FTA Report No. 0220

FTA RESEARCH
FEDERAL TRANSIT ADMINISTRATION

Pierce Transit Automated Collision Avoidance and Mitigation Safety Research and Demonstration Project

Final Report

PREPARED BY

Pierce County Public Transportation Benefit Area Corporation (Pierce Transit)

Washington State Transit Insurance Pool

U.S. Department of Transportation
Federal Transit Administration

JUNE
2022

COVER PHOTO

Courtesy of Virginia Tech Transportation Institute

DISCLAIMER

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Metric Conversion Table

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
LENGTH				
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
VOLUME				
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liter	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
NOTE: volumes greater than 1000 L shall be shown in m^3				
MASS				
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or “metric ton”)	Mg (or “t”)
TEMPERATURE (exact degrees)				
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C

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14. ABSTRACT
This report summarizes research performed under the Federal Transit Administration/Pierce Transit Automated Collision Avoidance and Mitigation Safety Research and Development project. The project goal was to research and facilitate development of collision avoidance warning systems/automated emergency braking (CAWS/AEB) for transit buses. The project team conducted research on five parallel tracks to address some of the challenging issues facing transit agencies, bus original equipment manufacturers (OEMs), and technology developers seeking to bring collision avoidance technology to the transit bus industry. This report documents the approaches taken for each track, describes the instrumentation developed for new approaches to testing and data collection, and describes the lessons learned along the way. The project did not provide a conclusive evaluation of CAWS/AEB, but it does document lessons learned and provides evidence for its applicability and potential for return on investment. It is hoped that continued research and development funding for CAWS/AEB will be provided by sponsoring agencies and that bus OEMs and technology suppliers will continue to research and develop the technology.

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Abstract

This report summarizes research performed as part of the Federal Transit Administration/Pierce Transit Automated Collision Avoidance and Mitigation Safety Research and Development project. The project goal was to research and facilitate development of collision avoidance warning systems/automated emergency braking (CAWS/AEB) for transit buses. The project team conducted research on five parallel tracks to address some of the challenging issues facing transit agencies, bus original equipment manufacturers (OEMs), and technology developers seeking to bring collision avoidance technology to the transit bus industry. This report documents the approaches taken for each track, describes the instrumentation developed for new approaches to testing and data collection, and describes lessons learned. The project did not provide a conclusive evaluation of CAWS/AEB, but it does document lessons learned and provides evidence for its applicability and potential for return on investment. It is hoped that continued research and development funding for CAWS/AEB will be provided by sponsoring agencies and that bus OEMs and technology suppliers will continue to research and develop the technology.

Executive Summary

Background

For the period 2014 through 2019, bus transit modes experienced 32,327 collisions, 99,186 injuries, 583 fatalities, and reported casualty and liability (C&L) expenses of $4,094,275,201. Over the period of 2003 to 2019, C&L expenses rose at twice the pace of inflation. [1] Although the National Transportation Safety Board has strongly recommended the application of collision avoidance systems and automated emergency braking (CAWS/AEB), the transit industry has lagged behind autos and trucks.[2] Prior research undertaken by the Washington State Transit Insurance Pool (WSTIP) and others indicated the potential for significant reductions in collisions if CAWS/AEB could be applied to transit buses.

Objectives

The project goal was to research and facilitate the development of CAWS/AEB for transit buses. The project scope was revised during the project to include the following parallel research tracks assigned to research partners:

- Quantifying Contributing Factors to Transit Bus Casualty and Liability Expenses Using the National Transit Database (NTD) – University of Washington (UW)
- Commercialization Potential for Transit Bus Automated Collision Avoidance Warning and Emergency Braking Systems – Veritas Forensic Accounting and Economics
- Developing and testing a 2D Flash Lidar Transit Bus Collision Avoidance Warning System – DCS Technologies, Inc.
- Evaluating the Accuracy of Transit Bus Collision Avoidance Warning Systems –UW
- Analyzing Unrestrained Passenger Motion During Transit Bus Braking – Virginia Tech Transportation Institute (VTTI)

Findings

Statistical analysis of NTD data for 273 transit agencies showed that collisions with vehicles and persons predicted 67% of the variation in bus C&L expenses and that a reduction of 100 collisions with motor vehicles could result in a decrease in C&L expenses of $4.42 million, and a decrease of 100 collisions with persons could result in a decrease of $16.7 million.

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[1] FTA National Transit Database https://www.transit.dot.gov/ntd/ntd-data.

[2] National Transportation Safety Board, 2015.,“The Use of Forward Collision Avoidance Systems to Prevent and Mitigate Rear-End Crashes.” Special Investigation Report NTSB/SIR-15-01. Washington, DC, https://www.ntsb.gov/safety/safety-studies/Documents/SIR1501.pdf.

Veritas reviewed 12 years of WSTIP transit agency member fixed-route bus claims and found that 45% of $59.9 million in liability claims and 38% of injuries could potentially be mitigated if a fully tested and operational CAWS/AEB system were to be implemented and adopted.

The potential return on investment was estimated by comparing the potential reductions in collision-related claims with estimated fully developed CAWS/AEB life-cycle costs on a per-vehicle-mile basis. Break-even costs for CAWS/AEB ranged from $3,000 to $17,000 per vehicle, depending on system effectiveness in preventing claims and system life expectancy.

DCS installed 30 Pedestrian Avoidance Safety System (PASS) CAWS/AEB units on Pierce Transit (PT) buses for a nine-month evaluation period. Based on a risk management assessment by PT staff, AEB and driver feedback functionality were disabled. However, system warning events were collected and logged. Data analysis showed that PASS recorded 1.2 warning events per bus operating hour. PASS units achieved a 200,000 Mean Distance Between Failures (MDBF) over a total of 930,091 project miles.

UW developed and installed transit video event detection and logging instrumentation, TELS, on four buses to collect data on system accuracy in terms of false positives and false negatives. Data were collected for three months and indicated that 93.5% of PASS detections were false positives and 2.6% were false negatives.

VTTI passenger motion instrumentation on two buses produced 649 passenger motion profiles (PMPs) among passengers who were seated, standing, in a wheelchair, and “seated unstable” if the passenger was holding a stroller, cane, or walker. Anonymized videos of head movements were measured and analyzed. Braking events did not exceed -0.3 g, and head movements did not vary significantly for different braking rates.

Conclusions

Although the project did not provide a conclusive evaluation of a CAWS/AEB system, it tested a 2D lidar sensor-based system, developed instrumentation and protocols to measure system accuracy and functionality, analyzed passenger motion during braking, and provided evidence for CAWS/AEB applicability and potential for return on investment.

Lessons learned were documented for several topics including:

- How to calculate return on investment for CAWS/AEB
- Procedures and protocols for testing CAWS/AEB
- Need for bus OEM participation

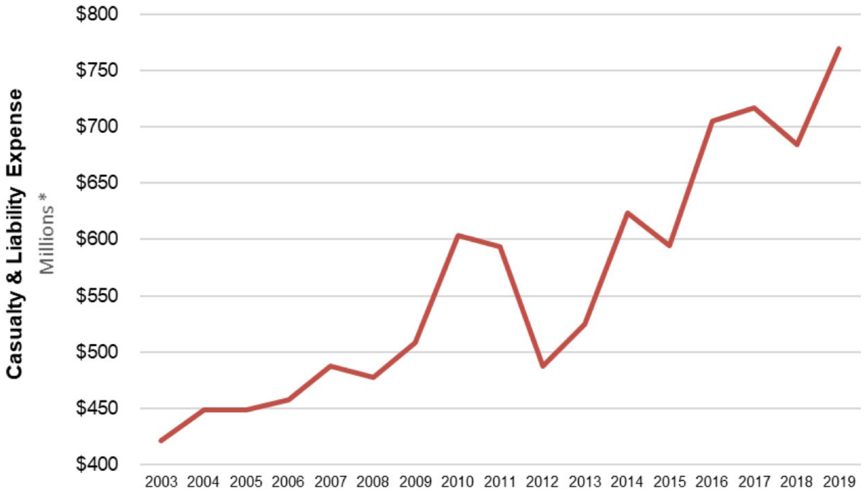
- Conducting research in the transit environment
- Retrofitting buses with advanced technology
- Data needs for future research on CAWS/AEB

It is recommended that continued research and development funding for CAWS/AEB be provided by sponsoring agencies and that bus original equipment manufacturers and technology suppliers continue to research and develop the technology.

Section 1

Project Background

Although transit bus passengers are more than four times safer than automobile passengers given rates of fatalities per 100 million passenger miles, buses can be made even safer.[3] According to the Federal Transit Administration's (FTA's) National Transit Database (NTD), for reporting years 2014–2019, bus transit modes reported 32,327 collisions, 99,186 injuries, and 583 fatalities and casualty and liability (C&L) expenses of $4,094,275,201, of which 67% are estimated to be directly correlated with collisions.[4] As shown in Figure 1-1, during 2003–2019, C&L expenses rose at twice the pace of inflation. Figure 1-2 shows the annual rate of bus collisions per 100 million revenue vehicle miles (VRM), which has been trending upward over time.



Source: Federal Transit Administration, National Transit Database
* Reporting Year Dollars

Figure 1-1 *Casualty & liability (C&L) expenses 2003–2019*

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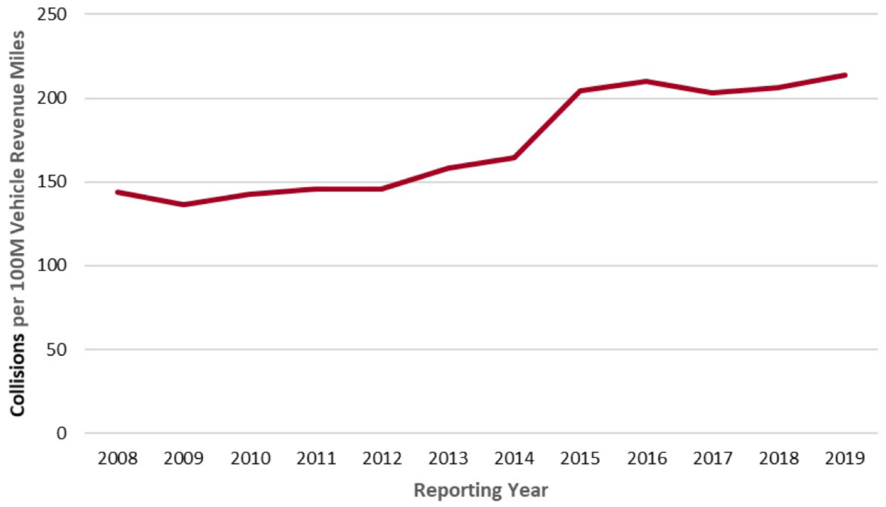
[3] US Department of Transportation, "National Transportation Statistics 2021," https://www.bts.gov/sites/bts.dot.gov/files/2021-12/NTS-50th-complete-11-30-2021.pdf.

[4] FTA National Transit Database, https://www.transit.dot.gov/ntd/ntd-data.



Source: Federal Transit Administration, National Transit Database
* Data prior to 2008 excluded due to changes in reporting

Figure 1-2 *Bus collisions per 100 million vehicle revenue miles*

Although the National Transportation Safety Board (NTSB) has strongly recommended application of collision avoidance systems and automated emergency braking (CAWS/AEB) on buses, the transit industry has lagged behind autos and trucks. This is attributed to the following factors:

- Transit buses are a niche market in the US, comprising about 100,000 vehicles, in comparison with the markets for autos and trucks.
- Bus original equipment manufacturers (OEMs) have not had the research and development resources needed to develop the technology nor the economic incentive to facilitate retrofits with CAWS/AEB.
- Transit buses operate in pedestrian-rich environments, which complicates development of algorithms for detection and warning that can avoid false positive (FP) detections.
- Autos and trucks provide restraints for passengers, whereas transit bus passengers are unrestrained and may be standing.

Previous Research

Staes et al. published “TCRP Synthesis 145, Current Practices in the Use of Onboard Technologies to Avoid Transit Bus Incidents and Accidents, a Synthesis of Transit Practice,” in 2020.[5] This report provided a comprehensive literature review and documented transit agency experience with on-board technologies intended to improve safety by reducing accidents. The report included seven

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[5] Staes, L., J. Godfrey, J. Flynn, M. Spicer, G. Saliceto, R. Yegidis, “TCRP Synthesis 145, Current Practices in the Use of Onboard Technologies to Avoid Transit Bus Incidents and Accidents,” 2020, https://www.nap.edu/login.php?action=guest&record_id=25716.

case studies of technology deployments, most in pilot studies and a few in fleet-wide deployments. Five of the case studies used technologies that provided warnings to drivers of impending collisions, two provided audible warnings to pedestrians that the bus was turning, and two provided warnings both to drivers and pedestrians. One case study reported an earlier pilot test with autonomous emergency braking, but the agency “decided not to pursue this technology at the time, however, due to FP alarms, ‘jerky’ autonomous braking that led to slips and falls, and engine throttle problems.”[6]

Spears et al. documented the “Active Safety-Collision Warning Pilot in Washington State,” conducted by the Washington State Transit Insurance Pool (WSTIP), which indicated the potential for automated bus CAWS/AEB to reduce bus collisions. That study indicated that collision warning systems had the potential to reduce forward collisions by 72% and pedestrian/cyclist collisions by 43%. These rates were applied to the historic costs for claims in which WSTIP members were involved; the net result was an estimated reduction in vehicular claims of $13.1 million and a reduction in pedestrian claims of $6.9 million. The total reduction of $20.0 million amounted to an estimated 58.5% potential reduction in claims due to collisions for all buses insured by the WSTIP. The study also indicated that greater reductions in collisions might be possible with AEB.

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[6] *Ibid.*

[6] Spears, M. J., J. M. Lutin, Y. Wang, R. Ke, S. M. Clancy, “Active Safety-Collision Warning Pilot in Washington State’” Final Report for Transit IDEA Project 82, National Academies of Sciences,

Section 2

Project Scope

The goal of this project was to test and evaluate CAWS/AEB for transit buses and provide information to bus manufacturers, CAWS/AEB developers, and transit agencies.

The initial Pierce Transit (PT) proposal was to deploy 176 buses equipped with second-generation CAWS and to equip 30 of those buses with AEB provided by another vendor. The initial scope was subsequently modified to eliminate further deployment of CAWS and reallocate resources to focus on automated braking.

When the project was conceived, an existing CAWS was to be used to trigger a separate AEB system. The CAWS vendor and PT were unable to reach agreement on contractual issues, and that vendor did not participate in the project. Consequently, the AEB system vendor agreed to undertake development of a sensor package to trigger deceleration and braking, which led to the inclusion of an Alpha testing phase in the project scope.

Go/No-Go Decision Making

To facilitate the project and mitigate the risks involved, PT staff adopted a go/no-go decision-making process that involved developing an organizational structure, establishing a series of discrete stages and decision-points to advance the project, and including specific review activities to be accomplished. The process was documented in a paper published by the Transportation Research Board,[8] which is included as Appendix A.

Ultimately, the go/no-go process decision-making resulted in deployment of 30 buses operating in revenue service equipped with CAWS/AEB and data loggers in data-collection mode only. A key factor in arriving at this decision was the unavailability of the bus OEM to provide engineering consultation to confirm safe operation of the retrofit package. In addition, PT determined that significant resources would need to be devoted to train all bus operators on the CAWS/AEB, although these systems would be operational on only 30 of its 176 buses.

The CAWS/AEB systems were put into service, but no warnings were provided to operators and no active braking was initiated. Each system logged events from the CAWS detectors and transmitted data to a server via a cellular data connection provided by PT. Because drivers had no interaction with the CAWS/AEB, surveys of driver interactions with the CAWS/AEB and their assessments of it were not part of the study.

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[8] Soule, Heidi H., Adam Davis, Andrew Krum, Yinhai Wang, Ruimin Ke, Dave Valadez, Dan Sellers, Steve Roberts, Luke Fischer, Jerome M. Lutin, "Risk Mitigation Planning for Revenue Service Testing of Bus Automated Emergency Braking," *Transportation Research Record,* 2675(5), 2021, 193–200.

Parallel Research Tracks

The revised project scope included five parallel research tracks shown below; research processes and findings are documented in individual sections of this report:

1. Quantifying Contributing Factors to Transit Bus C&L Expenses Using the NTD – University of Washington (UW)
2. Commercialization Potential for Transit Bus Automated Collision Avoidance Warning and Emergency Braking Systems – Veritas
3. Developing and Testing a 2D Flash Lidar Transit Bus Collision Avoidance Warning System – DCS
4. Evaluating the Accuracy of Transit Bus Collision Avoidance Warning Systems – UW
5. Analyzing Unrestrained Passenger Motion During Transit Bus Braking – Virginia Tech Transportation Institute (VTTI)

COVID-19 Pandemic Impacts

The project was significantly affected by the COVID-19 pandemic. Key partners DCS in Indiana and VTTI in Virginia were unable to travel to Washington state to work on equipment installed on buses because of travel-related restrictions imposed in response to the pandemic. Some work was performed by PT maintenance and IT personnel, and VTTI had a Washington-based staff member who was able to remove and replace instrumentation needing service. The pandemic affected the bus OEM as well because of travel restrictions and the need for its engineering staff to refocus on bus ventilation. VTTI's data collection on passenger motion was hindered by a sharp drop in transit ridership, which greatly reduced the numbers of standing passengers.

