Automated Truck Mounted Attenuator

May 2021 | Final Report

SAFE-D
SAFETY THROUGH DISRUPTION

Virginia Tech Transportation Institute
Virginia Tech

Texas A&M Transportation Institute

San Diego State University
Leadership Starts Here

Disclaimer

The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the information presented herein. This document is disseminated in the interest of information exchange. The report is funded, partially or entirely, by a grant from the U.S. Department of Transportation's University Transportation Centers Program. However, the U.S. Government assumes no liability for the contents or use thereof.

TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No. VTTI-00-022	2. Government Accession No.	3. Recipient's Catalog No.

4. Title and Subtitle Design and Development of an Automated Truck Mounted Attenuator	5. Report Date May 2021 6. Performing Organization Code:
7. Author(s) Elizabeth E. White Michael A. Mollenhauer Jean Paul Talledo Vilela	8. Performing Organization Report No. Safe-D Project VTTI-00-022
9. Performing Organization Name and Address: Safe-D National UTC Virginia Tech Transportation Institute 3500 Transportation Research Plaza Blacksburg, VA 24061	10. Work Unit No. 11. Contract or Grant No. 69A3551747115/ [Project VTTI-00-022]
12. Sponsoring Agency Name and Address Office of the Secretary of Transportation (OST) U.S. Department of Transportation (US DOT)	13. Type of Report and Period Final Research Report 14. Sponsoring Agency Code

15. Supplementary Notes

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.

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. 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, which has happened at an increasing rate in Virginia since 2011. Although various efforts have been made to improve TMA driver crashworthiness, the most effective way to protect TMA drivers may be to remove them from the vehicle altogether. During this project, a consortium consisting of VTTI, VDOT, DBi Services, and Transurban collaborated to design and build an automated TMA system (ATMA) that will remove the driver in future phases from the TMA vehicle in mobile and short duration work zone operations using a short following distance leader-follower control concept. The resulting ATMA successfully operates at speeds up to 15mph in environments with dependable GPS signal and at commanded following distances between 50-400 feet. The ATMA features a LIDAR-based system to detect and respond to obstacles and has an extensive internal and external human-machine interface to support communications between system operators and external road users.

17. Key Words Automated vehicle, truck-mounted attenuator, work zone safety, automated driving system	18. Distribution Statement No restrictions. This document is available to the public through the Safe-D National UTC website, as well as the following repositories: VTechWorks, The National Transportation Library, The Transportation Library, Volpe National Transportation Systems Center, Federal Highway Administration Research Library, and the National Technical Reports Library.

19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 37	22. Price $0

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

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. 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, which has happened at an increasing rate in Virginia since 2011. Although various efforts have been made to improve TMA driver crashworthiness, the most effective way to protect TMA drivers may be to remove them from the vehicle altogether. During this project, a consortium consisting of VTTI, VDOT, DBi Services, and Transurban collaborated to design and build an automated TMA system (ATMA) that will remove the driver in future phases from the TMA vehicle in mobile and short duration work zone operations using a short following distance leader-follower control concept. The resulting ATMA successfully operates at speeds up to 15mph in environments with dependable GPS signal and at commanded following distances between 50-400 feet. The ATMA features a LIDAR-based system to detect and respond to obstacles and has an extensive internal and external human-machine interface to support communications between system operators and external road users.

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 project team would also like to thank Dave Rush (VDOT) for providing his subject-matter expertise throughout this program.

Table of Contents

List of Figures

List of Tables

Introduction

Truck mounted attenuators (TMAs) have the potential to improve safety in work zones by providing a physical barrier between work crews and passing traffic or errant vehicles. Transurban, the Virginia Department of Transportation (VDOT), DBi Services, and their contractors regularly conduct work on active roadways for maintenance, construction, and clean-up activities on roads throughout Virginia. They currently use TMA vehicles to provide an added measure of safety in mobile and short-duration work zones. However, even with energy-absorbing crash barriers and safety restraint protections, TMAs are currently operated by a human driver who is put at risk of injury when the TMA 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.

In 2015, VDOT conducted an analysis of TMA crashes that occurred in Virginia during 2011–2014 [1]. From analysis of crash reports, the report indicates that TMA crashes increased from 2011–2014 with annual increases of 53%, 27%, and 36%, respectively [1]. Most of these crashes occurred on interstates in the Northern Virginia, Hampton Roads, and Richmond regions, where traffic congestion and urban roadway configurations create additional safety challenges. While VDOT does not directly capture the number of annual TMA deployments, they did obtain a rough measure of TMA use through the number of planned work zones that included lane closures and required TMA presence. They found that the number of planned work zones increased from 2011 to 2013, corresponding to additional planned work zones, but the crash rate still increased in 2014 while the number of planned work zones in 2014 actually decreased (Figure 1) [1].

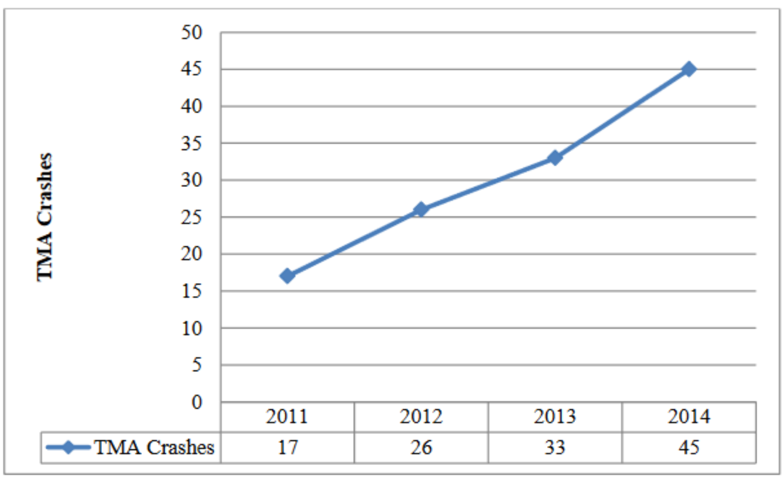


Figure 1. Graph. TMA crashes in Virginia 2011–2014.

Although various efforts have been made to improve TMA 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.

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 addition to safety improvements, automated TMA (ATMA) vehicles could also improve work efficiency by eliminating the need for an additional driver to perform this relatively mundane and dangerous task. Therefore, our consortium partners, Transurban, VDOT, and DBi Services, all have a vested interest in facilitating the development and deployment of effective ATMA systems.

Background

At the beginning of this project, an initial review of the marketplace suggested that there were no commercial off-the-shelf ATMA systems available that were proven and ready to turn over to road work crews for use in their daily operations. There was at least one company working on an ATMA product that had conducted several demonstrations of basic automated control functionality. In early discussions about ATMAs, the Virginia Tech Transportation Institute (VTTI) and Transurban agreed to conduct a product and technology search to identify organizations that might be able to deliver an ATMA to a desired specification. In parallel, an analysis of TMA use cases was conducted to determine how they are used in the field and what types of sensing and automated control features would be needed to produce a successful ATMA system that could be deployed in normal operations. The use cases provided a basis to generate operational requirements to evaluate commercially available products or to specify the requirements for an ATMA system if no sufficient off-the-shelf system is available. The result of this analysis project was a determination that no off-the-shelf ATMA product yet existed that was ready for deployment in live work zone operations.

As such, this project aimed to develop and demonstrate an ATMA system and control concept with the goal of removing the TMA driver from the vehicle in mobile and short-duration work zone operations using a short following distance leader-follower control concept. This system would enable a lead vehicle (LV) driver to perform their normal TMA operational tasks while monitoring and controlling the ATMA in the at-risk TMA position in mobile work zone operations.

Method

Task 1: Project Management

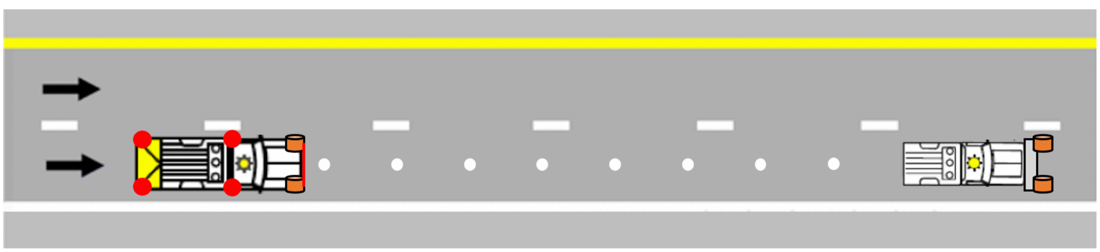
VTTI led project management tasks throughout the project while keeping the other consortium members apprised of the project status. Status update meetings were held with representatives from VDOT, the Virginia Transportation Research Council (VTRC), DBi Services, and Transurban on a consistent basis via remote conferencing. As part of this task, the team members completed all milestones and deliverables within the approved budget and schedule. The project team also briefed the Pennsylvania Department of Transportation (DOT), Colorado DOT, the IOO/OEM forum, and the American Traffic Safety Servicers Association (ATSSA) on the goals and progress of the project. The technology transfer activities and education and workforce development activities were also conducted under Task 1.

Task 2: Finalize ATMA System Design

As a result of a previous research program with Transurban, VTTI created an initial preliminary set of functional and performance requirements during the planning stages of this project. Those requirements were expanded, refined, and documented during this task.

The project team aimed to develop an ATMA system that could be rapidly migrated into operational field trials by designing for a tight leader-follower positioning requirement within the dynamic work zone operations platoon configurations. By creating a system designed and customized for a shorter following distance (50[1]-400 feet), some of the complexity of the operational control, safety monitoring, object detection, potential for incursion, potential for communications loss, etc., could be minimized. In addition, VTTI's design included a robust user interface that would allow the LV driver to monitor and maintain situation awareness of the following vehicle (FV) behavior.

Under this task, VTTI engineers finalized the design and build plan to produce one LV and FV technology package, also known as the "ATMA Technology Package," to support the leader-follower ATMA implementation. The LV package was designed to mount on a receiver hitch, making it relatively portable between vehicles. The FV package was designed as a permanent installation that will remain on the TMA vehicle that was supplied by DBi Services. The detailed design documentation was then presented to the subject matter experts from the consortium member organizations for review and feedback during the biweekly stakeholder meetings. VTTI conducted multiple design iterations and reviews with the stakeholder group until a final acceptable design was agreed upon. The finalized design features and equipment are shown in Figure 2.



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

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

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

Figure 2. Illustration. Final ATMA system features and equipment.

---

[1]The Virginia Work Area Protection Manual (VWAPM) requires TMAs to follow at a minimum of 120 feet from the work vehicle for mobile operations on two-lane roadways, and a minimum of 240 feet for mobile operations on multi-lane roadways in order to safely handle the roll-ahead distances if a TMA is struck. VTTI understands this operational requirement but designed the ATMA system to operate at a following distance of 50 feet in certain cases, such as staging and testing. The human-machine interface that displays following distance will include a clear indication of the 120-foot minimum distance for operations in the future.

In the final design, the LV controls the FV and defines the driving path and commanded speed and headway for the FV. The LV can be any model of vehicle but must include a front hitch receiver for mounting the technology package to the vehicle.

Key elements of the design are further discussed below. This package of sensors provides redundant positioning information to ensure that operating performance standards are maintained during periods of degraded performance from one or more of the sensor channels. The redundant design also supports expanded future TMA use cases with only software updates.

Communications

Communication between the LV and FV is facilitated by a set of 900-MHz links (AvaLAN AW900xTP-PAIR 900 MHz). These links provide an encrypted channel over which the system information is relayed.

- Theoretical line of sight range up to 40 miles with 15-dBI antenna
- 128 bit AES encryption, FIPS 197 - NIST Certified
- Remote diagnostics and link analysis with browser interface
- Radio can be configured as an access point or client
- Rugged outdoor enclosure meets IP66 Standard

The system information is compressed and down-selected to the minimum required information for the system to function. The lower frequency allows for more robust communication where there are line-of-sight obstructions. The team first started with a higher frequency radio but ultimately migrated from a 2.4-GHz system down to the 900-MHz system to improve communications reliability. This was done to reduce the amount of occlusion and drop-out related to the higher frequency system. The wireless links provided sufficient bandwidth to facilitate the effort; however, they were operating near bandwidth capacity. In order to remove overhead and delay caused by streaming video over the same communication link as used for critical operational information, the system was fitted with a supplemental wireless closed circuit TV system.

The system was developed with extensibility in mind. As such, the system can be fitted with Dedicated Short-Range Communications (DSRC) or connected vehicle-to-everything (C-V2X) supporting SAE J2735 and J2945/x V2X protocols. This provides an additional measure of safety as auto manufacturers start to include vehicle-to-vehicle (V2V) technology on new and automated vehicles and may be enhanced for vehicle-to-worker (V2W) applications. (VTTI has V2W prototypes.)

Path and LIDAR map information are provided by the LV while the system is in an automated mode. This information is used to localize the FV and inform where it should drive. The path in the world can be tied to GPS or Simultaneous Localization and Mapping (SLAM) waypoints depending on the availability of GPS or suitability terrain features that support the generation of an accurate SLAM map. As the LV operates in automated mode, the path is automatically updated and provided to the FV. The initial offsets of the vehicles are provided by the GPS systems. This allows the map and path to have a known location in world coordinates.

Sensors

- GPS: GPS information is provided via Novatel L4 units connected through an Advanced Data Link (ADL) Vantage unit that communicates with the VTTI base station. This is easily reconfigurable to other base station units providing Global Navigation Satellite System/real-time kinematic (RTK) corrections. Additionally, as per the specification, satellite-based RTK corrections can be enabled. In the interest of time on the activation of the satellite-based RTK corrections, the system was fitted with the ADL unit. This provides the same level of centimeter-based accuracy with a configurable per-site operational component. Each vehicle is fitted with the same GPS and ADL units configured according to their vehicle location and orientation.

- LIDAR (FV): Two state-of-the-art LIDARs were installed and positioned on the forward left and right corners of the FV to provide forward object detection to monitor the immediate surrounding environment. Two additional LIDARs were installed on the LV to facilitate object detection and avoidance for targets near the vehicle.
- Inertial Measurement Unit (IMU) (LV + FV): An IMU provides additional kinematic inputs into the navigation system but also provides an independent indicator of impact (resulting in immediate vehicle braking and stoppage as a failsafe mode).

Controls

Waypoint Commands and Communication

Waypoint generation while in FOLLOWING mode allows the Control Operator (the passenger in the LV that controls the human-machine interface [HMI] tablet) to issue a HOLD command through the HMI. This waypoint can be placed at the current LV position or issued at the current FV position. The FV will perform a soft stop upon reaching the waypoint and remain stationary until released to support ATMA positioning that maximizes protection for the work crew. System feedback is visualized within the HMI and allows the operator to know when the system is in HOLD, as shown in Figure 3.

