AUTOMATED LAST MILE CONNECTIVITY FOR VULNERABLE ROAD USERS – REAL-WORLD LOW SPEED AUTONOMOUS VEHICLE DEPLOYMENT

FINAL REPORT

DECEMBER 2022

AUTHORS

Kevin Grove, Andy Alden, Cristian Druta

Virginia Tech Transportation Institute

US DEPARTMENT OF TRANSPORTATION GRANT 69A3551747125

DISCLAIMER

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Automated Last Mile Connectivity for Vulnerable Road Users – Real-World Low Speed Autonomous Vehicle Deployment		5. Report Date December 2022 6. Source Organization Code
7. Author(s) Grove, Kevin; Alden, Andy; Druta, Cristian		8. Source Organization Report No. CATM-2022-R8-VTTI
9. Performing Organization Name and Address Center for Advanced Transportation Mobility Transportation Institute 1601 E. Market Street Greensboro, NC 27411		10. Work Unit No. (TRAIS) 11. Contract or Grant No. 69A3551747125
12. Sponsoring Agency Name and Address University Transportation Centers Program (RDT-30) Office of the Secretary of Transportation–Research U.S. Department of Transportation 1200 New Jersey Avenue, SE Washington, DC 20590-0001		13. Type of Report and Period Covered Final Report: Jan. 2017– Dec. 2022 14. Sponsoring Agency Code USDOT/OST-R/CATM
15. Supplementary Notes:		

16. Abstract

An EasyMile EZ10 low speed autonomous vehicle (LSAV) was deployed on a route between the Virginia Tech Transportation Institute campus and a nearby bus transit stop to study prospective user attitudes and acceptance regarding trust in technology, system safety, and personal security. The LSAV operated on this route within normal travel lanes and interacted with mixed public traffic that included the full range of transportation users from pedestrians to heavy vehicles.

The findings of this deployment work are shared in a lesson-learned format in the hope that the knowledge gained through this research and technology deployment will inform future LSAV implementations and provide insights into how automated technologies should be applied and regulated considering real-life usage aspects

This report is one of two produced for the larger study. While this report focuses on the actual deployment of the LSAV, the other focuses on vulnerable road users and their prospective use of this technology.

17. Key Words		18. Distribution Statement	
Shuttle, Vulnerable Road User, VRU, Aged, Elderly, Senior, Low Speed Autonomous Vehicle, Automated, last mile, transit		Unrestricted; Document is available to the public through the National Technical Information Service; Springfield, VT.	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 32	22. Price …

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

TABLE OF CONTENTS

LIST OF FIGURES

EXECUTIVE SUMMARY

Low-speed autonomous vehicles (LSAVs) are being deployed in various scenarios to enhance mobility for a wide variety of transportation users. Current applications include providing last-mile connectivity between rider origins/destinations and fixed transit stops and circulating shuttles in areas such as business districts, military bases, parking lots, and theme parks. LSAVs' low-access height, integration of self-deploying wheelchair ramps, and high levels of automation also provide opportunities for improved mobility for those with physical or cognitive challenges. LSAVs are typically highly automated battery-electric vehicles that transport up to eight passengers at speeds below 15 mph on predefined and previously mapped routes. An attendant/operator may also be present during operation depending upon manufacturer and service provider policies, state and federal regulations, operational conditions and route complexity, and the specific assistive needs of prospective riders.

An EasyMile EZ10 LSAV was deployed on a route between the Virginia Tech Transportation Institute (VTTI) campus and a nearby bus transit stop to study prospective user attitudes and acceptance regarding trust in technology, system safety, and personal security. The LSAV operated on this route within normal travel lanes and interacted with mixed public traffic that included the full range of transportation users from pedestrians to heavy vehicles.

The findings of this deployment work are shared in a lesson-learned format in the hope that the knowledge gained through this research and technology deployment will inform future LSAV implementations and provide insights into how automation should be applied and regulated considering real-life usage aspects.

This report is one of two produced for the larger study. While this report focuses on the actual deployment of the LSAV, the other focuses on vulnerable road users (VRUs) and their prospective use of this technology.

DESCRIPTION OF PROBLEM

By 2030, one of every five Americans will be at retirement age, and seniors will outnumber children for the first time in history (U.S. Census Bureau, 2018; see Figure 1). For now, driving remains the primary means for seniors to stay mobile and independent (Davis et al., 2011). However, older drivers generally experience a greater safety risk of causing and being injured in crashes (Li et al., 2003; Stutts et al., 2009). The Baby Boomers driving these demographic trends also have high expectations for remaining active and engaged as they age. Thus, the needs of older adults will increasingly challenge our transportation policies, processes, and infrastructure. Providing mobility alternatives for seniors and others with disabilities in a manner that is safe, efficient, and environmentally friendly is crucial, and this will remain a major challenge for our nation throughout most of the remainder of this century.