Section 3

Business Case for CAWS/AEB

In addition to the human costs of collisions, there are measurable economic costs reflected in insurance claims and other casualty and liability expenses incurred by transit agencies. This project explored the potential for development and deployment of CAWS/AEB from the standpoint of bus OEMs and system developers that may be able to develop and offer CAWS/AEB at prices that are both affordable and profitable and from the perspective of transit agencies that may need to justify their procurements on the basis of benefit/cost as well as reducing fatalities and injuries. This project explored collision cost savings potentials on two levels—industry-wide using data from the NTD and agencies reporting annual operating, expense, and safety data, and within Washington state by using specific incidents and claims reported to WSTIP by its member transit agencies.

Estimating the Cost of Collisions Using NTD Data

As reported to the FTA NTD, C&L costs include "the cost elements covering protection of the transit agency from loss through insurance programs, compensation of others for their losses due to acts for which the transit agency is liable, and recognition of the cost of corporate losses."[9]

UW developed two models based on NTD data—a model to assess exposure to collisions and a model to assess the quantitative relationship between collisions and C&L expenses at the agency level. The exposure model showed that the number of collisions was highly sensitive to the regional travel time index (TTI), which is defined as "the ratio of travel time in the peak period to the travel time at free-flow conditions."[10] Numbers of collisions also had significant positive correlations with the rate of bus mechanical failures and the number of hours worked by full-time operators as well as average speeds in revenue service and the regional commuter stress index (CSI) another measure of peak period traffic congestion.[11] One surprising finding was a significant negative correlation between the number of collisions and the number of hours worked by part-time drivers.

The collision expense model used structural equation modeling (SEM) to estimate the degree to which numbers of collisions could predict C&L expenses. The research team aggregated NTD data over five years (2015–2019) to help account for the autocorrelation of premiums and collisions in previous years for 273 transit agencies reporting non-zero collision data. The SEM model produced two significant independent variables, the number of bus collisions with motor

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[9] "National Transit Database (NTD) Glossary | FTA," https://www.transit.dot.gov/ntd/national-transit-database-ntd-glossary.

[10] Schrank, D., L. Albert, B. Eisele, and T. Lomax, "Urban Mobility Report," Texas A&M Transportation Institute, June 2021, http://tti.tamu.edu/documents/mobility-report-2021.pdf.

[11] *Ibid.*

vehicles and the number of bus collisions with persons. The resulting SEM model had an R-square statistic of 0.671, which can be interpreted as the numbers of collisions with vehicles and collisions with persons, together predicting 67% of the variation in total C&L expenses. The model coefficients can be used to measure elasticities for both types of collisions. A reduction of 100 collisions with motor vehicles could result in a decrease in C&L expenses of $4.42 million, and a decrease of 100 collisions with persons could result in a decrease of $16.7 million. Appendix B provides detail on the data and analysis used for exposure and cost modeling.

Estimating Return on Investment

Veritas Forensic Accounting and Economics (Veritas) reviewed 12 years of WSTIP transit agency member fixed-route bus claims and found that 45% of $59.9 million in liability claims and 38% of injuries could potentially be mitigated if a fully tested and operational system was implemented and adopted by member transit agencies. WSTIP's records contain specific fields that can be used to compare and evaluate claims cost and potential outcomes. The project team reviewed event data for over 8,600 claims and compared the event specifics with the CAWS system's capabilities to identify events that could be technologically impactable. The project team also reviewed NTD data.

For this report, the project team applied detection and braking capabilities for a non-specific, 150-degree field-of-view, forward-looking system to determine whether an event could be affected by a CAWS/AEB system. After reviewing WSTIP transit agency historical events, the project team estimated that 25% of WSTIP member claims could be technologically impactable and 75% would not be impactable by the system. The 25% of claims categorized as technologically impactable comprised 38% of the injuries recorded by WSTIP.

The project team also obtained historical data from the NTD for transit agencies across the US. The project team applied the data and findings from their review of WSTIP's records to NTD data, and WSTIP event-caused claims and liability expenses incurred were compared with what WSTIP members reported to the NTD for C&L costs. This comparison was made to establish a ratio of event-caused claims and liability expenses as a percentage of C&L costs (i.e., event costs as a percentage of insurance premiums).

Veritas also calculated return on investment for CAWS/AEB based on WSTIP claims experience. The majority of what is reported to the NTD for C&L costs comprises insurance premiums. The project team needed to establish what percentage of premiums could reasonably be calculated as claims and liability expenses, also known as a loss ratio. For 2015–2019, event-related claims and liability expenses for WSTIP members equaled, on average, 58.52% of the C&L costs reported to the NTD (i.e., 58.52% of premiums). Table 3-1 summarizes the potential claims cost reductions for NTD reporting agencies if 58.52% of C&L costs reported to the NTD (i.e., premiums) were equal to the amounts of claims and liability expenses that events caused for agencies with service area populations like those of WSTIP members (i.e., under 1 million).

For purposes of this report, three levels of efficacy were assumed for a fully tested and functional CAWS/AEB system at 25%, 50%, and 75%. Table 3-1 summarizes the potential break-even cost for the acquisition and implementation of CAWS/AEB based on technologically impactable events. As shown, it would be possible for a transit agency to estimate the value of the system over its useful life on a bus and the price point for a vendor on the basis of system effectiveness.

Appendix C contains more details on the data and analysis performed by Veritas for this project.

Table 3-1 *Potential Return on CAWS/AEB Investment for NTD Reporters with Populations of Less Than One Million*

Scenarios	Potential Saved C&L Expense per Mile	Less Maint. Expense per Mile	Saved C&L Expense per Mile	System Life Expectancy Miles Needed to Break Even	Break Even Cost for CAWS/AEB – Assuming 37,080 Miles per Year		
					6 Years – 222,480 miles	*8 Years – 296,640 miles*	*10 Years – 370,800 miles*
Scenario 1 – 25% Reduction	$0.017	($0.006)	$0.011	595,301	$3,070	$4,093	$5,116
Scenario 2 – 50% Reduction	$0.034	($0.006)	$0.028	297,651	$6,807	$9,076	$11,345
Scenario 3 – 75% Reduction	$0.050	($0.006)	$0.044	198,434	$10,544	$14,059	$17,574
Current Life Expectancy of System							Unknown

Note: The lifetime maintenance expense at the date of this report was unknown. However, for the 30 systems installed for 930,091 miles, $6,000 in repairs and maintenance was incurred (i.e., $.006 per mile).

Section 4 CAWS/AEB System Tested

Pedestrian Avoidance Safety System (PASS)

The Pedestrian Avoidance Safety System (PASS) was developed initially as an SAE Level 1 system. It automatically decelerates the vehicle when an imminent pedestrian collision is identified by the detection and warning system. The system provides active (automatic deceleration) assistance to the driver in avoiding or reducing the severity of a collision. It uses a standalone microprocessor-based controller with proprietary sensor fusion algorithms to integrate pedestrian detection and warning sensor systems with the vehicle powertrain and brake systems. Monitoring the CAWS warning data and vehicle dynamics (speed, direction, throttle, and brake position, etc.), the system determines within a fraction of a second if automatic action is required.

The vendor developed a pedestrian and forward vehicle detection sensor package to detect and calculate the potential for imminent collisions with a bus. The sensor package uses an array of three light detection and ranging (lidar) sensors, as shown in Figure 4-1. The sensor arrays are attached to a mounting bracket immediately below the foldable bicycle rack, as shown in Figure 4-2.[12]

Figure 4-1 *PASS sensor assembly design drawing*

Source: DCS

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[12] DCS Technologies, Inc., and VTTI, "FTA-Pierce Transit Collision Avoidance and Mitigation SRD Project Alpha Test Quicklook Report," March 18, 2019.

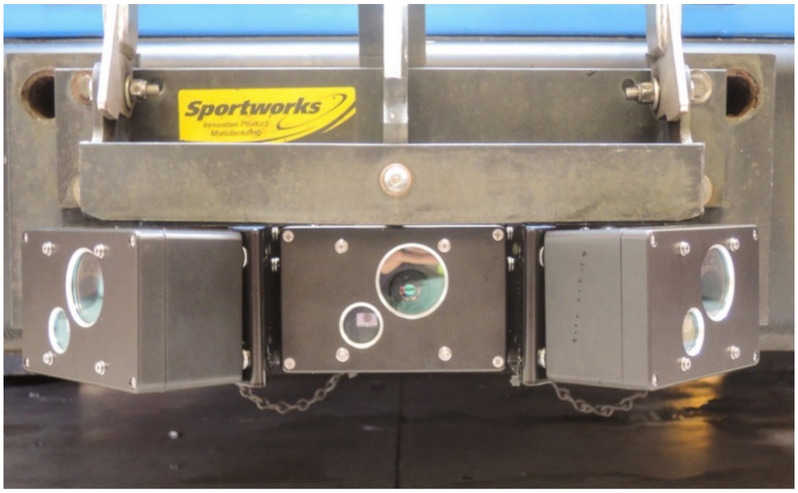

Figure 4-2 *PASS sensor array on front of bus*

Source: DCS

PASS Testing at Virginia Smart Roads Facility

The sensor array had been tested on several types of vehicles but had not been deployed on a bus. Consequently, the decision was made to conduct closed-course testing (“Alpha testing”) at VTTI on the Virginia Smart Roads facility to characterize the system’s capabilities and fine tune it. VTTI and the vendor jointly developed a test plan for simulating collisions with pedestrians, vulnerable road users (VRUs), and forward collisions with vehicles.[13] For collision avoidance with VRUs, a simulated intersection was constructed to represent one that PT buses regularly traverse that included lane markings and stop lines, a streetlight, a bus stop pad and shelter, a curb parking lane in which a vehicle could be parked to occlude vision of a pedestrian stepping from the curb, and a crosswalk equipped with a computer-controlled belt that can propel a VRU manikin across the crosswalk at walking or running speed. Figure 4-3 shows a drone view and graphical overlay of the test track intersection, Figure 4-4 shows the bus braking automatically for the VRU at the simulated intersection during a test, and Figure 4-5 shows a simulated rear-end collision avoidance maneuver, with the bus braking for an inflatable dummy vehicle towed in front of the bus.

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[13] *Ibid*.

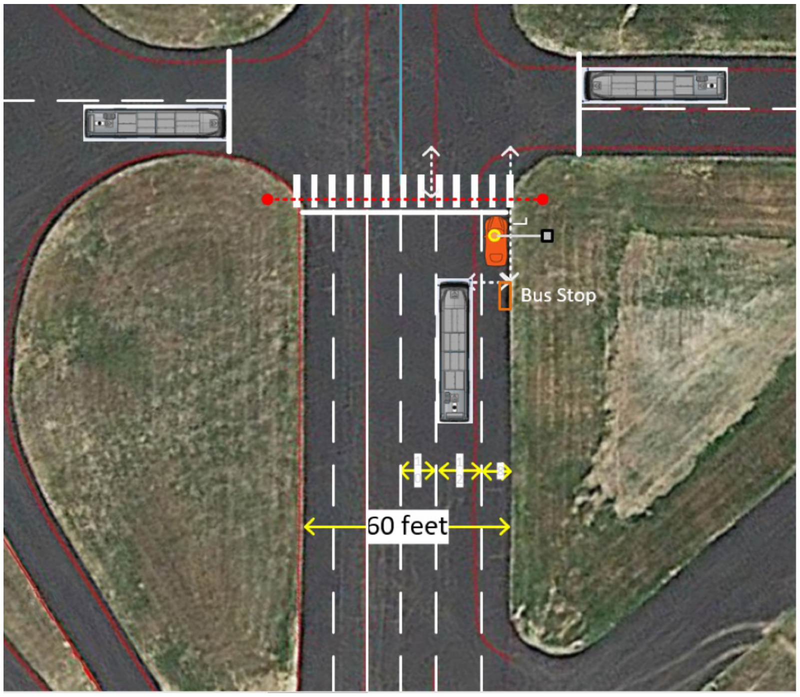

Figure 4-3 *Drone view and superimposed graphics for test intersection at VTTI*

Source: VTTI

Figure 4-4 *Photo of bus stopping for VRU manikin*

Source: VTTI

Figure 4-5 *Forward collision testing with dummy vehicle*

Source: VTTI

Most Alpha testing was conducted during two vendor site visits to VTTI, one in mid-March and one in late April 2019. More than 400 test runs were conducted, including collision avoidance bus runs at various speeds with static VRUs, walking and running VRUs, occluded VRUs, and forward collision avoidance with simulated moving vehicles. Day and night testing was conducted for VRUs and vehicles, and weather testing under simulated rain and fog conditions was conducted on April 30, 2019, and May 7, 2019. The technology was fine-tuned during the testing sessions, and performance was deemed satisfactory for deployment in the next project phase.

PASS data-loggers automatically collected and transferred vehicle and PASS telematics data to DCS servers. PT provided DCS access to an on-board cellular modem on each vehicle under test (VUT) for wireless data transfer. Early beta testing with VUTs (buses 230–233) provided an opportunity to exercise the PASS data collection hardware and software as well as data reduction processes.

PASS Installations at Pierce Transit

PASS systems were installed on 30 New Flyer Low Floor (LF) buses, from the initial alpha system on bus 230 in March 2019 to full fleet installation of production units completed in September 2020. Official data collection for all PASS-equipped buses commenced later that month and continued through July 2021. For November 5, 2020–July 31, 2021 (after the final PASS software update), 4,607 log files were collected over 930,091 operational miles from the 30 project vehicles. Table 4-1 summarizes high-level fleet metrics (total PASS warning events, estimated bus operating hours or uptime, and warning events per hour) and warning event metrics per bus for the nine-month period.

Table 4-1 *Summary PASS Data Collection Metrics, November 5, 2020–July 31, 2021*

	PASS Warning Events	Bus Uptime (est. hours)	Events/Hour
Fleet Totals	42,343	34,001.5	1.2
Per-Bus Metrics			
Average/Day	9.2	7.4	1.5
Minimum/Day	0.0	0.5	0.0
Maximum/Day	75.0	23.1	18.0

Data measured at the instant of a PASS warning event provided some insight into vehicle operating conditions and operator behavior. During the data collection period, PASS operated in data collection mode only. PASS event signals were logged and sent to the server via telematics. No warnings were provided to drivers, and no automatic deceleration or braking was applied. Graphs were developed to illustrate braking events under manual operation of the bus solely by the driver. Preliminary decomposition of the full data set is included in Appendix D.

All PASS maintenance items were tracked throughout the project. PASS was designed and tested to meet a minimum 100,000 miles mean distance between failure (MDBF). The total test fleet vehicle mileage for PASS production equipment was approximately one million miles. With five component failures logged during the project timeframe, MDBF was calculated to be 200,000 miles.

Section 5

Using CAWS/AEB Data for Crash Risk Hot Spot Mapping

The project demonstrated the ability to capture activations of CAWS/AEB systems from data loggers and transmit them to a central server to create a database that could be used to examine variations in the frequency of near misses along bus routes. Locations with clusters of pedestrian or vehicular near misses were termed “hot spots.” This information could be used as a basis for recommending route modifications and physical infrastructure improvements to better protect pedestrians and mitigate the potential for bus collisions with other vehicles.

The process integrated data transmitted from the CAWS/AEB data loggers with route, bus stop, and schedule data from the PT computer-aided dispatch/automated vehicle location (CAD/AVL) system and data platform. A density-based clustering algorithm (DBSCAN) grouped events on every route and identified clusters. Road information was used to determine the road segment boundary for each high-risk cluster. DBSCAN was applied to spatial clustering for high-risk regions rather than individual road segments. More detail on the data fusion and analysis processes is included in Appendix E.

Figure 5-1 shows sample point clouds of pedestrian and vehicular events captured from the data logger installed on PT bus 233 during the project. Figure 5-2 shows an enlarged section of the vehicular event map from Figure 5-1, focused on the intersection of Pacific Avenue and South 24th Street in Tacoma, Washington. At this intersection, buses on several routes heading south on Pacific Avenue turn left onto South 24th Street. A bus stop is located on the south side of South 24th Street close to the corner. The event cluster may result from conflicts between left-turning buses and northbound vehicles. Bus operations and safety staff can use this information to prioritize this location for further examination by checking with bus drivers and making field observations.