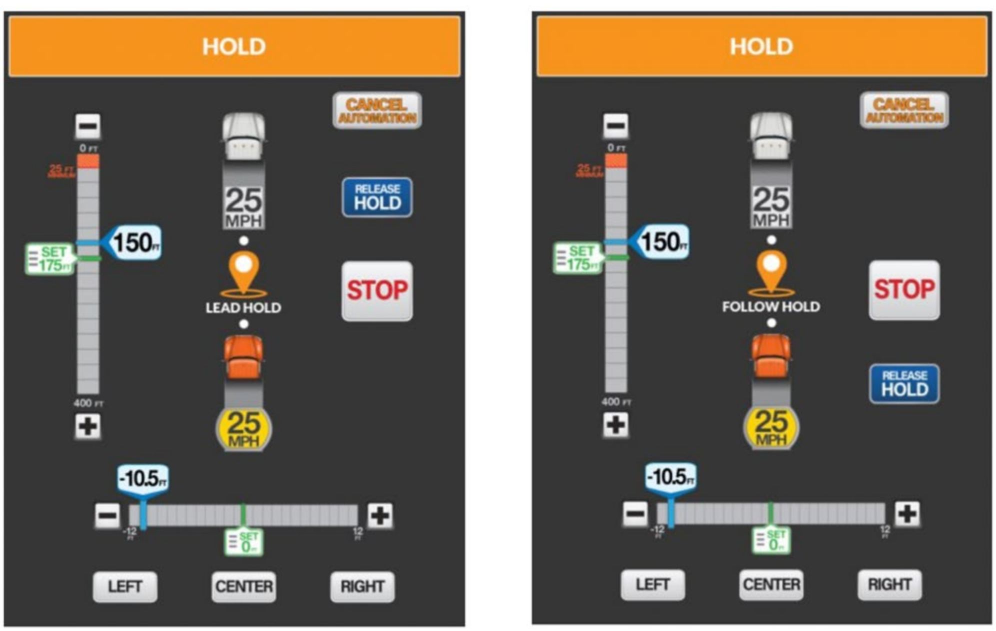


Figure 3. Screen capture. Lead HOLD (left) and Follow HOLD (right) HMI screens.

Simultaneous Localization and Mapping (SLAM)

As the LV operates in automated mode, it can generate a map from LIDAR data to use for navigation in a GPS-denied environment. The quality of the map is highly dependent on the features available within the environment. Urban canyons (tunnels, overpasses, city streets) would allow the system to generate a well constrained set of features and provide an accurate path to localize on. Barren highway or streetscapes provide fewer features to localize on but are also less likely to have GPS limitations.

In general, SLAM systems will generate an initial map of the environment and then optimize the map to reconcile feature alignment within the space. Once this optimization is complete, the map is then transferred to the FV to localize against. In order to design the ATMA system to be used in real-world operations in any ad hoc environment, there was no option to pre-map the environment. Instead, the map and path had to be streamed as the map was being built. The streaming nature of the map and path while the system is building the map makes the map prone to distortion, as the optimization is carried out in real time.

Safety Zone Monitoring

Two state-of-the-art LIDARs were installed and positioned on the forward left and right corners of the FV to provide forward object detection to monitor the immediate surrounding environment. The positioning of the LIDARs on the corners of the vehicle provided an envelope in front of the FV, as well as side detection. The envelope is shown in Figure 4. Forward detection ranges for objects of interest are generally within a 40-meter (131-ft) radius of the LIDAR mount points. The envelope of detection proceeds at 60 degrees off horizontal to the rear and sides of the vehicle based on the point cloud library filters in place.

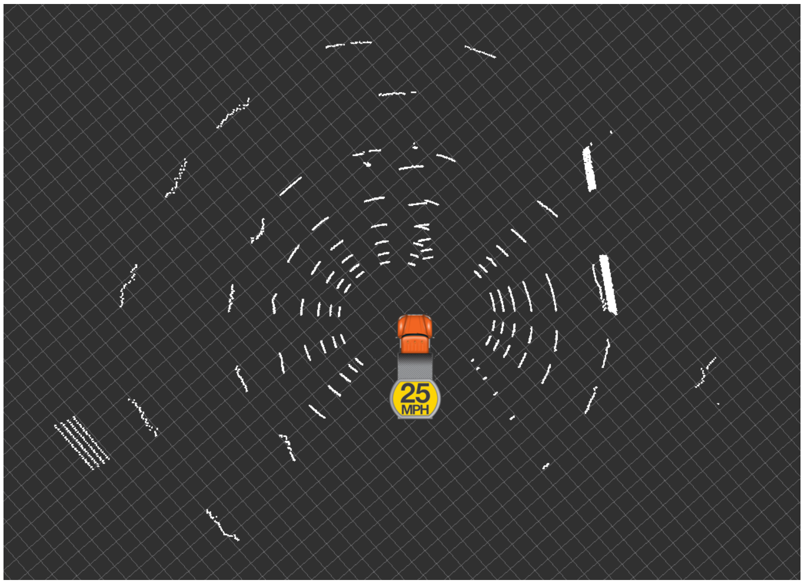


Figure 4. Illustration. LIDAR envelope around the ATMA vehicle.

Obstacle detection is facilitated by way of a clustering algorithm run on the FV. This ensures that the FV is always aware of its environment. The clustering algorithm is tuned to detect cone-sized (~2 feet tall by 1.5 feet wide or greater) objects. As this is a safety critical component, failure of this sensor system would result in an ERROR condition and the vehicle would come to a controlled stop.

VTTI Data Acquisition System and CPU

The system used three computer systems to provide the required computational capacity across the LV and FV. The LV utilized VTTI's FlexDAS unit, which provides a Core i7 Skylake processor in an automotive-grade unit. The FV contained a FlexDAS unit as well as a more powerful automotive grade GPU system for higher computability. This CPU/GPU system is the Nuvo-8208GC system, which was configured for dual RTX-2080 GPUs. The upgraded compute platform of the Nuvo-8208GC provided the ability to perform the LIDAR and mapping computations without overly taxing the FlexDAS system, which was not designed for the large compute throughput of multi-LIDAR processing.

Emergency Stops

VTTI included several emergency stop (e-stop) functions in the ATMA design to provide redundancy. Each type of e-stop will automatically transition the ATMA vehicle to a safe stop and hold the brake, regardless of the current state. Table 1 shows the ATMA response, description, and requester of the disruption along with whether the system continues to be engaged or not.

Table 1. ATMA Emergency Stop Functions

ATMA Response	Description	Requested By
Hard Stop	• ATMA applies maximum braking and keeps current course (system engaged). Once stopped, the ATMA will be in a non-automated state.	• External wireless e-stop button • Externally pressed mushroom button or bumper stop bar
Soft Stop	• ATMA applies light to medium braking (unless other operating conditions force harder braking. • System remains engaged.	• LV HMI tablet (HOLD button) • ATMA HMI tablet (HOLD button) • System algorithms
Emergency Stop	• ATMA disables power to all automated systems and returns the vehicle to factory control (system is disengaged).	• ATMA internal mushroom button

Operational States

The various operational states supported by the ATMA system were also defined in Task 2. The final state diagram is shown in Figure 5, and detailed descriptions of each of these states and how to transition between them are included in the Design Specification Document created as part of Task 2.

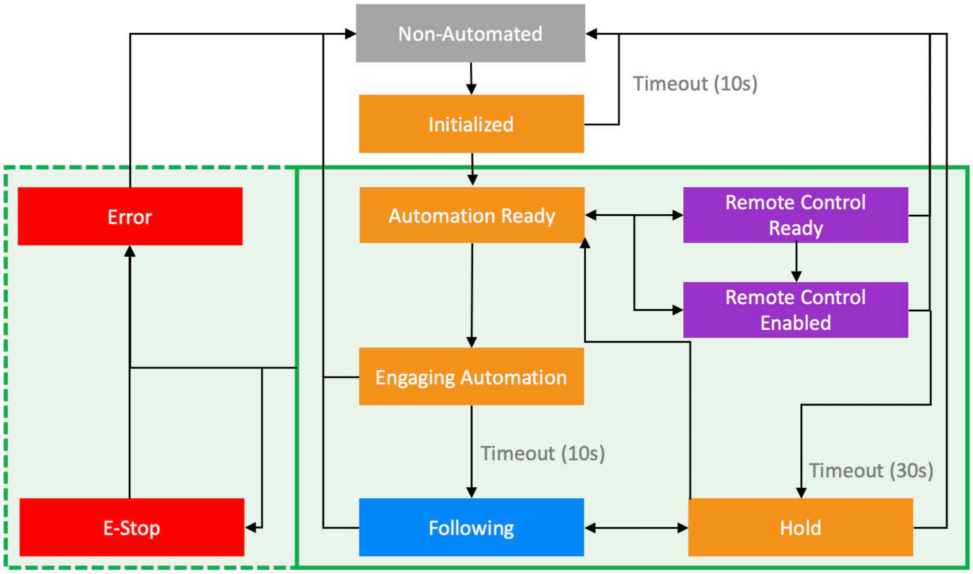


Figure 5. Diagram. ATMA system states.

Task 3: Build the ATMA System

During Task 3, VTTI built the ATMA System as documented in Design Specification developed in Task 2. During this task, all equipment was installed on the TMA vehicle according to the Design Specification document.

In parallel, an LV system was built to support initial testing on the Smart Roads. The LV technology package was built to be portable from vehicle to vehicle utilizing a front hitch, so that multiple leader vehicle platforms may be used as long as the vehicles have a front hitch. VTTI used one of its fleet vehicles for initial implementation and test activities. This LV system is shown in Figure 5.

Figure 5. Photo. LV package installed on the front hitch of a VTTI fleet vehicle.

VTTI then conducted initial testing on the Smart Roads to verify basic operations and adherence to the Design Specification developed in Task 2.

Task 4: Test the ATMA System

At the conclusion of Task 3, VTTI produced an ATMA leader-follower system that was ready to begin testing on the Smart Roads to evaluate compliance with the Detailed Design Specification and Initial ATMA Test Plan Documents developed in Task 2.

Prior to testing activities, project personnel submitted a test plan to both the ATMA Consortium stakeholders and the VTTI Smart Road Safety Review Board for review and gained approval to conduct testing. All testing activities utilized 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. VTTI integrated multiple means to shut down and stop the ATMA during testing from both onboard and remote systems to help ensure safe initial operations. Each of these systems was checked for proper functionality prior to testing sessions.

During testing, the VTTI-developed DAS captured system parametric data as well as multiple channels of video. The testing utilized VTTI's local RTK base station equipment to provide differential GPS corrections to the ATMA and the lead vehicle. These data were used to evaluate such vehicle performance metrics as lateral tracking stability, range between vehicles, and latency, and will allow for reconstruction of any unexpected behaviors. Testing was also performed using both GPS and GPS-denied system operations. To simulate operations in GPS-denied areas during testing, the GPS sensor was deactivated so that no GPS signals were received by the system.

VTTI personnel carried out the initial test plans in a variety of conditions on the Virginia Smart Roads in Blacksburg, Virginia. The testing began on the Surface Street section of the Smart Roads, which is a flat, configurable environment conducive to relatively short testing routes. Once confidence was gained operating the ATMA system, testing migrated to the Highway section of the Smart Roads. The Highway section is a 2.2-mile long controlled test track built to Federal Highway Administration standards that contains curves and turnarounds of varying radii and both flat and graded sections (see Figure 5 for an overview of the test area) that resemble an interstate highway.

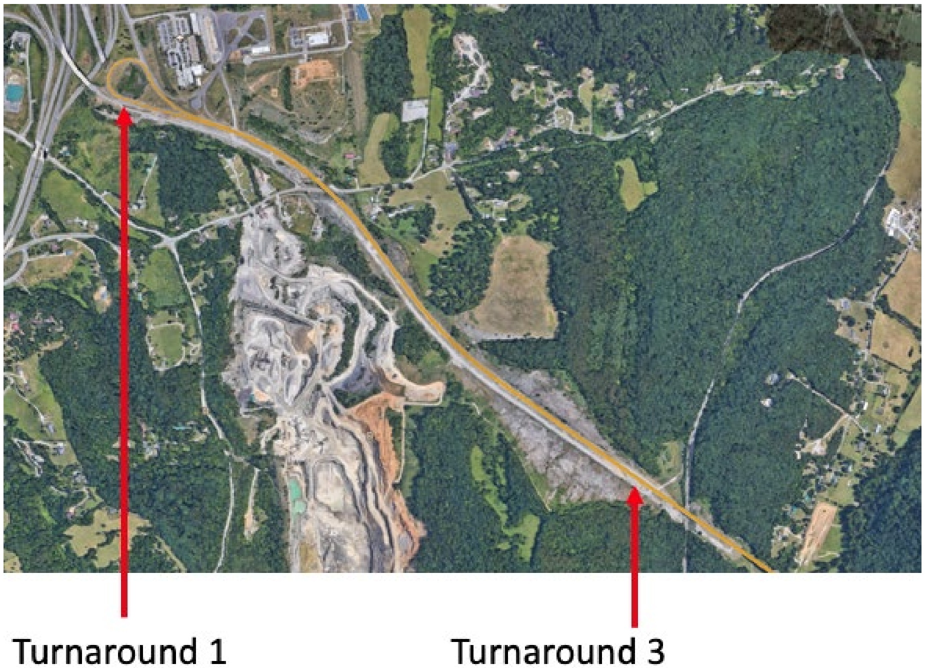


Figure 6. Map. Location of initial testing on Smart Roads.

Prior to any testing, the VTTI team validated that the integrated safety features were functional and reliable (i.e., integrated shutdown and e-stop functions).

The preliminary testing focused on lateral and longitudinal tracking accuracy. To accomplish this, a series of three repeatable tests were performed, starting from Turnaround 3 going uphill to Turnaround 1 (which has a radius of approximately 204 feet [62 meters]), and back downhill to Turnaround 3. The tests were repeated at three different speeds: 5 mph, 10 mph, and 15 mph. The results of this testing are included in the Testing and Performance Results section below.

In additional to the lateral and longitudinal tracking accuracy testing, the object detection feature was tested. VTTI utilized a remote-controlled, human-shaped robot in the object detection testing (Figure 7). During this testing, the robot was driven in the forward path of the ATMA system, which successfully came to a soft stop in advance of colliding with the robot. When the robot was removed from the forward path of the ATMA, the system was successfully able to resume automation. This test was repeated three times at various time-to-collision ranges.

Figure 7. Photo. Object detection testing with the VTTI robot.

Initial performance test results were shared with the ATMA Consortium members on October 22, 2020. At the request of the consortium, VTTI completed additional performance testing and presented those results to the consortium on November 30, 2020. Testing beyond the Smart Roads (for example, on the Transurban I-95 Express Lanes) is expected for a future ATMA project phase.

