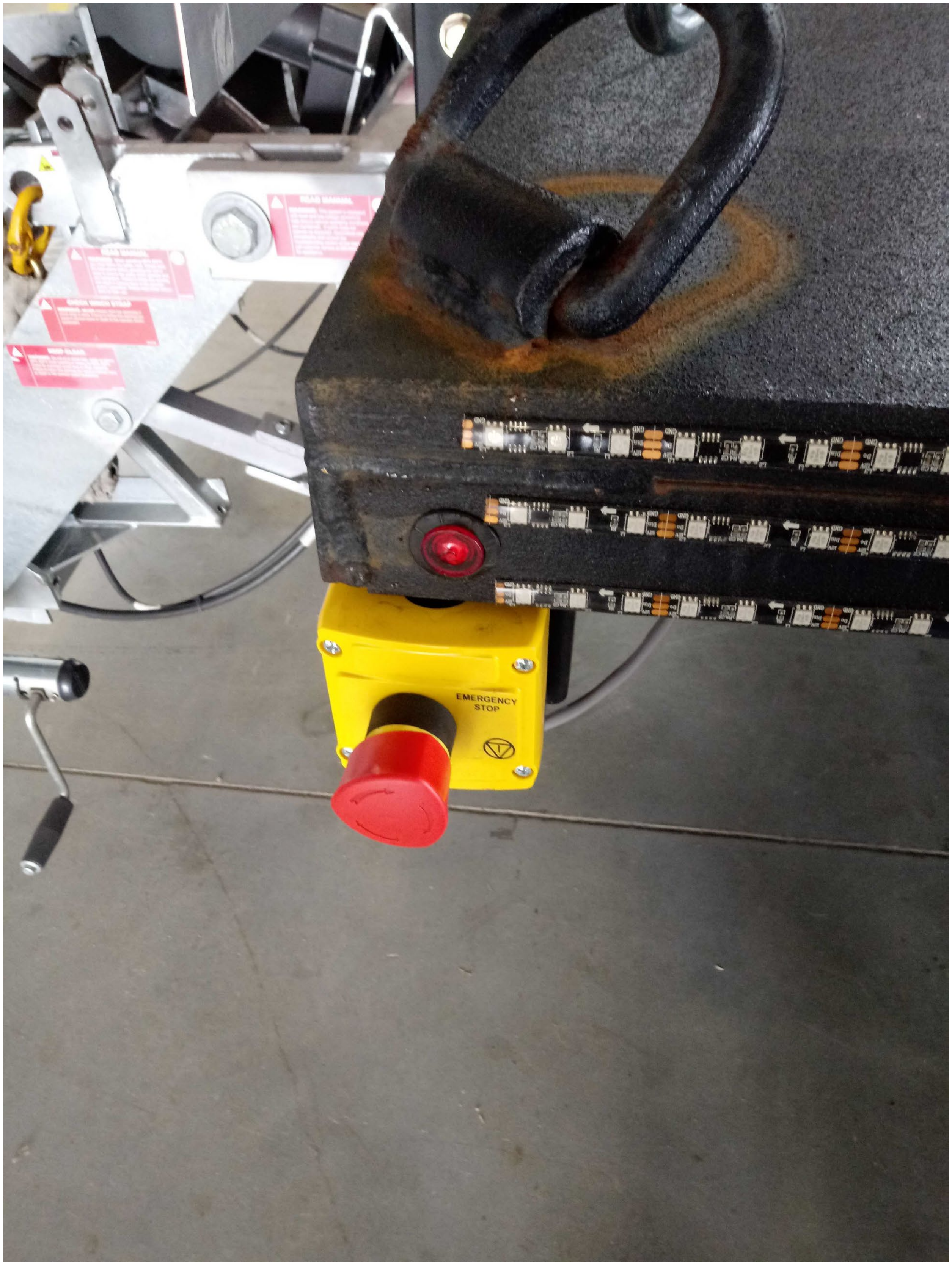


Image 8: One of Four ESTOPS on the bed

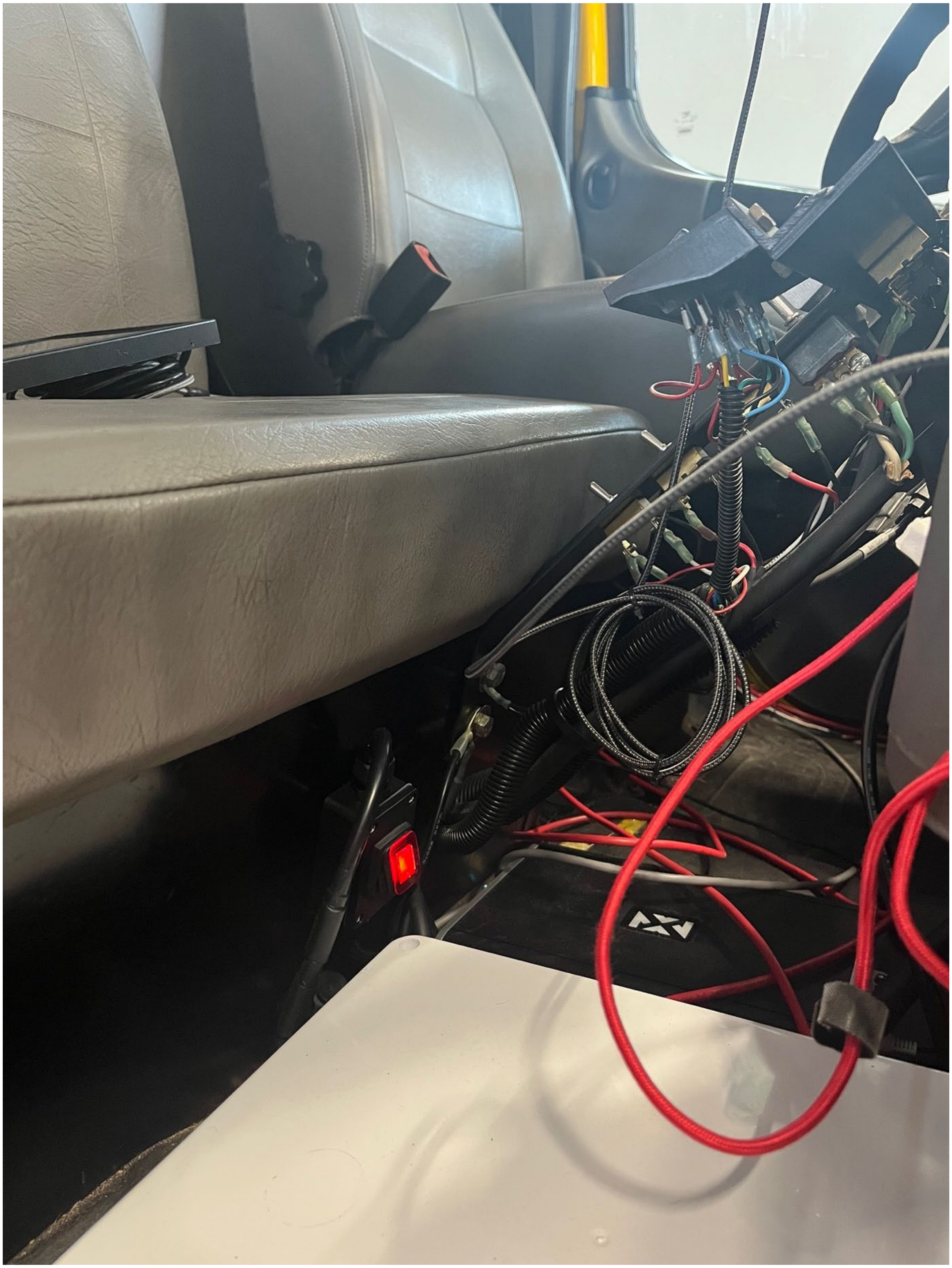


Image 9: Wireless modem and computer display power button (red)

Shut Down

Follow First:

1. Turn off the follow vehicle.
2. Wait for GPU shutdown ~2 minute, fan will stop and yellow LEDS inside of GPU will turn off, in cabin screen will countdown shutdown and eventually go blank.
3. Flip internal cab power button (Image 9) to turn off screen and modem
4. Turn both automation key switches off in cab. Image 6
5. Overnight shutdown:
    a. Once the GPU fully shuts down pop all four breakers to fully cut power to the automated system.
6. Unplug tablet charger and hdmi screen power in the cab of the follow.