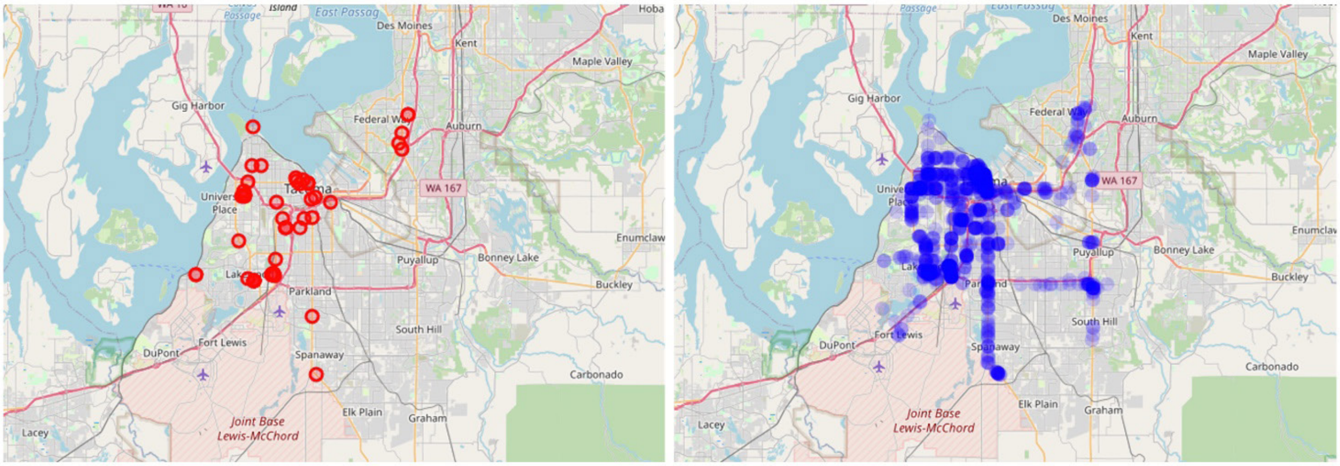

Figure 5-1 *Pedestrian (red dots) and vehicular (blue dots) CAWS event point clouds from Bus 233 data logger*

Source: UW

Figure 5-2 *Enlarged vehicular point cloud at intersection of South 24th Street and Pacific Avenue*

Source: UW

Figure 5-3 shows an enlargement of the pedestrian event point cloud from bus 233's data logger for a segment of 6th Avenue adjacent to Wright Park in Tacoma, Washington. Several bus stops are shown in the map overlay.

Figure 5-4 shows a Google Streetview photo looking east on 6th Avenue from the intersection with South I Street in Tacoma. The bus stop in the foreground is served by PT Route #1. Dense trees and parked cars along the street, coupled with the potential for higher pedestrian activity connected with the park, may increase the risk of pedestrian events. Safety supervision may determine a need for increased driver awareness in this area.

Figure 5-3 *Pedestrian event point cloud enlargement near bus stops on 6th Avenue*

Source: UW

Figure 5-4 *Photo looking east on 6th Avenue at intersection with I Street*

Source: Google Streetview 2021

Section 6

Testing for False Positives and False Negatives

For buses equipped with CAWS/AEB, false positives can produce an uncomfortable ride and irritate drivers. False negatives are more serious because they can lead to a collision. False positives and false negatives both can erode confidence in the technology. The following terms and definitions are used as a basis for discussing CAWS/AEB system accuracy:

- **CAWS Warning Event** – A CAWS/AEB algorithm-derived event indicating that a safety and/or collision threshold has been met or exceeded. The event typically triggers a driver alert (visual and/or audible) and/or collection of vehicle and CAWS/AEB telematics data.
- **Dangerous Condition/Event** – Includes scenarios internal and external to the CAWS/AEB-equipped vehicle. Internal: bus passengers are exposed to g-forces above a predetermined threshold (e.g., 0.3 g) as a result of a panic stop or evasive maneuver. External: the bus and an external object (vehicle, VRU, fixed object) are on an imminent collision trajectory requiring an immediate action ("break in the chain of events") to prevent injury, fatality, or property damage.
- **False Positive (FP)** – A CAWS warning event that cannot be correlated to a dangerous condition/event through review of objective evidence.
- **False Positive Rate (FP Rate)** – Number of FP CAWS warning events over the total number of actual non-dangerous objects/events, whether correctly identified or not by the system under test. FP can be analyzed against several metrics (e.g., miles, hours, CAWS warning events, objects detected). Each FP analysis can capture a unique measure of system performance. Transit agency policy and/or the operational environment will determine which FP (metric) is most critical or informative.
- **False Negative (FN)** – An external dangerous condition/event that was not identified by the CAWS/AEB system. Identification of FN events must be supported with objective evidence.
- **False Negative Rate (FN Rate)** – Number of FN events over the total number of actual dangerous events, whether detected or missed by the system under test.

Transit Event Logging System (TELS)

Given the challenge of manually checking and recording the large amount of data associated with FPs and FNs, UW's Smart Transportation Applications and Research Laboratory (STAR Lab) developed a new on-board video processor, the Transit Event Logging System (TELS). This system used existing cameras on the buses to automatically filter out events less likely to contain an imminent collision, help detect near misses, and help identify FPs and FNs. The video processor used an Nvidia Jetson TX2 embedded system to receive a continuous feed from a forward-facing camera whenever the bus engine was running.

Video clips were stored continuously in a buffer for immediate retrieval. The video feed was processed through an object detector that categorized objects as VRUs or vehicles and measured their trajectory and closing rate (time to collision) with respect to the bus. If the trajectory and time to collision appeared to lead to an imminent collision, the processor recorded it as a near miss and stored video scenes before and after the event. The TELS continuously searched its video feed for VRUs and vehicles. If a VRU or vehicle was estimated by the TELS to be at risk of collision, it checked to determine whether PASS had sent an alert signal. If no signal was received from PASS, the video clip was stored and labeled as a potential FN. Figure 6-1 shows a sample video of a vehicle in front of the bus that the TELS determined to be a false negative. The TELS created a box around the target vehicle, shown in red.

Figure 6-1 *False negative example: Missed conflict event with vehicle at intersection*

Source: UW

The PASS system triggered the TELS processor when PASS's lidar detectors identified an imminent collision. The TELS then retrieved a video clip for several seconds before and after the signal and checked the video for the presence of a VRU or vehicle. If neither was identified, the clip was saved for analysis and labeled as a potential FP. In addition, random samples of video could be downloaded and manually checked for the presence of VRUs or vehicles to verify the accuracy of the TELS and patterns that may have been missed by both PASS and the TELS.

False Positives and False Negatives Testing Results

For each of the four buses equipped with the TELS, three months of data (May 1–July 31, 2021) collected after the final project PASS update were used for evaluation. The results are shown in Table 6-1. The overall share of FPs was 93.5%. Nearly 60% of the FP events were attributed to finding no actual high g event, and nearly 40% of FPs were attributed to the object not being on the travel path of the VUT. A few (less than 3%) FPs were attributed to the potential for the VUT to decelerate at a rate below 0.3 g. In nearly 60% of the FP events, objects were detected as having potential conflicts with the VUT, although in some cases, the objects did not pose a risk to the bus (e.g., snow on the bike rack). None of the PASS or TELS incidents logged was associated with an actual vehicular or pedestrian collision.

Table 6-1 *Summary Using PASS Events, May–July 2021*

Vehicle #	PASS Events	FPs	Share of FP
Bus 230	445	417	93.7%
Bus 231	669	603	90.1%
Bus 232	582	553	95.0%
Bus 233	785	747	95.2%
Total	2,481	2,320	93.5%

FN statistics for the four TELS-equipped buses from May 1, 2021, to July 31, 2021, are presented in Table 6-2 and Table 6-3. Within the 441 FNs, 16 were pedestrian-related events and 425 were vehicle-related events. These events were classified according to which of the three PASS sensors triggered the event. The center PASS sensor triggered 283 signals, the left sensor triggered 134, and the right sensor triggered 24 signals. There were 150 FNs recorded when the bus speed was low (0 to 10 mph), and nearly half of the events (203) occurred between 10 mph and 20 mph, 60 occurred between 20 and 30 mph, and 28 occurred over 30 mph. In total, 69 of the events occurred in the morning between 5:00 and 9:00 AM, 192 were from 10:00 AM to 2:00 PM, 167 were between 3:00 and 7:00 PM, and only 13 occurred in the evening after 7:00 PM. None of logged PASS or TELS FN incidents was associated with actual vehicular or pedestrian collisions. Two of the PASS-equipped buses experienced collisions in which other vehicles struck the buses. Neither of those collisions occurred within the PASS operational design domain.

Detailed documentation of the TELS and data collection process is provided in Appendix F.

Table 6-2 *FN Statistics, May–July 2021*

Vehicle #	Total Events	False Negatives	False Negative %
Bus 230	3,854	95	2.5%
Bus 231	2,854	93	3.3%
Bus 232	4,850	79	1.6%
Bus 233	5,627	174	3.1%
Total	17,185	441	2.6%

Table 6-3 *FN Events Summary*

Type	Pedestrian 16, vehicle 425
Position	Front 283, left 134, right 24
Speed	0–10 mph 150, 10-20 mph 203, 20-30 mph 60, >30 mph 28
Time of Day	5–9am 69, 10am–2pm 192, 3–7 pm 167, >7p, 13
Total	441

Section 7

Passenger Motion Testing

Although collision avoidance and emergency braking systems have been successfully developed for trucks and autos and are in widespread use, none has yet been deployed for transit buses. Unlike auto and truck passengers, transit bus passengers are unrestrained and may even be standing. Consequently, automated braking for transit buses must be designed to avoid injuring passengers during deceleration, more precisely defined as negative acceleration.

Passenger motion on a transit bus may occur for multiple reasons. A passenger may choose to change posture, change seats, transition from standing to sitting or from sitting to standing, or manipulate a personal article or assist other passengers (e.g., children). A passenger may also move as a result of the bus's motion because of a bus operator's control action (e.g., brake pedal) or driver-assisted technology activation (e.g., AEB). It is difficult to determine the intent of each passenger. However, it is valuable to observe and measure the resulting motion of individual passengers near events of brake pedal activation to instruct future bus braking automation systems that may be developed to reduce collision events outside the bus while reducing unintended consequences inside the bus.

VTTI was tasked to develop a methodology to measure and evaluate the effects of manual and automated braking on bus passengers to draft a standard for autonomous braking for buses. VTTI developed a passenger motion capture system that records the forces acting on passengers, receives signals from the CAWS/AEB system via the bus's controller area network (CAN bus), and captures videos of passenger motion. Images were blurred to protect individual privacy. VTTI's institutional research board reviewed and approved the protocol. Figure 7-1 shows blurred video of two passengers on the bus and static reference points used to measure head motion during braking events.

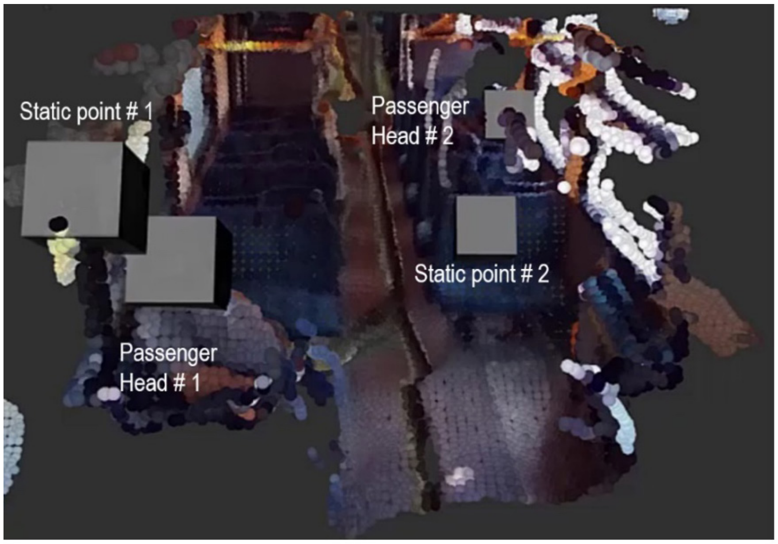

Figure 7-1 *Sample image of transit bus passenger motion from field data collection*

Source: VTTI

Passenger Motion Data Collection System

The system used software developed by VTTI running on a Neousys Technologies Nuvo in-vehicle edge computer using an Nvidia graphics card. The Nuvo collected the following data elements for two PT buses on 2-TB hard-drives—passenger motion stereovision measures, blurred interior camera (for motion verification), blurred forward camera (braking event context: vehicle, pedestrian, or other), vehicle CAN (e.g., brake status, speed), vehicle motion (i.e., accelerometers, 20 Hz), vehicle location (i.e., GPS 5 Hz), and PASS on the vehicle CAN (i.e., warning and caution signals).

The VTTI passenger motion instrumentation on the two buses produced 649 passenger motion profiles (PMPs) among passengers who were seated, standing, in a wheelchair, and "seated unstable" if the passenger was holding a stroller, cane, or walker. Anonymized videos of head movements were measured and analyzed. Braking events did not exceed -0.3 g, and head movements did not vary significantly for different braking rates.

The measurement process applied in this field investigation was selected primarily because it was non-contact and could attempt to measure natural behavior. Passengers might behave very differently in a controlled lab or test track experimental methodology. This collection procedure was novel, as was the software developed to post-process the PMPs for each passenger. Another strength of this approach was the simultaneous collection of data for multiple passengers and full scenario internal and external data. Although one approach with multiple measures was selected to analyze passenger motion during this investigation, the vehicle and passenger data could be organized in many other ways in the future. This is because of the naturalistic approach that assumes very little at the time of collection but provides full scenario information.

Passenger Motion Observations and Findings

This study observed that most transit bus braking maneuvers occurred below 0.3 g. The measured forces on seated passengers during Level 3 braking were 0.10 g in the backward direction and 0.09 g in the forward direction. Previous research on the topic of transit passenger motion and balance had sought to determine the limits of forces that passengers may be able to resist to avoid falling. This naturalistic collection of passenger motion found that the total motion and forces acting on passengers in typical transit bus operations did not vary significantly by low to moderate braking level or posture. This finding could be applied to the development of automatic braking assistance features for transit buses.

Drivers were observed to brake the bus with deceleration rates below 0.3 g. The result of this analysis supports the current training and natural human driving skills present among transit bus drivers. This finding illustrates that transit bus drivers choose to maneuver buses in a way that is protective of their passengers while still critically responding to the traffic, pedestrians/bicyclists, and environment outside. Future braking assistance and AEB systems should imitate driver braking profiles except where a critical and verifiable risk exists for pedestrians or bicyclists outside the bus and aggressive maneuvers are necessary to mitigate or avoid a collision.

Findings based on multiple calculations, including forward, backward, and total displacement, along with speed and acceleration over hundreds of samples of seated passenger motion events, suggest that unrestrained passengers do not move significantly differently between braking levels. The lack of distinction among braking levels for seated passengers may have implications for the development of future driver-assist automation technologies. During the project, the developer of the PASS system was careful to limit the amount of braking force applied across the vehicle during PASS warning activations. This approach is reasonable for new driver assistance features to reduce interference during the driving task, especially as system reliability is under development. However, another consideration of the developer was to limit braking automation to avoid unintended consequences on passengers. These findings suggest that when reliability and the correct balance of sensing and perception are developed in transit bus collision warning systems, passengers will generally react similarly to a range of low to moderate automatic braking assistance levels and vehicle maneuvers.

More information on the instrumentation and data collected for passenger motion analysis can be found in Appendix G.

Section 8

Lessons Learned

Return on Investment

The evidence examined in this project suggests the potential for a return on investment for transit agencies if fully tested and functional CAWS/AEB systems are available for retrofit on transit buses. There does not appear to be a "one size fits all" solution. The business case will vary from agency to agency; however, an agency should be able to estimate the potential benefits on the basis of in-house data on collisions and expenses as well as costs and performance data provided by vendors. Historical agency averages can be computed for the expected amortization life of the CAWS/AEB system or the expected life of the vehicle. Anticipated savings will depend on the proportion of C&L expenses that result from collisions, and the proportion of those collisions that could be prevented or mitigated by CAWS/AEB.

Testing CAWS/AEB

In the fall of 2019, the PASS-equipped bus tested at VTTI was returned to PT, and the vendor was ready to install PASS on an additional three buses. PT maintenance and safety staff then became more involved in the testing and safety review process. To facilitate the project and mitigate the risks involved, PT staff adopted a go/no-go decision-making process that involved developing an organizational structure, establishing a series of discrete stages and decision-points to advance the project, and determining specific review activities to be accomplished.

System retrofits provide a challenge. The lidar sensors are a line of site measurement device. Mounting of sensor array was restricted to available areas on the front of the bus that had an unobstructed view to detect objects. The sensor array could not be located behind the windshield due to the glass attenuating the lidar signal. The optimal mounting location would have been directly below the front windshield. However, the bike rack had already laid claim to that area. The sensor array was eventually mounted to an area below the bike rack mount.

Lidar sensor technology coupled with sub-optimal sensor array mounting locations, provided detection challenges during a subset of driving scenarios. Highly-reflective objects, such as road signs, reflective tape, and raised road reflectors, became obvious generators of FPs or noise. These types of objects saturated the sensors and made the objects seem larger than actual size. Many of the FPs due to highly reflective objects were mitigated with sensor mounting adjustments and object detection algorithm improvements. Further advancements to drive down remaining FPs could be additional sensor augmentation or fusion. A system that used computer vision (CV) would ignore these objects because their shapes often do not resemble the shapes of VRUs. The lidar sensors also did not provide signals that distinguished between pedestrians and vehicles, which would have been possible with CV.

The 2D sensors could not be located behind the windshield because of glass interfering with lidar radiation, thus limiting their placement. In addition, the sensor field of view encompassed only forward collision avoidance and did not cover blind spots along the sides of the bus and behind the driver. Where the vision system is mounted is best determined as early in the design process as possible. Objects already fixed to the bus, such as bike racks and bikes on a bike rack, can create interference for certain mounting locations. Other mounting locations, such as the mirrors, have a higher potential to collide with objects in the environment, such as tree branches, than other mounting locations.