Task 5: Demonstrate Prototype ATMA on Smart Roads

During this final task, VTTI planned to invite the ATMA Consortium members to Blacksburg for a one-day prototype demonstration and project review on the Virginia Smart Roads. However, due to COVID-19 travel and other restrictions in place at the conclusion of this project, the ATMA Consortium agreed that an in-person demonstration would not be possible. Instead, VTTI created a video to showcase the ATMA's leader-follower capabilities in a variety of operational conditions, the associated HMI used by the lead vehicle, and the overall system design and integration. The resulting video is discussed in further detail in the Technology Transfer/Marketing Video section below. This video was filmed in September 2020 and shared with the ATMA Consortium in October 2020.

Results

The results from the Task 4 testing activities are discussed below. To determine lateral and longitudinal tracking accuracy, Robot Operating System (ROS) bag files were collected that show the message data flowing in the system in a "bag" file format. This file type was used for debugging during the development stage and also for data collection for data review and inspection. ATMA ROS bag files were analyzed by converting the data to .CSV format and then analyzing the LV and FV's (ATMA) position and orientation (pose) data in Universal Transverse Mercator (UTM) units. From this, the spline curve was calculated, and error was calculated between the UTM Easting units (x-axis) and the UTM Northing units (y-axis).

Lateral Accuracy Results

Speed and Grade

A series of three repeatable tests was performed starting from Turnaround 3 going uphill to Turnaround 1 and back downhill to Turnaround 3. The tests were repeated at three different speeds: 5 mph, 10 mph, and 15 mph. The root mean square error (RMSE) of lateral accuracy for each test speed and grade is shown in Table 2. The overall lateral accuracy results are shown in Figure 8. More detailed test results can be found in Appendix A: Additional Test Results.

Table 2. RMSE of Lateral Accuracy by Speed and Grade

Speed (mph)	Uphill	Downhill	Average
5	0.11	0.07	0.092
10	0.16	0.23	0.198
15	0.13	0.16	0.145
Average	0.135	0.166	0.151

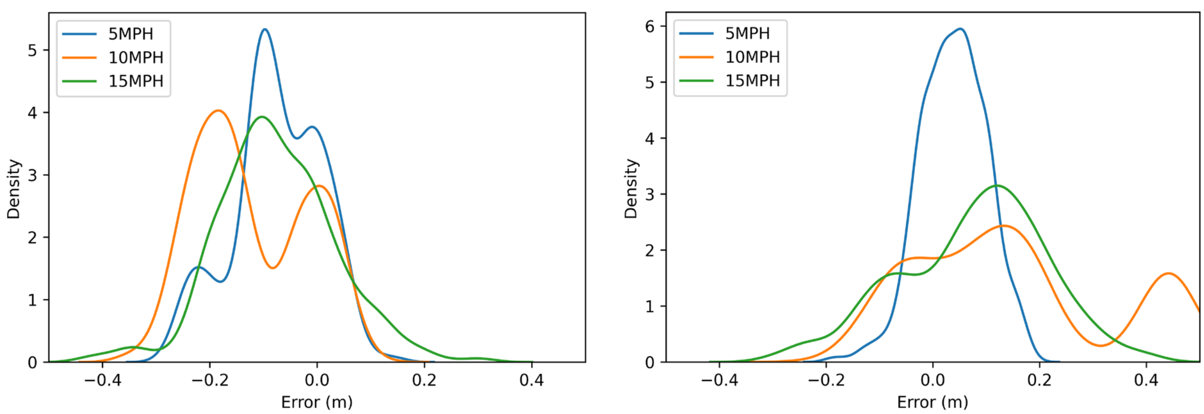


Figure 8. Graphs. Frequency of lateral error for 5-mph, 10-mph, and 15-mph uphill tests (left) and downhill tests (right).

Curve Results

To understand the potential differences in performance of the ATMA system on a curve versus a straight roadway, the data from Turnaround 1 of the Smart Roads were analyzed. A more detailed view of Turnaround 1 is shown in Figure 9. Turnaround 1 has a radius of approximately 204 feet (62 meters). The inscribed circle is indicated in yellow in the figure, and the orange line represents the primary lane centerline.

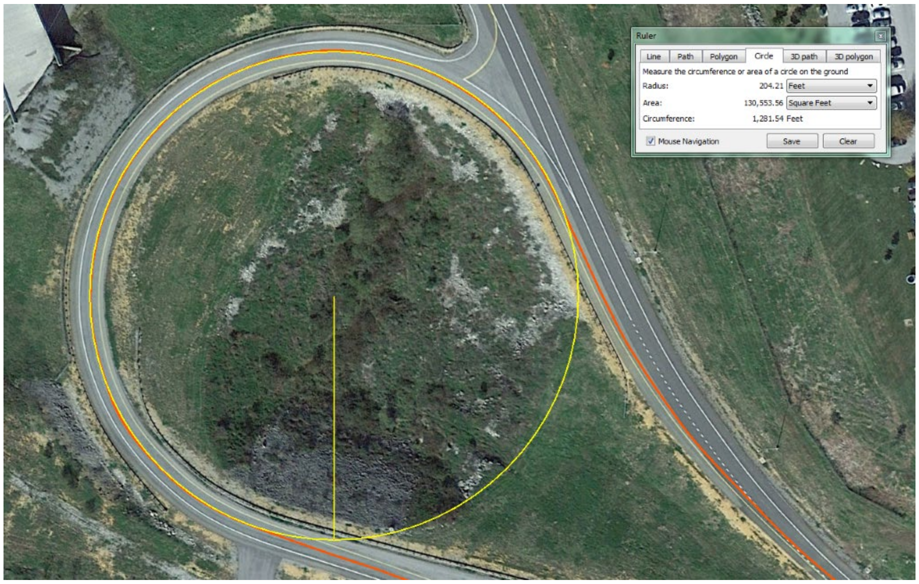


Figure 9. Photo. Turnaround 1 of the Smart Roads Highway section.

The RMSEs of lateral accuracy for each test speed around the curve are shown in Table 3. The overall lateral accuracy error results are shown in Figure 10. More detailed test results can be found in Appendix A: Additional Test Results.

Table 3. RMSE of Lateral Accuracy on a 204-ft Radius Curve

Speed (mph)	RMSE (meters)
5	0.12
10	0.23
15	0.16
Average	0.17

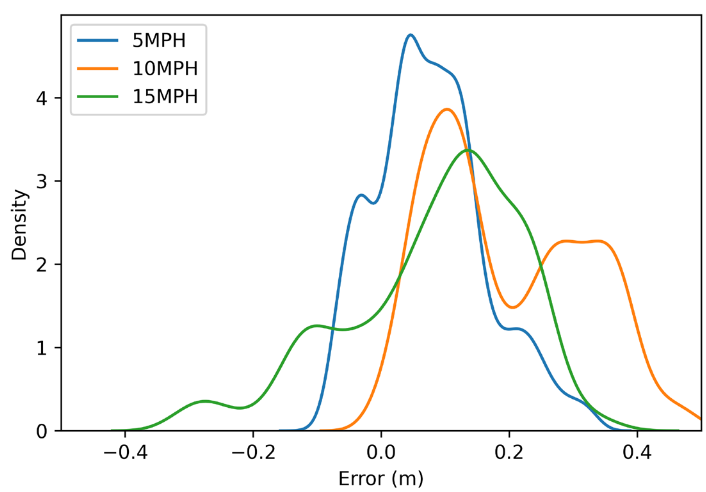


Figure 10. Graph. Frequency of lateral accuracy error on a curve by speed.

Longitudinal Accuracy Results

Again, a series of three repeatable tests was performed starting from Turnaround 3 going uphill to Turnaround 1 and back downhill to Turnaround 3. The tests were repeated at three different speeds: 5 mph, 10 mph, and 15 mph. More detailed test results can be found in Appendix A: Additional Test Results.

Speed and Grade

The RMSE of longitudinal accuracy for each test speed and grade is shown in Table 4. The overall longitudinal accuracy results are shown Figure 11. More detailed test results can be found in Appendix A: Additional Test Results.

Table 4. RMSE of Longitudinal Accuracy

Speed (mph)	Uphill	Downhill	Average
5	2.17	1.79	1.98
10	9.90	10.53	10.22
15	13.93	29.48	23.05
Average	9.94	18.10	14.60

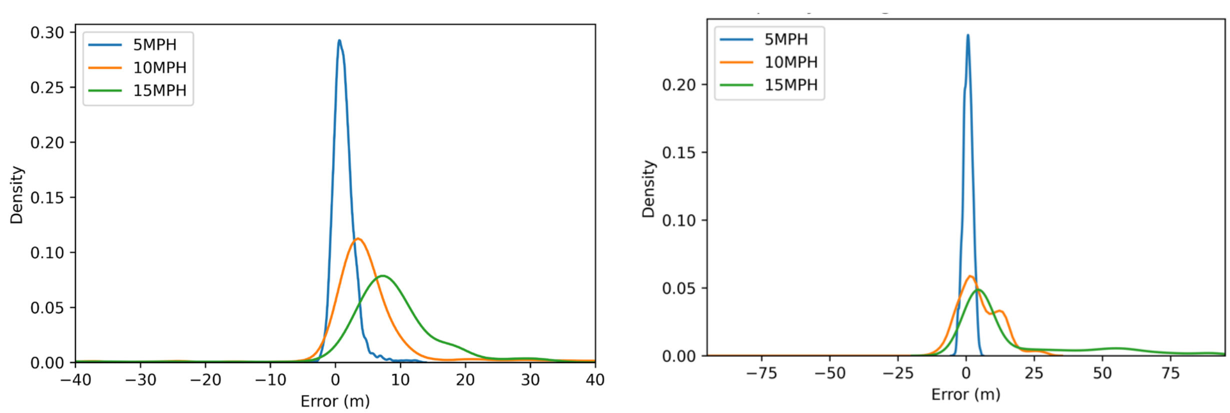


Figure 11. Graphs. Frequency of longitudinal error for 5 mph, 10 mph, and 15 mph uphill tests (left) and downhill tests (right).

Curve Results

The RMSE of longitudinal accuracy for each test speed around the curve is shown in Table 5. The overall longitudinal accuracy error results are shown in Figure 12. More detailed test results can be found in Appendix A: Additional Test Results.

Table 5. RMSE of Longitudinal Accuracy on a 204-ft Radius Curve

Speed (mph)	RMSE (meters)
5	1.48
10	5.57
15	7.16
Average	5.30

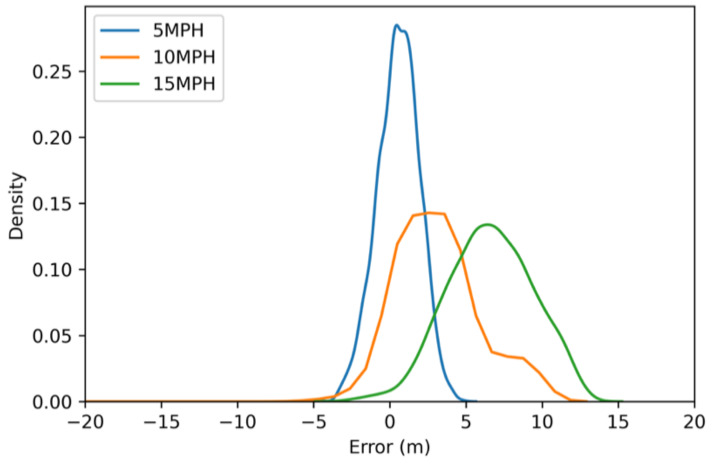


Figure 12. Graph. Frequency of longitudinal accuracy error on a curve by speed.

Discussion

Lateral Accuracy

Lateral tracking accuracy is a critical performance metric in ATMA operations to ensure the following vehicle can safely maneuver throughout the operational environment. Accurate lateral control was achieved in a GPS-enabled environment and longitudinal accuracy is adequate for the 50- to 400-foot following distance use cases. The average lateral tracking accuracy results of ±0.14 meters (6 inches) are on par with a competing commercial ATMA product that is currently being tested and has been reported to have a lateral accuracy of ±4 inches [2]. Lateral tracking accuracy was found to be very good on both straight and curved roadways. The average lateral accuracy RMSE on a relatively straight roadway was found to be 0.143 meters, which approaches the limits of dynamic control of the vehicle. The system also had good performance on a tight curve, with an average RMSE of 0.17 meters. As to be expected, there was a direct relationship between lateral tracking accuracy and speed (RMSE increases as speed increases, on both hills and curves). Also, there tended to be a lateral shift to the right going downhill, and a shift to the left going uphill. Those lateral shifts can be attributed to the Pure Pursuit algorithm running on the ATMA system, and the look-ahead distance used for the lateral control implementation.

Longitudinal Accuracy

While accurate lateral tracking accuracy is a critical performance measurement, precise longitudinal tracking accuracy is not as critical for ATMA system operations. Results from Task

4 show that longitudinal tracking provides good accuracy (±2 meters) at low speed and ±22 meters at higher speeds. VTTI incorporated a smoothing speed control feature into the system's longitudinal control to more smoothly accommodate different roadway scenarios such as uphill, downhill, straight, and curved maneuvers. Also, the ATMA maximum speed threshold is currently set to 16 mph so the time required for the FV to close a gap between vehicles on command was limited by the maximum speed.

Sources of Error

The resulting lateral tracking accuracy is nearing the limits of control precision dictated by the electromechanical linkages in the steering system. The remaining lateral tracking error results from the IMU, GPS accuracy, and lateral control filtering algorithms that ensure smooth FV steering while in automation. The main sources of longitudinal tracking accuracy error are most likely attributed to measurement errors by the system sensors and, again, filtering to ensure smooth speed control. Most of the longitudinal error occurs at the onset of automation when the FV is closing a gap between the vehicles and the system is limited by the maximum speed threshold.

Figure 13 shows ATMA's Integrated Navigation Solution (INS), which likely introduces differential GPS and IMU lateral and longitudinal error. The INS combines three-dimensional position estimates from the vehicle wheel encoder, GPS, and orientation/acceleration as a three-dimensional vector from the IMU. The extended Kalman filter fuses measurements from the three sources to obtain an optimal estimate of the system state. Each source introduces an error to the estimation: GPS-RTK (0.1 meters), IMU (0.3° heading/0.04 mg).

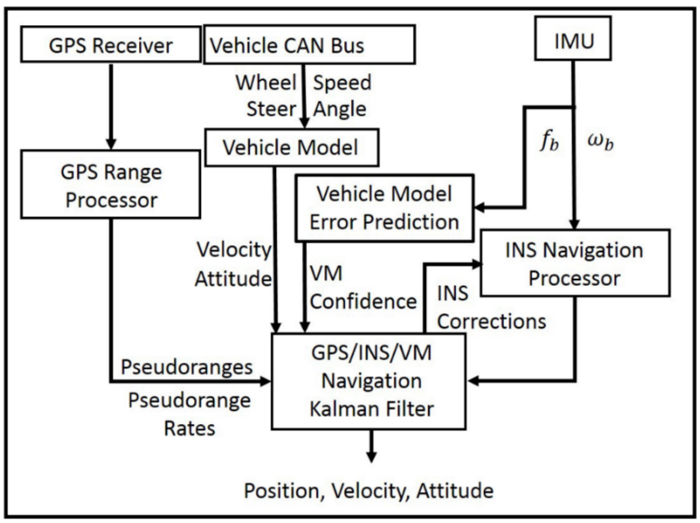


Figure 13. Diagram. ATMA INS, which is used for both lateral and longitudinal controls.