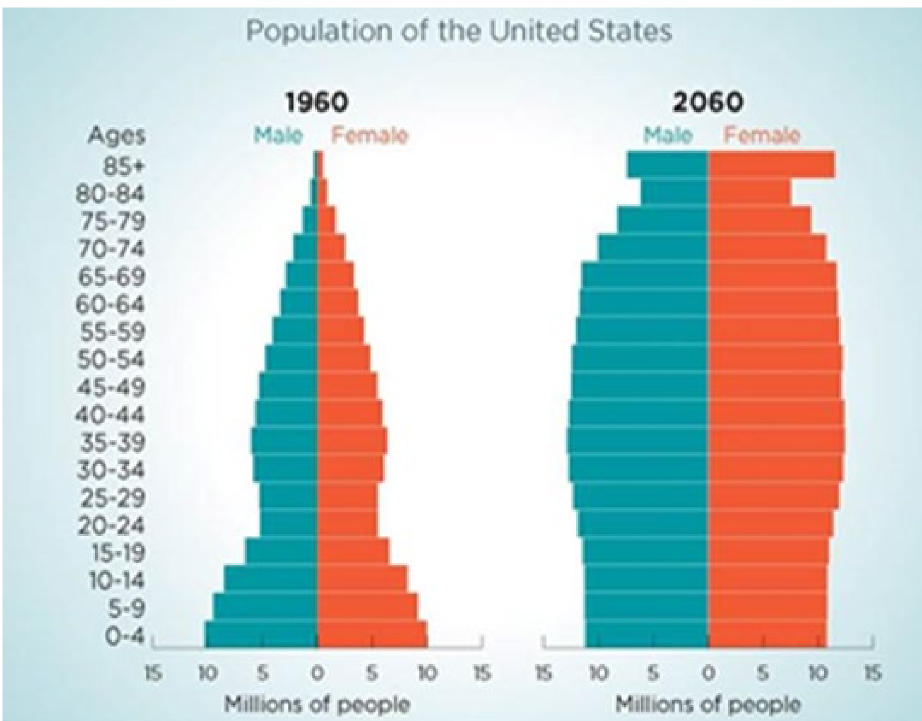

Figure 1. Our aging society – projected demographic shifts from 1960 to 2016 (U.S. Census Bureau, 2018).

While Americans with Disabilities Act (ADA) paratransit has done much to address the transportation needs of vulnerable road users (VRUs), the long-term economic and environmental sustainability of this approach is questionable. New and innovative methods of expanding public transportation access to VRUs are needed to ensure equitable and appropriate connectivity while allowing transit operators to improve the sustainability of their operations. Based on how heavily VRUs are leveraging fixed-route options, one approach is to develop first and last mile (i.e., "Last Mile") solutions that improve bidirectional access between users' homes and destinations and existing fixed-route nodes. Last Mile solutions can also provide VRUs with access to goods and services within a short range of their homes that would not otherwise require public transit.

There is little doubt that automated driving system (ADS) technologies will play a key role in an envisioned future where older persons as well as others who are transportation-challenged can more safely access the resources they need to maintain their health, well-being, and sense of connectedness. As technology has evolved and our modes of transportation diversify, low-speed autonomous vehicles (LSAVs) have emerged as perhaps the most promising means of providing practical, safe, efficient, and convenient local mobility to meet these needs.

Automated Last Mile connectivity systems have been proposed to provide VRUs with efficient, convenient, and timely on-demand access to existing fixed-route transit systems. The primary components of these systems are the LSAVs and the scheduling and routing environment that controls their automated operation. Highly accessible, low-speed, and environmentally friendly electric vehicles that are homed and charged at transit stops are envisioned for this application. Real-time, demand-responsive services of this type typically require a high level of integrated trip planning that may be challenging to VRUs due to cognitive, economic, and physical limitations. These challenges may be further complicated by the autonomous nature of these LSAVs and the respective lack of a vehicle driver or attendant available to render aid.

These LSAVs typically operate at or below 15 mph and are designed for roadways with relatively low complexity (e.g., no signalized intersections) and to transport passengers over relatively short distances. These characteristics make LSAVs candidates for providing Last Mile connectivity between fixed-route transit and a rider's destination. This connectivity can improve the mobility of individuals for whom the last mile may present difficulties. This could include older populations who may have limited mobility, especially those who do not have access to a vehicle or do not drive on their own.

Virginia Tech Transportation Institute (VTTI) researchers learned from transit agency officials in Blacksburg, Virginia (i.e., Blacksburg Transit), that residents of a local senior living community (Warm Hearth) who use Blacksburg Transit's service consistently travel to a few common destinations via bus service. This consistency suggested that an LSAV such as the EasyMile EZ10 (Figure 2) could provide value either within the community (to reach the closest fixed route stop to Warm Hearth's facilities) or at their destinations (mobility within a cluster of businesses or services).

Figure 2. EasyMile EZ-10 shown near its parking space at the front of VTTI's main building entry.

Scope and Purpose of the Last Mile Study

While LSAV technology has the potential to improve mobility for seniors, little is known about the attitudes older populations have towards these types of vehicles. Additionally, it is unknown if the EasyMile LSAV would meet the needs of older populations in terms of operation, comfort, or trust. Existing literature lacks data from participants who have had the chance to observe an LSAV and discuss its strengths or weaknesses.

Though some work has been done to document the attitudes of older populations (65 and over) toward automation in general, this focus group study was designed to gather the feedback of older participants by having them view and respond to videos of what it is like to approach and ride in an LSAV. The original idea for the study was to allow the participants to ride in the LSAV and hold in-person focus groups, but plans were changed due to the COVID-19 pandemic. Focus group participants took part in an online focus group and had the opportunity to share their thoughts and opinions about the LSAV. This research study will contribute to the knowledge base regarding the attitudes of seniors toward LSAVs. The methods and findings of that portion of the study are reported in an accompanying CATM project report titled *Automated Last Mile Connectivity for Vulnerable Road Users – Participant Survey Study* (Baker et al., 2022).

During the course of this study, the research team realized that much of their experience with deploying the LSAV at VTTI in support of the larger study was novel and of probable interest to others considering the use of this or similar technologies. With this in mind, this report was produced in order to share the lessons learned in this LSAV implementation with others.

APPROACH AND METHODOLOGY

LSAV Acquisition and Implementation

LSAV Acquisition

In early 2017, VTTI met with several automated vehicle suppliers and transit stakeholders in order to acquire a test vehicle. The process was challenging, as these vehicles are highly developmental and were in high demand.

