Evaluation Tools for Low-Speed Automated Vehicle (LSAV) Transit Readiness of the Area

November 2022 | Final Report

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SAFETY THROUGH DISRUPTION

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TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No. VTTI-05-113	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Evaluation Tools for Low-Speed Automated Vehicle (LSAV) Transit Readiness of the Area		5. Report Date 11/22/2022 6. Performing Organization Code:
7. Author(s) Yubin Hong, Sheila Klauer, Mike Mollenhauer, Jean Paul Talledo Vilela, Noah Goodall, Michael D. Fontaine		8. Performing Organization Report No. VTTI-05-113
9. Performing Organization Name and Address: Safe-D National UTC Virginia Tech Transportation Institute in cooperation with the Virginia Transportation Research Council		10. Work Unit No. 11. Contract or Grant No. 69A3551747115/Project 05-113
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 Start Date:01/01/2021 End Date: 12/31/2022 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

Automated shuttles are small, low-speed (generally less than 25 mph) vehicles that do not require a human operator, though to date all have included an onboard human attendant. This project aims to assess the limitations that the EasyMile EZ10 Gen 3 low-speed automated vehicle (LSAV) encountered while operating on public roadways. The primary interests are to evaluate the infrastructure elements that posed the most challenges for the LSAV during its deployment. Further, the EasyMile EZ10 Gen 3 is advertised as being capable of operating at SAE International Level 4 Automated Driving System capability in certain ODDs. Accordingly, the team deployed the LSAV with the expectation that it would be operated at SAE Level 2 capability. The human safety operator was required to intervene in scenarios beyond the vehicle's automated functional capability. The results of this analysis indicated that the LSAV operated at a lower than expected speed, experienced a high frequency of disengagements, and had a regular need for safety operator intervention. These results suggest that the EZ10 Gen 3 vehicle is not yet operating at SAE International Level 4 capability on routes with moderate complexity.

17. Key Words	18. Distribution Statement
Automated vehicles, Public transportation, LSAV, First/last mile service, Naturalistic data, Safety analysis	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)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	20	$0

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

Abstract

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Acknowledgements

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Introduction

Automated shuttles are small, low-speed (generally less than 25 mph) vehicles that "do not require a human operator, although early demonstrations all have included an onboard human attendant to observe passengers, record data, answer questions, and serve as a safety operator if needed" (Valdes et al., 2018). The Federal Transit Administration has included these vehicles in their Strategic Transit Automation Research Plan (2018), intending to address two main service challenges: (1) first/last-mile connections and (2) serving low-demand corridors and areas (Nesheli et al., 2021).

Multiple deployments of these low-speed automated vehicles (LSAVs) have been carried out across the US in locations such as Ann Arbor, MI, and Arlington, TX, as well as in larger cities such as Minneapolis, MN; Rochester, MN; Denver, CO; and Las Vegas, NV (Kolodge et al., 2020; Haque et al., 2020; AECOM Technical Services, 2020). In all of these deployments, research was conducted to assess rider acceptance and operating performance. While rider acceptance was generally high for most locations, the northern deployments found that the shuttles did not operate well in extreme weather conditions (e.g., heavy snowfall and cold temperatures reduced electric battery life). Additionally, several programs also found that the human operators were taking control of the LSAV more frequently over time, perhaps to avoid a hard braking event, which could potentially result in safety conflicts with other road users and passenger injury or discomfort, as these events are unexpected and sometimes without apparent reason. The speeds at which the LSAVs travel are slower than surrounding traffic, which may impact traffic flow and contribute to unsafe interactions between the LSAV and other road users (e.g., drivers may try "to beat" the LSAV by passing illegally or turning in front, which can cause the LSAV to stop suddenly).

The Relay pilot project (https://www.fairfaxcounty.gov/transportation/autonomous-shuttle-pilot) began in 2020 as a partnership between the Virginia Tech Transportation Institute (VTTI), Fairfax County, Dominion Energy, the Virginia Department of Rail and Public Transportation (DRPT), the Virginia Department of Transportation (VDOT), George Mason University, and EDENS (Mosaic developer) to deploy and evaluate the effectiveness and safety of a low-speed automated shuttle in Merrifield, VA. This Relay deployment project was conceived by Fairfax County's Department of Economic Initiatives to expand the county's research base, position Fairfax and the Commonwealth of Virginia as leaders and innovators in smart community initiatives, strengthen economic assets, and diversify the local economy. With a $200,000 grant from the DRPT, a $50,000 match from Fairfax County, and a partnership with Dominion Energy, this pilot is the first state-funded autonomous public transportation demonstration project in Virginia. The goals and purpose of the project included the following:

1) Position Fairfax County and Virginia as leaders and innovators in electric connected autonomous vehicle (CAV) technology.
2) Deepen the innovation ecosystem and develop smart community emerging sectors
3) Grow local businesses and attract new businesses to Fairfax County in CAV and CAV-related industries
4) Expand the CAV technology research base, including public attitudes, CAV integration into a public transportation environment, and infrastructure communication technology

5) Determine the operational and economic viability of an autonomous shuttle as a business generator, first- and last-mile mobility solution, and a public space activator
6) Arrive at a better understanding of urban transportation design and its importance in integrating technology in public spaces and civic infrastructure.

The deployment utilized an EasyMile EZ10 Gen 3 (Figure 1) low-speed autonomous electric shuttle operating at a maximum of 12 mph on a circulator route on public roads in Merrifield, Virginia, located in Fairfax County. The EZ10 has been used in over 200 deployments, holds up to 12 passengers, and features a complete set of sensors, including LiDAR, cameras, and real-time kinematic corrected GPS. The EZ10 Gen3 is about 6 feet wide, 13 feet long, and 9 feet tall. There are two operating modes: manual mode, in which an operator must manually drive the vehicle using a remote-control unit (used to prepare the vehicle for autonomous mode and/or when the operator needs to drive outside the predefined trajectory or for any other necessary intervention), and an autonomous mode, in which the vehicle is self-driven by EZ Drive (EasyMile's navigation software) and follows programs and missions. According to the EZ10 Gen3 User Guide, when using EZ Drive, the EZ10 can be safely operated in the following conditions of operation:

- Up to medium-high snowfall (but snow may slow down or stop the vehicle)
- Up to medium (0.4 in/h) or heavy rain (> 0.4 in/h; but rain may slow down or stop the vehicle)
- Water accumulation or flow (up to 0.4 in of water at 12.4 mph or 0.8 in of water at 6.2 mph; but water dispersion may affect components under or around the vehicle)
- Ice or snow on the road (up to 0.4 in of snow or ice; but slippery ground may cause safety issues and E-stops due to a loss of friction)
- Humidity between 5% and 95%
- Wind up to 31 mph
- Dust, fog, or vapor up to 3.2 ft visibility
- Temperature during operation between 14–113 degrees Fahrenheit
- Temperature during storage between 23–94 degrees Fahrenheit in charge mode and 32–95 degrees Fahrenheit when not in charge
- Slope up to 15% for a limited time
- Payload up to 1.1 US ton

Figure 1. Fairfax Relay EasyMile autonomous electric shuttle.

The SAE J3016 standard defines five levels of driving automation capability and whether a driver or Automated Driving System (ADS) is expected to be in control of the vehicle (see SAE International's website for a detailed graphic representation of levels; SAE International, 2021). The EasyMile EZ10 Gen 3 is advertised as being capable of operating with SAE International Level 4 ADS capability in certain operational design domains (ODDs). However, a route was chosen for this deployment that would satisfy a legitimate transit need rather than a restricted ODD. As a result, the route included more operational complexity and higher traffic volumes than a typical EasyMile LSAV deployment. As a result, the team approached the deployment with the expectation that the LSAV would be operated at SAE Level 2 capability, with the human safety operator being required to intervene in scenarios that were beyond the vehicle's automated functional capability.

The shuttle operated between the Dunn Loring-Merrifield Metrorail Station and the corner of Merrifield Town Center Drive and District Avenue in the Mosaic District to provide first- and last-mile transportation to passengers (Figure 2). The LSAV route was comprised of two to four travel lanes in an urban business area with a 25 mph speed limit. On this route, the LSAV traveled through two signal-controlled intersections and multiple intersections controlled by stop signs.

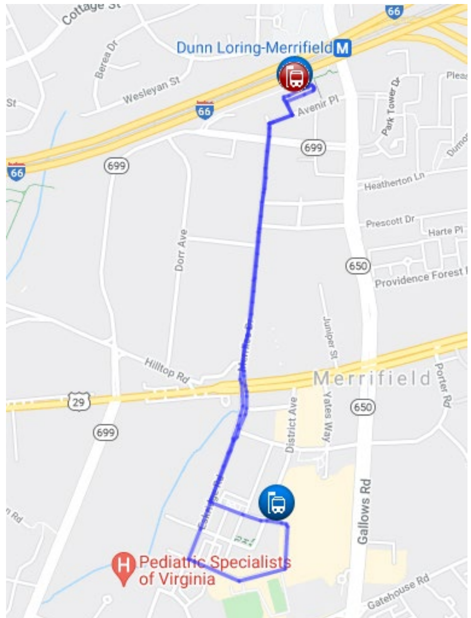

Figure 2. Fairfax Relay autonomous electric shuttle route.

The LSAV was operated by a third-party mobility company called Transdev and ran Monday through Thursday between the hours of 10:00 a.m. and 2:00 p.m. In compliance with National Highway Traffic Safety Administration regulations, a human safety operator was onboard at all times to monitor safety while the LSAV was in operation.

Purpose and Scope

The results documented in this report represent an evaluation of the EasyMile EZ10 Gen3 vehicle between October 2020 and May 2021. These results are a summary of the vehicle's performance and reflect the configuration and capability of the automated technology and the infrastructure-related limitations that the vehicle encountered during this period. This project aims to assess the infrastructure-related safety implications of having a low-speed, autonomous shuttle operating on public roadways in mixed traffic. The primary interests are as follows:

1. Based on the results from the safety analysis, what are the infrastructure elements and traffic conditions that have negative effects on LSAV performance?
2. What limitations should be considered while planning for a potential LSAV or automated transit vehicle deployment?
3. How can transit planners adjust and improve the deployment program as it unfolds?

Methods

Overview

In this study, the VTTI research team was responsible for the following tasks:

1. Instrumented the LSAV with a data acquisition system (DAS)
2. Obtained/compiled data to identify five event types of interest
3. Performed video coding on these events
4. Identified undesirable infrastructure elements for the LSAV
5. Constructed a checklist of items to consider when planning a future automated transit deployment for transit planners

Instrumentation of the LSAV

As part of this pilot program, VTTI instrumented the shuttle with a DAS and cameras. VTTI also was able to collect the traffic Signal Phase and Timing (SPaT) data that was broadcast from two large, signalized intersections that were included on the LSAV's fixed route. Data collection began in October 2020 and is ongoing; however, this final report will provide results only from the first seven months of data collection (October 21, 2020, through May 18, 2021).

VTTI instrumented the LSAV with a DAS that was designed in-house at VTTI; this DAS (referred to as FlexDAS) was developed previously and then functionality was modified for this specific application. Figure 3 shows a diagram of the DAS installation at the rear of the LSAV shuttle in the left, lower space (marked #1). The GPS antenna was mounted near the window at the top of the LSAV (marked #3). The FlexDAS was primarily responsible for collecting and storing the continuous video from five separate cameras, kinematic acceleration and orientation data from an inertial measurement unit, and vehicle location and speed from the GPS sensor. The labels in the image correspond to the following:

1. FlexDAS
2. Constant power fuse tap
3. GPS antenna
4. Chassis Ground
5. Ethernet extensions and SSD

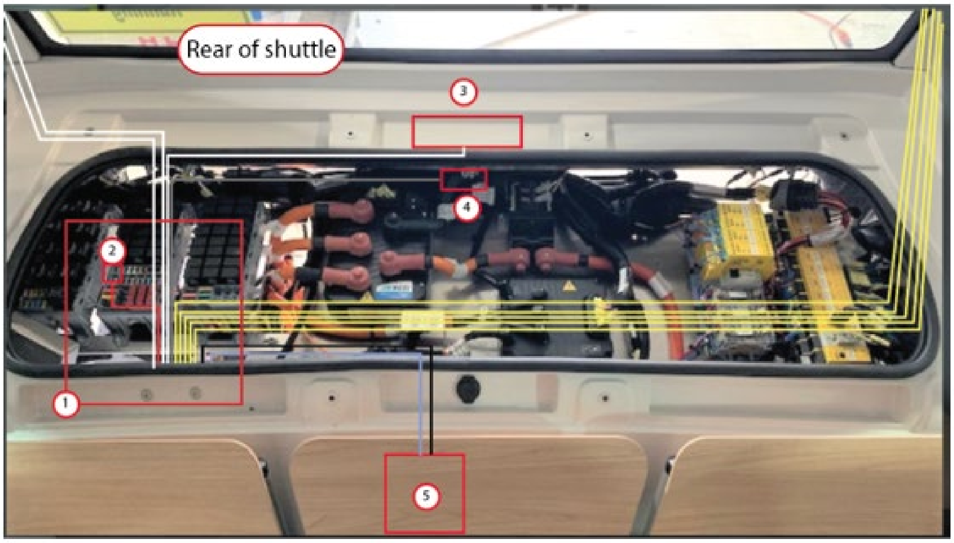

Figure 3. Diagram of the location of the VTTI FlexDAS at the rear of the LSAV.

There were five cameras installed onboard the LSAV shuttle, each of which collected continuous video when the LSAV was in operation. These five cameras recorded (1) the forward view, (2) inside the shuttle, (3) toward the left side of the shuttle, (4) the rearward view, and (5) toward the right side of the shuttle. The external cameras provided 360-degree coverage around the LSAV, allowing the research team adequate visibility of conditions around the vehicle during the disengagement events. These camera views were selected to capture traffic interactions with a wide variety of road users, including pedestrians and pedal-cyclists, as well as the impact of the disengagements on any passengers onboard at the time of the event. Cameras captured the forward view, inside the LSAV shuttle, the outside left side of the shuttle, the outside rear of the shuttle, and the outside right of shuttle.