Lateral control is based on two subsystems, the steering controller and the electromechanical link. Figure 14 shows the software control loop of the steering controller being used to actuate the steering wheel by using a proportional-integral-derivate (PID) controller and using the steering wheel angle as feedback to the system. The controller calculates the error continuously between the desired setpoint (Target Steering Angle) and the measured output (Steering Handle Feedback) and applies a correction based on the K, D, and I gains for the proportional, integral, and derivative terms. The controller was tuned to cover different scenarios, including straight and curve maneuvers, but likely introduces some error.

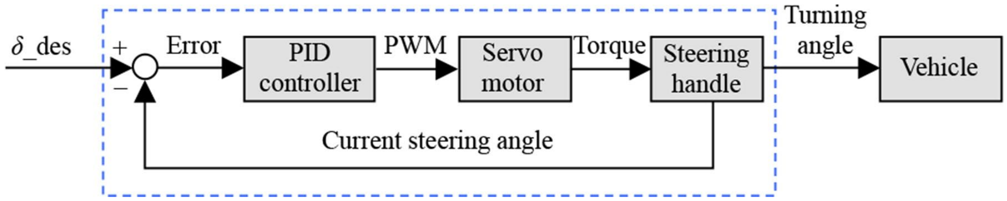


Figure 14. Diagram. The control loop of the steering controller.

Minimal error can also likely be attributed to the electromechanical link (Figure 15), which includes a motor and reduction gear, both of which have physical limitations for the software controller requests (0.1° resolution)

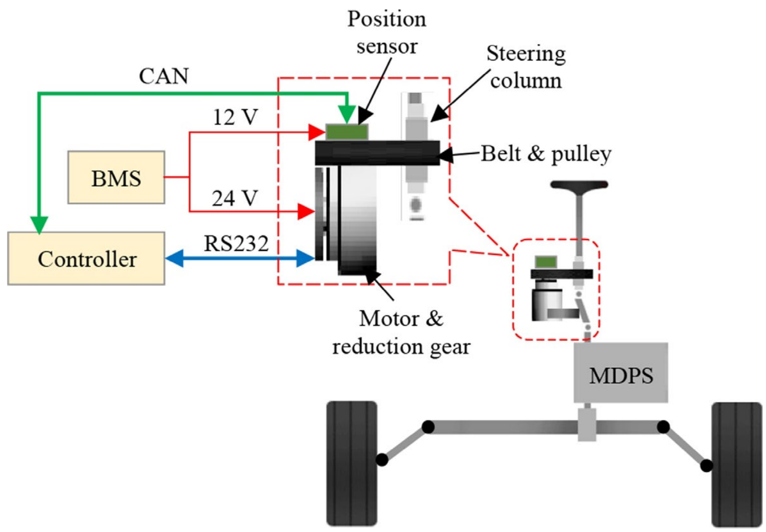


Figure 15. Diagram. Electro-mechanical link.

Conclusions and Recommendations

At the conclusion of this project, the VTTI team designed and built a leader-follower ATMA system that works under the following operational design domain 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 ATMA system successfully monitors, detects, and responds to object intrusions in the safety zone (the area between the LV and FV) using the LIDAR-based system.

The team also achieved another important goal of the project: to design and develop an internal HMI system that would allow the control operator to control the lateral and longitudinal offsets of the FV, 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 control the vehicle with minimal attentional demand that is safe for use while driving. The ATMA system also has a remote operation feature that utilizes a joystick to control the FV at a range of up to 500 meters.

After the initiation of the project, the research team accepted another project goal to support operations in GPS-enabled and GPS-denied environments. Progress was made towards implementing a means to operate in a GPS-denied environment, but further development and testing will be required in future phases to prove reliability in this environment. A LIDAR-based SLAM model was developed that maps physical features near the roadway from the LV 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 for forward object detection rather than LIDAR-based mapping. As such, the accuracy and range of the LIDAR units used in the SLAM model were limited, and ultimately the lateral tracking accuracy suffered. One option to resolve this issue would be to specify a different class of LIDAR unit that would provide the resolution and range necessary for LIDAR mapping. However, higher performance LIDAR units are likely cost prohibitive for a commercially viable product, and other technologies may be more effective. VTTI has explored the substitution of the Pronto.ai camera-based perception system as an alternative to the LIDAR-based SLAM approach, and the performance and economics of the approach seem encouraging. Moving to a camera-based perception and mapping system would allow three of the four LIDAR units to be removed from the required technology package, which will significantly reduce the cost of the LV/FV system. At least one LIDAR unit would still be needed in near-term solutions to perform safe and reliable object detection in front of the ATMA.

The team also gained valuable insight when testing the wireless communications technologies that were utilized to pass information between the LV and FV. Initially a 2.4-GHz radio system was chosen, but line-of-sight restrictions resulted in unreliable communications. A 900-MHz system that provided longer theoretical range was utilized instead. This system had less line-of-sight restriction and adequate bandwidth for the leader-follower data flow. The 900-MHz system resulted in improvements in both range and reliability of the communications.

In addition to achieving the major technical objectives, VTTI successfully worked with the consortium partners to obtain their subject matter expertise and feedback and incorporate it into the project. VTTI is currently pursuing opportunities with the initial consortium partners to continue development of the ATMA system and migrate to testing on public roadways.

The team anticipates completing a second phase of design and development of the ATMA system. This phase will focus on expanding the operational design domain to include freeway operations (speeds up to 45 mph) and better performance in GPS-denied environments. A technology refresh is also anticipated to leverage new, more capable products that have entered the market since the onset of this project, such as improved sensing and localization components. Additionally, the team anticipates utilizing a rear radar system to facilitate collision detection and traffic monitoring and expanding the remote operator capabilities to include an aerial view. In future phases, the team will involve stakeholders to support a phased migration from closed test-track testing to public roadways testing and performance analysis.

Additional Products

The Education and Workforce Development (EWD) and Technology Transfer (T2) products created as part of this project are described below and are listed on the Safe-D website here. The final project dataset is available on the Safe-D Dataverse.

Education and Workforce Development Products

Design Workshop

Meeting slides that were presented during a Design Workshop held at VTTI on March 11, 2020 with ATMA consortium partners and TMA subject-matter experts from Virginia.

Training Document

Training documentation that can be used to train TMA management and operators on the purpose and use cases of ATMAs, functions and use of the ATMA system, and an overview of the internal and external human-machine interfaces.

ATMA Integration Plan

This Integration Plan includes recommendations for a progression of ATMA testing phases prior to use on live, public roadways. The plan includes the nature of testing to be conducted, goals to be accomplished, criteria for successful completion, recommended facilities, and personnel and staffing recommendations, and an overview of recommended training for management-level stakeholders, ATMA operators, and operational work crew members.

Technology Transfer Products

Intellectual Property Disclosure

An ATMA Technology Package invention disclosure has been filed with Virginia Tech's (VT's) LINK intellectual properties team that includes the software developed for this project along with the hardware specifications for the prototypes system. A collaborative agreement was executed between consortium members that manages the control of the ATMA Technology Package. Each partner in the consortium has the opportunity to use the ATMA Technology Package on their own vehicles to support fleet operations during and after the duration of the original project. If the project is successful, DBi Services will be given the first right of refusal to exercise an option to commercialize the ATMA Technology Package outside of their own fleet and operations. If they choose to exercise this right, they will negotiate with VT's LINK intellectual property management group to negotiate a royalty bearing license to use the ATMA Technology Package. If they choose not to exercise this right, VT's Link group will seek out other potential commercialization outlets, such as other TMA vehicle providers, heavy truck manufacturers, road maintenance service providers, etc. Regardless of project outcomes, Transurban, VDOT, and DBi Services will contribute to the ATMA development project as stakeholders by providing subject matter expertise in the areas of system design, operations, and fleet management.

Technology Transfer/Marketing Video

The team created a video called "Work Zones of the Future" to showcase the ATMA operating in a mobile work zone scenario along with two other connected vehicle work zone products the research team is working on: the Smart Vest (Safe-D UTC project 04-104) and the Work Zone Builder application that is currently in development. The video can be accessed at the here.

This video was shared with the entire Virginia Tech community on October 10, 2020 and is posted on their website. The video was also provided to the consortium partners to share with through their marketing channels.

The project team is pursuing additional funding from consortium members to advance the ATMA system and reduce recurring costs to produce the unit. The result of the next phase of development should be an ATMA system that is commercialize and tested on live roadway operations.

Data Products

The dataset uploaded to the Safe-D Dataverse DOI: 10.15787/VTT1/AT0RHF contains raw sensor data that was aggregated to inform the autonomous system control. A total of four final test/performance drives were conducted with the ATMA System to produce this data, and those test drives were completed along the Virginia Smart Roads Surface Street and Highway sections. Each of the four resulting test drive datasets includes a set of ROS topics that is in bag file form, each of which contains the following types of data: Lidar, IMU, GPS, and vehicle speed.

References

1. Cottrell, B. H. Investigation of Truck Mounted Attenuator (TMA) Crashes in Work Zones in Virginia. Final Report VTRC 16-R7. Charlottesville, VA : Virginia Transportation Research Council, 2015.

2. Weldon, T. & Nylen, A. CDOT - Autonomous Truck Mounted Attenuator Deployment Application Update. Denver, CO : CDOT, 2020.

Appendix

Lateral Accuracy Test Results

5-MPH Test

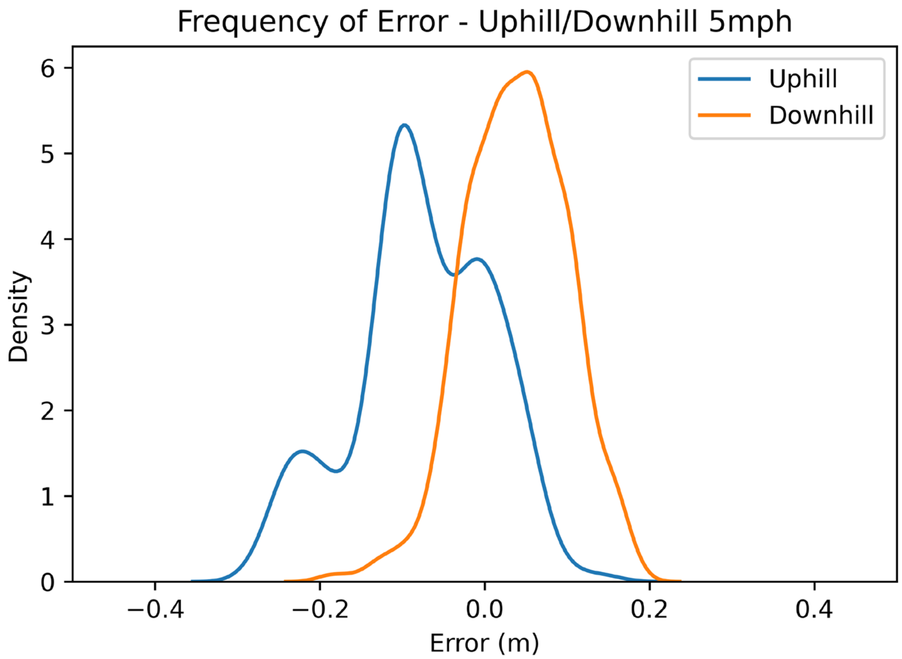


Figure 16. Graph. Frequency of lateral error – uphill/downhill, 5 mph.

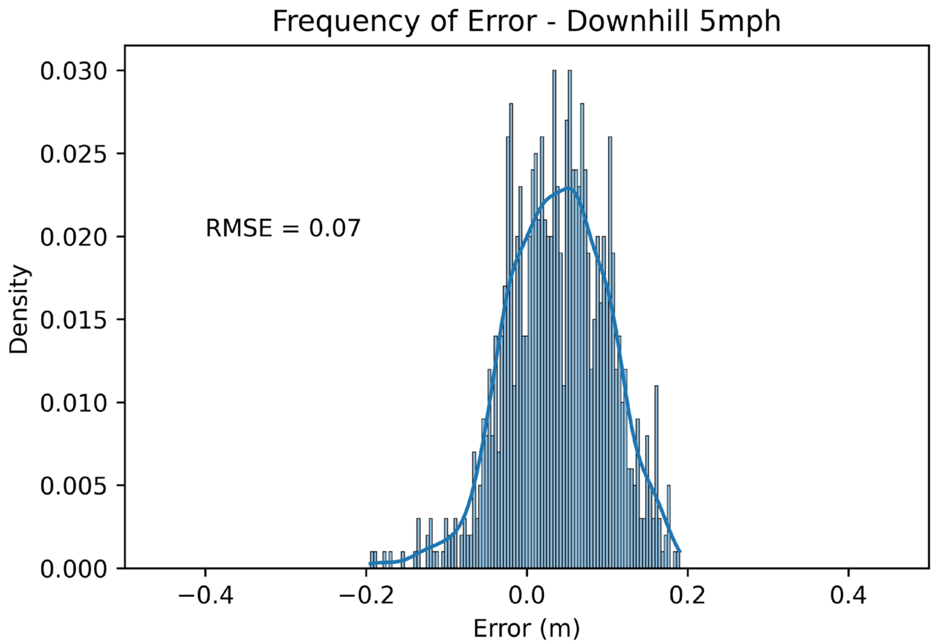


Figure 17. Graph. Frequency of lateral error – downhill, 5 mph.

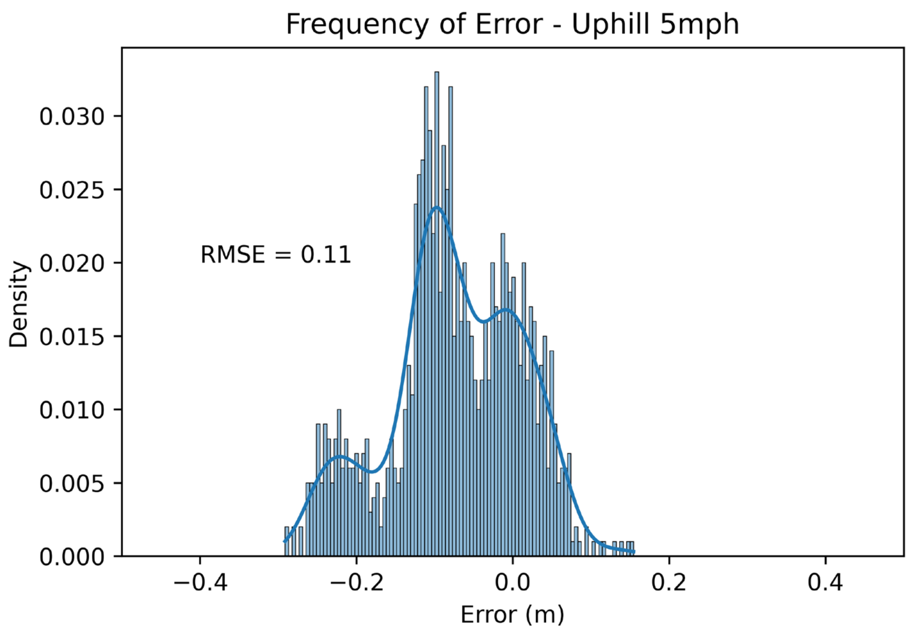


Figure 18. Graph. Frequency of lateral error – uphill, 5 mph.