Lead Second:

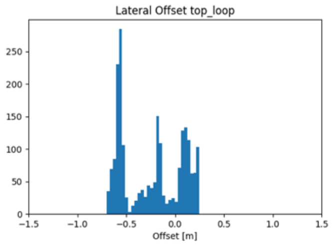
7. Power off Lead vehicle
8. Unplug the tablet charger
9. Everything should now be powered off(both vehicles).

ROSBAG DATA

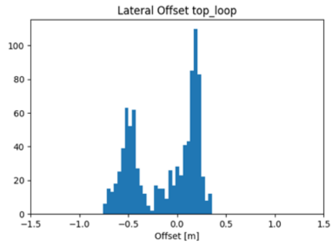
Located in /Data with current timestamp. Both vehicles record Rosbags automatically.

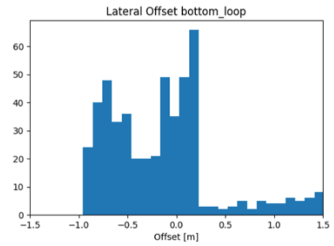
Appendix B: Lateral Error in Tight Curves and Straight-Aways

5MPH

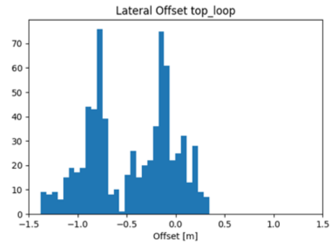


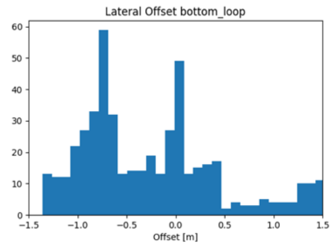
15MPH



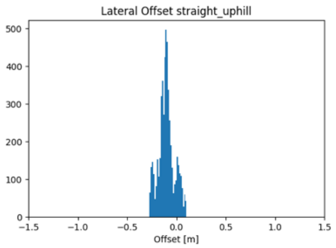


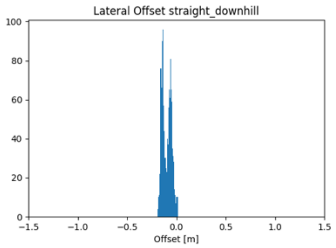
25MPH



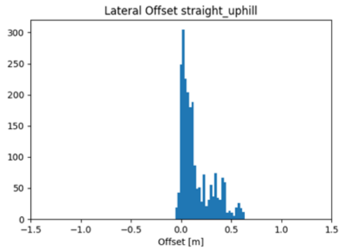


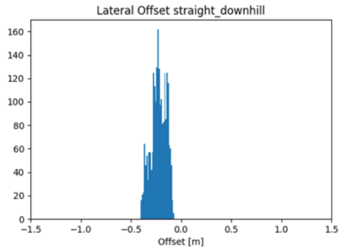
5MPH



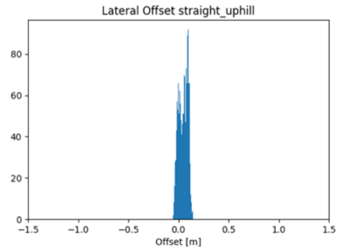


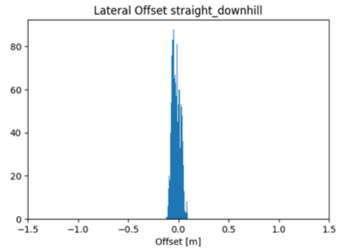
15MPH





25MPH





Appendix C: ATMA Adoption Sentiment Survey

1. What are your main concerns with implementing an ATMA?

2. Would implementing an ATMA be

   Easy - Moderately Easy - Neutral - Difficult - Impossible

- What are some adaptations to this technology or additional features that may improve safety or operability?

3. How willing would you be to use an ATMA system in one of your work zones?

   Scale of 1-10

4. Do you feel that the presence of an ATMA would increase the level of safety at your work zone?

   Strongly Agree/Disagree

5. What could be improved or shown to increase your level of confidence in an ATMA system?