The LSAV's route included the traversal of two large arterial intersections at US 29 and Merrilee Drive and Prosperity Avenue and Merrilee Drive. The US 29 and Merrilee Drive intersection was already outfitted with a Dedicated Short Range Communications (DSRC) Road Side Unit radio and interface to the traffic signal controller that allowed the broadcast of SPaT data over SAE J2735 communication protocols. VTTI added a second DSRC Road Side Unit and controller interface to the Prosperity Avenue and Merrilee Drive intersection to support safe intersection traversal there as well. In addition, EasyMile installed a DSRC Onboard Unit to receive the SPaT data and feed it into their automated control systems. Due to the low speed of the LSAV, a third party Transit Signal Priority (TSP) system was also installed at both intersections, which was intended to allow the LSAV to request an extension of the green phase for up to 15 seconds so it would have adequate time to fully traverse the intersection before the yellow and red phases were initiated. VTTI forwarded the SPaT data to a data archive server so it could be used to evaluate the reliability and performance of the LSAV under this control scheme.

Event Type Definitions and Video Coding

Data were recorded continuously via the onboard VTTI FlexDAS while the LSAV was operational. Given that it was not possible to review every second of the continuous video, specific segments of video during which any of the following events were reported were selected for review by trained data coders. The events were identified through the disengagement report provided by the LSAV manufacturer. The types of identified events were:

- E-stops
- Soft Stops
- Circumventions
- SPaT Violations

E-stops, events where the LSAV safety system logic initiated a hard brake maneuver (averaging 0.3 g deceleration) culminating in a complete stop, were identified using a monthly disengagement report provided by EasyMile. This deceleration rate was enough to cause unsecured objects or passengers to slide off seats if not belted in or holding on. These reports included a Universal Time Coordinated time stamp for each disengagement that could be correlated to the DAS timestamp recorded with the video and sensor data. All of these events were reviewed by trained data coders and further classified as valid or invalid. Valid events were those where there was a clear obstacle or threat present in the video, and invalid events were those where it was not possible to determine an apparent reason why the system performed such a stop or what "obstacle" was detected by the software.

Soft stops were manually initiated by the human operator in response to a situation they observed where they wanted to bring the vehicle to a less aggressive stop. The soft stop event resulted in braking to a stop with a 0.05 g rate of deceleration. Over time, operators learned which situations would likely result in an E-stop or unsafe condition and would initiate a soft stop to avoid a more aggressive E-stop. Soft stops were also documented in the disengagement report provided by EasyMile. Additionally, after some of these soft stops, the human operator also needed to maneuver around an obstacle manually (e.g., encountering a double-parked vehicle within the path of travel defined for the LSAV). The periods of time where the safety operator was manually controlling the vehicle were defined as circumventions and are detailed further below.

As described above, circumvention events were when the human operator took manual control of the LSAV and physically maneuvered around an obstacle using controls located onboard the LSAV. Circumvention events typically occurred after either an E-stop or soft stop disengagement. Circumventions were also reviewed by data coders to look for any safety-critical situations that may have occurred while the operator was maneuvering the vehicle. The total numbers of events by trigger type are presented in Figure C-1 in Appendix C.

Traffic signal conflicts were defined as events where the LSAV was found to be operating within the confines of the intersection when the traffic signal had turned yellow or red for the LSAV's lane, and the direction of travel and the opposing traffic had a green signal. Theoretically, the SPaT and TSP should have kept this condition from occurring, but the research team did find a number of occasions where it was observed in the data and video record for both equipped intersections. Archived SPaT data from the two intersections were synchronized with LSAV GPS timestamp and position data from the FlexDAS to identify any time when the LSAV was observed within the intersection during a yellow or red phase. VTTI had SPaT data for two intersections: Merrilee Drive and US 29 (northbound and southbound), shown in Figure C-2, and Prosperity Avenue and Merrilee Drive (northbound and southbound), shown in Figure C-3. Both are busy arterial intersections with multiple turn lanes from each approach and a physical size that required significant time to cross, given the LSAV's 12 mph operating speed. The frequencies of SPaT triggered events (including instances where the LSAV was within the intersection during changes to yellow or red phases) by intersection during the seven-month data collection period are shown in Figure C-4.

Event Coding Procedures

The video and DAS onboard the LSAV allowed trained data coders at VTTI to review the video surrounding the event of interest and identify potential contributing factors, environmental conditions, and the role of other road users for these events. There were two parts to the data coding for E-stops: soft stops and circumventions. The first part of the coding protocol was conducted for every disengagement event identified in the dataset. The variables in the first protocol reported the trigger type and reason for the trigger, as well as environmental conditions, passenger presence, and the potential role of other road users in the event. The second part of the data coding protocol sought to provide a more detailed classification of context if a safety-critical event or interaction was determined to have occurred. For this protocol, a safety-critical event was defined as any event where the operator's, passengers', or other road users' safety was compromised, resulting in a crash, near-crash, crash-relevant conflict, or proximity conflict. If a safety-critical event also occurred as a result of this triggered event, additional variables were coded that provided information regarding the sequence of events surrounding the event and the role of other road users. The variables that were coded as part of this review are listed in Table 1. The complete data coding protocol that the data coders followed is provided in Appendix A.

Table 1. Data Elements Included in the LSAV Data Coding Protocols for the Safety Analysis

Variable	Options
Trigger type	Reason for the triggered event, either stopped shuttle or a SPaT violation
Trigger reason	Reason that the vehicle may have come to a stop
Road users present	Were other road users (i.e., vehicle, pedestrians) present when triggered event occurred
Road user position	Position of other road users in relation to LSAV
Traffic density	Level of traffic flow or Level of Service at the time of the triggered event
Weather	Weather condition at time of event
Surface condition	Surface condition at the time of the event
Pre-incident maneuver	LSAV maneuver just prior to the triggered event
Passenger presence	Were passengers onboard at time of triggered event and, if so, seating location
Passenger seat belt/seat belt unknown	Any seatbelt location where no seatbelt was worn (due to camera angle, sun glare, it was sometimes not possible to detect if seatbelt was being worn or not)

Variable	Options
Passenger ages	General age group of passenger(s) onboard LSAV
Passenger effects	Were passengers negatively impacted by sudden stopping of the vehicle (i.e., stumbled, fell, etc.)
Provoked behavior	Any illegal, unsafe, or aggressive behaviors provoked in other road users surrounding the triggered event (e.g., other vehicle takes right-of-way)
How many safety critical incidents took place surrounding the event	Any conflicts with LSAV (direct) or other road users (indirect) surrounding this triggered event
If safety critical event occurred:	
Precipitating event	Action that started the safety critical conflict (e.g., LSAV slowed to a stop)
LSAV Fault	Whether LSAV was at fault, partial fault, or not at fault for the occurrence of the safety critical event
Interaction count	Number of conflicts occurring within the triggered event
Direct/Indirect	Whether the interaction involved the LSAV (direct) or only involved other road users (indirect)
Interaction severity	If the interaction was a crash, near-crash, or critical incident
Interaction type	Similar to type of crash/near-crash (e.g., road departure, rear-end strike)
Interaction nature	Type of conflict (e.g., conflict with lead vehicle)
LSAV Evasive Maneuver	Whether the LSAV performed an evasive maneuver
Other actors	Other type of road user(s) involved
Location of other actors	Other road user(s)' position(s) in relation to the LSAV
Other actor pre-incident maneuver	Other actor's maneuver prior to the triggered event
Other actor behavior	Other actor's behavior that may have contributed to triggered event (i.e., illegal pass)
Visual obstruction	Any visual obstructions as part of the natural environment that may have contributed (i.e., hill crest)
Infrastructure Contributing Factors	Any infrastructure contributing factors (i.e., roadway alignment)
Incident notes	Text box where the coder could write anything additional that was not captured in the above coding protocol

For the traffic signal conflicts, the coding was further simplified to only record whether the LSAV was within the bounds of the intersection (defined as between the stop bar at the entry of the intersection and the crosswalk at the exit of the intersection) at the time of the signal phase change. Data coders also recorded whether the signal was yellow or red. If the signal was red, the LSAV Event Reduction protocol was also completed (See Table 1).

Segmentation of the Route

In addition to the manual reduction of events, an automated reduction process relating the triggered events and safety-critical events to different segments on the route was performed to examine the effect of different infrastructure elements on the LSAV's performance. This reduction was achieved by constructing a GPS map of the deployment route. The whole route was broken into 54 sections, and the GPS coordinates for the four corners of each section were identified and recorded. These coordinates served as a geofence for each of the route sections. For each of these 54 sections along the route, the research team utilized video data, Google Earth, and VDOT knowledge to determine the infrastructure elements of interest that were present. The LSAV's performance was measured using kinematics data, rates of triggered events, and safety-critical events. For each identified triggered event and safety-critical event during the previous reduction process, the GPS location of the event was coded and localized to different sections of the route according to the GPS map constructed. The GPS map and the infrastructure elements coded are shown below in Figure 4 and Table 2. The list of all route sections is included in Appendix B.

Table 2. Infrastructure Variables Included in the LSAV Data Coding Protocols for the Infrastructure Analysis

Infrastructure Variables	Definition	Examples
Route section type	Type of route section	Road segments /signal controlled intersections, etc.
Lane configuration	Number of lanes, turning lanes and bike lanes	Two-lane road with bike lane, etc.
Clear marking	Whether there is clear marking on the road or not	Without clear marking/with clear marking
Special elements	Open areas, parking lot entrances, visual obstructions and other special elements worth noting	Loading area, residential areas, bus terminals etc.

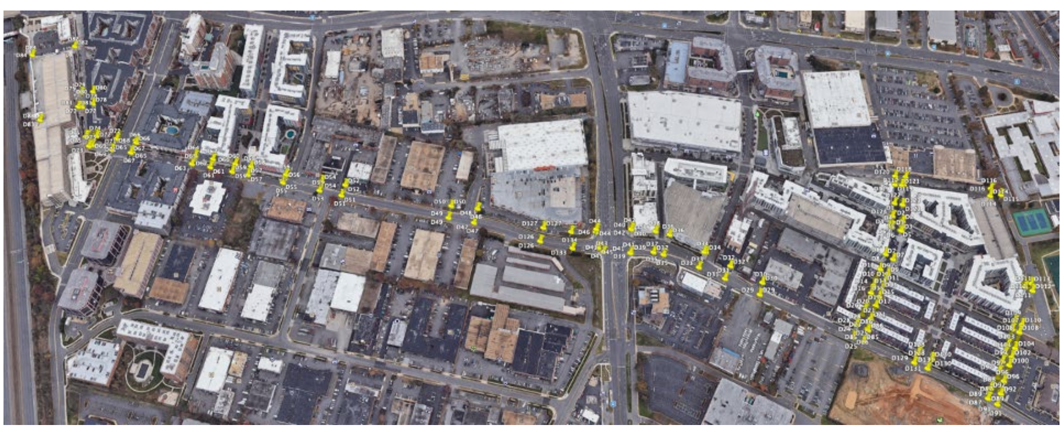

Figure 4. Route GPS map with GPS coordinates.

Using the GPS map and results from the safety analysis, the research team was able to relate the LSAV's performance with different infrastructure elements along the route. After all the events were coded and assigned to different route sections, the event rates under different infrastructure elements were calculated using the triggered event and kinematic data gathered for each route section and collapsed across the infrastructure element. This provided the research team the ability to compare the LSAV's performance under different infrastructure elements and configurations. The research team identified some infrastructure elements that can pose a threat to LSAVs and the most complex configuration of infrastructure elements for the LSAV. The infrastructure configurations were identified by locating the most problematic route sections and analyzing the infrastructure elements present in these sections. The research team identified the three route sections with the highest rates of triggered events.

Intelligent Transit Service Interview

To better apply the results from the LSAV deployment to future deployments for automated transit buses, the project team presented results from the LSAV deployment to Intelligent Transit Service experts at Blacksburg Transit. Results were presented and critical information was obtained through an interview with these ITS experts. The experts provided valuable information from the point of view of transit operators, planners, and management. Their unique perspectives revealed more limitations of the LSAV system itself that should be considered while planning an automated transit deployment project. They also made a comparison between conventional transit buses and automated transit systems and pointed out that experiences and planning protocols for conventional transit buses were still applicable to automated transit systems. Based on their recommendations and results from the project, a checklist of comprehensive recommendations was developed for transit planners to consider before planning for future automated transit system deployments.

Results

The following results sections are organized by the flow of the reduction. An overview and infrastructure-related distribution of triggered events are presented first since these events served as a basis for further reductions. The second part presents the distribution of safety-critical events by infrastructure elements. A total of 41 safety-critical events were identified based on the reduction of the triggered events. Finally, the results from kinematic data analysis and the most problematic route sections identified are presented.

Per the defined scope of the research effort, these results were evaluated for data collected during the first seven months of data collection (October 21, 2020, through May 19, 2021). When appropriate, the results are presented in event rates per mile traveled to make for a standardized comparison. It is important to note that these data were collected during the height of the first wave of the COVID-19 pandemic. Thus traffic patterns, pedestrian traffic, and even passenger presence represented in these data may not reflect the type, frequency, or severity of interactions that may have been seen during non-pandemic times. However, these data represent the best data available for this analysis. Therefore, while the results derived from this data set provide information regarding this pilot deployment, the results should also be interpreted with the aforementioned caveat in mind. In addition, the results section provides descriptive statistics only, as this pilot project is focused on one LSAV vehicle operating on a limited schedule (Monday through Thursday from 10:00 a.m. until 2:00 p.m.).

Overview of Triggered Events

The total numbers of E-stop, soft stop, and circumvention events per mile traveled by month of data collection are presented in Figure C-5. The events per mile/month metric provide an indication of how well the LSAV's automated control systems were able to manage the operational requirements and complexities of the route. Higher frequencies of disengagement suggest the automated control capabilities could not fully manage the interactions on the route without exiting automated control or relying on human intervention. The rate of soft stops was highest, followed by circumventions and then E-stops. Additionally, it appears that the rate of soft stops increased over time, whereas the rate of E-stops appeared to decrease over time. The rate of circumventions was similar to soft stops in that it appeared to increase over time.