10-MPH Test

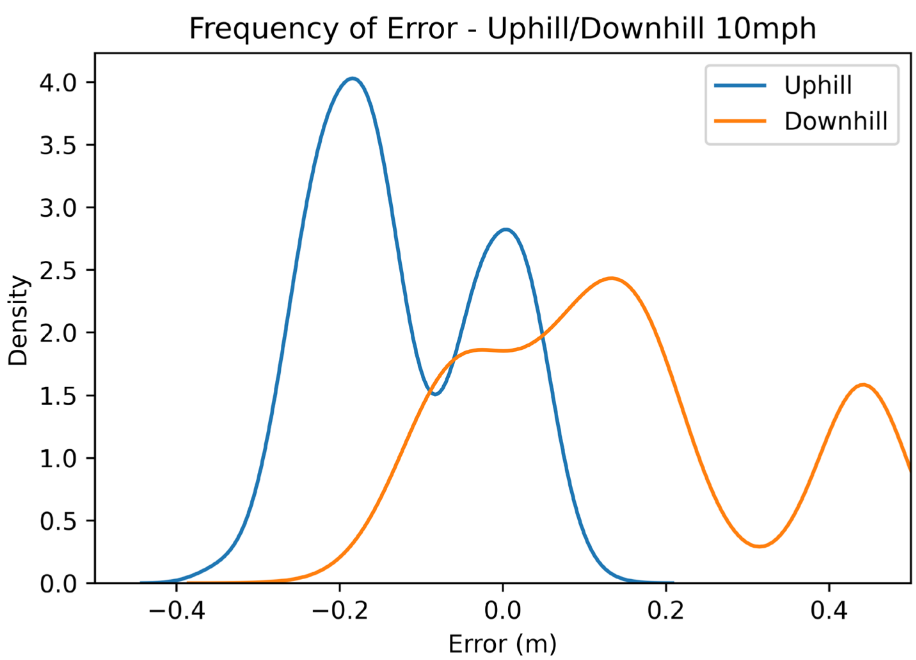


Figure 19. Graph. Frequency of lateral error – uphill/downhill, 10 mph.

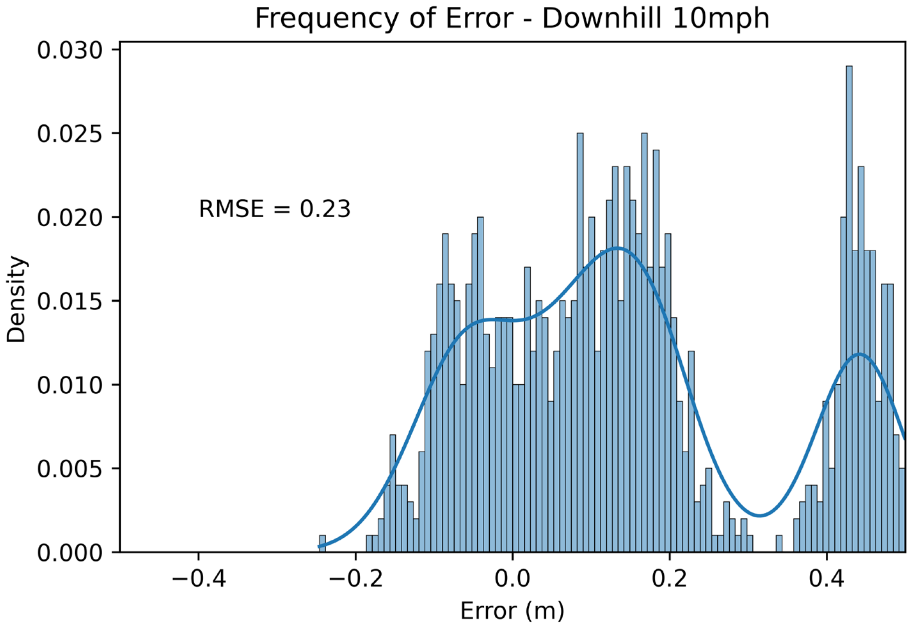


Figure 20. Graph. Frequency of lateral error – downhill, 10 mph.

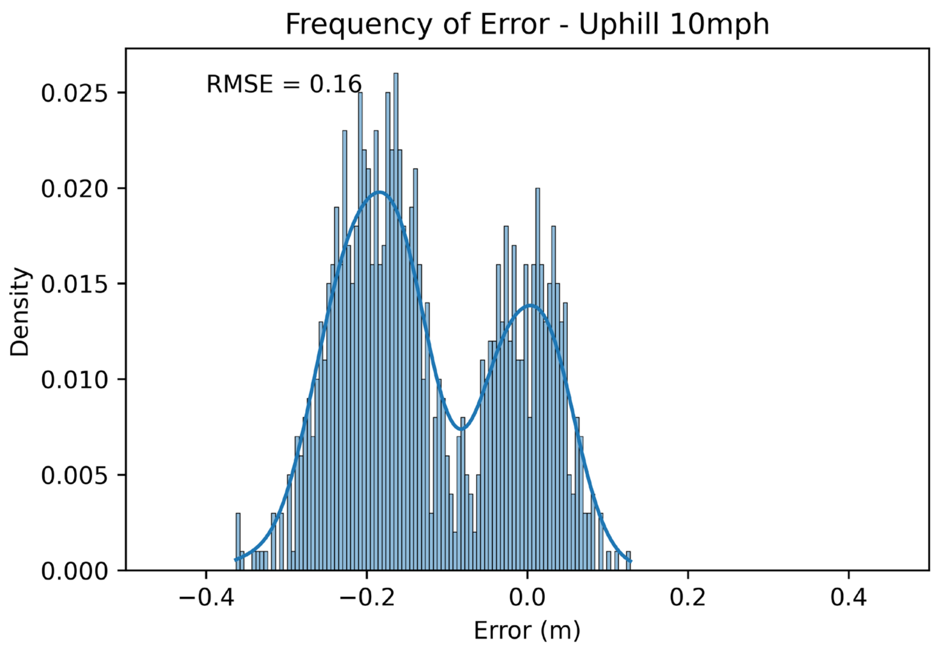


Figure 21. Graph. Frequency of lateral error – uphill, 10 mph.

15-MPH Test

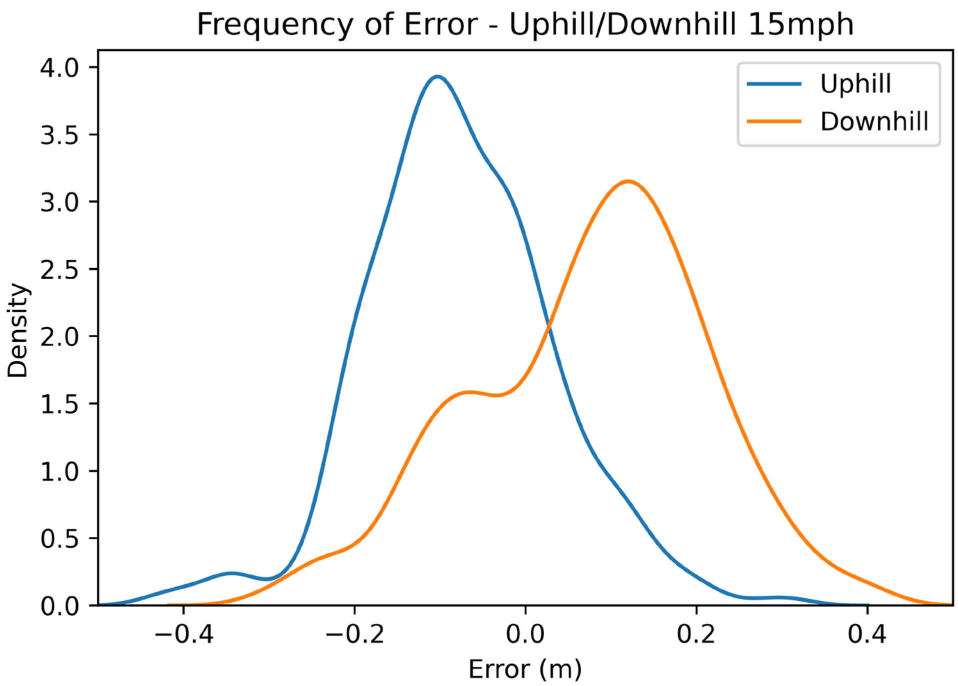


Figure 22. Graph. Frequency of lateral error – uphill/downhill, 15 mph.

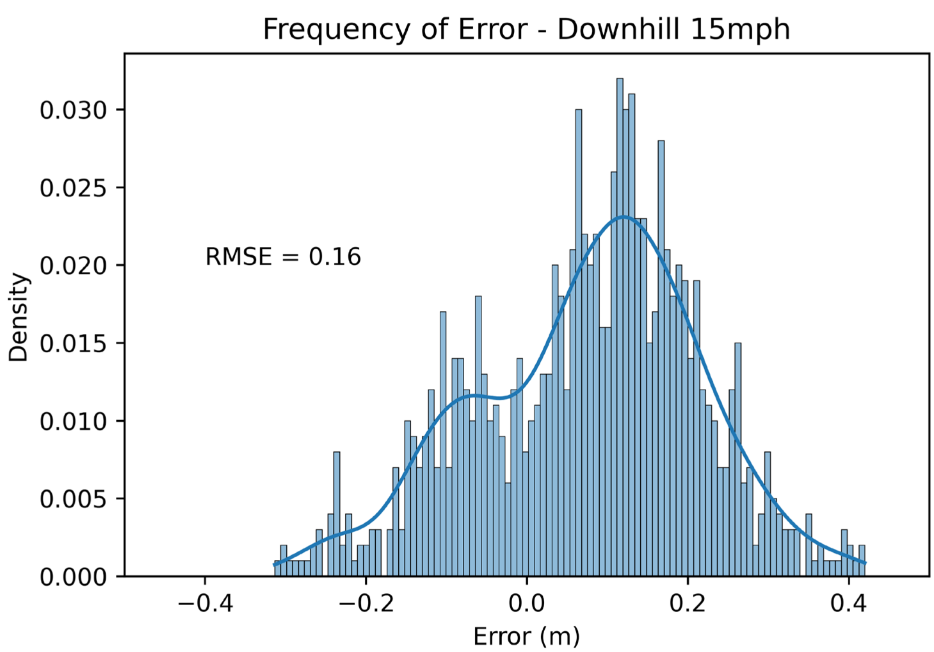


Figure 23. Graph. Frequency of lateral error – downhill, 15 mph.

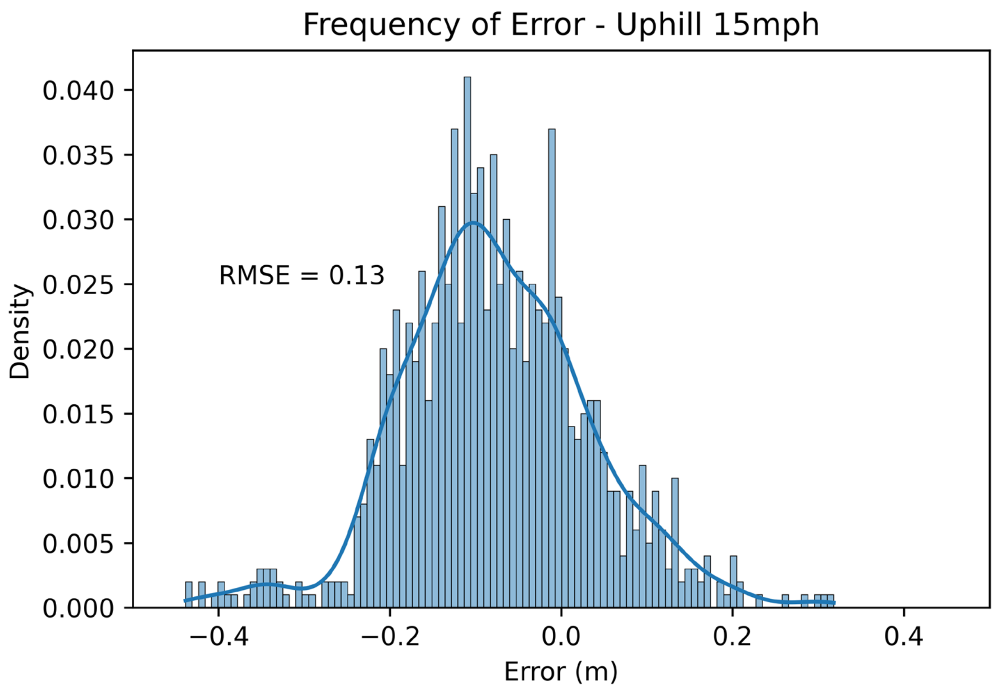


Figure 24. Graph. Frequency of lateral error – uphill, 15 mph.

Combined Data Comparison – Downhill

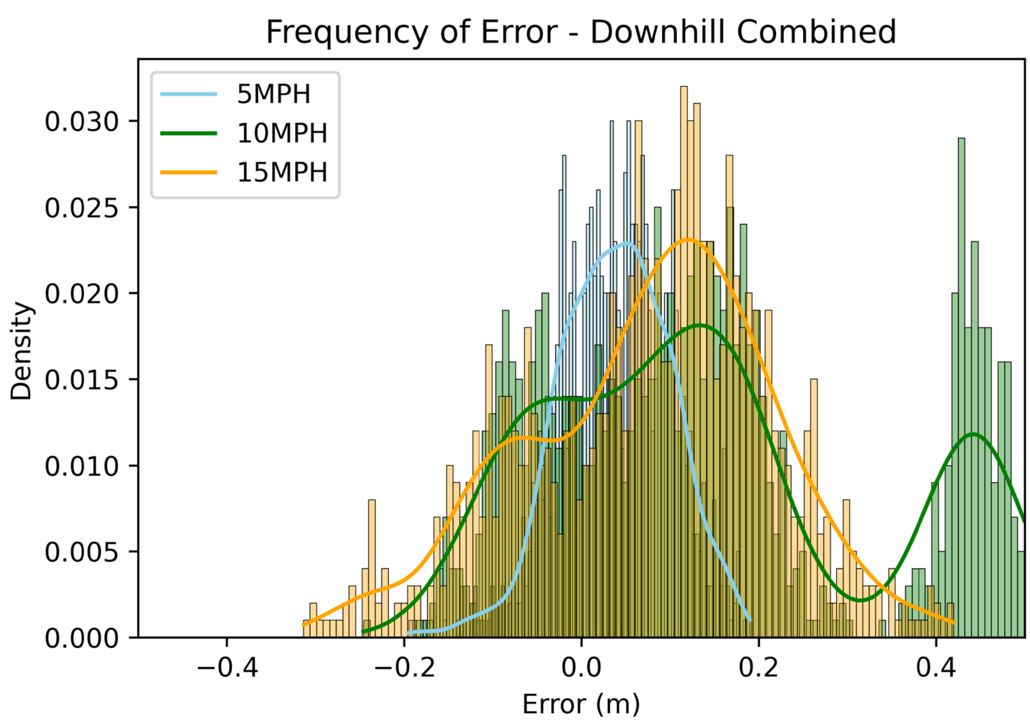


Figure 25. Graph. Frequency of lateral error –downhill, combined.