VTTI investigated how an LSAV might be best acquired to meet immediate research needs while taking into consideration potential future projects. Researchers and administrators met with LSAV vendors, rode in demo vehicles, and toured their respective production facilities. Major suppliers included Local Motors, EasyMile, and Navya. VTTI visited Local Motors' facility in Knoxville, TN in the Summer of 2017 to learn more about their Olli platform.

VTTI then worked to determine the feasibility of each supplier's vehicles for testing purposes, and in terms of project budget constraints.

Based on this review and a survey of online literature from other vendors, VTTI developed a performance specification in compliance with Virginia acquisition procedures. This specification was developed in consideration of application-specific factors as well as LSAV state-of-the-art capabilities. Application factors included many aspects that spanned planned usage, route characteristics, expected weather, rider comfort, vehicle storage, operational constraints, etc.

In the fall of 2017, VTTI created a specification package accounting for the current capabilities of automated electric shuttles and published a request for bids in order to acquire an appropriate test vehicle. Difficulties were encountered acquiring a test vehicle. For instance, public policy and regulation were noted as a key barrier to the testing and deployment of automated shuttles.

In early 2018, VTTI submitted a public request for bids to industry to acquire a suitable low-speed autonomous shuttle that could be used for project testing. VTTI's request was based on the specifications developed in the previous quarter. After a series of clarifications, a revised bid request was issued and two vendors responded. Both of these vendors manufacture vehicles in France.

VTTI closed the bidding, selected EasyMile as the supplier, and negotiated final acquisition in the summer of 2018, but the vehicle was not delivered to specifications. VTTI worked with the supplier in order to negotiate delivery of another vehicle, as well as new collaboration opportunities on future research. VTTI received the replacement vehicle from the supplier in early 2019; this EasyMile EZ-10 Gen 2 LSAV vehicle met all original specifications for the project.

The interest from suppliers and stakeholders may allow for a wider scope in data collection. This includes development platforms that give VTTI additional access to customized vehicles, lease options to allow testing of multiple vehicles, and partner transit stakeholders that could provide access to additional testing locations and populations. Automated shuttle platforms could be used for data collected from VRUs.

In terms of research, testing, and post vehicle acquisition, VTTI's facilities offered a realistic use case for an LSAV that also presented a challenging roadway environment. Although there is a fixed transit stop for the local bus service for VTTI's facilities, it is located a half mile away from VTTI's buildings. The route between the front door and the fixed transit stop lacks sidewalks and features mixed traffic in a parking lot and on a two-way private road, a traffic circle, and a steep grade. This route takes approximately ten (10) minutes to walk but could be challenging for individuals with physical impairments or during poor weather.

VTTI's LSAV

The EasyMile EZ10 vehicle purchased by VTTI for this, and other projects, was state-of-the-art when acquired. Further description of the vehicle's characteristics and capabilities follows.

- The vehicle is designed to carry as many as ten (10) passengers with some sitting and some standing. While not originally equipped with safety belts for sitting passengers, they were later added per National Highway Transportation Safety Administration (NHTSA) directive; this also meant a decrease in the passenger capacity rating.
- The vehicle is bidirectional, which allows flexibility with respect to minimized maneuvering for alignment of the doors with passenger loading areas. Sensors that provide situational awareness to the ADS are symmetric across both the lateral and longitudinal centerlines of the vehicle.
- The battery-electric vehicle features four-wheel drive, which provides better traction in inclement weather and on hills.
- The vehicle's ADS is ostensibly capable of Level 4 (L4) operation per SAE International standards. Implied capabilities for this level of automated driving are that "These automated driving features will not require [a human operator to] take over driving" (SAE International, 2021).
- The vehicle's ADS relies upon error-corrected global navigation satellite systems (GNSS) including GPS, data from multiple light detection and ranging (lidar) sensors,

inertial measurement units, and precise measurement of wheel rotation (odometry) for automated navigation. This data, coupled with time, provides for precise estimation of position and assessment compliance with the pre-determined route. Low-mounted lidar sensors provide collision avoidance with nearby objects such as vehicles, pedestrians, and road hazards.

- Although physically capable of higher speeds of about 20 mph, the vehicle was limited by NHTSA certification to a top speed of 12.5 mph and frequently operated at much lower speeds. Manual driving by an operator is limited to just several mph.
- The LSAV featured a capable climate control system for heating and cooling.
- The onboard operator can quickly take control of the vehicle to stop or move it manually. Passengers also have ready access to emergency stop pushbuttons located at several places inside the vehicle.
- Lighting displays at either longitudinal end of the vehicle provide an indication of operational status to those outside.
- The LSAV is equipped with a self-deploying wheelchair ramp and manual securements for a wheelchair or other mobility assistance device within the vehicle cabin. Two electrically operated doors provide cabin access, and the adaptable suspension allows the vehicle to lean to the loading side to provide easier access when the ramp is deployed (Figure 3).

Figure 3. Views of VTTI's EasyMile LSAV parked with doors open (left) and in leaning mode with entry ramp deployed (right).

The Last Mile Route

For purposes of this and future studies, as well as providing a future regular shuttle service between VTTI and Blacksburg Transit's nearest stop, a suitable route was developed. The route eventually chosen features the following:

- In-travel lane LSAV operation with mixed traffic operating at a posted 25 mph speed
- A fully operational bus stop that services VTTI's employees and other commercial interests in the area
- A highly visible and public setting with uncontrolled access
- A small roundabout at the approach to VTTI's campus
- Road slope variability that might challenge the LSAV's climbing abilities and traction in adverse weather
- Ready access to the Virginia Smart Roads test facilities through a controlled access point.