Data coders recorded the reason that the LSAV stopped for each disengagement event. Since the FlexDAS was not able to record any system-generated data regarding disengagement causation, the reason classification was determined in this protocol by evaluating the video and FlexDAS sensor data relative to the context of the event. Figure C-6 shows the rate per mile traveled for each of these reasons for stopping/circumvention by event type. Note that the most frequent reasons for stopping included oncoming traffic, parked vehicle, and pedestrian presence. Additionally, the rates of events per mile traveled that were coded as other and unknown reasons were quite high, which will be further explained below.

The unknown category accounts for those events where the analyst simply could not identify a likely reason for the event to have triggered in the available video and FlexDAS data sources. Some potential causes of unknown triggers include changes in the shape or density of foliage near the roadway, sensor malfunctions, or system defects. EasyMile support staff was made aware of this issue and communicated their plans to provide a technology upgrade that they claim will help resolve or reduce the occurrence of these unnecessary E-stops. The installation of this upgrade did not take place in time for the VTTI team that is reviewing the data to make any conclusions about its effectiveness.

Triggered Events Results by Infrastructure Elements

The distribution of triggered events by infrastructure elements revealed some of the challenges the LSAV faced in real-world environments. These results further show in detail the safety limitations of the LSAV's ADS. All LSAV-triggered events reported were placed on the route map to create a heat map, which aimed to clearly show the locations on the route where the LSAV was experiencing the most disengagements. Figure 5, Left shows the distribution of all the soft stops and circumventions during the LSAV's operation. These soft stops and circumventions are also uniformly distributed, with some segments not containing any soft stops or circumventions. Figure 5, Right shows a heat map of all E-stops that were identified during the LSAV's operation. Again, the distribution of event locations is relatively uniform across the route segments, with slightly fewer issues near Merrifield Cinema Drive. Figure C-7, Figure C-8, and Figure C-9 show the rates of triggered events under different infrastructure elements.

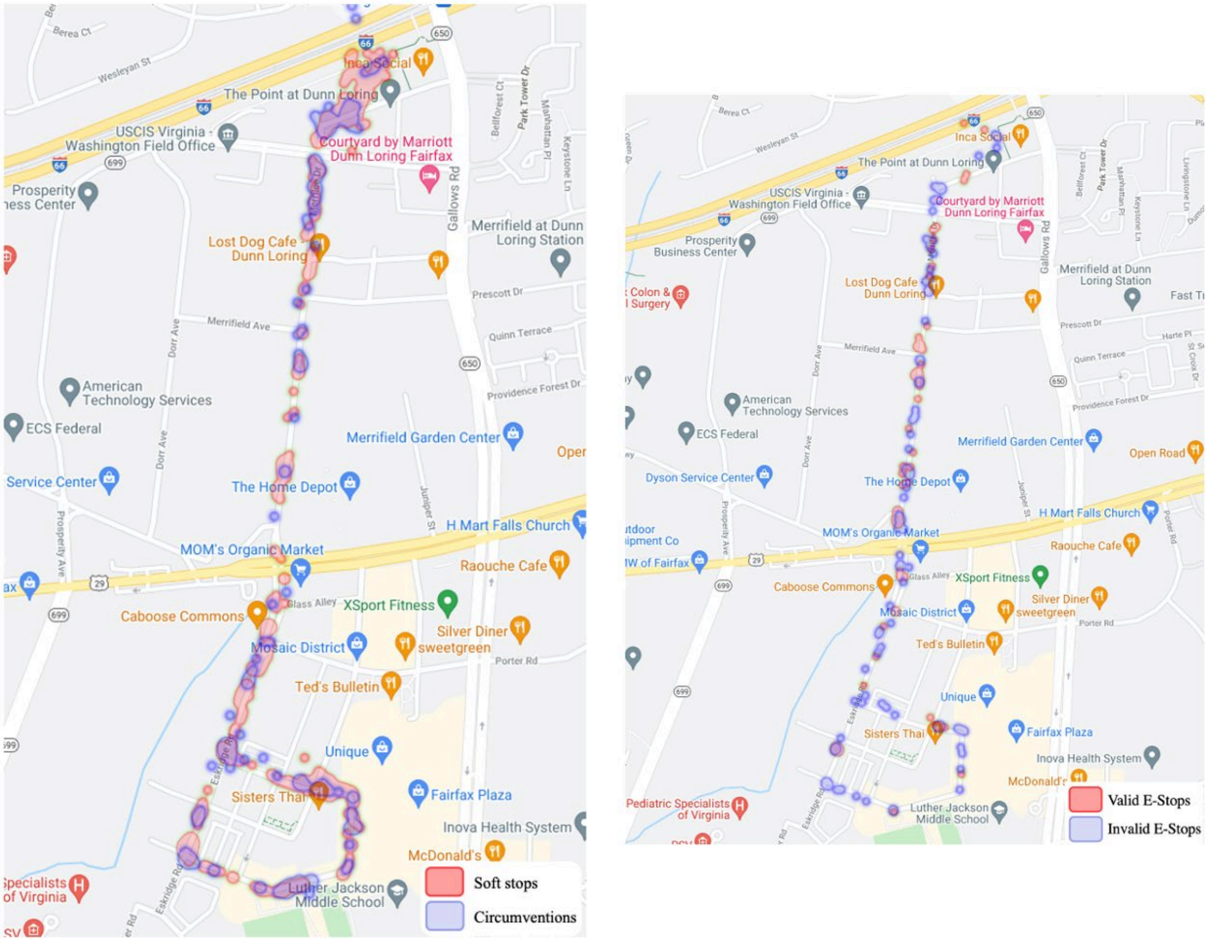

Figure 5. Left: distribution of soft stops and circumventions along the LSAV route – red represents soft stops and blue represents circumventions. Right: distribution of E-stops along the LSAV route – red represents valid E-stops and blue represents invalid E-stops.

The research team found that route sections with stop sign-controlled four-way intersections showed the highest rates in circumvention and soft stops, while route sections with T-intersections showed the highest rate for valid E-stops (see Figure C-7).

The results from Figure C-8 showed that route sections with three-lane roads (shared turning lane in the middle) had the highest rate of soft stops and valid E-stops compared to other types of lane configurations.

It is clear from the results in Figure C-9 showed that route sections with no clear marking on the pavement showed higher rates of soft stops and circumventions while route sections with clear marking had higher rates for valid E-stops.

Safety-Critical Event Results

The following results will discuss those E-stops, soft stops, and circumventions that also resulted in a safety-critical incident. Recall that 41 of these events were further coded as safety-critical events. A crash relevant conflict is defined as any circumstance that requires an evasive maneuver on the part of the subject vehicle or any other vehicle, pedestrian, cyclist, or animal that is less urgent than a rapid evasive maneuver (which is defined as a Near Crash), but greater in urgency than a "normal maneuver" to avoid a crash. A crash avoidance response can include braking, steering, accelerating, or any combination of control inputs. There were no crashes observed during the data gathering period.

Figure C-10 shows that stop-sign controlled four-way intersections had a significantly higher rate of safety-critical events when compared to other route section types.

The results from Figure C-11 show that route sections with three-lane roads (shared turning lane in the middle) had the highest rate of safety-critical events when compared to other types of lane configurations.

When designated turning lanes were present in the route section, the LSAV experienced higher rates of safety-critical incidents, as shown in Figure C-12. Right turn lanes were more problematic than left turn lanes. Parking lot entrances could be problematic as well, especially when several parking lot entrance ramps converged into a single route section.

Kinematics Data Analysis Results

Kinematic data can serve as a reliable indicator of the LSAV's performance on public roads. The LSAV's operational speed was designed to be 12 mph, and the speed limit along the route was 25 mph. The 14 mph speed was due to the limitations of the LSAV's automated systems and their conservative automation algorithm. However, the actual operating speed calculated using the gathered kinematics data was determined to be significantly lower than the purported 14 mph operational speed.

As seen in Figure C-13 and Figure C-14, the results showed that the LSAV did not reach its planned operational speed of 14 mph. For intersections and open areas along the route, the average speed was between 4 to 8 mph, with T-intersections showing the highest speed distributions and Y-intersections showing the lowest speed distributions. The average speed distribution was relatively consistent across different types of road segments, around 6 mph. The lowest speed distribution was seen on two-lane roads, and the highest was on multilane roads, which is consistent with the trend seen in regular traffic. To evaluate the effect of triggered events on the LSAV's average speed, the research team also conducted the same kinematics analysis without triggered events, finding no significant change in the results.

Most Problematic Locations Along the Route

The research team identified a total of three route sections as the most problematic for the LSAV. Three intersection type route sections and three road-segment type route sections were selected based on the number of triggered events recorded within them. Interestingly, the two lists of three matched up perfectly. For each of the road segments identified as problematic, the intersections following the road segments were identified as problematic. Thus, the two lists were combined into one list of the most problematic locations: the intersection in front of Dunn

Loring-Merrifield Metrorail Station, the intersection of Eskridge Rd and Merrifield Cinema Dr, and the open area on Merrifield Town Center Dr. The location, view, and LSAV's movements were captured to give the reader a more intuitive understanding of the infrastructure elements at these locations.

1. Intersection in front of Dunn Loring-Merrifield Metrorail Station. LSAV is traveling east bound and turning left (Figure C-15).
2. Intersection of Eskridge Rd and Merrifield Cinema Dr. LSAV is traveling south bound and turning left (Figure C-16).
3. Open area on Merrifield Town Center Dr. LSAV is following the road, which curves significantly to the left (Figure C-17).

Discussion

This infrastructure analysis focused on different infrastructure elements' effects on the LSAV's performance. Specifically, the effects of different intersection types, lane configurations, and clear markings were investigated. From the results, it is clear to the research team that stop sign-controlled four-way intersections and three-lane roads had the highest rate of safety-critical events when compared to other segment types/lane configurations. The research team assumed that the multi-lane, signalized intersections would be problematic initially, but the results suggested that they were not. This could be due to the fact that the deployment team communicated the SPaT information to the LSAV to ensure its clearance of the intersection. Three-lane roads had associated safety concerns due to vehicles passing the LSAV, potentially into oncoming traffic, and cutting in front of the LSAV, causing the E-stops. For triggered events, stop sign-controlled four-way intersections showed the highest rates of circumventions and soft stops, which can be attributed to the LSAV's conservative driving algorithms.

Additionally, the operator was more likely to intervene with the LSAV's regular operation when there are no clear lane markings. This is also confirmed by the higher number of valid E-stops when clear markings were present, which can be counterintuitive. Turning lanes can be problematic for the LSAV as well. When left-turn lanes, residential areas, open areas, and curvy roads are present, the rates for soft stops are significantly higher. The three most problematic locations along the route also confirmed that left turn lanes and left turn movements showed the highest rate of triggered events. However, the rates were higher for valid E-stops and safety-critical events when a right-turn lane was present. This could be due to the operator not paying as much attention when the LSAV is turning right since it is an easier maneuver compared to turning left.

Interestingly, the research team was informed by ITS experts that these infrastructure configurations are also problematic for conventional transit buses. This indicates that the LSAV's developers could use the experiences and feedback from conventional transit bus drivers to improve the LSAV's driving algorithm. Moreover, the research team saw an increasing rate of soft stops during the seven months of data gathering. A report from the LSAV deployment in

Ann Arbor, MI, also confirmed that human operators onboard intervened with the LSAV's normal operation more frequently as the deployment progressed. This was not necessarily for safety purposes but the comfort of passengers. This suggests that human operators adapt to a different intervention behavior during LSAV deployment, which shows that there is room for improvement of the ADS itself. The reasons and circumstances for the different operator interventions observed can serve as valuable feedback for the manufacturer to improve their algorithm as well. Neither the deployment management company nor the manufacturer provided such a feedback loop for current deployments.

The LSAV's low speed is also concerning from a safety perspective. Based on the collected data, the LSAV was determined to travel at an average of about 6–8 mph on the route, which has a posted speed limit of 25 mph. This was also confirmed by the operations report provided by the manufacturer/deployer. The LSAV's lower speed has several negative effects on the surrounding traffic environment. First, the LSAV's lower speeds can create a shockwave effect and increase traffic congestion on the road segment. Moreover, the LSAV's lower speed contributes to the illegal and risky passing behavior of following drivers. After reviewing the results from this study, gathering opinions from transit experts, and reviewing experiences from other deployments, the research team recommended limiting the operation of LSAVs in a normal traffic environment.

Other LSAV system limitations were identified through interviews with ITS experts. The research team believed that ITS experts' observations were relatable to the scope of this study and thus should be taken into consideration when evaluating the LSAV's performance and limitations. One of these limitations is that LSAVs currently do not have the ability to understand the riding positions of their passengers. The interview with ITS experts from Blacksburg Transit revealed that it is beneficial for a conventional bus driver to have a general understanding of onboard passengers' positions. This knowledge is taken into consideration to ensure passenger safety onboard while bus drivers make emergency or evasive maneuvers. Currently, there are no LSAVs that have the ability to perform this task, which makes some of the maneuvers abrupt, uncomfortable, and potentially risky for passengers onboard. Another limitation of LSAVs is their lower passenger capacity. The LSAV in this study did not see many passengers during the data gathering period. This could be due to the COVID 19 pandemic. However, ITS experts at Blacksburg Transit have pointed out that the low capacity of the LSAV can be problematic for its practicality even outside of the pandemic, especially paired with its lower speed. The research team suggests that the current ridership data and current transit routes be examined and studied before deployment of the LSAV to best take advantage of its functionalities. Based on the research team's findings, the LSAV is best used to fill the gap of first/last mile services and should be used on routes with lower conventional transit ridership.