Examination of data from this project showed that for many events that could trigger warnings or braking, the driver was aware of or already acting to avoid a collision when the CAWS/AEB sensor was activated. This suggests that driver actions also should be incorporated into CAWS/AEB reaction algorithms to avoid unnecessary warnings. For example, if a driver anticipates a potential collision and has taken their foot off the accelerator or initiated braking, a CAWS warning could be perceived as an annoyance and an FP.

Although the TELS instrumentation was developed to evaluate PASS, the TELS results could not be considered “ground truth.” Establishing “ground truth” for determining accuracy in the FP and FN identification process should include collecting randomly sampled events to avoid the introduction of error by the measuring system. In addition, collection of roadway geometry data would have been helpful to more accurately calculate acceleration/deceleration values. Analysis of real-time data collected on bus motion was complicated by the presence of noise in signals received from various sensors. It also would have been beneficial to have had noise filtering algorithms available in the data processing stream. It would have been helpful to have had an established consensus on terminology and definitions of key performance metrics and evaluation criteria for transit-specific collision avoidance systems.

The CAWS/AEB initial testing was conducted with buses in non-revenue service on a closed course, the Virginia Smart Road facility. This facility was specifically constructed for vehicle testing with staff experienced in motor vehicle testing, safety, and data collection. However, variations in local weather, environment, and roadway conditions will require testing on routes in each transit agency’s service area. For example, in contrast to the gentle grades and generally level simulated urban intersection on the Smart Road test track, PT buses operate on streets with steep grades in the Tacoma area, which required some readjustments to the PASS system. Although the availability of a suitable location for closed-course testing is highly desirable, an agency seeking to test

CAWS/AEB on its fleet should develop a local area testing plan in consultation with local roadway authorities and the CAWS/AEB vendor.

A controlled experiment approach to revenue service testing was proposed for this project but could not be implemented because of the withdrawal of one vendor and concerns raised in the risk mitigation planning process. In a controlled experiment, some buses would have been equipped with CAWS/AEB and others would not, although all buses in the test would have been equipped with a common data collection system that would have allowed for comparison between both groups. A variation on that approach also was planned, in which buses would have been instrumented to measure braking and collision avoidance performance without warnings or braking for a period to establish baseline performance measures. After a defined baseline period, drivers would have been trained on the system, warnings and braking would have been activated, and data would have been produced from the instrumentation to compare before and after operational performance.

Little guidance on performance, design, and testing standards and regulations was available during the period of this project to aid in evaluating the CAWS/AEB systems. The project team corresponded with state and federal agencies and reviewed documents available from standards organizations. Given the unavailability of relevant information, the transit agency took a conservative approach to testing, as documented in Soule et al., 2021.[14]

This lack of standards and regulations may inhibit other transit agencies from undertaking this type of research. However, given the dynamic nature of autonomous driving systems and advanced driver assistance systems, it is expected that the information gap will be filled over time. Those interested in continuing with CAWS/AEB research and development are urged to stay informed about the work of regulatory bodies such as the National Highway Traffic Safety Administration (NHTSA) and standards development organizations such as the Society of Automotive Engineers (SAE) and the Institute of Electronic and Electrical Engineers (IEEE).

Many transit agencies already have on-board data collection systems that can be valuable tools for evaluating changes in vehicle operation due to CAWS/AEB and can potentially become part of the CAWS detection system. In this project, the UW connected its TELS system for measuring CAWS accuracy to existing Apollo video cameras and recorders. The TELS used images from the forward-facing Apollo cameras to identify FP and FN warnings. Most recording systems also include interior cameras that can be used to study passenger and driver motion, and many event recorders measure and log bus location, speed, turning

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[12] Soule et al., “Risk Mitigation Planning for Revenue Service Testing of Bus Automated Emergency Braking,” *Transportation Research Record*, 2675(5), 2021, 193–200.

movements, and deceleration rates. In addition, historical examination of video clips from previous collisions can be used to estimate the number of collisions and degree to which they could have been mitigated or prevented by CAWS/AEB.

Bus OEM Participation

OEM participation was needed and should have been agreed upon before project initiation. OEM engineering assessment and approval of PASS integration was sought by PT maintenance staff for safety assurance. An inability to obtain OEM approval was a key factor in the decision to eliminate the planned in-service testing phase with active CAWS/AEB. When the request for assistance was made to the OEM during the project, engineering staff were unavailable because of reassignments in response to the COVID-19 pandemic. The OEM also indicated that the technology for the year 2008 bus models being tested had been superseded in current production models, so the effort would not have been useful for retrofitting newer buses with CAWS/AEB. More relevant technical data could have been obtained if newer buses had been used.

Conducting Research in the Transit Environment

The primary mission of transit agencies is to provide safe and reliable transportation to the public. Transit agencies are highly visible and responsible for providing consistent, good service daily with no interruptions or disruptions. On average, fares pay for only about 25% of the cost to transport a passenger. For agency staff, resources are highly constrained. Most transit agencies are governed by public boards or other governmental bodies. The responsibility for funding and operating transit ultimately rests with state and local governments that are sensitive to safety, costs, and customer complaints. These constraints frame the background for the collaboration needed for a successful project. Research into technology to improve safety involves many unknowns in terms of resource requirements and potential outcomes, creating a scenario diametrically in conflict with normal transit operations.

The lesson learned is that champions for transit research projects are needed at the highest levels of the agency. They are the ones who can allocate the resources needed and can get things done. Additionally, vendors and researchers need to be sensitive to the needs and mission of the transit agency.

The time needed for contract negotiations was underestimated. There were lengthy negotiations with one vendor involving intellectual property and integration with equipment supplied by a second vendor. The negotiations did not lead to contract execution, and the first vendor did not participate in the project. That necessitated modification to the scopes of work and reallocation of resources among other partners, which delayed the project. The lesson learned is to confirm early in the proposal stage that all partners agree on data sharing and integration of components.

The time needed for board approvals was underestimated. Transit agency boards typically meet monthly. Several weeks are needed for staff work, preparation of resolutions and supporting documentation, and internal approvals before each board meeting. In this project actions were needed by the PT board and the WSTIP board that had to be sequenced one after the other. The lesson learned is to understand the needs and time requirements for agency approval processes when building the project schedule.

Scope changes led to the need for additional expertise and testing facilities. When a proven sensor was no longer available to trigger the PASS AEB system, it was necessary to develop an alternative solution, which had to be tested under closed course conditions. The lessons learned were that having a creative engineering team can provide alternative solutions when issues arise, and that access to a testing facility and experienced technical staff should have been a priority in preparing the proposal. Fortunately, there were partners on the team who could meet those needs.

Retrofitting Buses with Advanced Technology

Building hardware and software systems for retrofit and use in a legacy bus presents different challenges than building stationary systems or integrating systems into new automotive designs. If federal funding is used for bus purchases, buses must remain in service for at least 12 years; most agencies seek to keep buses in service even longer, typically 15–18 years. To reap the benefits of advanced safety technology as soon as possible, retrofits are needed.

Most buses in use now were not designed to anticipate installation of sensors, additional heat-producing electrical equipment, additional antennae, and additional sources of electromagnetic interference. Nor were the electrical systems designed to power numerous electronic components that would be sensitive to fluctuations in voltage. As a result, several lessons were learned.

Locating sensors on the front of the bus was a challenge. Lidar sensors needed unobstructed fields of view and could not be located inside behind the windshield. Folding bicycle racks took up much of the prime sensor real estate on the front of the buses. The vendor overcame this challenge by attaching the sensors to a bracket under the bicycle rack. The lesson learned here is the need for flexibility in sensor placement requirements, and a bit of engineering creativity.

Equipment space is at a premium. In addition to the sensor package, space was required for the PASS data logger, the actuation unit, and connections to the CAN bus. In addition, space was needed on four of the buses for the Jetson video processors and on two of the buses for the Nuvo passenger motion processors. Additional space in other locations was needed for GPS antennas and cameras associated with the Jetson and Nuvo processors.

Most of the equipment was installed in an existing, locally-fabricated electrical cabinet above the left front wheel well immediately behind the driver. Space in the cabinet was already being used by the Orion CAD/AVL equipment, Orca fare collection equipment, Apollo video system and recorder, and the bus radio system. PT granted permission to reposition some of the existing equipment within the cabinet to accommodate some new components. The lesson learned is to size new retrofit equipment as compactly as possible and look for opportunities to relocate existing equipment to accommodate new components.

Bus electrical power can be unstable. DC voltage on test buses was found to vary widely—in one example, 9–34 volts. In addition, power on the direct battery circuit, from which most of the electronics were powered, could be “knifed” or cut off unexpectedly in the middle of data and software uploads and downloads. The lessons learned are to use ruggedized automotive grade power regulators and to build robust operating systems that can reboot and restore automatically.

Data Needs for Future Research on CAWS/AEB

Determining the return on investment for CAWS/AEB for the industry and for individual transit agencies would benefit from integration, conflation, and extensions for several data sources. This research relied on four primary sources for estimating the monetary cost of collisions—1) FTA NTD Safety and Security (S&S) Time Series tables, which provided numbers of collisions with vehicles and persons; 2) FTA NTD Operating Expenses Tables, which provided C&L expense data; 3) FTA NTD tables for fleet characteristics and utilization; and 4) the WSTIP loss database, which provided collision costs paid through claims settled and expenses recovered through subrogation.

NTD C&L expenses, fleet characteristics, and utilization tables are reported only for full-reporter agencies, generally those operating 30 or more vehicles. S&S tables also include data from transit operators with fewer than 30 vehicles. S&S data are reported by calendar year, whereas C&L and most other data are reported by fiscal year for the reporting agency. Therefore, for those agencies with fiscal year reporting that does not align with the calendar reporting, correlations between different data sources can introduce time difference error in the analysis.

C&L expense reporting aggregates insurance premiums and other forms of self-insurance, which are difficult to link with numbers and severities of collisions. The research team aggregated data over five years to help account for autocorrelation of premiums and collisions in previous years. Modeling the cost-effectiveness of collision avoidance technology through reductions in C&L expenses could be greatly improved if collision-related expenses could be reported on a case-by-case basis.

To identify collisions that could and would be mitigated by the technology, it is important to have the appropriate data fields with which to juxtapose the technologies' capabilities. For example, having a detailed description of an event is very helpful, but in many cases, we did not have the point of impact on the transit vehicle. This data field would have been very helpful in matching loss scenarios with the technology's capabilities. Additionally, it would be very helpful to have loss data with the technology in use to be able to juxtapose the loss profiles of before and after the implementation of the technology.

One promising data source not used in this study that could become an important resource is USDOT's Major Safety Events Database.[15] This database includes records for individual safety events that meet specific reporting requirements, including property damage thresholds, injuries, and fatalities. Detailed information is presented for each collision event. It is expected that various types of vehicle automation technology will be introduced to the bus transit industry in the future. To anticipate this and enable data collection that would permit performance to be analyzed, it would be beneficial to add fields to major events such as whether buses were equipped with CAWS/AEB and whether it was operational during the event. To the extent feasible it also would be helpful if the incident records included costs of personal injury or fatality claims attributed to each event.

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[15] US Department of Transportation, "Major Safety Events," Major Safety Events | Department of Transportation - Data Portal

Section 9 Conclusions

This report summarizes the research performed under the FTA/PT Automated Collision Avoidance and Mitigation Safety Research and Development project. The original project scope and evaluation measures were revised several times throughout the project. Despite unanticipated challenges, including withdrawal of the vendor for the proposed CAWS and a global pandemic, the project team was able to conduct research on five parallel tracks to address some of the challenging issues facing transit agencies, bus OEMs, and technology developers seeking to bring collision avoidance technology to the transit bus industry.

NTD data were analyzed to estimate the degree to which reductions in bus collisions with persons and vehicles could reduce C&L expenses for transit agencies. Twelve years of bus transit insurance claims were analyzed and used to develop factors to estimate the potential return on investment for transit agencies seeking to equip buses with CAWS/AEB. A 2D lidar CAWS/AEB was developed and pilot-tested to provide data on system performance and testing protocols. A CAWS event data logger system was developed and tested on 30 buses to demonstrate event data collection as a tool to evaluate system performance and to locate clusters of CAWS events (hot spots) that may indicate geographic locations with higher risk for collisions. Instrumentation was developed to evaluate the accuracy of CAWS in terms of false positive and false negative detections. Instrumentation also was developed to capture anonymous video and measure passenger motion during braking to determine braking standards that would avoid injuries to bus passengers during emergency braking.

This report documents the approaches taken for each track, describes the instrumentation developed for new approaches to testing and data collection, and details the lessons learned along the way. The project did not provide a conclusive evaluation of CAWS/AEB, but it does provide encouraging evidence for its applicability and potential for return on investment. It is recommended that continued research and development funding for CAWS/AEB be provided by sponsoring agencies and that bus OEMs and technology suppliers continue to research and develop the technology.

Appendix A

Risk Mitigation Planning for Revenue Service Testing of Bus Automated Emergency Braking

Heidi H. Soule, Adam Davis, Andrew Krum, Yinhai Wang, Ruimin Ke, Dave Valadez, Dan Sellers, Steve Roberts, Luke Fischer, Jerome M. Lutin, “Risk Mitigation Planning for Revenue Service Testing of Bus Automated Emergency Braking,” Transportation Research Record, 2021, Vol. 2675(5) 193–200, National Academy of Sciences https://doi.org/10.1177/0361198120985857

Abstract

In 2017 the FTA awarded Pierce Transit (PT) of Lakewood, Washington, a $1.66 million grant for a bus collision avoidance and mitigation safety research and demonstration project. The project scope includes installation of an advanced technology package, the Pedestrian Avoidance Safety System (PASS) that uses light detection and ranging (lidar) sensors to trigger automated deceleration and braking. Thirty transit buses are being equipped with PASS and will be monitored using telematics to transmit and collect critical test data. The test plan includes collecting data while operating the buses in “stealth mode” with PASS detecting and logging events but not activating brakes automatically or warning the drivers. At the conclusion of “stealth mode” operation, PT will make a go/no-go decision on whether to activate PASS’s automatic deceleration and braking functionality for revenue service with passengers. This paper describes the risk mitigation process developed to determine if the system is safe enough to allow operation in revenue service. The process includes: broad stakeholder engagement, constituting an ad-hoc working group within PT to advise executive management, development of decision-making criteria, consultation with state and Federal officials on regulatory requirements and compliance, review of applicable standards and engineering test protocols, engineering consultations with the bus original equipment manufacturer (OEM), and road testing to simulate revenue service, collect data, and obtain feedback from drivers and maintainers.

Introduction

This project was conceived to address significant problems faced by the transit bus industry. Although buses are one of the safest modes of transportation, the transit industry experiences significant numbers of injuries and fatalities each year and incurs significant casualty and liability expenses. In 2018, the most recent year for which cost data is available, US transit agencies reported for rubber tire transit modes 4,767 collisions, 16,348 injuries, 84 fatalities, and

$684 million in casualty and liability expenses.[16] Lutin et al. showed that 74 percent of high value bus insurance claims (over $100,000) were attributed to collisions.[17] They laid out a roadmap for improving bus safety through adoption of autonomous braking assistance for drivers.

The importance of safety in public transportation is underscored by the fact that Congress directed the FTA "to create and implement a National Public Transportation Safety Plan (National Safety Plan) under the Moving Ahead for Progress in the 21st Century (MAP– 21) Act, which authorized a new Public Transportation Safety Program (Safety Program) at 49 U.S.C. 5329. Public Law 112–141 (2012)."[18] FTA was given oversight responsibility for safety and each public transit agency receiving Federal funding was required to take specific actions to increase safety.

Safety Risk Management

For the National Cooperative Highway Research Program Project 102(02), "Impacts of Regulations and Policies on CV and AV Technology Introduction in Transit Operations," Gettman et al. provide an overview of safety assurance considerations and automotive safety analysis methodologies that could be applied to automated road transit vehicles.[19] They cite FTA rulemaking under 49 CFR 673 that requires each transit agency to adopt a Public Transportation Agency Safety Plan.[20] Under Subsection § 673.25 Safety risk management, "a transit agency must develop and implement a Safety Risk Management process for all elements of its public transportation system. The Safety Risk Management process must be comprised of the following activities: safety hazard identification, safety risk assessment, and safety risk mitigation." This paper focuses on safety risk mitigation aspects of a research and development project that differ significantly from how safety is addressed in normal transit operations.

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[16] National Transit Database, Safety and Security Time Series Data," https://www.transit.dot.gov/ntd/data-product/safety-security-time-series-data and "2018 Annual Database Operating Expenses," https://www.transit.dot.gov/ntd/data-product/2018-annual-database-operating-expenses, Federal Transit Administration.

[17] Lutin, J. M., A. L. Kornhauser, J. Spears, L. F. Sanders, "A Research Roadmap for Substantially Improving Safety for Transit Buses through Autonomous Braking Assistance for Operators," *Compendium of Papers*, Paper Number 16-1246, 95th Annual Meeting of the Transportation Research Board, Washington, DC, January 12, 2016.

[18] Federal Transit Administration [Docket No. FTA–2015–0017] Z RIN 2132–ZA04 "National Public Transportation Safety Plan," *Federal Register*, Vol. 82, No. 11, January 18, 2017, pp. 5628-5636.