Figure 4, Figure 5, and Figure 6 provide views of the VTTI campus, the LSAV routes, and relevant site features.

Figure 4. An aerial view of the VTTI campus showing the LSAV route extending from the entrance to VTTI Building 2 to the Blacksburg Transit bus stop (maroon line). Orange line indicates other routes that were considered.

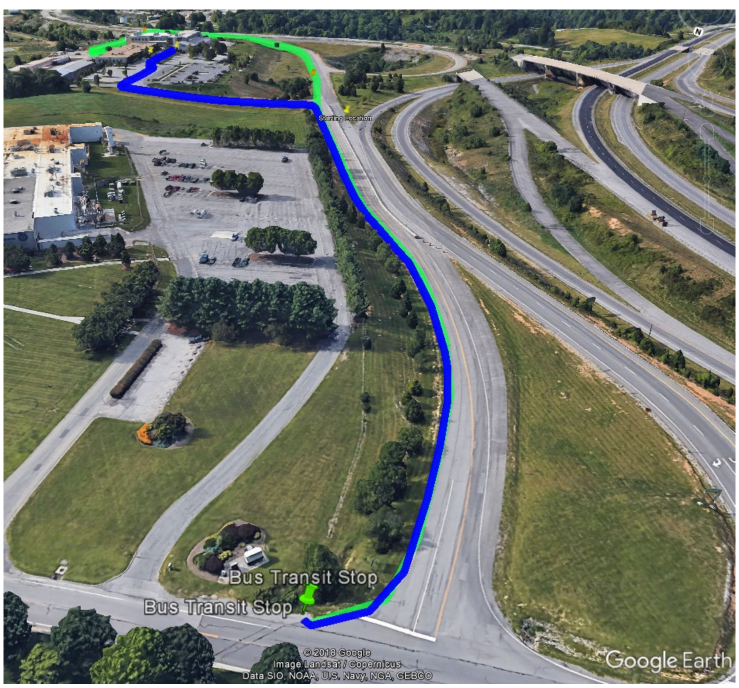

Figure 5. An aerial view of the route (blue line) between the Blacksburg Transit bus stop and VTTI's main building.

Figure 6. An aerial view of the LSAV's route through VTTI's parking area with termination at the front entry of the main building lobby (maroon line).

Route Preparation

Substantial modifications of and enhancements to the route were undertaken in late 2018 to enable operation of the LSAV there. These modifications included the following:

- Installation of pavement markings and signage for a designated loading/parking area at the main building entrance (Figure 7).
- Extensive additional signage along the route to enable vehicle navigation and to provide road user awareness for safety (Figure 8). This includes the periodic installation of large reflective targets required for vehicle orientation using lidar.
- New pavement to facilitate LSAV loading and parking near the bus stop and new pavement markings to facilitate the vehicle's crossing traffic (Figure 9).

Figure 7. View of the LSAV's designated parking area that was installed near the entrance to the lobby of VTTI's main building.

Figure 8. Photographs of the varous signs that were installed along the LSAV's route to provide notification to the public traffic using the road.

Figure 9. Views of the constructed pulloff and loading area (left) and travel lane crossing zone installed near the Blacskburg Transit bus stop.

Route Mapping

Once route improvements were completed, extensive virtual mapping of the route was performed by an EasyMile representative located onsite. This was accomplished by operating the vehicle manually and autonomously along the route numerous times while onboard sensor measurements were recorded to produce a virtual three-dimensional map that defined the vehicle's operating environment.

Regulatory Approval

As an "experimental" vehicle, an exemption to Federal Motor Vehicle Safety Standards (FMVSS) was required from NHTSA before the LSAV could be operated in the U.S. VTTI worked with EasyMile to secure this exemption. The exemption included restrictions on where and when the vehicle may operate, whether safety drivers were required, requirements for end-of-life disposition, and specifications for safe operating parameters such as maximum travel speed and passenger safety measures.

Operator Training

While NHTSA vehicle certification exemption issues were being worked out, VTTI worked with EasyMile to train four LSAV operators whose individual presence onboard was required for safe and legal operation. During the one-week training process, prospective operators received written and in-vehicle instruction. One operator received additional "Chief Operator" training on diagnostic and maintenance procedures. Two additional operators were later trained to help ensure scheduling flexibility. All operators were VTTI employees who had other research responsibilities in addition to being a designated LSAV operator. The initial training of the operators took place in November 2018, and LSAV route mapping was completed in December 2018. Infrastructure improvements were completed in early 2019 and final NHTSA approval soon followed. VTTI began to operate the LSAV along the designated route in 2019.

Coordination with the Transit Provider

In order to make the deployment as realistic as possible, VTTI's operators attempted to synchronize the shuttle's operations with Blacksburg Transit's operations. Two different bus routes serviced VTTI's bus stop. Both routes run every 15 minutes, but the buses are scheduled to arrive at the stop 5 minutes apart. VTTI set up the schedule for its LSAV operations such that it would leave VTTI's front door, arrive at the bus stop before the first bus, wait for both the first and second bus to make their scheduled passes, and then return to VTTI's front door. The decisions of when to depart from the front door and the bus stop were made by the operator. If a bus did not arrive on schedule, or if unexpected issues along the route caused LSAV delays, operators had the authority to adjust the LSAV schedule as required to re-synchronize the schedule.