An additional objective of this analysis was to apply knowledge gained to future automated transit systems. The main difference between LSAVs and automated transit systems are their passenger capacity and operation speed. Automated transit systems are designed to travel at 45 to

55 mph with the passenger capacity of a normal transit bus. Due to speed differences between the LSAV and automated transit systems, it is difficult to generalize some of the limitations identified from this analysis since these limitations are related to the LSAV's lower speed. However, the interview with ITS experts revealed that some of the limitations identified for the LSAV were also applicable to conventional transit buses. Thus, the research team argues that when designing deployment routes for automated transit buses, the guidelines for planning conventional transit buses should still apply. Moreover, this infrastructure analysis revealed that the mismatch between the speed limits along the route and the operational speed of the LSAV is quite problematic for normal operation of the LSAV. Thus, the research team suggests that when designing for future deployments of automated transit systems, the speed limit of the route should not exceed the designed operational speed of the proposed system.

Conclusions

Analysis of video data gathered from the 7-month deployment revealed the following:

1. Four-way stop sign controlled intersections and three-lane roads with a turning lane in the middle were generally problematic for the LSAV. Three-lane roads had safety concerns due to vehicles passing the LSAV, potentially into oncoming traffic, and cutting in front of the LSAV, causing e-stops.
2. Signalized intersections were not as problematic as the research team predicted. The LSAV was caught operating in the intersection during the yellow or red phase at least once a week, but the research team did not observe any safety-critical events and only a few triggered events.
3. Turning lanes are, in general, problematic. Right turn lanes see the highest rates of safety-critical events and e-stops, while left-turn lanes saw more circumventions and soft stops, which could be due to the operator not paying as much attention when the LSAV is turning right since it is an easier maneuver compared to turning left.
4. Residential areas, open areas, curvy roads, and segments without clear lane markings saw more circumventions and soft stops. This indicates that the human operator was more likely to intervene with the normal operation of the LSAV when these infrastructure elements or characteristics were present, which could be a representation of the LSAV's safety limitations, since human operators did not trust the ADS under these scenarios.
5. Some of the infrastructure elements (four-way stop sign controlled intersection and three-lane roads) identified as problematic for the LSAV are also known to be problematic for current transit buses. Thus, when planning for an LSAV deployment, current transit planning criteria may still apply.
6. LSAVs' low speed (6 to 8 mph) affects their efficiency and the traffic environments around them. The LSAV's lower speed induces illegal and risky passing behavior for following drivers, as well as shockwave effects along the route.
7. LSAVs currently do not have the ability to understand the positions of their passengers, which will make some of the automated maneuvers abrupt, uncomfortable, and potentially risky for passengers onboard. These maneuvers can be reduced through more comprehensive training of onboard human operators.

8. The LSAV's low passenger capacity can be problematic for its practicality, especially paired with its lower speed. LSAVs are currently best used to fill in the gap of first/last mile services instead of replacing current conventional transit buses and thus should be used on routes with low conventional transit bus ridership rates.

From these conclusions drawn, the research team developed the following checklist of recommendations for future LSAV or automated transit system deployments.

Desirable Route Characteristics

- ☐ **Low traffic volumes and speed limits**. LSAVs have low speeds (25 mph or less), and thus only roads with low traffic volumes and speed limit less than 25 mph should be considered.
- ☐ **Low passenger ridership**. LSAVs have low speed and passenger capacity, and thus routes with large ridership for conventional transits should <u>not</u> be considered.
- ☐ **Well -maintained pavements and clear pavement markings**. LSAVs perform best on roads with clear pavement markings. Well maintained pavements along the route would also be ideal for LSAVs.
- ☐ **Few unsignalized intersection turning movements**. These movements tend to be problematic for the LSAV—signalized intersections are safer in general.
- ☐ **Minimize visual obstructions and vegetation near the road**. Removing visual obstructions will improve system performance, and thus vegetation should also be trimmed. Falling leaves from trees may create unintended automated stops in the fall.
- ☐ **Dedicated right of way for LSAV**. Given their low speeds, negative safety interactions with other road used should be minimized by providing a dedicated right of way for LSAVs. These might include designated lanes and controlled access routes.
- ☐ **SPaT information for signalized intersections**. If traffic signals are present along the route, consider providing TSP to ensure the LSAV can clear the intersection during a green phase. Since LSAVs' speeds are much slower than most vehicles, TSP can ensure that they are not trapped in the intersection during a yellow or red phase.

Organizational Needs

- ☐ **Experienced operators**. Experienced human operators or bus drivers are ideal for performing as safety monitors.
- ☐ **Provide appropriate operator training**. To supplement standard training for transit operators, additional training should include sensitivity training for passenger safety, limitations of the automated system, potential risky situations LSAVs can experience and countermeasures for such situations.
- ☐ **Safety monitoring and feedback loop**. A transparent, precise, and efficient feedback loop based on ongoing safety monitoring of the deployment between trained operators, deployment organizers, law enforcement, and LSAV manufacturers would be helpful. Feedback from the operators should include results and concerns from ongoing safety monitoring.

Additional Guidance to Automated Transit

- ☐ **Higher operational speeds**. For automated transit systems with higher operational speeds, the speed limit of road segments along the route should not exceed the operational speeds of the systems.

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 located on the Safe-D Dataverse.

Education and Workforce Development Products

The results of the project were presented in poster format at Transportation Research Board Annual Meeting 2023. They were also presented through slides in class sessions for the Human Factors in Transportation class.

Technology Transfer Products

The finishing product for the project is a checklist for future low speed automated vehicle deployments. It has been submitted to our sponsors at Virginia Department of Transportation.

Data Products

A list of all safety critical events recorded during the data gathering period is provided on the Safe-D Dataverse.

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Appendix A. Fairfax LSAV Triggers + Incidents

Task Name for Logs: Fairfax LSAV

Fund to Charge: 467166

Document Location: \\vtti.ad.vt.edu\Data\Projects03\467030\Reduction\

Software Needed: Hawkeye (current SCCM version), Excel

Collections: FairfaxLSAV

Security Group(s) Needed: Projects-Reductionists, Projects-IRB-Certified, Projects-467030-Reductionists,

Database Roles Needed: FairfaxLSAV_Reductionist

Project Overview:

This project will be a two-step process where several types of triggered events involving the Low Speed Autonomous Vehicle (LSAV) will be evaluated. Any related safety-critical incidents discovered during this triggered event reduction will have a secondary question reduction where additional information about those incidents will be annotated.

MANUAL EVENT REDUCTION

Videos to load:

- Front
- Rear
- Left
- Right
- Cabin

Variables to load:

- GPS.Speed
- FlexDasIMUBox.Accel_X
- FlexDasIMUBox.Accel_Y

TRIGGERED EVENTS AND BASELINES

Definition: This is an event triggered either manually by the Operator (e.g., using the controls inside the vehicle), automatically by the LSAV computers (e.g., when a close obstacle is detected), or through other data processing/sampling methods (e.g., signal phase change or baselines).

1. Trigger. **What type of triggered event occurs?**
   NOTE: If the expected trigger is not actually present (e.g., an E-stop where there is no stop), do not complete the annotation. In some cases, the info received from the customer was improperly translated to the wrong file/timestamps. Instead make a note in the excel log, do not date it as complete, and move on to the next trigger.
   a. <u>E-Stop, Valid</u> (Vehicle stops itself due to other road user or potential conflict)
   b. <u>E-Stop, Not Valid</u> (Vehicle stops itself due to sensor error or potential over-sensitivity, such as blowing leaves or trash, small object in road such as snow chunk, or perhaps unknown reason)
   c. <u>Soft Stop</u> (operator stops the vehicle manually)
   d. <u>Circumvention</u> (operator takes steering control)
   e. <u>Red Light</u> (Traffic signal turns red while LSAV is traversing intersection.)
   f. <u>Yellow Light</u> (Traffic signal turns yellow, but not red, while LSAV is traversing intersection.)

2. TriggerReason. **Reason for Triggered Event**. (Modified from Event Nature from 4.2 standard.) This is coded from the perspective of the LSAV.
   a. <u>No reason</u> (no obvious or discernible reason for triggered event)
   b. <u>Reaction to lead vehicle</u>
   c. <u>Reaction to following vehicle</u>
   d. <u>Reaction to oncoming traffic</u>
   e. <u>Reaction to vehicle in adjacent lane</u>
   f. <u>Reaction to vehicle cutting in from adjacent lane</u>
   g. <u>Reaction to merging or weaving vehicle</u>
   h. <u>Reaction to vehicle turning across another vehicle path (same direction)</u>
   i. <u>Reaction to vehicle turning across another vehicle path (opposite direction)</u>
   j. <u>Reaction to vehicle turning into another vehicle path (same direction)</u>
   k. <u>Reaction to vehicle turning into another vehicle path (opposite direction)</u>
   l. <u>Reaction to vehicle moving across another vehicle path (through intersection)</u>

m. Reaction to parked vehicle
n. Reaction to traffic light
o. Reaction to stop sign
p. Reaction to pedestrian
q. Reaction to pedestrian entering/exiting vehicle
r. Reaction to pedal cyclist
s. Reaction to animal
t. Reaction to obstacle/object in roadway
u. Reaction to infrastructure element (e.g. curb)
v. Other (leave a note, may include blowing leaves, trash, chunk of snow, etc.)
w. No reaction - SPaT – (vehicle continues through intersection - SPaT trigger only)
x. Unable to determine

3. RoadUsersPresent. **What type(s) of road users are present and close to the LSAV when the triggered event occurs? Check all that apply.** Include any road users that are within a ~10 feet radius (about the width of a traffic lane) of the LSAV OR are relevant to safe LSAV operations. (For example, do not include a pedestrian walking safely along the sidewalk and in no danger from the LSAV, even if within the ~10ft radius.)
   a. None
   b. Pedestrian
   c. Pedal cyclist
   d. E-scooter/Segway (both electric and foot-powered)
   e. Car (includes SUV, van, pick-up truck, includes parked)
   f. Motorcycle (includes parked)
   g. Large truck/bus (includes parked)
   h. Other

4. RoadUserPosition. **Position of other road users coded above relative to LSAV at start of triggered event?** Check all that apply, including any positions/spaces that are occupied by any of the above coded road user types.

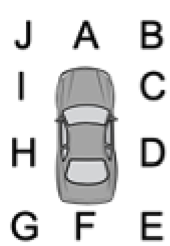

Figure 5. Regarding Motorist/Non-Motorist/Animal/Object Location. Subject vehicle is pictured. Location of conflicting vehicle, person, animal, or object is coded A-J in relation to subject vehicle.

5. TrafficDensity. **Traffic Density/Level of Service.** (Similar to Traffic Density from 4.2 standard.) What is the traffic flow and/or level of service at the start of the interaction?

NOTE 1: Intersections - For cases where the subject is stopped at or being influenced by an intersection, consider all surrounding traffic, the number of queued vehicles, how quickly a queue grows, the number of light cycles waited, the overall throughput rate of the intersection (including cross traffic), etc. For example, being stopped as first in queue with no lead vehicle does not necessarily mean LOS A1, and being stopped in a queue behind several vehicles does not necessarily mean LOS E/F. Consider how easily/quickly traffic would start moving again and the influence that other vehicles would have on the subject vehicle's maneuverability when the queue is able to begin moving.

NOTE 2: The LSAV travels slowly (max of 10-15 mph). This should not be a factor in determining traffic density. Consider the prevailing speed of other traffic (if present) and the presence/number of other vehicles present that affect overall maneuverability.

NOTE 3: Because the LSAV travels slowly, it's travel speed is unlikely to be affected by leading traffic in most cases. However, the LSAV is likely to affect the travel speed of following vehicles. This should be taken into account, especially when distinguishing between LOS A and higher densities. If following traffic is being affected by the LSAV's speed limitations, LOS B or higher may be an appropriate response.

a. LOS A1
b. LOS A2
c. LOS B
d. LOS C
e. LOS D
f. LOS E
g. LOS F
h. Unknown

6. Weather. **Weather condition at time of event?** (from V4.2 standard)

a. Clear/Partly Cloudy
b. Overcast
c. Wind Gusts
d. Fog
e. Mist/Light Rain
f. Raining
g. Snowing
h. Sleeting
i. Rain & Fog
j. Snow/Sleet & Fog
k. Other
l. Unknown

7. SurfaceCondition. **Surface condition at time of event?** (from V4.2 standard)

a. Dry
b. Wet
c. Snowy
d. Icy
e. Muddy
f. Oily
g. Other
h. Unknown

8. PreincidentManeuver. **LSAV maneuver just prior to triggered event?** (selected/modified from V4.2 standard)

a. Going straight, constant speed
b. Going straight, but with unintentional "drifting" within lane or across lanes
c. Going straight, accelerating
d. Going straight, decelerating
e. Turning right
f. Turning left
g. Changing lanes
h. Negotiating curve
i. Starting in traffic lane
j. Stopped in traffic lane
k. Parked, not in travel lane
l. Leaving a parking position
m. Entering a parking position
n. Other
o. Unknown

9. PassengersPresent. **Indicate all positions occupied by LSAV passengers (excluding the Operator).** Top indicates the top of cabin view/front of the LSAV, facing backward. Bottom indicates the bottom of the cabin view/rear of the LSAV, facing forward. The Operator should not be counted here; Standing denotes a non-Operator that is standing.

☐ Top L	☐ Top M	☐ Top R
☐ Bott L	☐ Bott M	☐ Bott R
☐ None	☐ Standing	☐ Other

10. PassengerSeatbeltNo. **Indicate all occupied seating locations where <u>no seatbelt</u> is worn (excluding the Operator).** None indicates all are either known to be wearing a seatbelt or are unknown (unknowns are identified next). <u>This should be a rapid assessment.</u> If not clear immediately, then code in next variable as Unknown.

☐ <u>Top L</u>	☐ <u>Top M</u>	☐ <u>Top R</u>
☐ <u>Bott L</u>	☐ <u>Bott M</u>	☐ <u>Bott R</u>
☐ <u>None</u>		☐ <u>Other</u>

11. PassengerSeatbeltUnknown. **Indicate all occupied seating locations with an <u>unknown seatbelt</u> status (excluding the Operator).** None indicates all are either known to be wearing a seatbelt or known to not be wearing a seatbelt.