[19] Gettman, D., J. S. Lott, T. Harrington, "Working Paper #2: Safety Assurance Considerations – Blending Transit and Automotive Safety Analysis Methodologies," National Highway Cooperative Research Program (NCHRP) Project 20-102 (02): Impacts of Laws and Regulations on CV and AV Technology Introduction in Transit Operations, March 2017, http://onlinepubs.trb.org/onlinepubs/nchrp/docs/NCHRP20-102(02)_WP2-Safety_Assurance_Considerations.pdf.

[20] Department of Transportation Federal Transit Administration, 49 CFR PART 673—Public Transportation Agency Safety Plans, *Federal Register*, Vol. 83, No. 139, July 19, 2018 / Rules and Regulations, https://www.govinfo.gov/content/pkg/FR-2018-07-19/pdf/2018-15167.pdf.

The project scope includes installation of an advanced technology package, the Pedestrian Avoidance Safety System (PASS) that uses lidar sensors to trigger automated deceleration and braking. While this project is intended to apply advanced driver assistance systems to improve operational safety, the introduction of new technology requires exploration of unknown risks. The project includes a strategy to mitigate risk by incorporating an explicit go/no-go decision-making process.

Pierce Transit Automated Collision Avoidance and Mitigation Safety Research and Demonstration Project

In 2017 the FTA awarded PT of Lakewood, Washington, a $1.66 million grant for an automated bus collision avoidance and mitigation safety research and demonstration project. Thirty transit buses are being equipped with PASS and will be monitored using telematics to transmit and collect critical test data. The test plan includes collecting data while first operating the buses in “stealth mode” with PASS detecting and logging events but not decelerating and braking automatically or warning the drivers. At the conclusion of “stealth mode” operation, PT will make a go/no-go decision on whether to activate PASS’s automatic deceleration and braking functionality for “revenue service,” which is defined as “the time when a vehicle is available to the general public and there is an expectation of carrying passengers.”[21] The fundamental principle for the testing protocol is to mitigate risk while establishing a set of baseline data to be compared with data collected during the “intervention,” activation of the new technology.

When the project was initiated, each partner was required to provide a safety plan to PT. PT made available a site-specific safety plan template for each vendor to work from. However, because PASS installation and Alpha testing were performed remotely off-site at Virginia Tech, PT maintenance and operations staff were not involved in the initial PASS installation and testing.

It was not until the Fall of 2019, when the PASS-equipped bus was returned to PT and the vendor was ready to install PASS on an additional three buses, that PT maintenance and safety staff became involved in the testing and safety review process. To facilitate the project and mitigate the risks involved, PT staff adopted a go/no-go decision-making process that involved developing an organizational structure, establishing a series of discrete stages and decision-points to advance the project, and specific review activities to be accomplished.

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[21] “Revenue Service (Miles, Hours, and Trips),” National Transit Database (NTD) Glossary, Federal Transit Administration, https://www.transit.dot.gov/ntd/national-transit-database-ntd-glossary#R.

Go/no-go decision-making could become a part of safety, research, and demonstration (SRD) projects featuring the installation of new technology on buses by other FTA grantees. Consequently, PT is documenting its experience with these activities. This paper describes the process developed to determine if the system is safe enough to allow operation in revenue service.

Background

In 2015, the Transportation Research Board (TRB) program Innovations Deserving of Exploratory Analysis (IDEA) awarded the Washington State Transit Insurance Pool (WSTIP) a $100,000 grant to conduct an active safety warning system pilot test.[22] Additional funding was contributed by Munich RE America, a worldwide reinsurer, Government Entities Mutual (GEM), a captive reinsurance company for public entities throughout the United States, and Alliant Insurance Services, an insurance broker focused on public entities. The Mobileye Shield+ collision avoidance system was installed on 38 buses at eight transit agencies in Washington State and data was collected for three months. That study indicated that collision warning systems had the potential to reduce forward collisions by 72 percent and pedestrian/ cyclist collisions by 43 percent. It also indicated that greater reductions in collisions might be possible with automated emergency braking. Based on those results, PT, which had participated in the WSTIP IDEA project, applied for, and received the FTA demonstration grant.

The device being tested in the FTA sponsored project is the Pedestrian Avoidance Safety System (PASS), developed by DCS Technologies, Inc. of Carmel, Indiana. PASS uses a pedestrian and forward vehicle detection sensor package to detect and calculate the potential for imminent collisions with the bus. It uses an array of three light detection and ranging (lidar) sensors attached to the front of the bus.[23]

PASS automatically decelerates the vehicle when an imminent pedestrian collision is identified by the detection and warning system. The system provides active (automatic deceleration) assistance to the driver in avoiding or reducing the severity of a collision. It uses a standalone microprocessor-based controller with proprietary sensor fusion algorithms to integrate pedestrian detection and warning sensor systems with the vehicle powertrain and brake systems. Monitoring the collision avoidance warning system (CAWS) warning

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[22] Spears, M. J., J. M. Lutin, Y. Wang, R. Ke, S. M. Clancy, "Active Safety-Collision Warning Pilot in Washington State'" Final Report for Transit IDEA Project 82, Transportation Research Board, May 2017, http://onlinepubs.trb.org/onlinepubs/IDEA/FinalReports/Transit/Transit82.pdf.

[23] Soule, H., S. Huck, A. Krum, Y. Wang, R. Ke, D. Valadez, D. Sellers, and J. Lutin, "Testing an Automated Collision Avoidance and Emergency Braking System for Buses," T*ransportation Research Record*, Vol. 2674(4), pp. 66-74.

data and vehicle dynamics (speed, direction, throttle, and brake position, etc.), the system determines within a fraction of a second if automatic action is required.[24]

Alpha testing of the PASS system was conducted at the Virginia Smart Roads facility located at the Virginia Tech Transportation Institute (VTTI) in Blacksburg, Virginia. PT shipped a 40-foot (12.2-m) New Flyer bus to the facility in early 2019 which was fitted by the vendor with PASS and instrumentation. Testing was performed to characterize PASS functionality and determine the operational design domain (ODD) using simulated vehicles for forward-collision detection and manikins to simulate moving and stationary pedestrians, vulnerable road users (VRUs).

Most of the Alpha testing was conducted during two vendor site visits to VTTI, one in mid-March and the second in late April 2019. More than 400 test runs were conducted including collision avoidance bus runs at various speeds with static VRUs, walking and running VRUs, occluded VRUs, and forward collision avoidance with simulated moving vehicles. Both day and night testing were conducted for both VRUs and vehicles. Weather testing under simulated rain and fog conditions was conducted on April 30, 2019, and May 7, 2019. The technology was fine-tuned during the testing sessions and performance was deemed satisfactory for deployment in the next project phase.[25]

Go or No-Go Decision Points

As PT moved forward from Alpha testing to the next phases of the project, it was faced with several go/no-go decisions:

- Allow the vendor to equip four buses with PASS at PT’s base facility in Lakewood, Washington - This was accomplished and provided PT operations and maintenance staff an opportunity to become familiar with the systems and understand the technical aspects that should be considered as part of the go/no-go decision-making process. The “go” decision was based on the successful completion of the alpha testing at VTTI.
- Equip 26 additional buses with PASS and operate in stealth mode only to collect data (in addition to four buses already equipped with PASS operating in stealth mode.) - Each PASS unit will be equipped with a data logger that will record PASS activation events. Table A-1 shows the data items to be captured. These installations do not include connections to activate automated deceleration and braking.

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[24] “Pedestrian Avoidance Safety System (PASS),” DCS Technologies, Inc., https://indd.adobe.com/view/3e0a09aa-80d1-47e0-a474-a2794aafddc9.
[25] Soule et al., “Testing an Automated Collision Avoidance and Emergency Braking System for Buses.”

Installation of PASS on the remaining 26 buses was intended to be a shared effort between PT maintenance staff and vendor personnel. The go/no-go decision for this activity was based on a demonstration of the first four PASS installations and the understanding that operation in stealth mode could be accommodated without compromising any of the existing bus safety functionality. Because it involved a significant expenditure of FTA grant funds, PT consulted with FTA.

Capturing PASS data in stealth mode operation will provide information on the frequency of actual and potential collisions, spatial and temporal clustering of potential collisions, acceleration/deceleration rates, and event timing. It was determined that this step would be a prerequisite to achieve the goal of revenue service testing and would allow much of the data collection to proceed even if the systems were not operated in active mode.

Table A-1 *PASS Data Logging*[26]

Data Item	Source
Bus number (for each event)	PASS System
Event ID Code (for each event)	PASS System
Time stamp (UTC/msec)	PASS System (GPS)
Event location (degrees x 10^{-6})	PASS System (GPS)
Bus heading (degrees x 10^{-1})	PASS System (GPS)
Bus speed (mph)	J1939 message*
Bus brake switch (application status)	J1939 message*
Bus throttle (percent)	J1939 message*
Bus longitudinal acceleration (g)	PASS System
Bus lateral acceleration (g)	PASS System
Bus yaw rate (degrees x 10^{-1}/sec)	PASS System
PASS operating mode**	PASS System
Object relative velocity (mph)	PASS System
Object distance (feet)	PASS System
Object time to collision (msec)	PASS System

*Note: J1939 message source is SAE std J1939 Controller Area Network bus (CANBus) on vehicle

**Note: modes = Stealth, CAWS only, CAWS+AEB, Faulted/Non-Op

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[26] *Ibid.*

- Equip four buses with the UW Transit Event Logging System (TELS) - TELS was designed to measure PASS's accuracy in terms of false positives and false negatives.[27] TELS is a data collection and analysis system only with no interfaces with bus foundational driving systems. At this writing, the initial TELS unit is undergoing testing of its ability to interface with existing cameras on the bus, communicate with PASS, and function reliably in operation. Deployment of all four TELS will depend on successful integration with PASS and on-board cameras, and determination that the installed equipment imposes no adverse effects on existing bus electrical and electronic systems.
- Equip one additional bus with VTTI Nuvo Data Acquisition System (DAS) for Passenger Motion analysis – No standards currently exist for bus deceleration and braking to ensure comfort and safety for seated and standing bus passengers. VTTI was tasked to develop a methodology to measure and evaluate the effects of manual and automated deceleration and braking on bus passengers to draft a standard for autonomous deceleration and braking for buses. The Nuvo DAS is a data collection and analysis system for analysis of passenger motion only with no connection to the bus foundational driving systems.[28] VTTI's initial Nuvo DAS was successfully installed and tested on PT bus #230 as part of Alpha testing at the Virginia Smart Roads facility. The second Nuvo DAS has been shipped to PT for installation.
- Activate all 30 PASS systems to initiate deceleration and braking – This step differs from the go/no-go decision points described above because when fully active, PASS will interface with the throttle and braking systems. Malfunctions could impact passenger comfort and safety. The process described below is intended to be used as the basis for this go/no-go decision.

Process for Revenue Service Testing Go or No-Go Decision Making

The go/no-go process includes the following activities:

- Stakeholder engagement and role definition
- Creation of an executive advisory working group
- Development of evaluation criteria and data collection requirements
- Regulatory requirements and compliance
- Original equipment manufacturer (OEM) engineering consultation
- Applicable standards and engineering test protocols
- Road testing to simulate revenue service, collect data, and obtain feedback from drivers and maintainers

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[27] *Ibid.*

[28] *Ibid.*

Stakeholder Engagement

Stakeholder engagement involves bringing together parties internal and external to PT involved in the project and others who may have oversight and funding responsibilities, operational responsibilities, contractual responsibilities, special knowledge, and/or regulatory authority:

- PT
- FTA
- Center for Urban Transportation Research, University of South Florida (CUTR)
- PASS Vendor - DCS
- WSTIP and research partners under contract to WSTIP
- Original equipment manufacturer (OEM) - New Flyer Industries
- National Highway Traffic Safety Administration (NHTSA)
- Other OEMs that are or could potentially be affected.

WSTIP provides insurance coverage for PT and 25 other transit agencies in the State of Washington. It is a public entity regulated by the state. WSTIP has taken an active role in researching collision avoidance technology as part of its loss prevention activities. It sponsored and funded the IDEA project and has taken an active role in this project by providing funding, overseeing the research partner contracts, and facilitating knowledge transfer to its member agencies and the broader transit industry.

Creation of an Executive Advisory Working Group

Subject to policies established by the Board of Commissioners, PT's Chief Executive Officer (CEO) is responsible for key administrative and business decisions for the agency. Under the CEO's authority, PT established an ad-hoc working group to inform and advise on decisions affecting the project that could impact operations and maintenance. The group includes the following members:

- Executive Director of Service Delivery and Support / Executive Safety Officer
- Executive Director of Maintenance
- Executive Director of Administration
- Risk Management

In addition, the creation of an internal Expert Maintenance Review Panel was recommended by the Acting Executive Director of Maintenance. Also recommended was the creation of an internal Safety and Training Review Panel. Both panels would have testing, evaluation, reporting and recommendation roles and responsibilities.

Development of Evaluation Criteria and Data Collection Requirements

A preliminary list of decision-making criteria was developed and refined early in the discussion about the go/no-go decision-making process. The criteria include three categories: Safety, Operations and Fleet Maintenance, and Data Collection.

Safety

- Functionality – Does system performance meet expectations as stated in the operational design domain (ODD) and specifications?
- Durability/Maintainability – What component failures have been experienced and what have been the maintenance requirements as documented in the trouble ticket log?
- False negatives – Do the rates of false negatives meet agreed-upon levels?
- Passenger Motion – Does brake activation meet standards for jerk, deceleration, smoothness of operation, and passenger comfort?
- Vehicle Safety – Does the system create adverse impacts on other vehicle systems?

Operations and Fleet Maintenance

- Reliability – Have the systems demonstrated the ability to operate continuously for a satisfactory period of operating hours between failures?
- Accuracy – Do the rates of false positives meet agreed-upon levels?
- Driver Acceptance – Human machine interface (HMI), Are warnings, alerts, and activations meeting the needs of drivers?

Data Collection

- Are the systems and loggers producing high-quality data and capturing, recording, and transmitting all the events and other required signals?
- Has driver and maintainer input been obtained and recorded?

Regulatory Requirements and Compliance

Regulatory authority over transit buses is codified at the federal and state level. The U.S. Department of Transportation is responsible for regulating motor vehicles at the Federal level and publishes relevant regulations through its modal administrations, including the National Highway Traffic Safety Administration (NHTSA), the Federal Motor Carrier Safety Administration (FMCSA) and FTA.

NHTSA publishes the Federal Motor Vehicle Safety Standards (FMVSS) which include braking systems. FMCSA regulates motor carriers (trucks and buses). In addition to public transit safety regulations, FTA has published rules for testing and approval of all transit buses acquired with federal funds. [29] Bus testing is conducted at the Thomas D. Larson Pennsylvania Transportation Institute (PTI) at Pennsylvania State University facilities in Altoona, Pennsylvania, and College Station, Pennsylvania.

To determine Federal requirement and standards applicable to this project, PT consulted with officials at FTA, FMCSA, and NHTSA. On January 27, 2020, PT reached out by email to officials at FTA and NHTSA with the following requests for information regarding:

- Whether the system being tested constitutes a significant change that would require testing by the Altoona bus besting facility mentioned above,
- Whether any waivers from FMVSS or other requirements would be needed from NHTSA,
- Who the appropriate contact at FMCSA is to determine whether FMCSA regulations or procedures will apply to this project, and,
- Whether there are other DOT officials with whom coordination is necessary.

PT received the following responses:

- “FTA does not anticipate that additional testing of buses equipped with the proposed systems would produce significantly different data in the tests that are performed during FTA ("Altoona") Bus Testing. … these modifications are being performed by a grantee to a limited number of buses that it already owns. The modifications do not constitute a new or modified production bus model, and therefore would not require FTA Bus Testing even if we did expect them to produce different test data.” – FTA Bus Testing Program, January 30, 2020
- “The technologies proposed by PT are technologies that are not currently covered by any NHTSA Federal Motor Vehicle Safety Standards (FMVSS), nor are there NHTSA New Car Assessment Program (NCAP) test procedures for these types of technologies. FMCSA regulates maintenance and inspection standards for regulated carriers, but many transit authorities are not subject to the FMCSA regulations because they are exempted at 49 CFR 393.3 (f)(2) "General Applicability"- "Transportation performed by the Federal Government, a State, or any political subdivision of a State, or an agency established under a compact between States that has been approved by the Congress of the United States;" – FMCSA Vehicle and Roadside Operations Division, January 28, 2020.

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[29] U.S. Department of Transportation, Federal Transit Administration, 49 CFR Part 665 [Docket No. FTA–2015–0019] RIN 2132–AB11 Bus Testing: Establishment of Performance Standards, a Bus Model Scoring System, a Pass/Fail Standard and Other Program Updates AGENCY: Federal Transit Administration (FTA), DOT. ACTION: Final rule, *Federal Register*, Vol. 81, No. 147, August 1, 2016 / Rules and Regulations, https://www.govinfo.gov/content/pkg/FR-2016-08-01/pdf/2016-17889.pdf.