The route featured several potential events, or decision points, that might require operator input. These decision points could be classified into two categories: hard stops and soft stops. A hard stop was a decision point where the vehicle would come to a complete stop before offering the operator control over when to proceed. This type of stop was programmed into the route for one point where the LSAV approached a stop sign while leaving the parking lot. A soft stop was a decision point where the LSAV required operator input to proceed but would allow the operator to issue the command before coming to a complete stop. This would allow the vehicle to "roll through" the decision point if the operator determined it was not necessary to stop. However, if the operator did not provide an input, the vehicle would come to a complete stop and would not proceed without operator clearance. Soft stops were programmed into the route where the LSAV would enter the traffic circle and where the LSAV would make an unguarded left turn across traffic.

VTTI created an operation schedule in the summer of 2019 and received Institutional Review Board (IRB) approvals to begin running the shuttle in scheduled service between VTTI's main entrance and the transit stop that services VTTI's facilities. Because the EZ-10 LSAV was not in regular service or fully ADA compliant, there were concerns with placing vulnerable populations in the vehicle until there was a high level of confidence in its safe operation. However, through extensive testing, by the end of 2019, VTTI established that the route between its front door and local transit stop was operationally safe. VTTI ran daily service and used the data to iterate the LSAV's navigation maps, gather data on transit times and typical roadway disruptions, and document the environmental conditions that led to disruptions.

Vehicle-Based Data Acquisition

To support this and future planned research, a VTTI data acquisition system (DAS) was installed on the LSAV. This system comprised an electronic data acquisition unit equipped with internal sensors, and external sensors and appurtenance such as cameras and antennas. This system can be configured to record continuous or event-triggered data on internal storage media. Multiple channels of video can be recorded. For this installation, forward- and rearward-looking as well as internal cabin viewing cameras were installed. Other data that the DAS can record includes, but is not limited to:

- Vehicle dynamics
    - Speed
    - Heading
    - Acceleration in 3 axes (i.e., x, y, and z)
    - Compass 3-axis (i.e., yaw, pitch, and roll)
- Location using error-corrected GPS

These and other data collected using VTTI's DASs can be analyzed by researchers using VTTI's proprietary data reduction and visualization software (Figure 10).

VTTI had also planned to record vehicle-based system data such as the occurrence of events like soft and hard stops, but this did not occur for a number of reasons related to manufacturer concerns about data security and potential adverse system impacts.

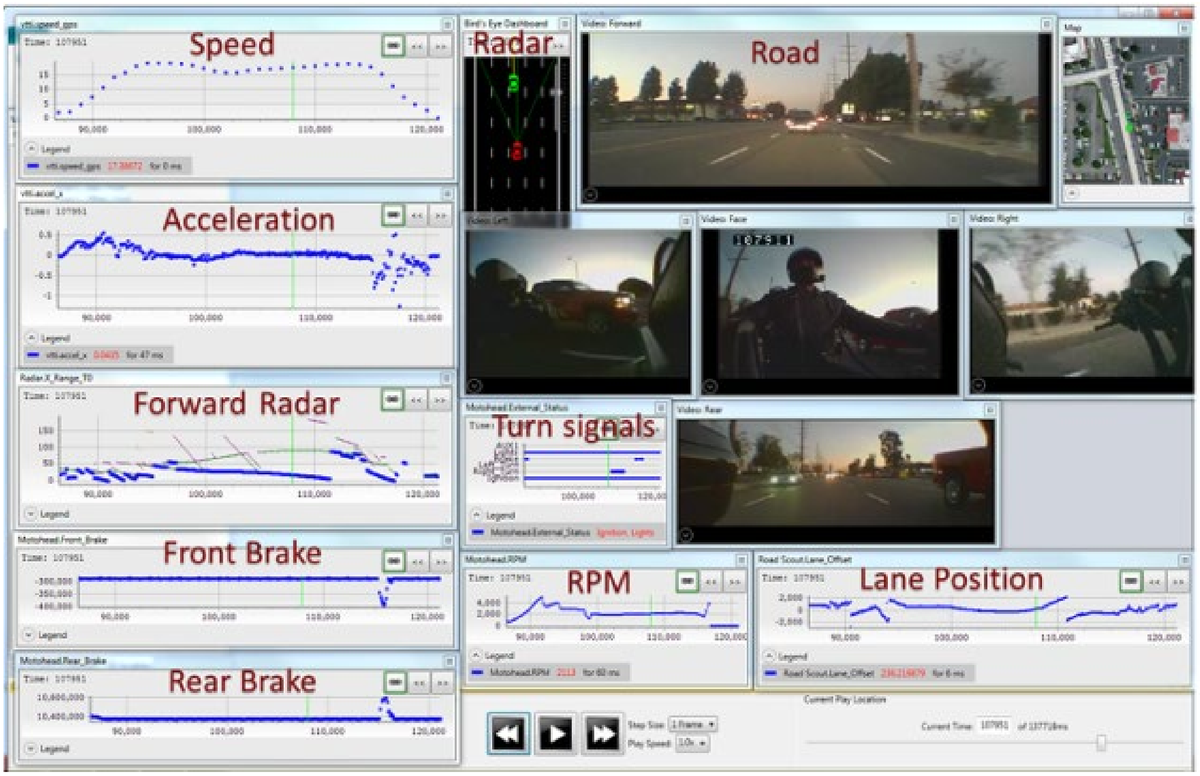

Figure 10. An example screenshot of VTTI's data visualization and reduction software.