☐ <u>Top L</u>	☐ <u>Top M</u>	☐ <u>Top R</u>
☐ <u>Bott L</u>	☐ <u>Bott M</u>	☐ <u>Bott R</u>
☐ <u>None</u>		☐ <u>Other</u>

12. PassengerAges. **Indicate all age groups represented by LSAV Passengers (excluding the Operator).** Check all that apply.

a. <u>Child</u> (pre-adolescent)
b. <u>Teenager</u> (adolescent)
c. <u>Young adult</u> (e.g., typical college-aged)
d. <u>Middle-aged adult</u>
e. <u>Elderly adult</u>
f. <u>Unknown</u>

13. PassengerEffects. **Indicate all effects of the triggered event experienced by one or more LSAV passengers (<u>including</u> the Operator).** Check all that apply.

<u>OPERATOR EFFECTS:</u>

a. <u>Op: Stumbled into passenger</u> (operator lost balance or fell, striking passenger)
b. <u>Op: Stumbled other</u> (operator lost balance or fell, without impact to passenger)
c. <u>Op: Grabbed support</u> (operator grabbed on to pole, seat back, another object, or passenger to stabilize)
d. <u>Op: Dropped or lost item</u> (item slid/fell out of operator's possession; motion of object was primarily downward while in air or sliding along floor)
e. <u>Op: Item launched</u> (item in operator's possession was thrown into air – motion of object was at least partially upward or significantly lateral in trajectory while in air)
f. <u>Op: Other</u>

PASSENGER EFFECTS:

g. Pass: Fell/slid out of seat (seated passenger fell out of seat or slid out of seat)
h. Pass: Stumbled (standing occupant other than operator lost balance or fell)
i. Pass: Grabbed support (seated or standing passenger grabbed on to pole, seat back, another object, or another passenger to stabilize)
j. Pass: Dropped or lost item (item slid/fell out of passenger's possession, or item on seat or floor slid out of control – motion of object was primarily downward while in air or sliding along seat/floor)
k. Pass: Item launched (item either in passenger's possession, on the floor, or on the seat was thrown into air – motion of object was at least partially upward or significantly lateral in trajectory while in air)
l. Pass: Other

14. ProvokedBehavior. **Are any illegal, unsafe, or aggressive behaviors provoked in other road users leading up to, during, or after the triggered event?** Includes behaviors that both do and do not result in a critical incident. Take care not to include behaviors things that only appear aggressive due to the inherent speed differential. Consider all behaviors observed leading up to the triggered event until the LSAV resumes normal operations afterwards (e.g., until the LSAV returns to normal movement after the E-stop). Check all that apply.

a. None
b. One vehicle (same direction) passes LSAV in oncoming lane
c. Multiple vehicles (same direction) pass LSAV in oncoming lane
d. Other road user takes right-of-way away from LSAV
e. Other road user is egregiously impatient/aggressive (other than described in other categories, e.g., aggressively passes in adjacent same-direction lane)
f. Other road user purposefully incites LSAV response (e.g., analyst suspects that pedestrian walks in front of LSAV in an attempt to 'test' it and make it stop. Or analyst suspects that another vehicle brakes or cuts-in close simply to see if the LSAV will respond.)
g. Other behavior (leave a note)
h. Unknown

15. IncidentCount. **How many critical incidents (including direct and indirect) took place leading up to and/or resulting from the triggered event?**

NOTE 1: Incidents may be between the LSAV and any other road user/object and/or between another road user and a third road user/object. Two interactions that are closely related (e.g., the evasive maneuver for one led to the second) should be counted as one incident here. If two interactions occur independently of each other, count them as separate incidents.

NOTE 2: Incidents should be safety-relevant in order to be counted here. (E.g., if an E-Stop is triggered when a following vehicle goes around to pass and then cuts in front of LSAV, that may or may not be a conflict but is an incident that should be counted here. If an LSAV action incites an unsafe or abnormal behavior in another road user, that should be counted here.)
NOTE 3: Count all incidents that occur leading up to or resulting from the triggered event, including during the time before the LSAV resumes normal operations. (E.g., if an E-Stop results in a 20 second stop, count all incidents that result during that time.)

a. Textbox

16. IncidentTimes. **Enter the start and end timestamps (approximately) of each incident counted above.** These are defined similar to Conflict Begin and Conflict End in the V4.2 standard.
NOTE 1: This should not be a time-consuming determination for this task. The goal is to provide a "pointer" to guide additional work. Within 1-2s is acceptable.
NOTE 2: The start and end timestamps should be separated by dashes, and if more than one incident is coded above, separate the timestamp pairs with a comma. For example, 2 incidents might appear here as "235540-239100, 244780-248450". If 0 incidents are coded above leave this blank.
a. Textbox

17. TriggerNotes. **Additional Notes. Describe any 'other' categories or unique conditions not evident from variables coded above.**
a. Textbox

If IncidentNum is zero (0), stop reduction here. For example, review would stop here for an E-stop triggered event that occurred for no obvious reason or with no other relevant road users present.

If IncidentNum is non-zero (>0), this triggered event will move on to a queue for further reduction (Incident Reduction, next page).

INCIDENT REDUCTION

This section will characterize incidents that lead to or result from the triggered events coded above. Each incident is comprised of one or more interactions, each of will be categorized by severity (crash, near-crash, crash-relevant conflict, or non-conflict).

18. TriggeredEventID. **Event ID of original triggered event**. (by which this incident was identified)
a. Textbox.

19. IncidentBegin. **Incident begin timestamp.** Similar to Conflict Begin from 4.2 standard; this should not be a time-consuming determination. If within ~1s, or ~20 frames considered acceptable for this effort.

   a. Textbox.

20. IncidentEnd. **Incident end timestamp.** Similar to Conflict End from 4.2 standard; this should not be a time-consuming determination. If within ~1s, or ~20 frames considered acceptable for this effort.

   a. Textbox.

21. PrecipitatingEvent. **Precipitating event** (Modified from Precipitating Event from 4.2 standard)

   a. LSAV lost control (e.g., tire blow-out, engine failure, poor road conditions, excessive speed, cargo shift)
   b. LSAV over lane line (right or left, drifting, not related to lane change)
   c. LSAV over road edge (right, left, or end)
   d. LSAV lane change, right
   e. LSAV lane change, left
   f. LSAV in intersection – turning right
   g. LSAV in intersection – turning left
   h. LSAV in intersection - passing through
   i. LSAV ahead, but decelerating (with or without a full stop)
   j. LSAV ahead, but at a slower constant speed
   k. LSAV ahead, stopped (at full stop prior to Incident Begin)
   l. LSAV from parking lane (Diagonal, perpendicular, or parallel. Includes loading/bus stop zone)
   m. LSAV, other
   n. Other vehicle ahead, but decelerating (with or without a full stop)
   o. Other vehicle ahead, but at a slower constant speed
   p. Other vehicle ahead, stopped
   q. Other vehicle lane change
   r. Other vehicle - traveling in opposite direction
   s. Other vehicle making U- turn
   t. Other vehicle - backing
   u. Other vehicle lane change - left in front of subject
   v. Other vehicle lane change - right in front of subject
   w. Other vehicle lane change - left behind subject
   x. Other vehicle lane change - right behind subject
   y. Other vehicle lane change - left, sideswipe threat
   z. Other vehicle lane change - right, sideswipe threat
   aa. Other vehicle lane change - left other
   bb. Other vehicle lane change - right other
   cc. Other vehicle oncoming - over left line

dd. Other vehicle oncoming - over right line
ee. Other vehicle from parallel/diagonal parking lane
ff. Other vehicle entering intersection - turning same direction
gg. Other vehicle entering intersection - straight across path
hh. Other vehicle entering intersection - turning onto opposite direction
ii. Other vehicle entering intersection - left turn across path
jj. Other vehicle entering intersection - right turn across path
kk. Other vehicle entering intersection - intended path unknown
ll. Other vehicle from driveway - turning into same direction
mm. Other vehicle from driveway - straight across path
nn. Other vehicle from driveway - turning into opposite direction
oo. Other vehicle from driveway - intended path unknown
pp. Other vehicle from entrance to limited access highway
qq. Pedestrian in roadway
rr. Pedestrian approaching roadway
ss. Pedestrian in unknown location
tt. Pedal cyclist/other non- motorist in roadway
uu. Pedal cyclist/other non- motorist approaching roadway
vv. Pedal cyclist/other non- motorist in unknown location
ww. Object in roadway
xx. Object approaching roadway
yy. Object in unknown location
zz. Other event not attributed to subject vehicle
aaa. Unknown

22. LSAVFault. **Incident causation. What role did LSAV play in the conflict?**
   a. Full LSAV fault
   b. Partial LSAV fault
   c. LSAV not at fault
   d. Unable to determine

23. InteractionCount. **How many interactions are there within/comprising the incident being assessed?** If 2 or less, code both interactions below (as Interaction 1 and Interaction 2). If more than 2, code the first two and describe the additional in the notes. They will be added to the coded data as needed.
   a. Textbox

24. Interaction(1-2)Direct. **Is the interaction coded here a direct interaction with the LSAV or an indirect interaction between two other road users or objects?**
   a. Direct (between LSAV and other)
   Direct interactions occur between the LSAV and other road users, elements, or objects. Direct interactions occur when:

- LSAV came in physical contact with another road user, object, or infrastructural or environmental element.
- LSAV swerves or stops abruptly to avoid a crash. (Note, an LSAV swerve can only be performed by the operator, not automatically.)
- Another vehicle or pedestrian swerves or stops abruptly to avoid a crash with LSAV.
- LSAV fails to yield the right-of-way to other road users (or another road user fails to yield right-of-way to LSAV), when yielding would be appropriate.
- LSAV stops in the middle of an intersection or in another place that would typically not be appropriate.
- Another road user performed an illegal or inappropriate pass to get around slower LSAV.
- Another road user performed an illegal or inappropriate turn to get around slower LSAV.
- Another road user performed an illegal or inappropriate stop to yield for LSAV.

b. Indirect (between 2 other)
Indirect interactions between other road users/elements as a result of LSAV actions can be identified. These are interactions where the LSAV induced other road users to interact in ways they would not have otherwise. Indirect interactions occur when:
- Another road user came in physical contact with another road user, object or infrastructural or environmental element while trying to avoid the LSAV.
- Another road user swerves or stops abruptly to avoid a crash with another road user, object, or infrastructural or environmental element while trying to avoid the LSAV.
- While attempting to get around or yield to the LSAV (either legally/appropriately or illegally/inappropriately) via passing, turning, or stopping, another road user has a conflict with a third road user or object.

25. Interaction(1-2)Severity. **Interaction 1(2) severity.** The interaction severity, similar to Event Severity (1-2) from 4.2 standard.
a. Crash
b. Near-crash
c. Crash-relevant conflict
d. Non-conflict

26. Interaction(1-2)Type. **Interaction 1(2) type. What type of interaction occurred?** (Similar to Incident Type (1-2) from 4.2 standard.)
a. Lane deviation (left or right)
b. Road departure (left or right)

c. Road departure (end)
d. Rear-end, striking
e. Rear-end, struck
f. Sideswipe, same direction (left or right)
g. Opposite direction (head-on or sideswipe)
h. Straight crossing path
i. Turn across path
j. Turn into path (same direction)
k. Turn into path (opposite direction)
l. Backing into traffic
m. Backing, fixed object
n. Pedestrian-related
o. Pedal cyclist-related
p. Animal-related
q. Other
r. Unknown

27. Interaction(1-2)Nature. **Interaction 1(2) Nature. What is the nature of the interaction that occurred?** (Similar to Event Nature (1-2) from 4.2 standard.)
a. Conflict with a lead vehicle
b. Conflict with a following vehicle
c. Conflict with oncoming traffic
d. Conflict with vehicle in adjacent lane
e. Conflict with merging or weaving vehicle
f. Conflict with vehicle turning across another vehicle path (same direction)
g. Conflict with vehicle turning across another vehicle path (opposite direction)
h. Conflict with vehicle turning into another vehicle path (same direction)
i. Conflict with vehicle turning into another vehicle path (opposite direction)
j. Conflict with vehicle moving across another vehicle path (through intersection)
k. Conflict with parked vehicle
l. Conflict with pedestrian
m. Conflict with pedestrian entering/exiting vehicle
n. Conflict with pedal cyclist
o. Conflict with animal
p. Conflict with obstacle/object in roadway
q. Single vehicle conflict
r. Other
s. Unknown

28. LSAVEvasiveManeuver(1-2). **Evasive maneuver by the LSAV in response to interaction 1(2).** (Similar to V1 Evasive Maneuver 1,2 from 4.2 standard.)
a. No reaction
b. Braked only

c. Steered to left
d. Steered to right
e. Braked and steered left
f. Braked and steered right
g. Accelerated
h. Accelerated and steered left
i. Accelerated and steered right
j. Other actions
k. Unknown
l. Not applicable (Interaction is not directly with LSAV)

29. OtherActor(1-2)Type. **Actor (1-2) Type of road user, feature, or object** (Similar to Motorist/Non-Motorist Type from 4.2 standard.)

a. Automobile
b. Sport utility vehicle
c. Van (e.g., minivan, standard, cargo, conversion)
d. Pickup truck
e. Light vehicle pulling trailer
f. Motorcycle or moped
g. Large truck/bus
h. Pedestrian
i. Pedal cyclist
j. Scooter/Segway
k. Other non-motorist (wheelchair, hoverboard, skateboard, skates, stroller/wagon)
l. Animal
m. Object, moving
n. Object, stationary
o. Other

30. OtherActor(1-2)Location. **Position of actor 1(2) relative to LSAV**. (Similar to Motorist/Non-motorist/Object/Animal Location from 4.2 standard)

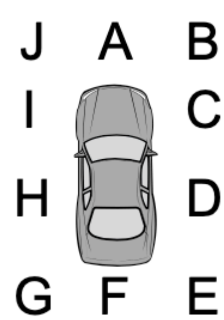

Figure 5. Regarding Motorist/Non-Motorist/Animal/Object Location. Subject vehicle is pictured. Location of conflicting vehicle, person, animal, or object is coded A-J in relation to subject vehicle.