A search was performed on the Revised Code of Washington (RCW) for state laws and regulations that might apply to the project.[30] The only relevant regulations were found in Section 46 Motor Vehicles. Under RCW Section 46.37.320 the Washington State Patrol (WSP) is authorized to:

> adopt and enforce rules establishing standards and specifications governing the performance of lighting devices and their installation, adjustment, and aiming, when in use on motor vehicles, and other safety equipment, components, or assemblies of a type for which regulation is required in this chapter or in rules adopted by the state patrol. Such rules shall correlate with and, so far as practicable, conform to federal motor vehicle safety standards adopted pursuant to the national traffic and motor vehicle safety act of 1966 (15 U.S.C. Sec. 1381 *et seq*.) covering the same aspect of performance, or in the absence of such federal standards, to the then current standards and specifications of the society of automotive engineers applicable to such equipment:[31]

PT Risk Management reached out to the WSP and received a response from the Office of Vehicle Equipment and Standards that there is no statute existing or under consideration pertaining to collision avoidance emergency braking systems and referred PT to the FMCSA, which had already been contacted.

OEM Engineering Consultation

When the project was initially conceived, the research team was not aware of the importance of engaging the bus OEM. Part way through the project the vendor sought to obtain answers on several technical issues from the OEM with limited success.

PT provided the OEM with additional information on the project goals and furnished a copy of the FTA-approved scope. Information was provided that the project was not intended to market a specific product but to increase and share knowledge with the transit industry. That led to a series of conference calls and development of a scope of services for the OEM engineering staff to provide support to the project, which is currently under review. PT is asking the OEM to review and evaluate the PASS to vehicle interface and, if necessary, provide engineering recommendations to improve safety and functionality.

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[30] Washington State Legislature, "Revised Code of Washington (RCW), Title 46, Motor Vehicles," December 16, 2019, update, http://leg.wa.gov/CodeReviser/RCWArchive/Documents/2019/Title%2046%20RCW.pdf.

[31] RCW, Title 46, Section 46.37.320.

Appendix B

Quantifying Contributing Factors to Transit Bus C&L Expenses Using the National Transit Database

Modeling Overview

The National Transit Database (NTD) published by FTA contains a detailed database of safety and security data for each reporting transit agency, as well as operating expense data, including C&L expenses. Statistical modeling techniques were applied to NTD data to examine how C&L costs change in relation to changes in the numbers of collisions, severity of collisions, and other possible risk factors. The objective of this effort was to help estimate the potential return on investment for collision avoidance warning systems (CAWS) and automated emergency braking (AEB) systems. Models using NTD data were shown to be applicable to US transit agencies nationwide.

This analysis was conducted in two steps. The first step—collision exposure modeling—looked at how various service and environmental risk factors contributed to the frequency of collisions. Collision probability per revenue mile was expressed as the product of the probability of traffic disturbances occurring and the probability that a transit vehicle operator would be unable to respond in time to avoid a collision. Based on this premise, a count model was fitted with information on transit operations and traffic congestion experienced by transit agencies. The second step—C&L cost modeling—examined how collisions of various types and their corresponding casualties contributed to C&L costs. A statistical analysis technique, structural equation modeling (SEM), was leveraged to model the relationships of observed and latent variables following defined causal chains.

Data Collection

The NTD is a data repository of financial, operating, and asset conditions of US transit systems. NTD data include agency funding sources, capital and operating expenses, safety events reporting and statistics, transit services provided and consumed, vehicle and facility inventories, and transit employees.[39] "Agencies receiving funding from the US Department of Transportation through the Urbanized Area Formula Program (5307) or Rural Formula Program (5311) are required to submit data to the NTD in uniform categories."[40]

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[39] "NTD | FTA," https://www.transit.dot.gov/ntd.

[40] "2021 NTD Reporting Policy Manual | FTA," https://www.transit.dot.gov/ntd/2021-ntd-reporting-policy-manual.

Applicable Standards and Engineering Test Protocols

In October 2018, the US Department of Transportation (USDOT) published "Preparing for the Future of Transportation, Automated Vehicles 3.0, (AV 3.0)" a Department-wide policy statement on multimodal automation.[32] Although AV 3.0 reaffirms the authority of USDOT to "establish motor vehicle safety standards that allow for innovative automated vehicle designs," the policy supports the development of voluntary standards and self-certification rather than a Federal regulatory approach and approval process.

The approach to standards taken by PT is consistent with USDOT policy stated in AV 3.0. The vendor adopted best automotive engineering practices in conducting alpha and beta testing and applied appropriate standards. The following references documentation for relevant standards applied by the vendor.

- SAE J1739_200208 "This document introduces the topic of potential Failure Mode and Effects Analysis (FMEA) and gives general guidance in the application of the technique."[33]
- SAE J1939_201808 "Serial Control and Communications Heavy Duty Vehicle Network – Top Level Document This top-level document provides a general overview of the J1939 network and describes the subordinate document structure. The document includes definitions of terms and abbreviations which are used among the various J1939 subordinate documents."[34]
- SAE J3029_201510, Forward Collision Warning and Mitigation Vehicle Test Procedure – Truck and Bus "This SAE Recommended Practice (RP) establishes uniform powered vehicle level test procedure for Forward Collision Avoidance and Mitigation (FCAM) systems (also identified as Automatic Emergency Braking (AEB) systems) used in highway commercial vehicles and coaches greater than 4535 Kg (10,000 lb) gross vehicle weight rating (GVWR). This RP does not apply to trailers, dollies, etc. and does not intend to exclude any particular system or sensor technology. These FCAM systems utilize various methodologies to identify, track and communicate data to the operator and vehicle systems to warn, intervene and/or mitigate the longitudinal control of the vehicle."[35]
- European New Car Assessment Programme (Euro NCAP) Assessment Protocol – Vulnerable Road User Protection[36] - This protocol includes two parts, Pedestrian Impact Assessment and Pedestrian AEB Assessment. No comparable US standards were found to be available.

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[32] US Department of Transportation, "Preparing for the Future of Transportation, Automated Vehicles 3.0," October 2018, https://www.transportation.gov/av/3.

[33] SAE International, https://www.sae.org/standards/content/j1739_200208/.

[34] SAE International, https://www.sae.org/standards/content/j1939_201808/.

[35] SAE International, https://www.sae.org/standards/content/j3029_201510/.

[36] European New Car Assessment Programme (Euro NCAP) Assessment Protocol – Vulnerable Road User Protection Version 10.0.3 June 2020, Assessment of AEB Vulnerable Road User Systems, https://cdn.euroncap.com/media/58230/euro-ncap-assessment-protocol-vru-v1003.pdf

Road Testing to Simulate Revenue Service, Collect Data, and Obtain Feedback from Drivers and Maintainers

An initial program for road testing has been proposed and is under consideration. Subject to satisfactory completion of the other steps described above, two buses equipped with PASS, TELS, and Nuvo are planned to be driven with PASS in active AEB mode with no passengers on board other than PT training staff and project partner engineering staff. Test plans expect each bus to be operated for a minimum of 40 hours over typical revenue routes in the PT service area. Road testing will allow correlation of collected system data and comparison with operator reviews of system activation, non-activation, and operator experience.

Conclusion

This paper described the risk mitigation plan that was developed for this research project to meet FTA requirements for a safety risk management process and to ensure consistency with PT's Public Transit Agency Safety Plan. The project was conceived to test new technology to assist transit bus drivers in avoiding and mitigating forward collisions with vehicles and VRUs. Its assumptions are based on data collected in a prior study conducted under the auspices of the TRB IDEA program.[37]

Transit agencies operate in a public environment that emphasizes predictable and safe operation. Conducting research runs counter to the industry culture. Developing and testing new safety technology brings with it the exploration of unknown risks. AV 3.0 points out some of the unpredictable factors involved:

"Public transportation operators should establish realistic expectations when implementing transit bus automation projects and demonstrations. As an example, transit agencies engaged in pilots to retrofit vehicles with advanced driver assistance capabilities, such as pedestrian avoidance and automatic emergency braking, might find that implementation may take longer than expected for a variety of reasons. Integration, test planning, contracting, and data management can present significant challenges that cause delay."[38]

It was impossible to anticipate that a global pandemic would interrupt the project, but it did, setting progress back by several months. In one sense, however, the delay did provide an opportunity to develop testing and risk mitigation plans more fully. It is hoped that by sharing the information developed for this project other transit agencies will be encouraged to engage in safety research and demonstration projects.

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[37] Spears et al., "Active Safety-Collision Warning Pilot in Washington State.'"

[38] US Department of Transportation, "Preparing for the Future of Transportation, Automated Vehicles 3.0."

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Author Contributions

The authors confirm contribution to the paper as follows: study conception and design: J. Lutin, H. Soule, A. Davis, A. Krum, Y. Wang, D. Valadez, D. Sellers; S. Roberts, L. Fischer; data collection: A. Krum, D. Valadez, D. Sellers, R. Ke, L. Fischer; analysis and interpretation of results: A. Krum, D. Valadez, D. Sellers, Y. Wang, R. Ke, L. Fischer; draft manuscript preparation: J. Lutin. All authors reviewed the results and approved the final version of the manuscript.

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This analysis leveraged several NTD products—1) C&L costs as a component of agency operating expenses, 2) safety and security time series data, 3) basic agency information, and 4) operating statistics reported by mode, type of service, day, and time period. This analysis focused on motorbus services directly operated by transit agencies. Therefore, only "directly operated service" (DO) was selected in Type of Service (TOS), and only "Motor Bus" (MB) was selected in Mode.

NTD C&L Costs

C&L expenses refer to "the expenses a transit agency incurs for loss protection."[41] If a transit agency is liable for someone's loss, it must report all applicable compensation in this item. C&L costs include 1) physical damage insurance premiums, 2) recovery of physical damage losses for public liability and property damage insurance premiums, 3) insured and uninsured public liability and property damage settlement payouts and recoveries, 4) other corporate insurance premiums, and 5) self-insured costs.

NTD Safety and Security Data

Safety and security (S&S) records in the NTD include counts of events, injuries, and fatalities, and are organized by agency, mode, TOS, and year. S&S records also include "reportable events"[42] and their associated casualties for riders, people waiting or leaving, pedestrians and bicyclists, employees and workers, other vehicle occupants, others, trespassers, and suicides. Event counts in S&S data provide counts per event type (e.g., collision, derailment, fire, security, and Not Otherwise Categorized), as well as collision counts per collision type (e.g., with motor vehicle, with person, with fixed object, with rail vehicle, with bus vehicle, and with other).

S&S records are organized in two levels of detail in the NTD. The first level is aggregated by event types per agency per year. Under this category, NTD provides 1) S&S records covering all "reportable events" and 2) records that cover "major events." Major events are a subset of "reportable events" that meet additional reporting thresholds, such as fatalities, injuries that require transport, significant property damage, evacuation, and collisions that require towing. Therefore, by definition, major events are more directly linked with casualties, while reportable, but not major, events are not.

The second level of S&S records available in NTD is "S&S major event details."[43] Records in this file are disaggregated and provide per-event information for

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[41] "NTD Glossary | FTA," https://www.transit.dot.gov/ntd/national-transit-database-ntd-glossary.

[42] "2019 NTD Safety & Security Quick Reference Guide – Non-Rail Mode Reporting," FTA, 2019, https://www.transit.dot.gov/sites/fta.dot.gov/files/docs/subdoc/141/2019-ntd-quick-reference-non-rail.pdf.

[43] "Major Safety Events | Department of Transportation Data Portal," https://data.transportation.gov/Public-Transit/Major-Safety-Events/9ivb-8ae9.

major events since 2014. These provide agency identification, event type, casualty details, and environmental factors at the time of event. These factors can be useful in predictions of event frequency and severity. This level of reporting does not provide C&L cost per event.

Service, Vehicle Breakdowns, Employees, and Other Statistics in the NTD

Service statistics for transit agencies are organized by mode, TOS, agency, and time period. Available time periods include average typical weekday, average typical Saturday, average typical Sunday, and annual total. Other measures include vehicles operated in maximum service (VOMS), vehicles available for maximum service (VAMS), vehicle miles and hours traveled during revenue and deadhead (vehicle revenue miles (VRM), vehicle revenue hours (VRH), vehicle deadhead miles (VDM), vehicle deadhead hours (VDH)). Unlinked passenger trips (UPT) and passenger miles traveled (PMT) are reported and are useful in modeling collision/event exposures. This analysis used only annual totals for these service statistics, but details from weekday and weekend services can be extracted for more complex and in-depth analysis in the future.

Vehicle breakdown statistics are also available in the NTD by agency, mode, and TOS, including the number of major and other mechanical failures for the fleet. Failure rates can be derived and included as risk factors for exposure analysis.

Numbers of employees and total working hours are accessible in the NTD. The dataset provides numbers of employees and working hours categorized by vehicle operations, vehicle maintenance, facility maintenance, general administration, and capital labor. It distinguishes between full- and part-time employees, which can be used to examine how average working hours per year for full- and part-time employees may contribute to the risks of bus collisions.

Agencies are also identified with urbanized areas (UZAs). The area and population of both the UZA and each agency's transit service area are provided. Several different agencies may be identified with the same UZA. For example, the King County Department of Metro Transit (KCM), the Pierce County Transportation Benefit Area Authority (PT), and the City of Everett (ET) are all associated with Seattle. Agencies in the same UZA will share the metrics on the UZA's population, area, and density.

Urban Mobility Report TTI and Commuter Stress Index

The second data source used was the 2021 Urban Mobility Report (UMR) by the Texas A&M Transportation Institute (TTI).[44] The UMR provides congestion evaluation indices, e.g., travel time index, for UZAs across the country that could be a determinant factor for transit vehicle collisions. Congestion indices for UZAs are derived from "big data" sources, e.g., "hour-by-hour speeds collected from a variety of sources on every day of the year on most major roads" from INRIX data and can be used for agency-level modeling. This analysis selected several indices from UMR spreadsheets and joined them with processed NTD data for exposure modeling.

This analysis used two indices from the UMR for modeling transit bus collision risks: travel time index (TTI) and commuter stress index (CSI). TTI is defined as "the ratio of travel time in the peak period to the travel time at free-flow conditions," and a value of 1.30 indicates a "20-minute free-flow trip takes 26 minutes in the peak period." This serves as a general indicator of UZA congestion. Similarly, for each UZA associated with a transit agency, CSI is "the travel time index calculated for only the most congested direction in each peak period (modeling an individual commuter's experience)." CSI shows the congestion that commuters are facing and may be used to estimate their stress levels during commute trips. CSI could be an informative variable related to the frequency of instances of dangerous driving behaviors that may create disturbances for transit bus operations. More detailed mathematical descriptions for TTI and CSI are explained in the UMR document. TTI and CSI data were extracted from the UMR database and were joined to NTD data tables by UZA name.

Data Analysis

Collision Exposure Modeling

Collisions from NTD were aggregated at the agency-level, and driver, vehicle, environment, and operational data were included from NTD annual reports by agency. Some factors were available only at UZA levels. In general, an occurrence-mechanism approach was adopted to distinguish factors' contributions to disturbances during transit operation and to operators' inability to avoid collisions.

Disturbances could be anything that interrupts the operation of a transit bus, such as jaywalking pedestrians, abrupt lane changing in heavy traffic, high

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[44] Schrank et al., "Urban Mobility Report," Texas A&M Transportation Institute, June 2021, http://tti.tamu.edu/documents/mobility-report-2021.pdf.

speed driving, etc. The occurrence of any disturbance was assumed to follow a Poisson process, in which the rate was constant through time. This resulted in time intervals between any two disturbances to be exponentially distributed. Moreover, as the exponential distribution was memoryless, the probability of any disturbance occurring was independent of the history, assuming that transit collisions are rare and isolated.

The probability that an operator was unable to handle an encountered disturbance could be viewed as the probability that his/her available perception/reaction time (APRT) was smaller than the needed perception/reaction time (NPRT). Although APRT is usually assumed constant in highway design, its real-world variation can be significant and therefore is better modeled as a random variable.

Because bus collisions are rare events, it was necessary to aggregate data to reduce excessive numbers of zeros in the data set. Counts revealed that of 285 agencies reporting positive C&L costs in 2019, 106 agencies reported zero collisions with motor vehicles, 199 agencies reported zero collisions with persons, 234 agencies reported zero collisions with fixed objects, and 264 agencies reported zero collisions with transit vehicles.

The research team linked the collision count of each transit agency with its total VM or VRM and its exposure to various risk factors. To be consistent in both exposure and cost analysis, the research team aggregated major events from 2015 to 2019 and included only the 273 agencies that reported non-zero C&L costs in each year. Other variables, depending on their nature, were either averaged or summed. Table B-1 shows the variables considered.

The research team developed the following hypotheses on how risk factors contribute to collision probabilities:

- P_o (Probability of encountering a traffic disturbance per vehicle mile): population density of UZA, population density of service area, traffic congestion, and commuter stress may contribute to the occurrence of disturbances. The research team was interested in whether the two density measures, i.e., population density in the UZA and population density in the service area, were significant, if commuter stress index was significant, and how they might help explain the disturbances.
- P_u (Probability that operator is unable to avoid disturbance): employee work hours, bus speeds, passenger loading, mechanical failure rates, traffic congestion, and driver stress may contribute to the probability of an operator being unable to avoid a collision. The research team wanted to test whether higher traffic congestion levels were related to higher collision rates and whether commuter stress applied to bus operators by using stress level as defined by TTI during peak hours.

- TTI and CSI could contribute to both P_f and P_o as described, under different assumed mechanisms, respectively.