Combined Data Comparison – Uphill

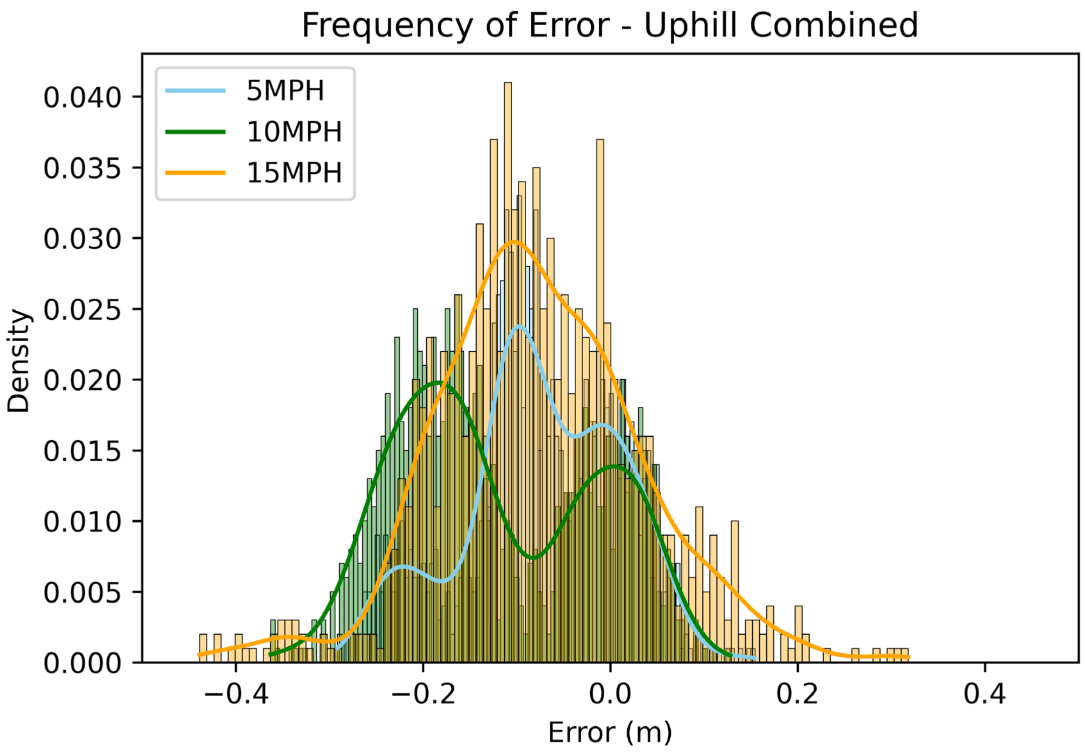


Figure 26. Graph. Frequency of lateral error – uphill combined.

Curve Results

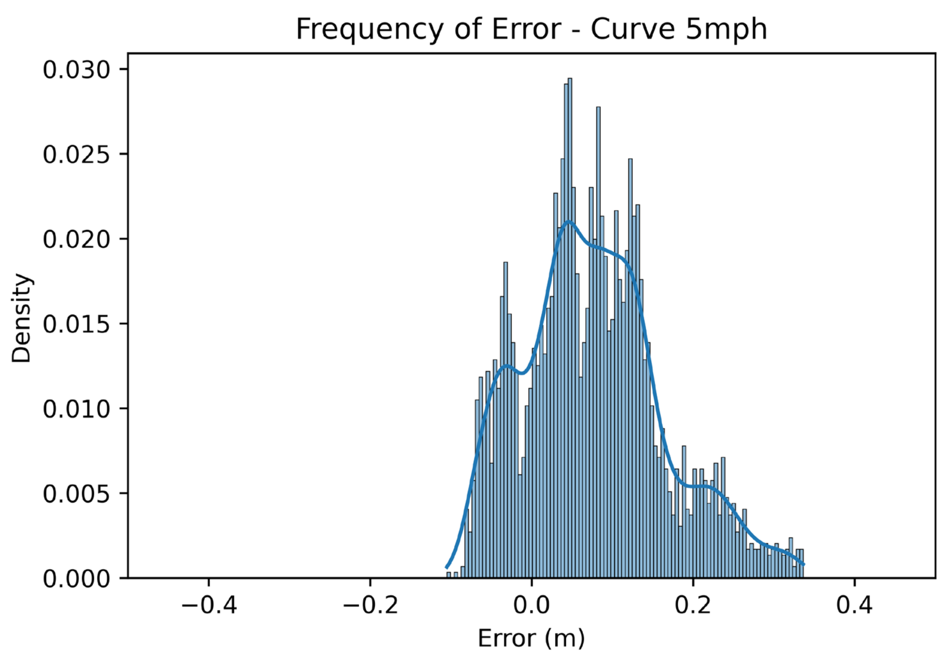


Figure 27. Graph. Frequency of lateral error – curve, 5 mph.

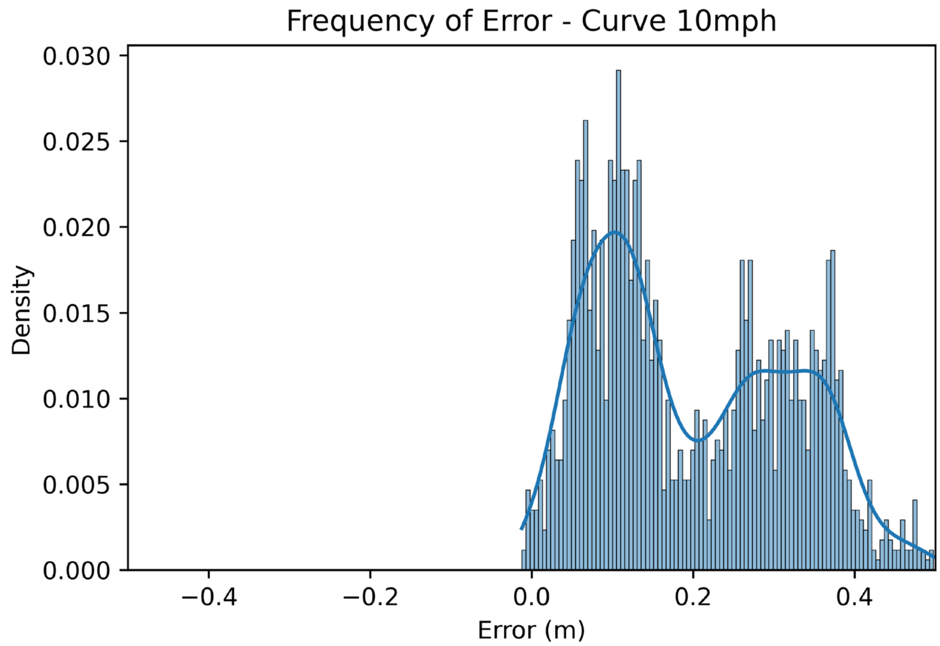


Figure 28. Graph. Frequency of lateral error – curve, 10 mph.

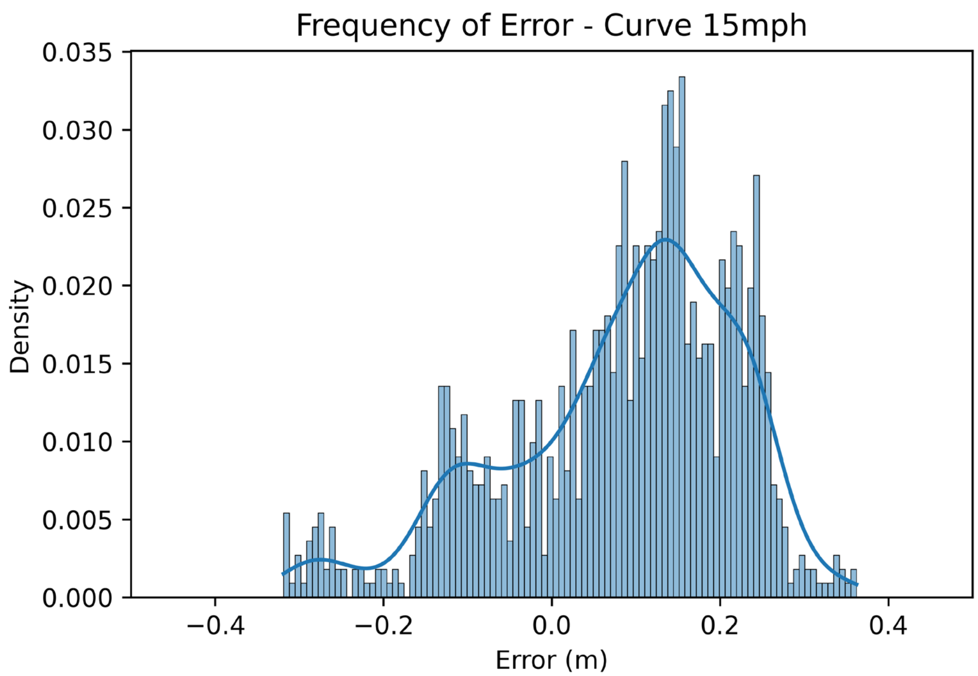


Figure 29. Graph. Frequency of lateral error – curve, 15 mph.

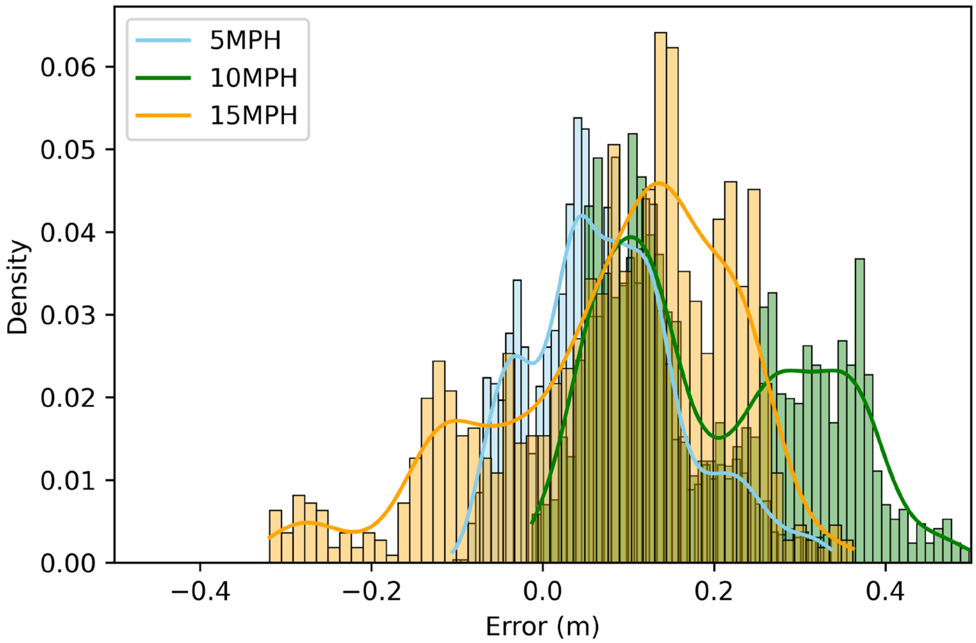


Figure 30. Graph. Frequency of lateral error – curves, combined.

Longitudinal Accuracy Results

5-MPH Test

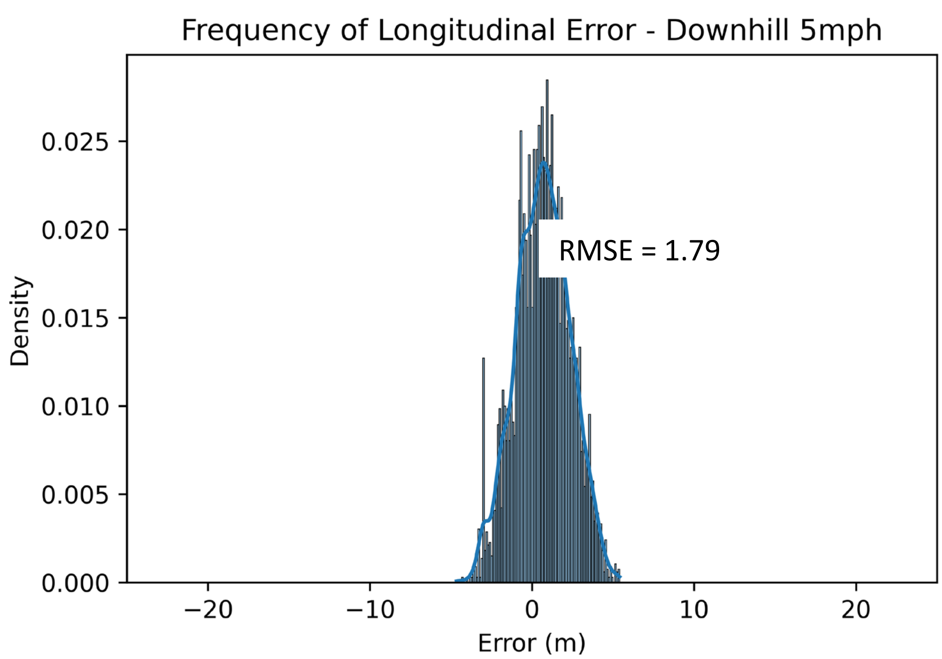


Figure 31. Graph. Frequency of longitudinal error – downhill, 5 mph.