31. OtherActor(1-2)PreincidentManeuver. **Pre-incident maneuver of other Actor (1,2) associated with this incident.** Similar to Motorist/Non-Motorist Pre-Incident Maneuver from 4/2 standard.

a. Not vehicle or person
b. Going straight, constant speed
c. Going straight, but with unintentional "drifting" within lane or across lanes
d. Going straight, accelerating
e. Going straight, decelerating
f. Starting in traffic lane
g. Stopped in traffic lane
h. Passing or overtaking another vehicle
i. Disabled or parked in travel lane
j. Leaving a parking position, moving forward
k. Leaving a parking position, moving backward
l. Entering a parking position, moving forward
m. Entering a parking position, moving backward
n. Turning right
o. Turning left
p. Making a U-turn
q. Changing lanes
r. Merging
s. Negotiating a curve
t. Backing up (other than for parking purposes)
u. Maneuvering to avoid an animal
v. Maneuvering to avoid a pedestrian/pedal cyclist
w. Maneuvering to avoid an object
x. Maneuvering to avoid a vehicle
y. Pedestrian static, in roadway
z. Pedestrian dynamic, in roadway
aa. Pedestrian static, not in roadway
bb. Pedestrian dynamic, not in roadway
cc. Other
dd. Unknown

32. OtherActor(1-2)EvasiveManeuver. **Evasive maneuver by other Actor 1(2) in response to interaction.** (Similar to Motorist/Non-Motorist Evasive from 4.2 standard.)

a. No driver/rider present (e.g., parked vehicle or bicycle)
b. Not vehicle or person
c. No reaction
d. Braked only
e. Released brakes
f. Steered to left
g. Steered to right

h. Braked and steered to left
i. Braked and steered to right
j. Accelerated
k. Accelerated and steered to left
l. Accelerated and steered to right
m. Pedestrian performed some type of evasive maneuver
n. Pedestrian did not perform any type of evasive maneuver
o. Other actions
p. Unknown

33. OtherActor(1-2)Behavior(1-3). **Behaviors performed or exhibited by Other Actor (1-2). List up to three, in the order they occurred.** (selected/modified from V4.2 standard)

a. None (or No Additional Behaviors)
b. Distracted
c. Illegal passing on right
d. Illegal passing on left
e. Other improper or unsafe passing
f. Cutting in, too close in front of other vehicle
g. Cutting in at safe distance but then decelerated, causing conflict
h. Cutting in, too close behind other vehicle
i. Other improper or unsafe merge/exit/weave
j. Other improper or unsafe lane change
k. Aggressive driving, specific, directed menacing actions (not for general use on passing, even if illegal, unless another aggressive indicator is present such as intimidation, directed horseplay, or road rage)
l. Aggressive driving, other (not for general use on passing, even if illegal, unless another aggressive indicator is present such as intimidation, directed horseplay, or road rage)
m. Wrong side of road, not overtaking
n. Following too closely
o. Making turn from wrong lane
p. Improper turn, wide right turn
q. Improper turn, cut corner on right turn
r. Improper turn, wide left turn
s. Improper turn, cut corner on left
t. Improper U-turn
u. Improper turn, other
v. Improper backing, did not see
w. Improper backing, other
x. Improper start from parked position
y. Disregarded officer or watchman
z. Signal violation, apparently did not see signal
aa. Signal violation, intentionally disregarded signal

bb. Signal violation, tried to beat signal change
cc. Stop sign violation, apparently did not see stop sign
dd. Stop sign violation, intentionally ran stop sign at speed
ee. Stop sign violation, "rolling stop"
ff. Other sign (e.g., Yield) violation, apparently did not see sign
gg. Other sign (e.g., Yield) violation, intentionally disregarded
hh. Other sign violation
ii. Non-signed crossing violation
jj. Right-of-way error, apparent recognition failure
kk. Right-of-way error, apparent decision failure
ll. Right-of-way error, other or unknown cause
mm. Delayed or insufficient braking
nn. Sudden or improper braking
oo. Sudden or improper stopping
pp. Parking in improper or dangerous location
qq. Speeding or other unsafe actions in work zone
rr. Avoiding pedestrian
ss. Avoiding other vehicle
tt. Avoiding animal
uu. Avoiding object
vv. Other
ww. Unknown
xx. Not vehicle or person

34. VisualObstruction. **Visual Obstruction.** (Similar to Visual Obstructions from 4.2 standard.)

a. No obstruction
b. Rain, snow, fog, smoke, sand, dust
c. Reflected glare
d. Sunlight
e. Headlights
f. Curve or hill
g. Building, billboard, or other roadway infrastructure design features
h. Trees, crops, vegetation
i. Moving vehicle (with or without load)
j. Stopped vehicle
k. Splash or spray of passing vehicle
l. Inadequate defrost or defog system
m. Inadequate roadway lighting system
n. Inadequate vehicle headlamps
o. Obstruction interior to vehicle
p. Mirrors
q. Broken or improperly cleaned windshield

r. Other obstruction
s. Multiple factors
t. Vision obscured - no details
u. Unknown whether vision was obstructed

35. InfrastructureFactor. **Infrastructure factors contributing to the incident.** (Similar to Infrastructure Contributing Factors from 4.2 standard.)
a. Roadway alignment
b. Roadway sight distance
c. Traffic control device
d. Roadway delineation
e. Roadway maintenance
f. Uneven road surface
g. Weather, visibility
h. Multiple factors
i. Other
j. Unknown

36. IncidentNotes. **Additional Notes. Describe any 'other' categories, unique conditions, or special incident characteristics not evident from variables coded above.**
a. Textbox

Appendix B. Automated Reduction

This section details variables that will be coded automatically through GPS matching and predetermined location-based characteristics of the LSAV route.

1. RoadSegment. **What segment of the shuttle route did the triggered event occur?** **(will be automatically coded, not for reduction task)**
    a. Textbox. Insert 1 through 20 as designated on map

2. IntersectionNum. **At or near what intersection did the triggered event occur?** **(will be automatically coded, not for reduction task)**
    a. Textbox. Enter number as designated on map.

3. InfraElements. **What infrastructure elements are present when the triggered event occurred?** (check all that apply within a certain radius of the LSAV) **(will be automatically coded, not for reduction task)**
    a. Crosswalk
    b. Stop sign
    c. Traffic light
    d. Taper and turning lanes
    e. Unmarked lanes
    f. Other (e.g., …)

4. TrafficFlow. **Traffic Flow** **(will be automatically coded, not for reduction task)**
    a. Not divided - simple 2- way trafficway
    b. Not divided - center 2-way left turn lane
    c. Divided (median strip or barrier)
    d. One-way traffic
    e. No lanes
    f. Unknown

5. RelationtoJunction. **Relation to Junction** **(will be automatically coded, not for reduction task)**

Segment ID	Segment Type	Segment Description
1	Road Segment	2 lane shared road with no clear marking
2	4-way stop-sign controlled intersection	two lane road without clear marking
3	Road Segment	2 lane shared road with no clear marking
4	T- intersection with stop sign controlled side street	2 lane road without clear marking
5	Road Segment	2 lane road

Segment ID	Segment Type	Segment Description
6	T- intersection with stop sign controlled side street	2 lane road
7	Road Segment	2 lane road
8	T- intersection with stop sign controlled side street	2 lane road
9	Road Segment	2 lane road
10	T- intersection with stop sign controlled side street	2 lane road
11	Road Segment	2 lane road
12	T- intersection with stop sign controlled side street	3 lane in the direction of travel
13	Road Segment	4 lane road
14	4 parking lot entrance	4 lane road
15	T- intersection with stop sign controlled side street	4 lane road
16	Road Segment	4 lane road
17	T- intersection with stop sign controlled side street	4 lane road
18	Road Segment	6 lane (4 in the direction of travel) road with 3 turning lanes
19	4-way intersection with traffic light controls	6 lane road
20	Road Segment	3 lane road (1 in the direction of travel)
21	T- intersection with stop sign controlled side street	3 lane road (1 in the direction of travel)
22	Road Segment	3 lane road (1 in the direction of travel)
23	T- intersection with stop sign controlled side street	two lane road with bike lane on one direction and buffer zone
24	Road Segment	2 lane road with bike lane
25	T- intersection with stop sign controlled side street	two shared lane road
26	T- intersection with stop sign controlled side street	two shared lane road
27	Road Segment	2 lane shared road
28	T- intersection with stop sign controlled side street	two shared lane road
29	Road Segment	2 lane shared road
30	Two parking lot entrance	two lane road
31	Road Segment	2 lane shared road
32	4-way intersection with traffic light controls	three lane road
33	Road Segment	3 lane road (1 in the direction of travel) with partial marking

Segment ID	Segment Type	Segment Description
34	2 way stop-sign controlled 3 way (Y) intersection	three to two lane road
35	Road Segment	2 lane road with no clear marking
36	T- intersection with stop sign controlled side street	three lane road
37	Road Segment	Bus terminal waiting area/lane, no clear marking/parking area
55	Road Segment	3 lane road (2 in the direction of travel)
56	T- intersection with stop sign controlled side street	3 lane road (2 in the direction of travel)
57	Road Segment	3 lane road (2 in the direction of travel)
58	Stop-sign controlled 4 way intersection	4 lane road
59	Road Segment	2 lane road
60	T- intersection with stop sign controlled side street	2 lane road
61	Road Segment	2 lane road
62	T- intersection with stop sign controlled side street	2 lane road
63	Road Segment	2 lane road
64	T- intersection with stop sign controlled side street	2 lane road
65	Road Segment	2 lane road
66	T- intersection with stop sign controlled side street	2 lane road
67	Road Segment	2 lane road
68	Road Segment	2 lane road
69	Road Segment	2 lane road
70	Open area/loading area entrance	no marking
71	Road Segment	2 lane shared road with no clear marking

Appendix C. Results Figures

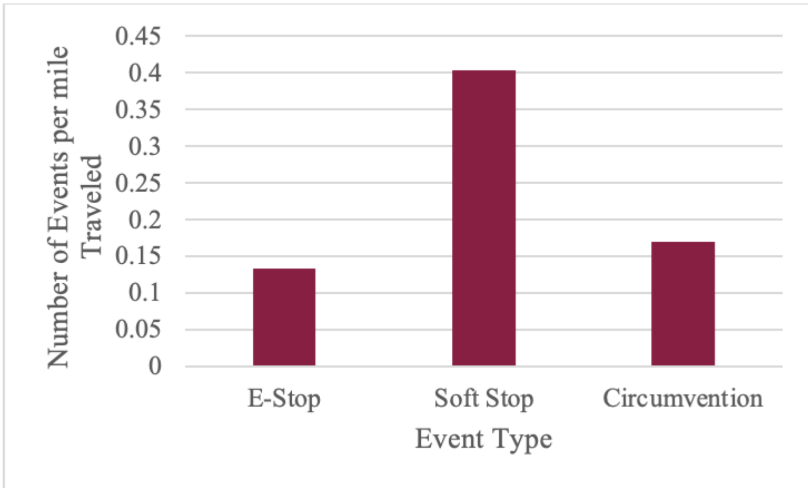

Figure C-1. Rate of E-stops, soft stops, and circumventions identified by EasyMile and reviewed by data coders at VTTI.

Figure C-2. Merrilee Drive/Eskridge Road and US 29 intersection.

Figure C-3. Prosperity Avenue and Merrilee Drive/Avenir Road intersection.

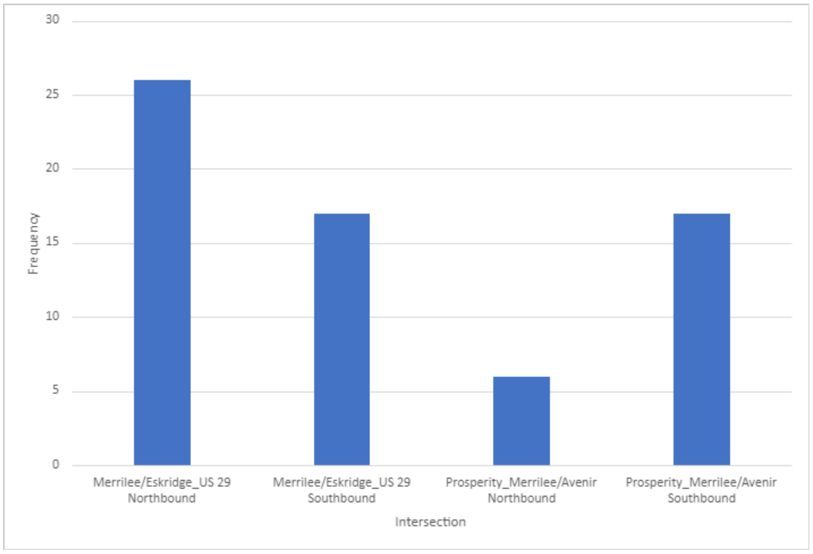

Figure C-4. Frequency of LSAV SPaT triggered events by intersection.

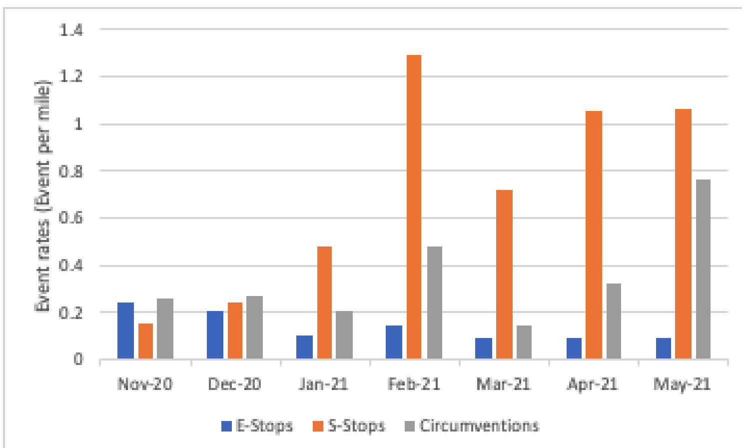

Figure C-5. E-stops, soft stops, and circumventions per mile traveled by month.