Table B-1 *Variables, Sources, Aggregation, Scaling Factors, and Their Contributions*

Variable	Definition	Source	Aggregation over 2014–2019	Scaling Factor	Contributing to
TOTALCOL	Total number of collisions of all types	NTD	Sum	–	–
VRM	Vehicle revenue miles	NTD	Sum	X 0.001	–
AAWHFT	Average annual working hours for full-time vehicle operations workers	NTD	Average per year then average over years	X 0.001	P_u
AAWHPT	Average annual working hours for part-time vehicle operations workers	NTD	Average per year then average over years	X 0.001	P_u
AVSPEEDTOT	Speed on all traveled miles (mph)	NTD	Divide total VM by total VH	X 0.1	P_u
AVSPEEDRVM	Speed on revenue miles(mph)	NTD	Divide total VRM by total VRH	X 0.1	P_u
AVSPEEDDH	Speed on deadhead miles (mph)	NTD	Divide total VDM by total VDH	X 0.1	P_u
AVPAX/M	Average passenger load per mile	NTD	Divide total PMT by total VRM	X 0.1	P_u
MECHFAIL	Mechanical failure counts	NTD	Divide total mechanical failure counts by total VM	X 0.0001	P_u
DENUZA	UZA persons per square mile	NTD	-	X 0.001	P_o
DENTSA	Transit agency service area persons per square mile	NTD	-	X 0.001	P_o
TTI	Travel time index	UMR	Average over 5 years	-	$P_{o,}$ P_u
CSI	Commuter stress index	UMR	Average over 5 years	-	P_o, P_u

Table B-2 presents the explanatory variables that were found to significantly affect transit bus collision risk at p=0.1 level. Of these seven variables, two had impacts on P_o and the other five on P_u. The model was programmed, and the coefficients were estimated in R. The likelihood ratio index was 0.520 for the converged model.

Table B-2 *Exposure Modeling Results*

Variable	Estimated Coefficient	Standard Error	P value
Intercept	-5.642	2.140	0.008
Variables affecting probability of encountering a traffic disturbance			
Travel time index (TTI)	3.068	1.043	0.003
Commuter stress index (CSI)	0.351	0.202	0.082
Variables affecting probability of operator unable to avoid collision			
Intercept	-14.905	4.554	0.001
Average annual working hours for full-time vehicle operations workers (AAWHFT)	0.281	0.089	0.002
Average annual working hours for part-time vehicle operations workers (AAWHPT)	-0.786	0.234	0.001
Average vehicle speed on revenue miles (AVSPEEDRVM)	0.181	0.022	0.000
Mechanical failure rate (MECHFAIL)	0.270	0.102	0.008
Travel time index (TTI)	0.515	0.166	0.002
Total number of observations	273		
Likelihood ratio index (ρ^2)	0.520		

Both TTI and CSI were found to contribute significantly to P_o, the probability of transit vehicles encountering a disturbance, while the two density measures were not significant and were dropped from consideration. The higher the TTI, the more congested the traffic is in comparison to free flow. The higher the CSI, the higher the stress will be for commuters driving in traffic with transit vehicles. They are more likely to engage in dangerous maneuvers. Busier traffic and greater commuter stress indicate greater chances for a bus operator to experience dangerous and unexpected events.

Five variables were found to contribute significantly to P_u, the probability of operator inability to avoid collisions when disturbances occur. Among them were the following:

1) The longer a full-time bus operator works, the larger the risk, possibly due to overtime work and fatigue.
2) The longer a part-time operator works, the smaller the risk. Longer hours for part-time employees could indicate increased experience in operating the vehicle.
3) Higher vehicle speeds on revenue miles contribute positively to collision probability. This is consistent with the fact that vehicles at higher speed are harder to stop.
4) Higher mechanical failure rates recorded in the study period also indicated greater chances of a mechanical failure that could affect collision avoidance.
5) Higher TTI contributes to higher collision probability because of greater congestion and traffic density along transit routes.

Table B-3 summarizes these marginal effects of significant variables on the three probabilities: 1) P_o, probability of encountering a traffic disturbance per vehicle mile, 2) P_u, probability that the operator is unable to avoid a disturbance, and 3) P_i, probability that a collision happens in a vehicle mile covered by agency i. P_i is defined as the product of P_o and P_u per agency.

Table B-3 *Average Direct Elasticity for Significant Variables on Three Probabilities*

Variable	Definition	P_o	P_u	P_i
AAWHFT	Average yearly working hours for full-time vehicle operations workers	-	0.55	0.55
AAWHPT	Average yearly working hours for part-time vehicle operations workers	-	-0.71	-0.71
AVSPEEDRVM	Speed on revenue miles	-	0.24	0.24
MECHFAIL	Mechanical failure rate of vehicles	-	0.56	0.56
TTI	Travel time index	3.20	0.60	3.80
CSI	Commuter stress index	0.38	-	0.38

The variable TTI (travel time index) contributes to both P_o and P_u, and thus its average elasticity with respect to probability of collision is the sum of those with respect to P_o and P_u. The numbers are readily interpretable. For example, the elasticity of a full-time employee's yearly working hours (in thousand hours) variable with respect to the probability of collision is 0.55. This means that a 1% increase in full-time employee yearly working hours will, on average, result in a 0.55% increase in collision probability. The travel time index variable has the largest marginal effect on the probabilities: its elasticity with respect to the probability of collision is 3.80. This indicates that, for a 1% increase in TTI, agencies, on average, are 3.8% more likely to have a collision per thousand VRM. The average speed variable has the smallest marginal effect. On average, a 1% increase in average revenue service speed indicates a 0.24% increase in collision probability.

C&L Cost Modeling

C&L costs include insurance premiums in addition to liability claims paid out each year by the transit agencies. Insurance usually pays for high value claims, and the cost of insurance claim payouts is recovered by the insurers through premiums received over time. Insurance premiums may increase or decrease depending on the claims history of the insured transit agency. Collisions, casualties, and C&L costs were aggregated over a five-year reporting period (2015–2019) to capture the effects of historical claims on insurance costs and annual C&L expenses.

The basic hypotheses in our SEM model for C&L cost included the following:

- The number of collisions by type (with motor vehicles, with person, with fixed object, with transit vehicle, etc.) do not contribute to C&L expenses directly. Instead, their effects on C&L cost are mediated by associated "cost" latent variables.
- Indicators of the "cost" latent variables are property damage (a cash value provided in the NTD), number of injuries associated with each type of collision, and number of fatalities associated with each type. This is a generalized notion of "cost." These severity indicators can be in aggregated forms, e.g., total injuries/fatalities due to collisions of the four types. They can also appear in broken-down forms, e.g., injuries/fatalities of passengers/ pedestrian/ bicyclists/ workers due to collisions of the four types. We tested both combinations.
- Different types of transit bus collisions and their induced "costs" do not interact, as each individual collision can only be in one category. Different paths merge only at the final C&L cost when the induced costs of the four collision types are summed.

Structural equation models (SEMs) are characterized by including two or more equations, which distinguishes them from the common single-equation regression models that include one response variable and multiple regressors. In SEMs, it is common for the dependent variable in one equation to be an independent variable in another equation. One way of dividing the variables is latent vs. observed. Latent variables are variables that are important in the model but for which there are no direct measures (either not recorded in a dataset or simply not observable). Observed variables, on the other hand, are those available in the dataset. A SEM is conveniently divided into two parts: the structural model and the measurement model. The structural model in a SEM prescribes relations between latent variables and observed variables that are not indicators of latent variables, e.g., regressions. The measurement model prescribes latent variables from its indicators, e.g., confirmatory factor analysis, and each latent variable can be related to multiple indicators.

The final SEM is shown in Figure B-1. Structural models are shown in black, and the measurement models are in red. Structural models in this proposed framework are those relationships that ultimately contribute to C&L cost, while measurement models are those that prescribe the latent variables with their associated indicators. Following the SEM symbols, the latent variables are drawn in ovals, measurable variables are marked in rectangles, and the direct relationships are marked with directed arrows. Each arrow is represented by a regression equation in the SEM, although they are not estimated individually as in linear regressions but altogether here in the SEM. For simplicity, the figure and the following tables do not present residual terms in the model, which are called "errors" (E) for measurable variables and "disturbances" (D) for latent variables.

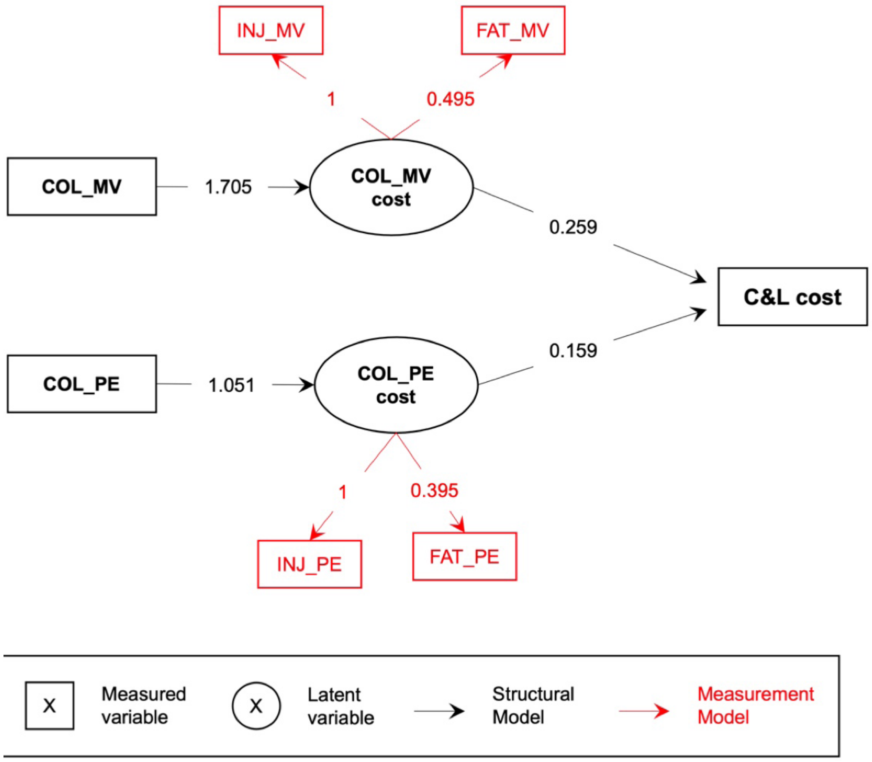

Figure B-1 *Final SEM model for C&L cost with significant paths and indicators*

Structural models shown in black, measurement models in red

The best SEM in terms of performance and conciseness included two paths to C&L cost. The two paths included one starting from number of collisions with motor vehicles (*COL_MV → COL_MV cost → C&L cost*) and the other starting from number of collisions with persons (*COL_PE → COL_PE cost → C&L cost*). Regression coefficients can be reported as unstandardized and standardized. Unstandardized coefficients are the default values returned by all statistical programs and were used here because they reflected the expected (linear) change in the response with each unit change in the predictor.

Equations (1) through (3) summarize the structural regression results of the final model described in Table B-4 and in Figure B-1.

$$\text{C\&L cost}=0.259 * \text{COL\_MV cost}$$

$$+\ 0.159 * \text{COL\_P cost}$$

$$+\ 0.004 * e\ (1)$$

$$\text{COL\_MV cost}=1.705 * \text{COL\_MV}\ (2)$$

$$\text{COL\_PE cost}=1.051 * \text{COL\_PE}\ (3)$$

Table B-4 *Structural Regression Results for the Final SEM (Unstandardized)*

Variables	Estimated Coefficient	Standard Error	z-value	P(>|z|)
Regression Equation: COL_MV cost ~ COL_MV				
COL_MV	1.705	0.031	55.708	0.000
Regression Equation: COL_PE cost ~ COL_PE				
COL_PE	1.051	0.004	236.268	0.000
Regression Equation: C&L cost ~ COL_MV cost + COL_PE cost				
COL_MV cost	0.259	0.025	10.173	0.000
COL_PE cost	0.159	0.028	5.710	0.000

Figure B-1 also depicts the two paths that were found to significantly contribute to C&L cost. The influence of the number of collisions was mediated by the latent cost variables, which were indicated by the total injuries and total fatalities due to collisions of that type. These latent cost variables were technically “unitless,” since they were not directly measurable. Therefore, to obtain a meaningful regression, it either the loading of one indicator per latent variable had to be fixed to one (marker variable identification) or the variance of every latent variable had to be fixed (factor variance identification). They were meant to define the “unit” or “scale” of the latent variables. This analysis chose the marker variable approach and let the program decide which indicator’s loading was fixed. Therefore, for every latent variable, there was one indicator variable having a unit loading, i.e., its marker. The numbers per arrow were interpreted as coefficients for that regression relationship, just as in Table B-4, which shows that the regression coefficient of collisions with motor vehicle was 1.705 if the regression was COL_MV cost against COL_MV. Interpretation of the measurement models (red) would always be discussed in the context of the variable indicator with a fixed loading. For example, a one-unit (the scale of INJ_MV, the marker) change in COL_MV cost would lead to a .495 increase in number of fatalities due to collision with motor vehicle(FAT_MV).

Table B-5 tests the significance of the paths ending in C&L costs. The significance of two paths shows that significant mediation effects only existed between the number of collisions with motor vehicles (COL_MV) and C&L cost, and between the number of collisions with persons (COL_PE) and C&L cost. The relationship between C&L cost and the number of collisions is presented in Equation (4). The intercept in Equation (4) is the expected value of the dependent variable, i.e., C&L cost, when its immediate predictors (the four latent variables) are equal to zero. The path coefficients in Table B-5 are directly interpretable. For example, the coefficient for the path COL_MV → COL_MV cost → C&L cost was 0.442, multiplying 1.705 from Equation (2) and 0.259 from Equation (1) together. Because the number of collisions with motor vehicles (COL_MV) was counted every thousand and the number of collisions with persons (COL_PE) was counted every hundred, the coefficients could be interpreted as a reduction of 100 collisions with motor vehicles (COL_MV), which would result in a decrease of $4.42M of C&L cost, while keeping other variables constant.

$$\text{C\&L cost} = 0.021 + 0.442 * \text{COL\_MV} + 0.167 * \text{COL\_PE} \quad (4)$$

Table B-5 *Path Significance Test for Final SEM*

Paths	Coefficient Estimate	Standard Error	z-value	P(>|z|)
COL_MV → COL_MV cost → C&L	0.442	0.044	10.085	0.000
COL_PE → COL_PE cost → C&L	0.167	0.029	5.748	0.000

Table B-6 presents the goodness of fit measures of the final model. Notice that from a statistical standpoint, these numbers indicate our model was acceptable. The preferred goodness of fit level for the comparative fit index (CFI) is 0.9 or 0.95 and above; and the preferred range for root mean square error of approximation (RMSEA) is less than 0.1. Therefore, the CFI of 0.974 outperformed the acceptance threshold, while RMSEA was close to a good fit.

Table B-6 *Goodness of Fit Measures for Final SEM*

Measure	CFI	RMSEA	R^2 for C&L Cost
Value	0.974	0.156	0.671

A regression model can be thought of as a mathematical equation that draws an imaginary line or surface through a cloud of data points. Regression models can be evaluated using the R-squared statistic, which has a maximum value of 1 and is a measure of how closely the model fits all the points. The closer the R-square is to 1, the better the fit. The R square for C&L cost was 0.671, and thus showed that the final model had significant explanatory power. For the sample of 273 reporting transit agencies, the R-squared statistic for the C&L Cost Model showed that the numbers of collisions with vehicles and collisions with persons predicted 67% of the variation in total C&L expenses.

Research Conclusions

This study explored how NTD data can be used to model C&L costs at the agency level in response to risk factors and the numbers of collisions and casualties. Using data products offered by NTD and external sources, we broke down the task into two steps—1) collision frequency modeling and 2) C&L cost modeling.

In the collision exposure modeling, a nested negative binomial (NB) count model was developed in which the probability of collisions occurring per transit revenue mile is modeled as a product of the probability of a disturbance occurring and the probability of an operator being unable to avoid a collision. Traffic congestion and commuter stress indicators were found to be significant for the probability of disturbance occurrences—the more congested the roads are, the more stressed commuters are, and the greater the chances for traffic disturbances. Operators' working hours, bus vehicle mechanical failure rates, and traffic congestion (again) were found to be significant for operators' inability to avoid collisions. Overtime for full-time workers, fewer hours (e.g., less experience) for part-time operators, less well-maintained vehicles, and denser traffic were found to contribute to greater chances for collisions.

In modeling C&L costs, a SEM with two paths showed that collisions with motor vehicles and collisions with persons contribute significantly to agencies' overall C&L cost. Property damage was found not to be a significant indicator of latent cost, but aggregated injuries and fatalities were. On the basis of the two-path model, path coefficients were interpreted as potential cost savings by unit reductions of scaled collision count variables. Additional detail on the methodology and data used for this task can be found online at Wang et al.[45]

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[45] Wang, Y., R. Ke, S. Yin, Z. Cui, "Quantifying Contributing Factors to Transit Bus Casualty and Liability Expenses Using the National Transit Database," Technical Report #2, FTA/Pierce Transit Automated Collision Avoidance and Mitigation Safety Research and Demonstration Project, University of Washington, 2021, http://www.uwstarlab.org/research/highlights/20211201_PT_FinalReport_NTD_Publish.pdf.