Last Mile Study On-Road Data Collection

With the implementation of the LSAV complete, VTTI was prepared to begin working with vulnerable populations to demonstrate the route and collect feedback in early mid-2020. However, with the onset of the COVID-19 pandemic, Virginia Tech's IRB decided to suspend all research that required interaction with human participants. In addition, NHTSA had recently restricted the ability of EasyMile's vehicles to carry public passengers in the U.S. due to a passenger injury that occurred during an LSAV emergency stop event (Shepardson, 2020). This was relevant to this study because of the LSAV's use restriction and in its implications on participant/passenger safety. Because the study was focused on a vulnerable population (senior adults), it was determined that firsthand participant exposure to the LSAV through actual travel would be removed from the data collection protocol. Thus, with the advent of COVID 19, the research team adopted alternative practices for exposing the participants to this technology with the intent of gleaning information on their attitudes regarding their prospective usage for improved mobility. The methods and findings of that work are reported in an accompanying CATM project report titled *Automated Last Mile Connectivity for Vulnerable Road Users – Participant Survey Study* (Baker et al., 2022).

FINDINGS, CONCLUSIONS, RECOMMENDATIONS

Lessons Learned

The research team feels that the findings of this portion of the overall project work are best presented in the format of lessons-learned in the hope that others planning to deploy an LSAV will benefit from what we learned during this project.

Managing Expectations

There is typically a lot of hype surrounding any new technology. The field of transportation and, in particular, automated driving technology, has been the subject of a great amount of publicity with exaggerations of capabilities and progress frequently shared in various forms via the media. To some degree, new technology is hyped by necessity to ensure there is ample venture funding and a large enough market share; both of these are factors that can make or break a company. As many early adopters of LSAV technology have learned, though the concept of low-speed automation is attractive for a variety of reasons, there are still multiple significant challenges that hinder widespread adoption. It's important that those planning an LSAV deployment proceed with their eyes wide open and with the issues described in the following sections in mind.

It's a System Not a Vehicle

As with many advanced technology products that are currently available, the tangible portion is only part of a larger system that is integrated with virtual and human components such as software, communications, route maps, and operators. The programming (firmware/software) that allows the vehicle to operate will almost certainly contain bugs and advances that will require updating, with corresponding downtime and likely licensing costs. Persistent subscriptions to external systems such as wireless communications and GNSS navigation and error correction packages with their respective ongoing costs will be required. Extensive route mapping using the LSAV itself or other mobile systems will be needed before deployment and when significant route/environment changes occur. LSAV attendants/operators require initial and continued training, as do those performing vehicle maintenance. And, as with any fast-evolving technology, obsolescence may occur more quickly than anticipated and desired. It is worth noting also that these types of systems are designed to function within a highly specific Operational Design Domain (ODD). If real world conditions fall outside the ODD, the system may become unreliable or dysfunctional.

Vehicle/System Function

The LSAVs available at any point in time may differ widely with respect to certain functionalities that may affect or limit their everyday operations in actual deployment. Features such as all-wheel drive, four-wheel steering, bidirectional travel, and vehicle kneeling may impact route choices respective to road grade, path termination and turn-arounds, and the placement of passenger loading zones and platforms. The use of options such as climate control may have a significant impact on vehicle range, in some cases decreasing range by as much as 50%.

Operator/Attendant Issues

Presently, the effective application of attendants/operators to ensure the proper operation of the LSAV and the safety of passengers and those external to the vehicle is critically important. While broadly touted as "driverless vehicles," LSAVs may well require that someone of authority ride onboard to limit vehicle access to those authorized to ride, ensure the security of the vehicle and passengers, take over control of the vehicle for its navigation if required, and assist riders with a variety of services ranging from providing route, schedule, and stop information to enabling physical ingress/egress and securement within the cabin and tracking abandoned personal belongings.

Though some of these functions may be provided by a remotely stationed attendant/operator, there are obvious limitations with this approach. Remote operation requires persistent, highly reliable, high-bandwidth, and low-latency, wireless communication between the LSAV and the remote station along the entire route. This is still a significant technical challenge and one that may be addressed as new technologies like 5G are deployed. A remote attendant/operator also would not be able serve as a direct deterrent to unauthorized access and potential onboard threats such as bad actors, fire, and unintended confinement within the vehicle, nor would they be able to render direct physical assistance with ingress/egress, securement of passengers or belongings, return of objects left behind, and first aid.

A third, hybrid option comprising the use of an onboard attendant with a remote operator is also worth considering. In this scenario, the attendant provides a physical presence for security and assistance while a more technically trained operator deals with potential operational issues. This reduces the training required for attendants and the fleet overall, as multiple LSAVs may be monitored by a single remote operator. This concept has been proposed for highway freight transport also. Transportation providers should consider carefully whether onboard attendant/operators should be used and what their functions are.

Rider Safety

Much of the development efforts for LSAVs have focused on autonomous navigation and human-machine interaction, as these are the primary challenges that must be overcome to enable this technology. The more conventional aspects of vehicle development, including passenger accommodation and safety, have not received as much attention under the assumption that these issues have already largely been worked out by the manufacturers of highway vehicles. LSAVs, though, face special challenges with respect to protecting passengers while accommodating the trappings of their everyday lives such as packages, pets, and personal mobility devices such as bicycles, wheelchairs, scooters, and walkers. While safety belts and handholds may be provided for passengers, these are passive systems that do not ensure the safety of everyone onboard during an abrupt stop as persons and possessions move about. Also, the crash worthiness of LSAVs may not be well defined, as NHTSA exemptions may allow for their deployment despite a potential lack of crash testing and certification.