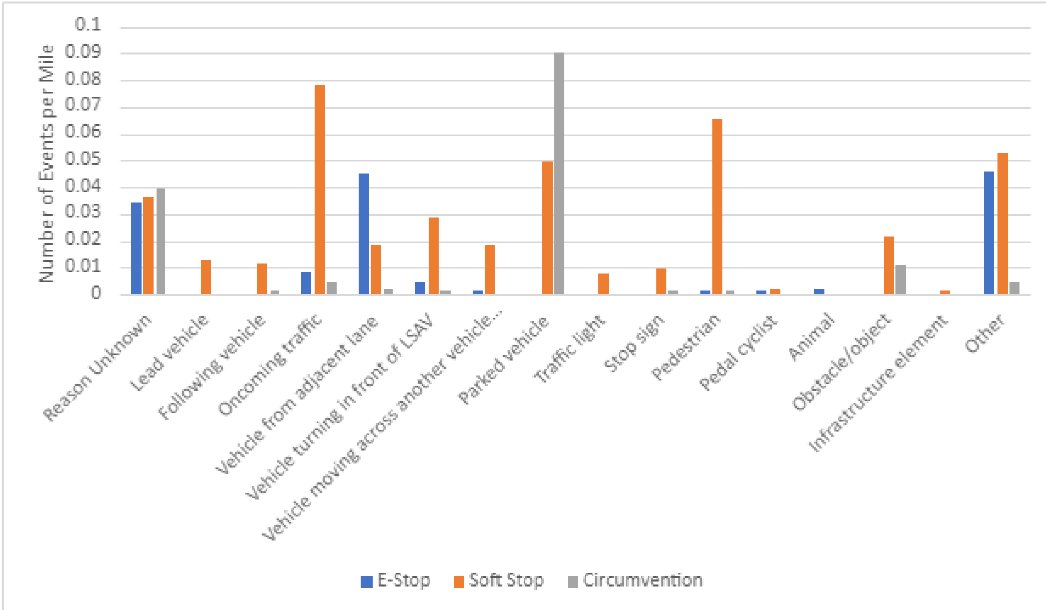

Figure C-6. Rates of reasons that an E-stop, soft stop, or circumvention occurred.

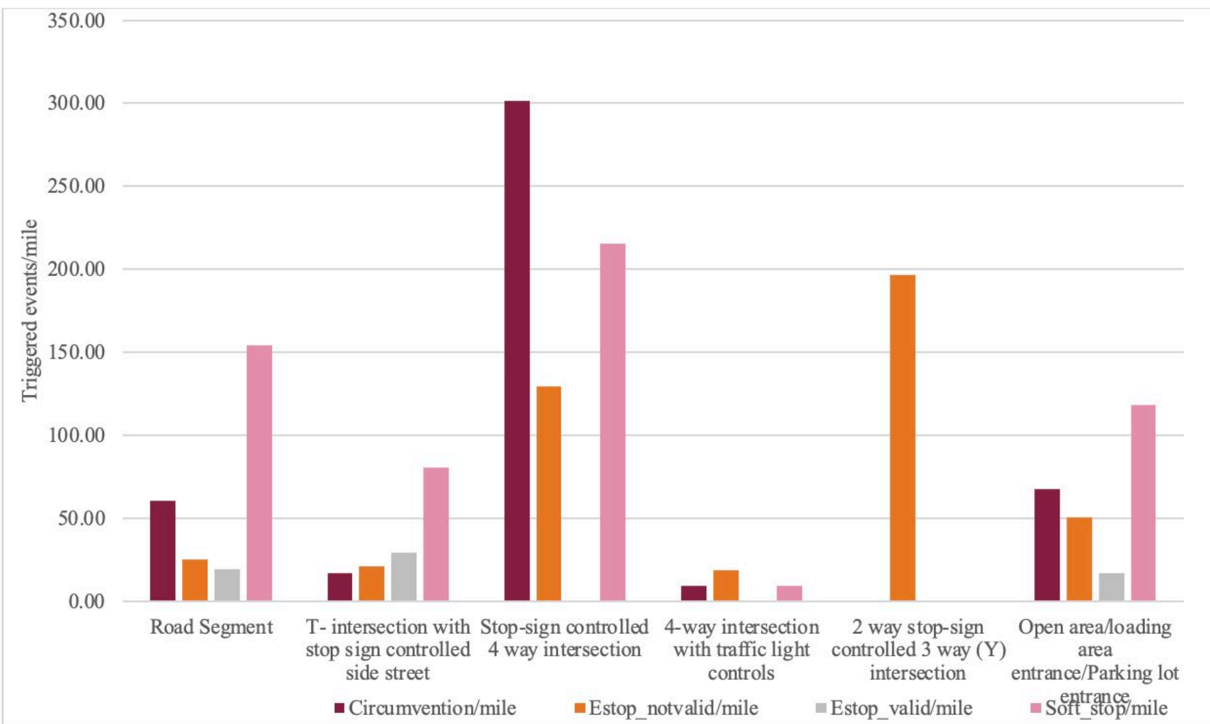

Figure C-7. Triggered event rates by route section type.

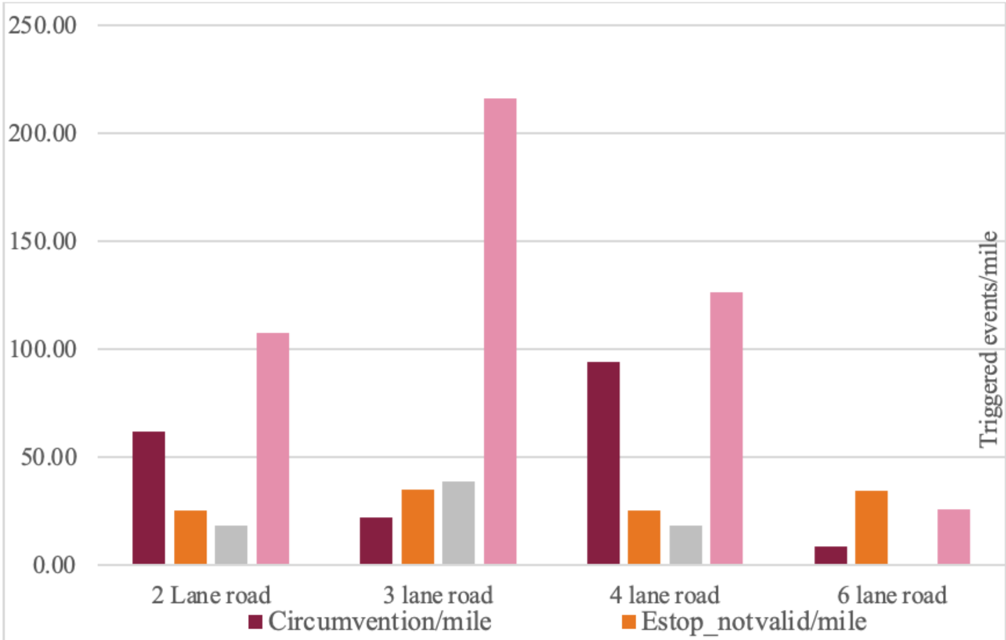

Figure C-8. Triggered event rates by lane configuration.

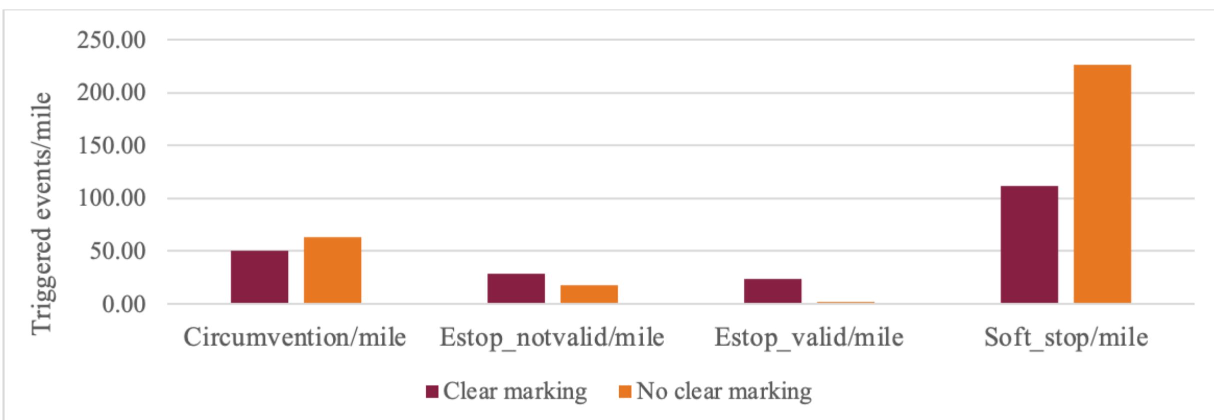

Figure C-9. Triggered event rates by lane marking.

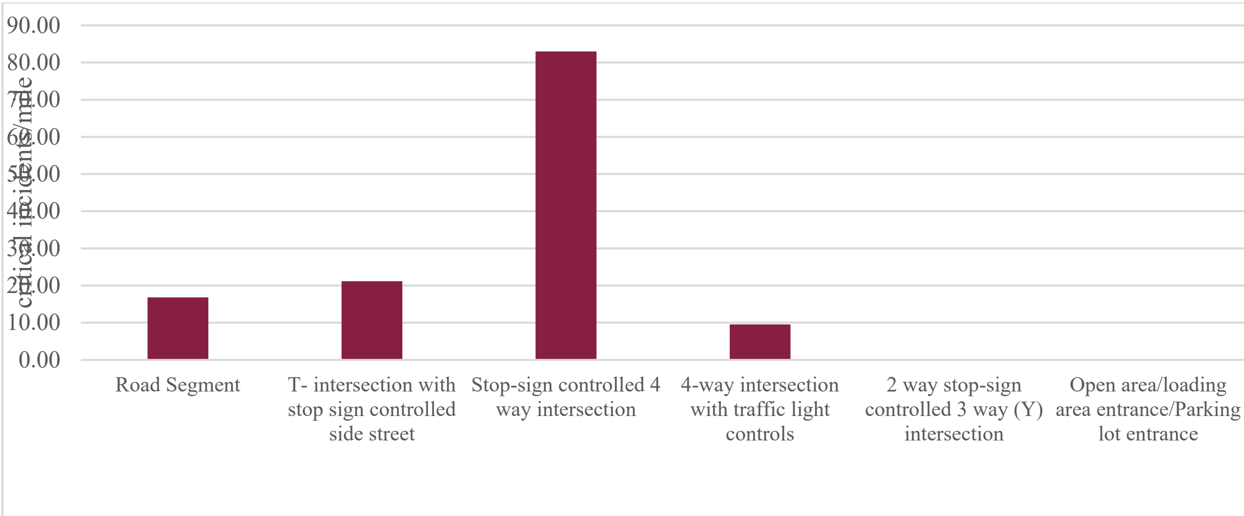

Figure C-10. Safety-critical event rate by route section type.

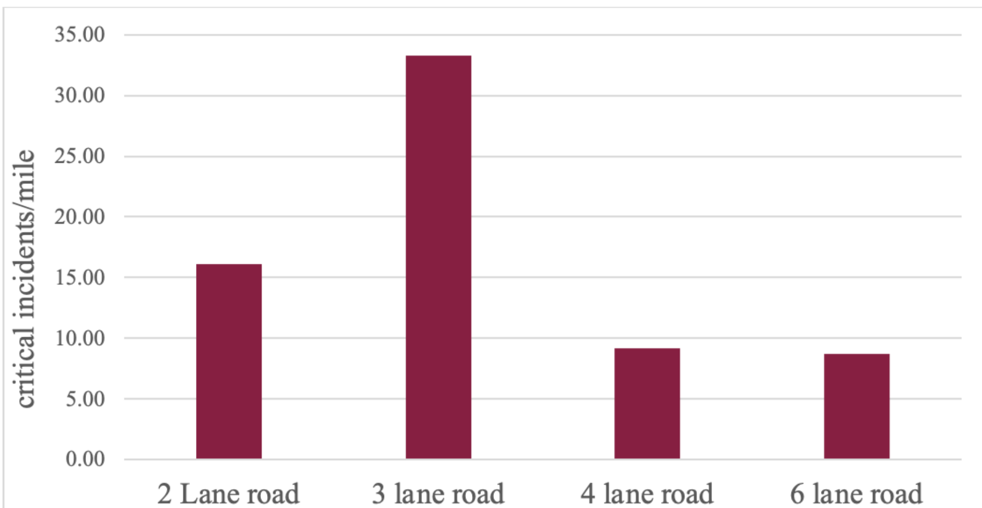

Figure C-11. Safety-critical event rate by lane configuration.

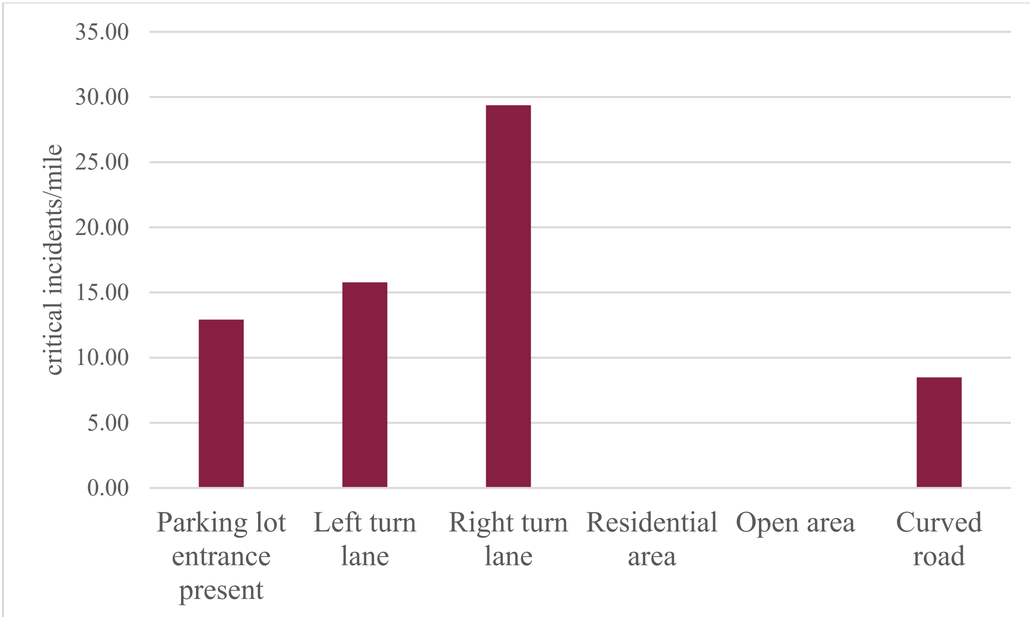

Figure C-12. Safety-critical event rate by special infrastructure elements.