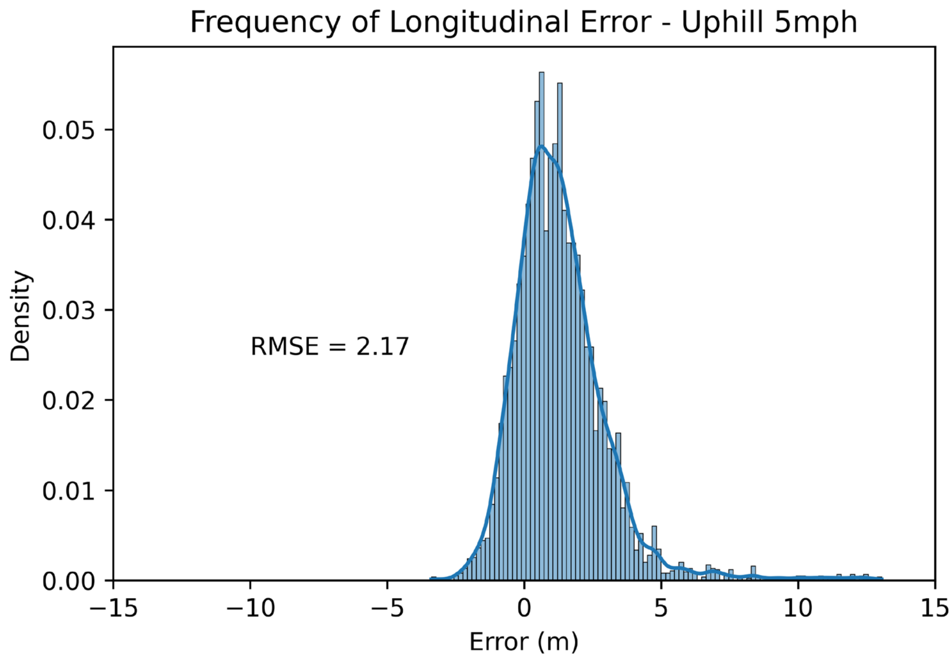


Figure 32. Graph. Frequency of longitudinal error – uphill, 5 mph.

10-MPH Test

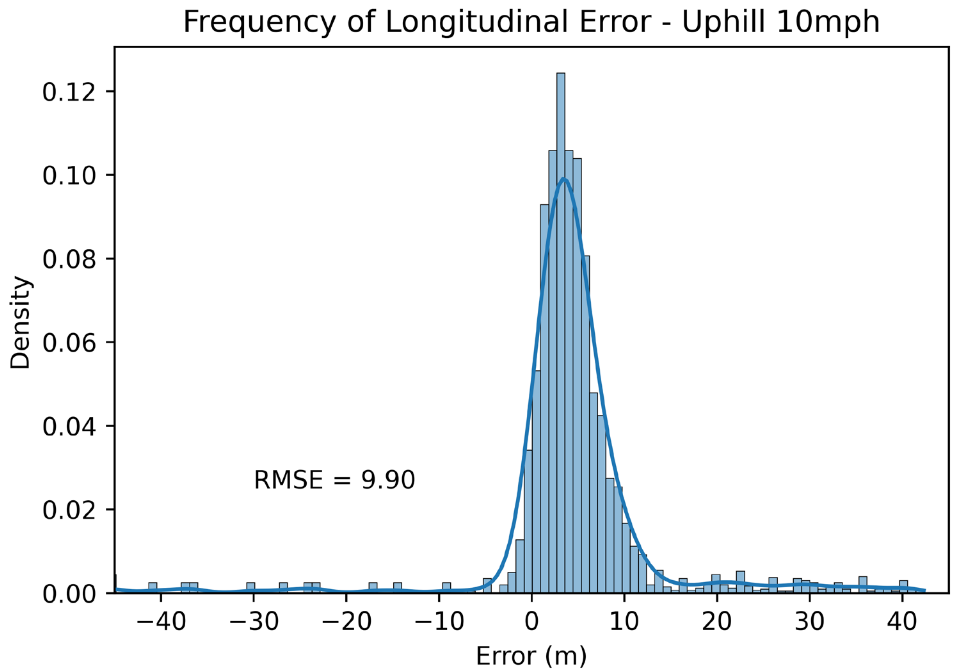


Figure 33. Graph. Frequency of longitudinal error – uphill, 10 mph.

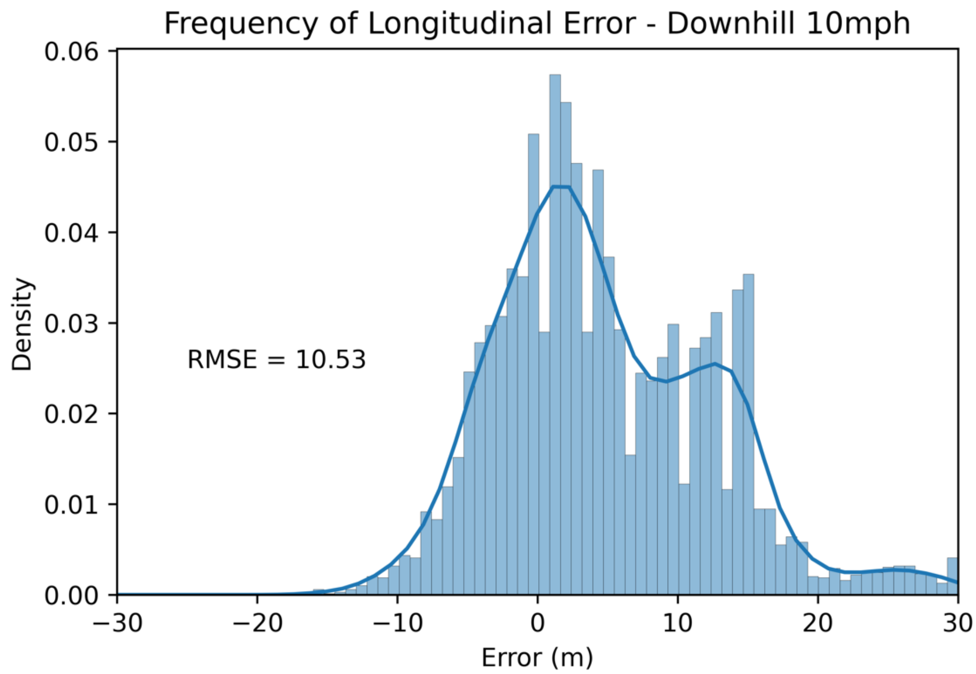


Figure 34. Graph. Frequency of longitudinal error – downhill, 10 mph.

15-MPH Test

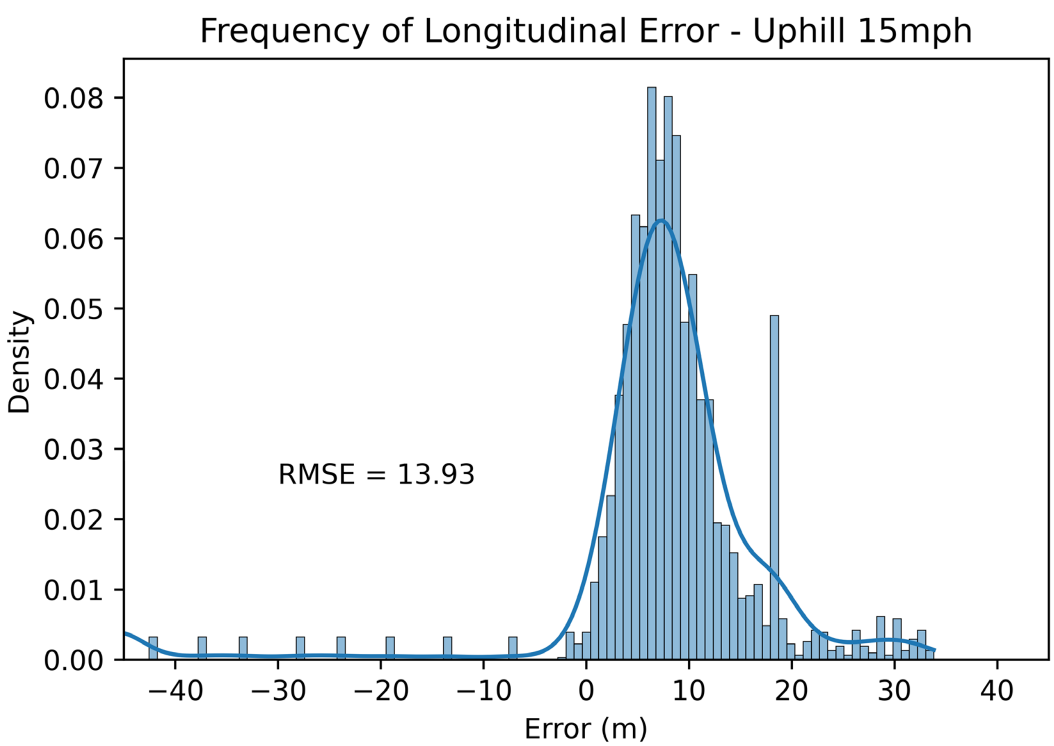


Figure 35. Graph. Frequency of longitudinal error – uphill, 15 mph.

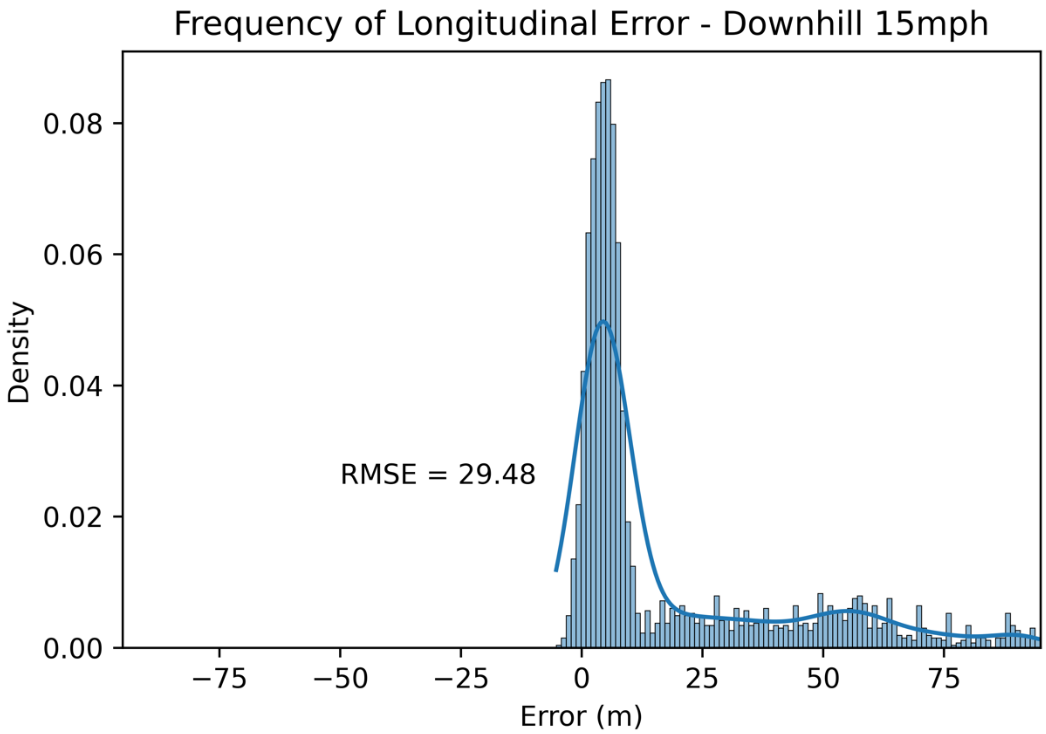


Figure 36. Graph. Frequency of longitudinal error – downhill, 15 mph.

Combined Data Comparison – Downhill

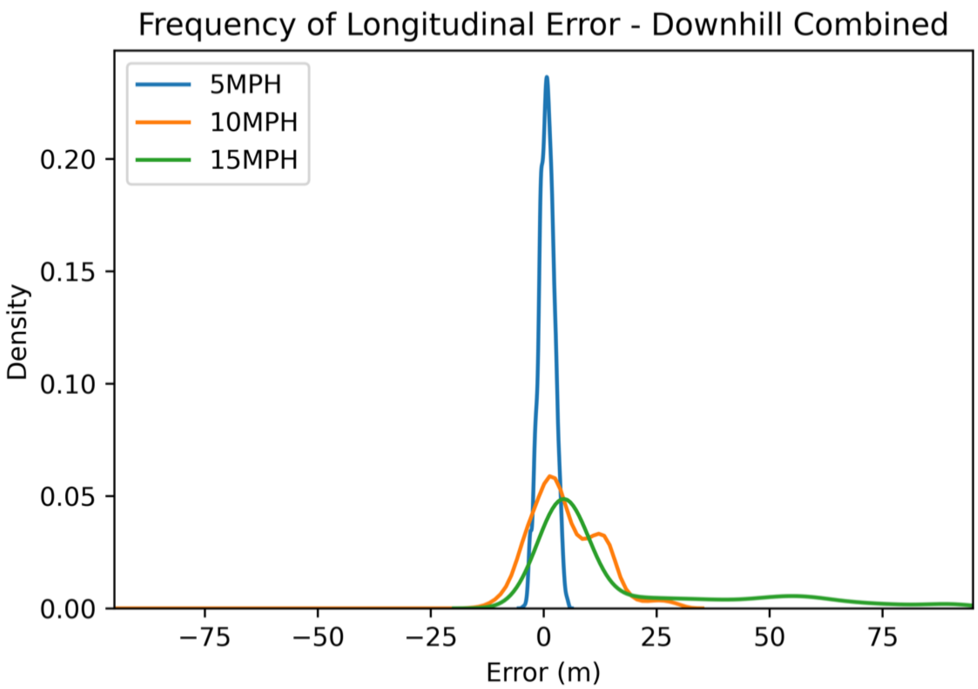


Figure 37. Graph. Frequency of longitudinal error – downhill, combined.

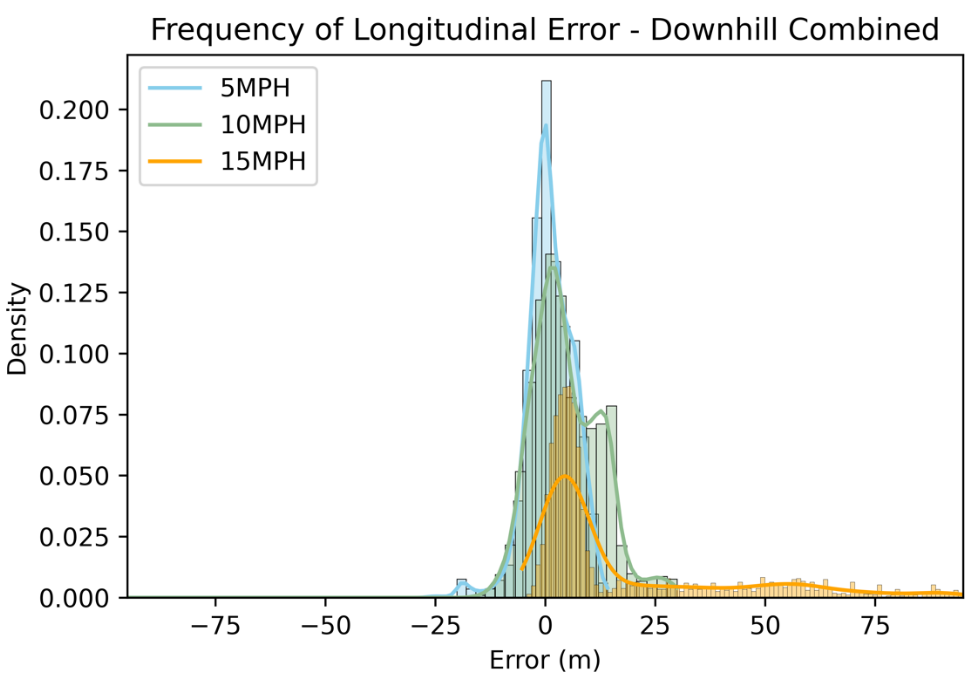


Figure 38. Graph. Frequency of longitudinal error – downhill combined.