Regulatory Considerations

Rapidly advancing technologies such as LSAVs provide a tough challenge to the regulating agencies charged with ensuring their safety while minimizing unnecessary constraints on their advancement. At the federal level, regulations such as the ADA and those promulgated by NHTSA may critically impact LSAV deployments. NHTSA FMVSS compliance and/or exemptions required for operation may be cancelled abruptly via moratorium should safety incidents—even those occurring elsewhere—cause concerns for the safety of all similar systems and those using them. This occurred with VTTI's LSAV after an emergency stop in a similar vehicle operating elsewhere in the U.S. resulted in the injury of a passenger (Shepardson, 2020). ADA regulations developed for conventional buses or cars may be inadequately defined to ensure the safety of riders while providing reasonable levels of liability protection for LSAV system operators. Those hoping to tap into federal funding for the purchase of an LSAV may find that the lack of full ADA compliance or "Buy American" policies may prevent that funding. At the state level, transportation and motor vehicle agencies may determine where and under what circumstances LSAVs may operate. This is particularly important when operation on public roads is planned.

The LSAV's Operational Design Domain

Current LSAV offerings rely upon highly detailed virtual maps that define their normal operating environment. While their navigational programming can accommodate a wide range of dynamic factors in their ODD, there are some factors that are especially challenging and that should be considered when planning and maintaining routes. Any objects that currently exist within the vehicle's path that are not included in its virtual operating environment map may be interpreted as obstacles and a potential threat. This may include foreign objects on the roadway or in the air. The encroachment of growing or windblown vegetation may create an aberration that affects or halts vehicle progress. Similarly, pedestrians, whether in designated crossing areas or elsewhere, may hinder vehicle progress when they do not yield to let the LSAV pass. In some cases, pedestrian crossing controls may be required where none existed before LSAV deployment. Communication between vehicles and pedestrians to allow each to understand the intent of the other continues to be a challenge for automated vehicle developers. Signalized intersections also require special consideration, as signal phase and timing data needs to be shared with the LSAV to enable its traversal, and timing may require modification to allow the slow-moving vehicle adequate time to clear the intersection. Vehicles parked adjacent to the LSAV's route may also create problems due to door openings and route encroachment from improper parking or ingress/egress. Weather-related obstacles, such as high water and accumulated or plowed snow, should also be considered.

Planned maintenance and modifications of the operating environment performed by authorized and unauthorized agents may also adversely affect vehicle operation if they occur without prior notification to LSAV operators. Construction zones and temporary pedestrian crossings are examples of this.

Traffic Impacts

An LSAV operating in a travel lane with mixed traffic on a public road may create traffic nuisances and safety risks. An LSAV is likely to cause traffic backups and aggressive and unsafe driver behavior when traveling at speeds less than 12.5 mph on a road with a posted speed limit of 25 mph. Speed differential between vehicles is a well-known contributor to crashes. These types of unfavorable behaviors were observed during the LSAV deployment at VTTI.

Vehicle Operating Data Acquisition

Those planning to deploy LSAVs may hope to collect data on operations, passengers, and the operating environment in order to better assess use characteristics and other factors that may affect future usage, benefit-cost analyses, potential additional deployments, and route expansion. While LSAV manufacturers may collect data that may be useful to these types of assessments, much of this information is deemed proprietary for a variety of competitive and risk management reasons. Any plans to obtain these types of data from the vehicle manufacturer should be solidified before purchase or lease of the system.

DISCUSSION

The process of testing new transportation technologies in the real world is a necessary step that can yield highly valuable information. However, the process often requires significant resources and can lead to negative perceptions if performance falls short of expectations. It is therefore important to consider the deployment aspects discussed above. This will allow transportation agencies to clearly define their goals, collect useful data and feedback during testing, and manage the expectations of operators, stakeholders, and users. VTTI's test deployment in support of a larger study resulted in lessons that required new training, changes in operation and scheduling, updated messaging to passengers, and other revisions to the initial plans. An iterative process that can quickly identify problems, devise solutions, and incorporate revisions such as these has a much greater chance of success.

While the limited testing at VTTI has helped uncover and organize the key issues described above, the diversity of ODDs and differing project goals means the answers to relevant issues will often be specific to each deployment. It is hoped that the key questions will aid future deployments and help public and private partners achieve their goals safely while maintaining buy-in from all parties. However, as with any new technology deployments, there will be unforeseen issues. Stakeholders should plan for iterations to address issues early in the process and revisit these discussions as lessons are learned. Priorities may shift over the course of the deployment for a variety of reasons, and it is important that all stakeholders buy into any plans for iterative improvements. By carefully considering the key issues discussed in this paper and deciding how best to meet stakeholder goals, it is possible to plan safe and effective deployments of new transportation technologies such as LSAVs.

Study Benefits

The research team would like to leave readers with a sense of optimism with respect to new mobility technologies such as LSAVs. Although numerous deployment challenges have been revealed here and in other work, overcoming these obstacles may ultimately reap many rewards such as those below:

- Improved mobility for those most challenged by conventional transportation options
- Reduced congestion, air emissions, and noise
- Improved transportation equity
- Reduced private vehicle usage with consequential need for parking and other infrastructure
- Promotion and diversification of multi-modalism and public transportation such as transit

- Travel safety improvements inherent with the application of driving automation.

Future Research

It would be helpful to explore further the willingness to use the LSAV in populations with mobility limitations. As reported in the Baker et al. (2022) CATM report accompanying this one, some of the participants with mobility limitations shared their willingness to try an LSAV, while some were concerned that without an operator present it would not be possible for them to use the LSAV (e.g., needing help locking down a wheelchair). Conducting further research on how to ensure this technology meets the needs of users with mobility limitations would be beneficial.

STUDY LIMITATIONS

As noted previously, the original intent of this work was to expose older participants to a new and exciting technology that may help ensure their future mobility and that of others. Unfortunately, the constraints on human research necessitated by the COVID-19 pandemic required that alternative research methods be employed to achieve project goals.