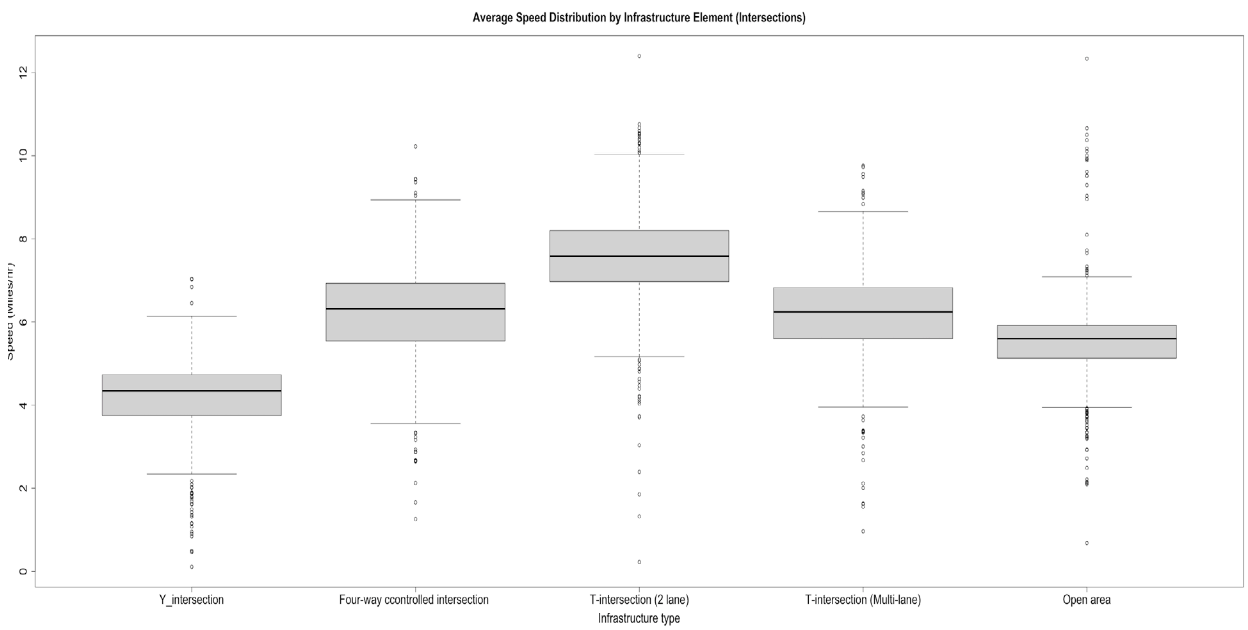

Figure C-13. Average LSAV traveling speed distribution by intersection types.

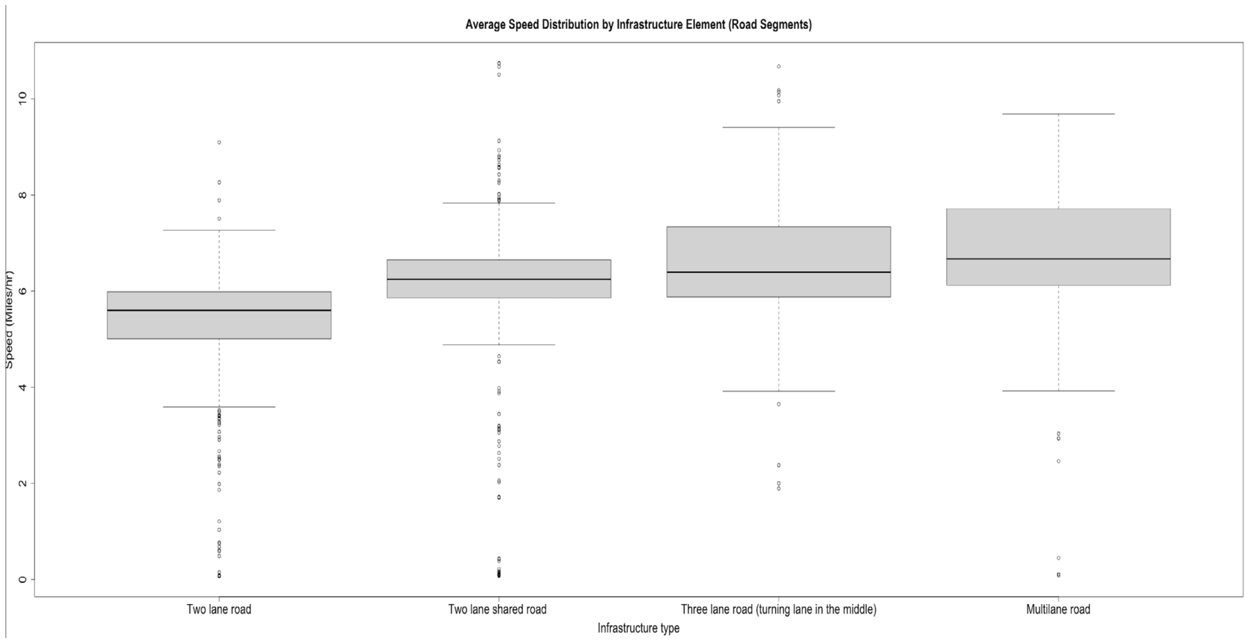

Figure C-14. Average LSAV traveling speed distribution by road segment types.

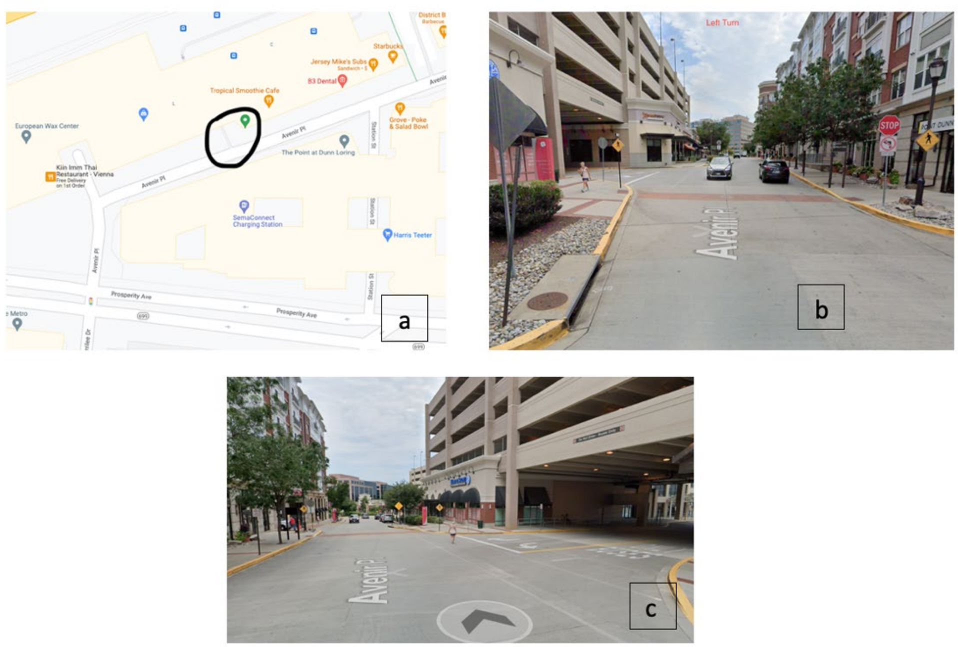

Figure C-15. a) Intersection at Dunn Loring-Merrifield Metrorail station. b) Front view of intersection at Dunn Loring-Merrifield Metrorail station (from LSAV's perspective). c) Opposite view of intersection at Dunn Loring-Merrifield Metrorail station.

Figure C-16. a) Intersection at Eskridge Rd and Merrifield Cinema Dr. b) Front view of intersection at Eskridge Rd and Merrifield Cinema Dr (from LSAV's perspective). c) Opposite view of intersection at Eskridge Rd and Merrifield Cinema Dr.

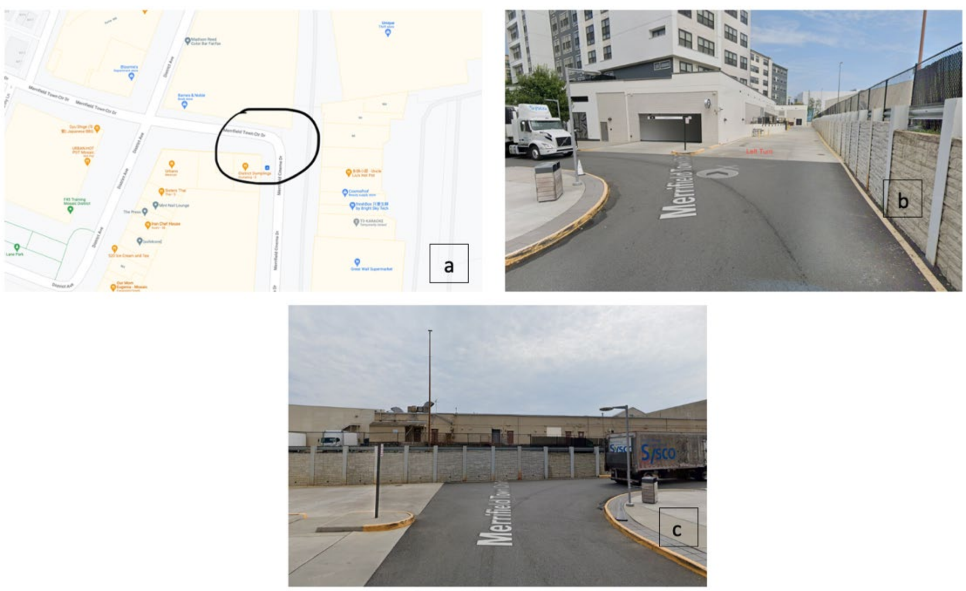

Figure C-17. a) Open area on Merrifield Town Center Dr. b) Front view of open area on Merrifield Town Center Dr (from LSAV's perspective). c) Opposite view of open area on Merrifield Town Center Dr.

Appendix D. Fairfax LSAV SPaT Trigger Validation

Validation Criteria:

Review the Triggered Event and determine validity based on the following criteria at the Start Time:

- The LSAV is within the bounds of a signaled intersection travelling in a lane that is controlled by a traffic signal displaying a red or yellow light.
  - The LSAV is considered to have entered the intersection when the length of the entire vehicle has passed the stop bar.
  - The LSAV is considered have exited the intersection when the front of the LSAV has entered the crosswalk on the far side of the intersection.
  - If there is no crosswalk then use the stop bar for the opposing direction of travel, estimate 6ft proceeding that (to account for crosswalk space), and consider if the LSAV has passed that point.
  - If the LSAV is approaching the end of the intersection and the traffic signal is no longer visible use the signal color on the last video frame it was visible.
- See Appendix A for further guidance and video examples.

Validation Question:

If the Triggered Event is valid what is the light color for the LSAV's lane. Red or Yellow?

- Events with a red light will go on to LSAV Triggered Event Reduction
- Events with a yellow light are compiled and sent back. Looking for 12 events in total, 1 has already been found so 11 additional are needed.

Appendix D. Checklist

The VTTI Research team has the following items for transit planners to consider before planning the route of a future automated transit system deployment.

DESIRABLE ROUTE CHACTERISTICS

- Low traffic volumes and speed limits. LSAVs have low speeds (25 mph or less). Only roads with low traffic volume and a speed limit of less than 25 mph should be considered.
- Low passenger ridership. LSAVs have low passenger capacity. Routes with large ridership for conventional transit should not be considered.
- Well-maintained pavement and clear pavement markings. LSAVs perform best on roads with clear pavement markings. Well-maintained pavement along the route is ideal for LSAVs.
- Few unsignalized intersection turning movements. These turns tend to be problematic for LSAVs. Signalized intersections are safer in general.
- Minimize visual obstructions and vegetation near the road. Removing visual obstructions will improve system performance. Vegetation should also be trimmed. Falling leaves from trees may create unintended automated stops in the autumn.
- Dedicated right of way for LSAVs. Given LSAVs' low speeds, negative safety interactions with other road users should be minimized by providing a dedicated right of way for LSAVs, for example, designated lanes and controlled access routes.
- Transit Signal Priority (TSP) for LSAVs. If traffic signals are present along the route, signal phase and timing (SPaT) information should be provided for the LSAV to ensure the LSAV can clear the intersection during a green phase. Since LSAVs' speeds are much slower than most vehicles, TSP, achieved by communicating SPaT information to LSAVs, can ensure they are not trapped in the intersection during a yellow or red phase.

ORGANIZATIONAL NEEDS

- Experienced operators. Experienced human operators or bus drivers are ideal for serving as safety monitors.

- Provide appropriate operator training. Besides standard training for transit operators, additional training should include sensitivity training for passenger safety, limitations of the automated system, and potential LSAV-specific risky situations and countermeasures.

- Safety monitoring and feedback loop. A transparent, precise, and efficient feedback loop between trained operators, deployment organizers, law enforcement, and LSAV manufacturers would be helpful. The feedback from operators should include results and concerns from ongoing safety monitoring of the deployment. Their hands-on experience with the automated system can be valuable for future deployments.

ADDITIONAL GUIDANCE FOR AUTOMATED TRANSIT

- Matching operational speeds. For automated transit systems with higher operational speeds, the speed limit of road segments along the route should not exceed the operational speeds of the systems.