Combined Data Comparison – Uphill

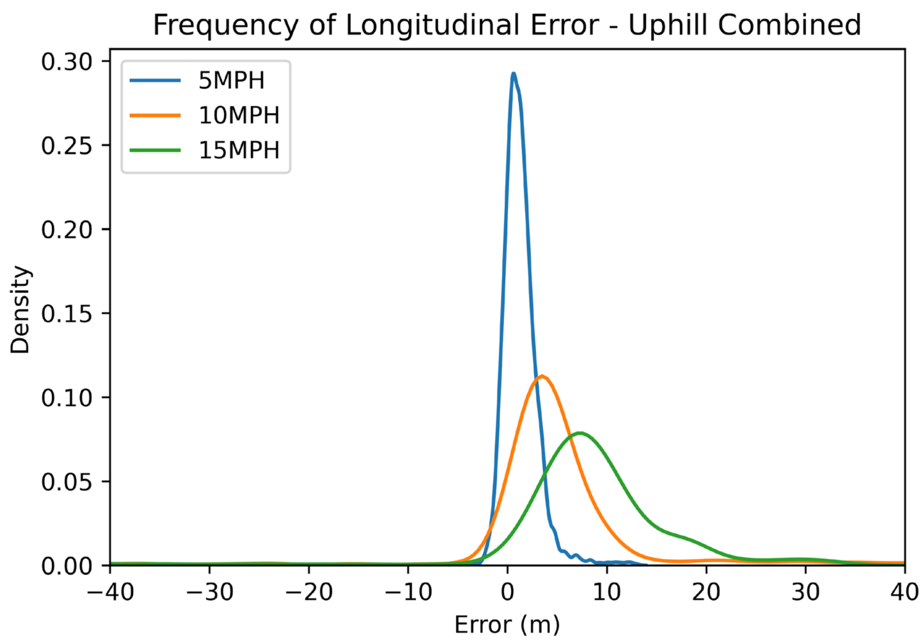


Figure 39. Graph. Frequency of longitudinal error – uphill, combined.

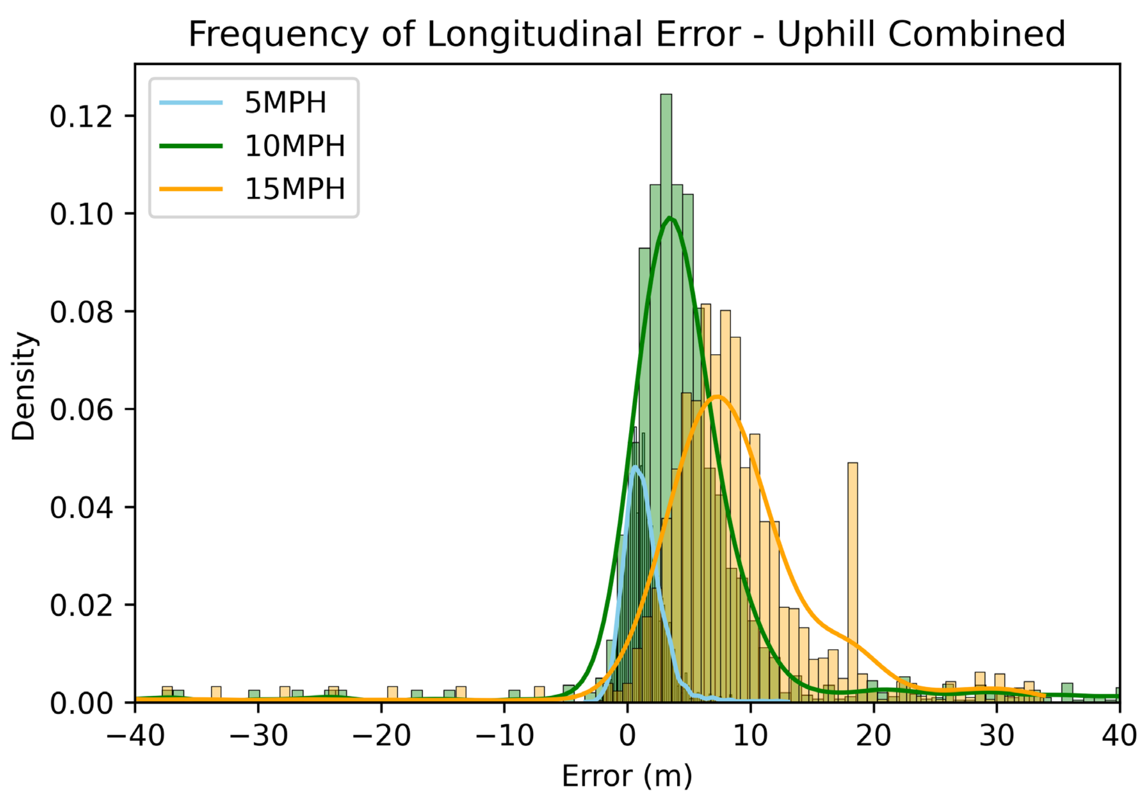


Figure 40. Graph. Frequency of longitudinal error – uphill, combined.

Curve Results

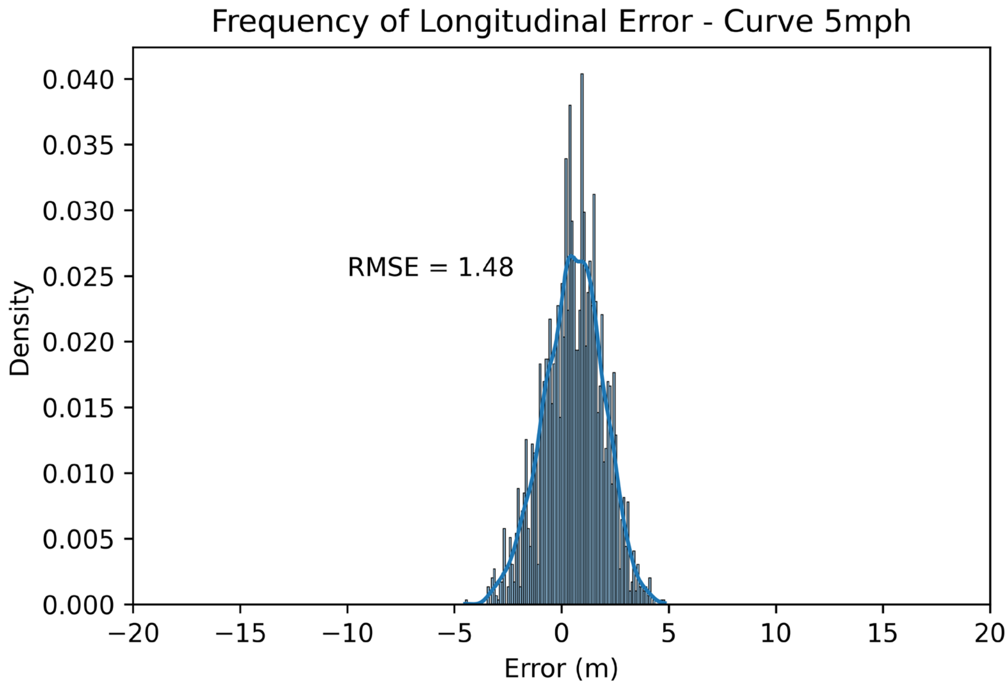


Figure 41. Graph. Frequency of longitudinal error – curve, 5 mph.

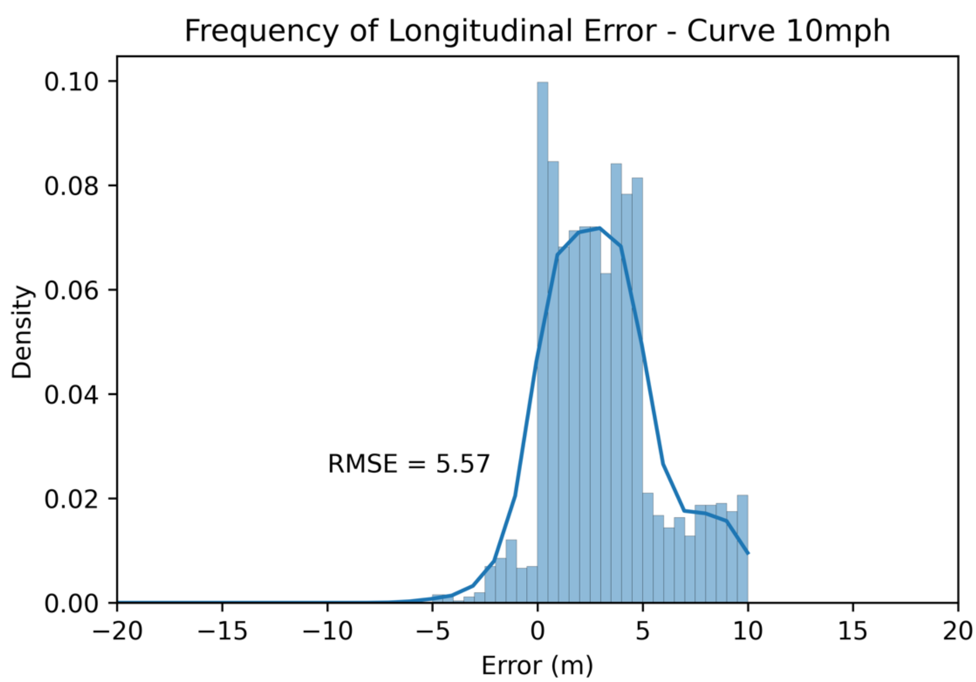


Figure 42. Graph. Frequency of longitudinal error – curve, 10 mph.

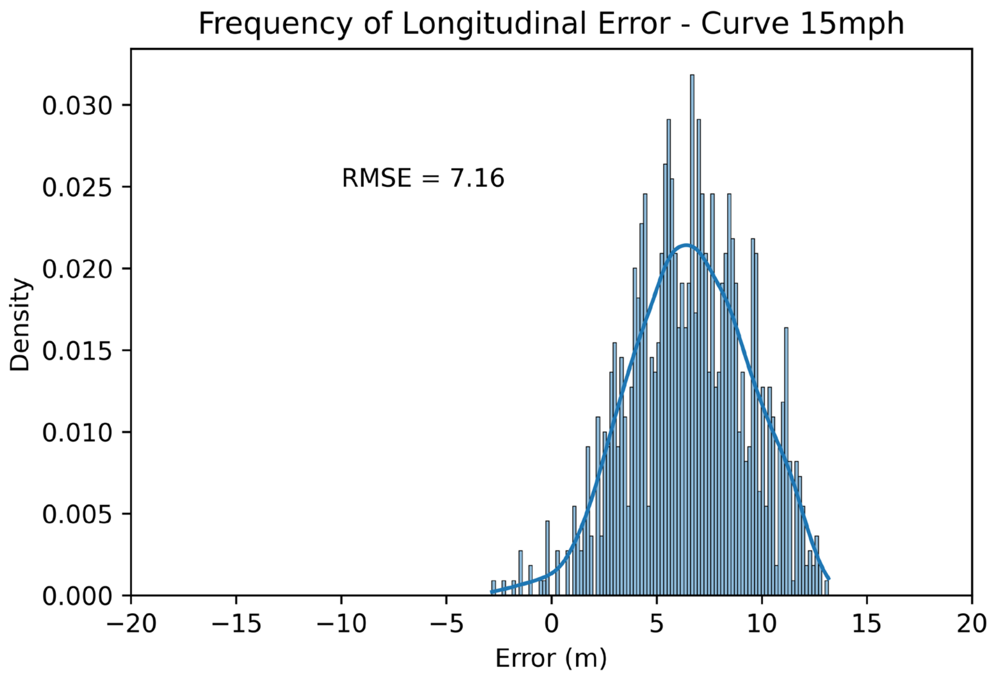


Figure 43. Graph. Frequency of longitudinal error – curve, 15 mph.

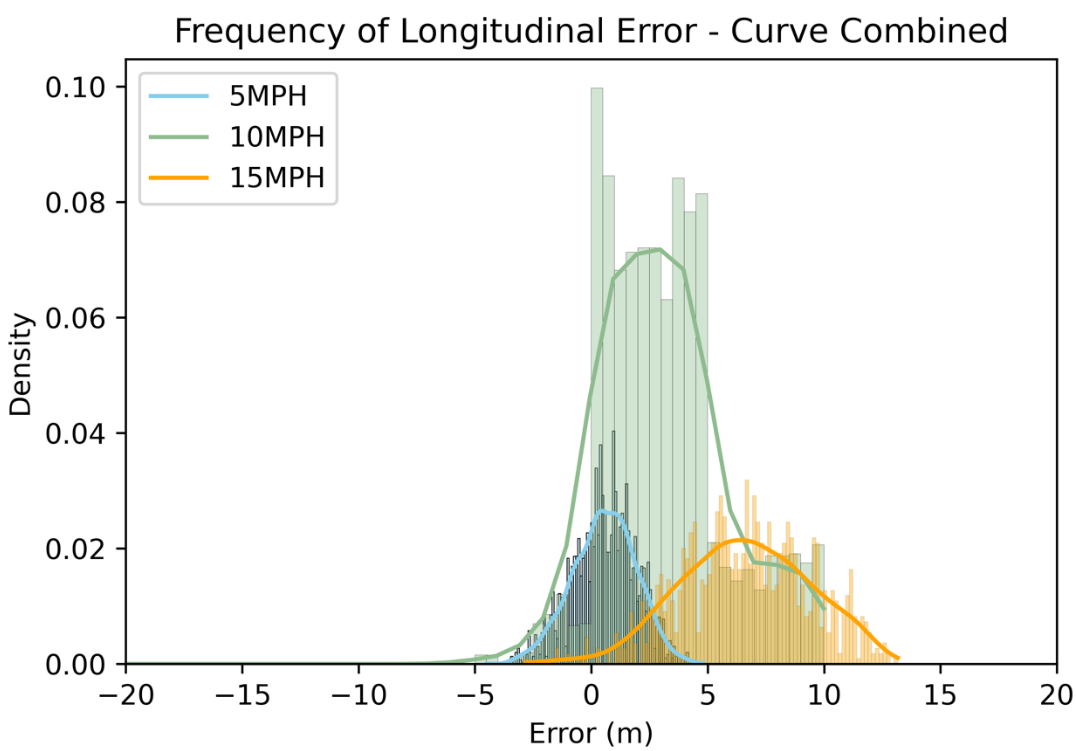


Figure 44. Graph. Frequency of longitudinal error – curve, combined.