The research team had also planned to include participants who had mobility limitations that might prevent them from driving, including those using mobility assistance devices such as wheelchairs or powered scooters. These plans were set aside when the team realized that the ADA accommodations offered by the acquired LSAV did not fully meet current ADA requirements. Consequently, the decision was made not to expose participants to additional risk that might result from vehicle shortcomings with respect to ADA factors.

Statement on COVID-19 Study Impacts

The timely completion and scope of this project was adversely impacted by the COVID-19 pandemic on multiple fronts. The primary COVID challenges revolved around revised rules for working with human participants and the risks presented by having multiple people share the confined space within the vehicle. This required a complete revision of experimentation plans, including recruiting, IRB, and safety compliance components. This ultimately resulted in a major change of scope from that originally envisioned with a primary effect on how participants were exposed to the LSAV technology and how focus group surveys were executed. In both cases, direct interactions between participants and the LSAV and between multiple participants were reduced to what could be achieved using multimedia presentations (i.e., video) and virtual meeting spaces (i.e., Zoom®).

ACKNOWLEDGEMENTS

The research team wishes to thank the following for their support on this project.

- The Center for Advanced Transportation Mobility at North Carolina A&T for their funding and other support
- Blacksburg Transit for their cooperation and encouragement
- The many employees at VTTI who contributed to making this deployment successful
- SAE International and the Association for Uncrewed Vehicle Systems International (AUVSI) for allowing us to publish and present preliminary findings of this work at their Business of Automated Mobility (BAM) Forum (Grove, 2021).

REFERENCES

Baker, S., Alden, A., Grove, K., Cristian, D., Hall, A., & Link-Owens, C. (2022). *Automated Last Mile Connectivity for Vulnerable Road Users–Participant Survey Study* (No. CATM-2022-R7-VTTI). North Carolina A&T State University. Transportation Institute. Center For Advanced Transportation Mobility.

Davis, M. G., Fox, K. R., Hillsdon, M., Coulson, J. C., Sharp, D. J., Stathi, A., & Thompson, J. L. (2011). Getting out and about in older adults: The nature of daily trips and their association with objectively assessed physical activity. *International Journal of Behavioral Nutrition and Physical Activity*, *8*(1), 116.

Grove, K., and Alden, A. (2021). *Low-Speed Autonomous Shuttles-Lessons Learned from Real-World Implementation.* No. 2021-01-1010. SAE Technical Paper.

Li, G., Braver, E. R., & Chen, L. (2003). Fragility versus excessive crash involvement as determinants of high death rates per vehicle-mile of travel among older drivers. *Accident Analysis & Prevention*, *35*(2), 227-35.

SAE International. (2021), *SAE Levels of Driving Automation Refined for Clarity and International Audience.* https://www.sae.org/blog/sae-j3016-update

Shepardson, D. (2020, February 25). U.S. agency slams brakes on self-driving EasyMile shuttles after passenger injury. Reuters. https://www.reuters.com/article/us-autos-selfdriving-idUSKBN20J2N6

Stutts, J., Martell, C., & Staplin, L. (2009). *Identifying behaviors and situations associated with increased crash risk for older drivers* (No. HS-811 093). National Highway Traffic Safety Administration.

U.S. Census Bureau. (2018). *Older people projected to outnumber children for first time in U.S. history.* https://www.census.gov/newsroom/press-releases/2018/cb18-41-population-projections.html

APPENDIX A: PUBLICATIONS, PRESENTATIONS, AND POSTERS RESULTING FROM THIS PROJECT

Publications:

Grove, Kevin, and Andrew Scott Alden. *Low-Speed Autonomous Shuttles-Lessons Learned from Real-World Implementation*. No. 2021-01-1010. SAE Technical Paper, 2021.

Presentations:

Volpe on *FTA Automated Vehicle Testing*, by Andy Alden, Blacksburg, VA (3/13/2018)

Pennsylvania AV Summit on *Automated Freight*, by Andy Alden, Pittsburgh, PA (4/9/2018)

WVAMPO/WVLTAP conference, *Autonomous Vehicles: Are We Ready?*, by Andy Alden, Morgantown, WV: (4/18/2018)

American Meteorological Society AV conference, by Andy Alden, Washington, DC: *Weather Impacts on AVs*, (4/25/2018)

APICS DC Metro DC Chapter Meeting, Future Transportation – *How Automation and Intelligent Systems Will Impact the Movement of People and Goods*, by Andy Alden, Greencastle, PA, (4/26/2018)

CTAV Young Professionals in Transportation - Training & Networking Symposium, *Transportation Trends,* by Andy Alden, Blacksburg, VA: (4/27/2018)

Virginia Unmanned Systems Advisory Board, *VTTI Overview on AV Research*, by Andy Alden, Richmond, VA; (August 22, 2019).

VTTI Onsite Demonstration of the CATM Last Mile Project Autonomous Shuttle and presentation on current research for Nissan Corp., by Andy Alden and Kevin Grove, (July 9, 2019)

Extended meeting on the topic of low-speed autonomous vehicle (LSAV) deployment in Virginia. Approximately 30 participants included representatives from Fairfax County, Virginia Beach and Dominion Electric Power. Presentation by Kevin Grove Kevin on VTTI's experience with the EasyMile LSAV as part of this project. (1/30/2020).

Hampton Roads Innovation Collaborative Tech Tuesday, *Developments in Ground Automation*, presentation and panel discussion by Andy Alden, (5/25/2021)

VDOT CAV Readiness Workshop, VTTI and CAV Issues and Research, by Andy Alden (6/3/2021)

NCAT CATM Symposium, Automated Last Mile Connectivity for Vulnerable Road Users – Project Update, by Andy Alden, 11/5/2018