Appendix C

Commercialization Potential for Transit Bus Automated Collision Avoidance Warning and Emergency Braking Systems

Safety Evaluation

A transit agency's purpose is to provide service to the public, and a key metric with which to measure that service is safety. A potential increase in safety or decrease in injury and fatality causing events has a direct impact not only on the quality of service provided but also the cost effectiveness of service. The project team reviewed event data for over 8,600 claims and compared the event specifics with the CAWS system's capabilities to identify events that could be technologically impactable. The project team also reviewed NTD data.

Findings

The project team reviewed WSTIP's historical loss records maintained for each of its members throughout the state of Washington. WSTIP's records contain specific fields that can be utilized to compare and evaluate claims costs and potential outcomes. The project team used Munich Re's Cause of Loss Categories, shown in Table C-1, to categorize claims.

Table C-1 *Cause of Loss Categories*

Animal Collision or Avoidance	Not At Fault
Backing	Not Collision Related
Bicyclist Collision or Avoidance	Non-Collision Passenger Injury
Collided With Fixed Object	Passing
Collided With Parked Vehicle	Pedestrian Collision or Avoidance
Drive Under Trailer	Rear-End
Driver Error or Traffic Violation	Right Turn
Failure To Clear Structure	Road Hazard
Head-on Collision	Sideswipe
Intersection	Sliding on Roadway
Lane Change	Cargo Related
Lane Departure	Theft
Left Turn	Turning Other
Mechanical Failure	Unknown
Motorcycle Collision or Avoidance	Weather
Non-Owned or Rental Vehicle	Glass Breakage Non-Vandalism

After categorizing WSTIP historical loss data into different causes of loss, the project team applied CAWS/AEB capabilities for a 150-degree forward-looking PASS system to WSTIP event and cause of loss details. This resulted in the identification of events that could be technologically impactable by the PASS system, such as rear-end, pedestrian, bicyclist, left turn, and head-on collisions, among others. Table C-2 summarizes WSTIP members' event history for fixed-route operations.

Table C-2 *WSTIP (25 Member Agencies) 2009–2020 Fixed-Route Loss History*

Description	Count	Per Year
Average Fixed-Route Vehicles	N/A	1,345
Average Miles Driven	N/A	55,552,702
Claims	8,661	787
Injuries	1,203	101
Fatalities	7	0.58
Total Expenses	$59,992,913	$4,999,409
Bodily Injury	$35,262,901	$2,938,575
Property Damage	$14,387,015	$1,198,918
Legal Expenses	$5,820,574	$485,048
Other Expenses	$3,798,280	$376,869

Potential Reductions Analysis

After reviewing WSTIP transit agency historical events, the project team found that 25% of WSTIP member claims were technologically impactable and 75% were not impactable by the PASS system. The 25% of claims that were categorized as technologically impactable comprised 38% of the injuries recorded by WSTIP.

Table C-3 summarizes 2009 through 2020 injuries caused by WSTIP's fixed-route motor buses, categorizing the injuries into two categories:

1. Technologically Impactable – Defined as an event that could be mitigated by a CAWS/AEB system. For this report, the project team applied CAWS/AEB capabilities for a 150-degree forward-looking PASS system to determine whether an event could be impacted by a CAWS/AEB system.

2. Not Impactable – Defined as all events that are outside of the capabilities of a 150-degree forward-looking PASS system.

For 2009–2020, 38% of the injuries fell into the technologically impactable category, with the remaining 62% of injuries being not impactable.

Table C-3 *WSTIP Injuries by Year, 2009–2020*

Year	Total Injuries by Year	Technologically Impactable	% of Total	Not Impactable	% of Total
2009	122	48	39%	74	61%
2010	124	44	35%	80	65%
2011	98	33	34%	65	66%
2012	95	27	28%	68	72%
2013	126	60	48%	66	52%
2014	98	30	31%	68	69%
2015	107	39	36%	68	64%
2016	84	35	42%	49	58%
2017	101	38	38%	63	62%
2018	114	50	44%	64	56%
2019	74	30	41%	44	59%
2020	60	26	43%	34	57%
Total	1,203	460	38%	743	62%

The project team also obtained from the NTD historical safety and security, agency, and operating expense data for transit agencies across the US.

Table C-4 summarizes NTD reporters' data for agencies whose service area populations are less than 1 million. All WSTIP transit agencies' service area populations are less than 1 million.

Table C-4 *NTD Reporter (<1 Million Service Area Population) 2015–2019 Fixed-Route Summary*

Description	Count	Per Year
Average Fixed-Route Motor Buses Operated In Maximum Service		13,289
Average Revenue Miles Driven		518,212,484
Collisions	5,775	1,155
Injuries	16,499	3,300
Fatalities	107	21

The project team applied the data and findings from their review of WSTIP's records to NTD's data. For purposes of this report, the project team assumed three levels of collision mitigation efficacy for a fully tested and functional CAWS/AEB system—25%, 50%, and 75% of technologically impactable events.

Table C-5 summarizes the assumed efficacy levels with NTD reporters' data for agencies whose service area populations are less than 1 million.

Table C-5 *NTD Reporter (<1 Million Service Area Population) Event Reduction Summary*

Description	Average Impactable per Year	Potential Per Year Reduction		
		At 25%	*At 50%*	*At 75%*
Collisions	289	72	145	217
Injuries	1254	314	627	941
Fatalities	5	1	3	4

The project team also reviewed NTD safety and security data for agencies with service area populations of greater than 1 million and found that directly operated motor buses had 4,187 collisions, 12,524 injuries, and 68 fatalities annually. Since 2015, miles have increased by 0.41%, and collisions, injuries, and fatalities have grown/(declined) by 1.02%, -1.41%, and 0%, respectively.

Figure C-1 shows three lines of NTD directly operated motor bus data for 2015–2019. The blue line shows NTD reported vehicle revenue miles, the green line shows NTD reported injuries, the red line shows NTD reported collisions. All three lines are relatively consistent year over year; however, injuries decreased slightly over those years.

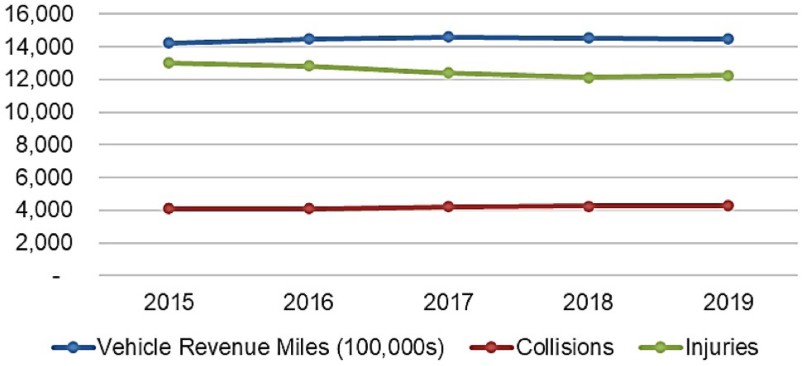

Figure C-1 *NTD directly operated motor bus*

For purposes of this report, the potential reduction in collisions, injuries, and fatalities for all NTD agencies was not calculated. However, it is evident from the data that a significant reduction in injuries could result in areas of greater population density.

Another area of potential increased safety as a result of the PASS system is a reduction in injuries that occur as a result of hard braking events. For example, WSTIP members sudden stop, slip and fall, and passenger events make up 18% of injuries each year (nearly 20 injuries per year).

Figure C-2 summarizes 2015–2019 collision counts by service area population, demonstrating how collision frequency grows as population density increases The R-squared values indicate the strength of relationship between collision frequency and population density. R-squared values range from 0 to 1, and the higher the R-squared value, the stronger the relationship or correlation between the two variables. The R-squared values for 2015–2019 ranged from 0.59 to 0.63. The figure also contains trend lines showing that each year collision trends increased except for 2018.

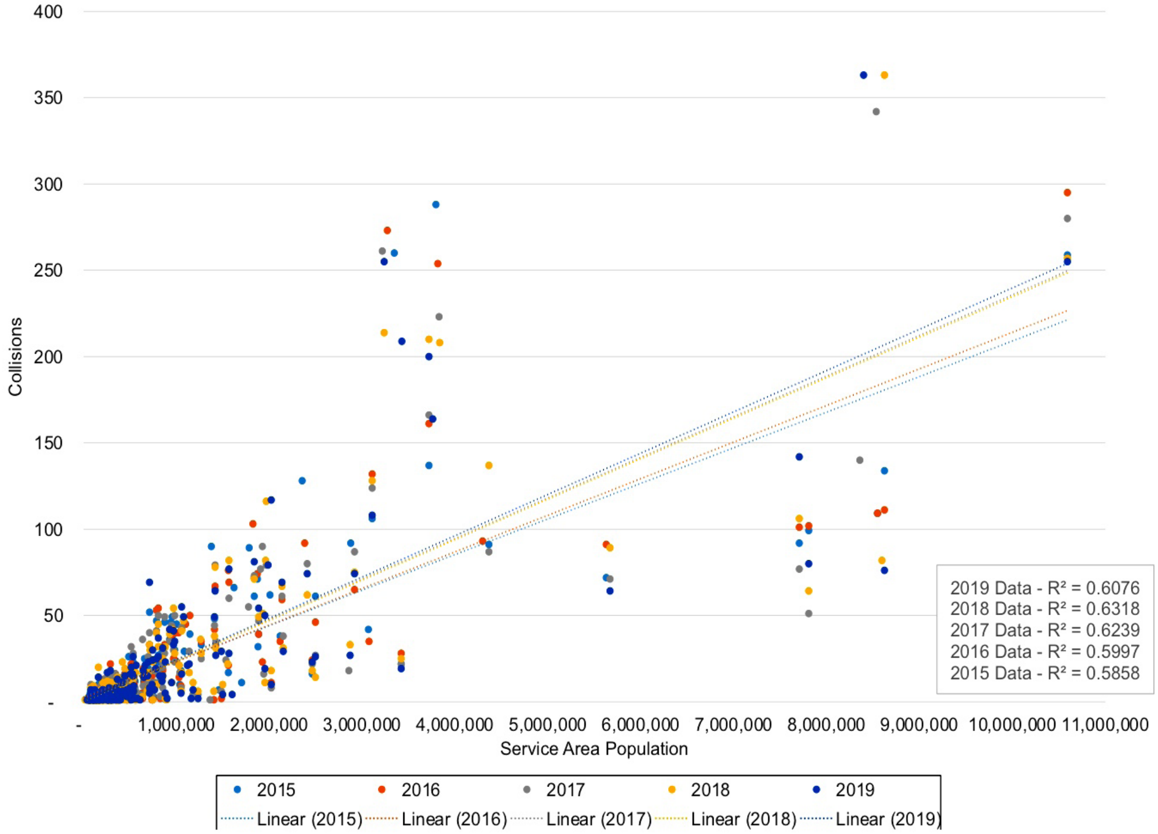

Figure C-2 *NTD collisions by service area population*

Return on Investment (ROI)

From an economic perspective return on investment is a key metric with which to measure the viability of a given system or decision. Return on investment (ROI) can be defined as “a performance measure used to evaluate the efficiency or profitability of an investment.”[46] The purpose of evaluating ROI in this project was to provide insight into potential cost reductions as a direct result of the PASS system for transit agencies with a focus on fixed-route motor buses.

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[46] Fernando, Return on Investment (ROI), https://www.investopedia.com/terms/r/returnoninvestment.asp.

Findings

Cost of the System

The initial purchase and installation of the system for this project was $10,000 per PASS system. Because of the limitations of the project scope, it is unknown how long the life of each system will be and what maintenance will be required. However, 30 systems were in place on buses for 930,091 miles, and during that time there were 4 lens failures.

Table C-6 summarizes the cost of the PASS system and potential maintenance expense over the life of the system.

Table C-6 *Cost of PASS System*

Item	Cost Per Unit	Units	Extended
Initial System Cost	$9,000	30	$270,000
Installation	$1,000	30	$30,000
Initial System & Install Cost	$10,000		
Maintenance/Repairs			
Sensor Replacement Cost-Sensor Failure	$1,500	2	$3,000
Total System Miles In Use			930,091
Potential Maintenance Expense per Mile			$0.003

In total, 30 PASS systems were installed for approximately 30,000 miles each. As the systems are in circulation for greater lengths of time, maintenance expenses likely will increase, and the rate of lens failures could increase. However, the 30 systems were rarely inspected during their time in circulation, and if lens integrity checks had been performed, the maintenance expense for the systems that failed would have been significantly cheaper than they were as complete sensor replacements.

Claims and Liability Expense Reduction

To identify the potential for cost reduction related to claims and liability expenses, the project team reviewed and categorized over 8,600 insurance claims for WSTIP member transit agencies, with a focus on fixed-route motor buses. WSTIP provided the project team with historical loss data for each of the member agencies.

Table C-7 summarizes annual claims and liability expenses incurred by WSTIP agencies for fixed-route operations.

Table C-7 *WSTIP Claims and Liability Expense by Year*

Year	Total C&L Expense	Technologically Impactable	% of Total	Not Impactable	% of Total	Fixed-Route Miles	C&L Expense per Mile
2009	$4,506,899	$2,733,480	61%	$1,773,419	39%	58,086,313	$0.08
2010	4,492,755	2,003,997	45%	2,488,758	55%	56,773,659	$0.08
2011	5,336,675	1,062,259	20%	4,274,416	80%	55,875,705	$0.10
2012	2,745,268	1,692,714	62%	1,052,554	38%	52,041,007	$0.05
2013	4,595,774	2,358,181	51%	2,237,593	49%	52,620,110	$0.09
2014	4,836,113	2,186,447	45%	2,649,666	55%	53,252,904	$0.09
2015	6,239,861	3,310,462	53%	2,929,400	47%	54,451,527	$0.11
2016	1,901,602	804,721	42%	1,096,881	58%	56,303,746	$0.03
2017	3,228,789	1,021,407	32%	2,207,382	68%	56,604,264	$0.06
2018	3,999,443	1,356,288	34%	2,643,154	66%	59,517,782	$0.07
2019	3,643,264	1,834,664	50%	1,808,600	50%	61,070,797	$0.06
2020	1,381,672	625,173	45%	756,498	55%	66,055,219	$0.02
Total	$46,908,115	$20,989,794	45%	$25,918,321	55%	682,653,033	$0.07

Table C-8 and Table C-9 summarize the types of events that result in claims and liability expenses. The tables also categorize the types of costs that make up claims and liability expenses, such as bodily injury, property damage, and legal expenses, among others. The data are composed of WSTIP historical claims information. The event categories and costs are then broken into the technologically impactable and not impactable categories. The tables show which event types could be impacted the most by a CAWS/AEB system.

Table C-8 *WSTIP Historic Claims by Category Loss Data Description*

Event Category	Bodily Injury	Incurred Expense	Property Damage	Legal Expense	Other Indemnity	Recovery/ Subrogation	Net Amount	% of Total
Bicyclist	$4,815,840	$332,539	$45,686	$418,138	$17,309	$1,913,706	$3,715,806	7.9%
Pedestrian	4,063,396	147,335	31,514	111,047	4,181	1,303,254	3,054,218	6.5%
Rear-End	6,132,614	591,751	1,030,497	1,152,250	60,612	122,856	8,844,869	18.9%
Sideswipe	2,105,516	183,789	209,477	264,010	36,065	709,179	2,089,678	4.5%
Collided with Parked Vehicle	1,431,847	126,875	782,438	138,805	50,102	115,951	2,414,116	5.1%
Left Turn	401,953	136,238	370,681	102,164	28,203	66,947	972,292	2.1%
Intersection	344,323	90,658	301,530	112,208	10,377	139,730	719,365	1.5%
Not Auto PI	6,850,774	897,311	937,831	1,275,841	35,732	2,145,156	7,852,333	16.7%
Other Categories	9,215,096	1,680,587	11,018,167	2,343,007	115,040	7,126,460	17,245,438	36.8%
Grand Total – Reviewed	$35,361,360	$4,187,082	$14,727,821	$5,917,471	$357,621	$13,643,239	$46,908,116	100.0%

Table C-9 *WSTIP Historic Claims by Category, Technologically Impactable Expenses*

Event Category	Number of Claims	% of Total	Technologically Impactable Expenses	Technologically Impactable Recovery/ Subrogation	Net Amount
Bicyclist	46	0.5%	$5,282,667	$1,913,614	$3,369,053
Pedestrian	98	1.1%	3,339,011	1,299,117	2,039,894
Rear-End	746	8.6%	8,965,198	122,856	8,842,343
Sideswipe	218	2.5%	2,516,920	707,534	1,809,386
Collided with Parked Vehicle	482	5.6%	1,917,010	95,106	1,821,904
Left Turn	235	2.7%	713,543	53,360	660,183
Intersection	183	2.1%	839,895	130,458	709,437
Not Auto PI	1,699	19.6%	-	-	-
Other Categories	4,954	57.2%	1,924,864	187,270	1,737,594
Grand Total – Reviewed	8,661	100.0%	$25,499,108	$4,509,315	$20,989,794

Figure C-3 depicts historical claim volumes and costs for the years 2009 through 2020 for WSTIP by member. Historically, claim volumes have remained static. However, starting in 2018 the volume of claims has decreased. Claims costs, however, reached their peak in 2015 and have decreased since.

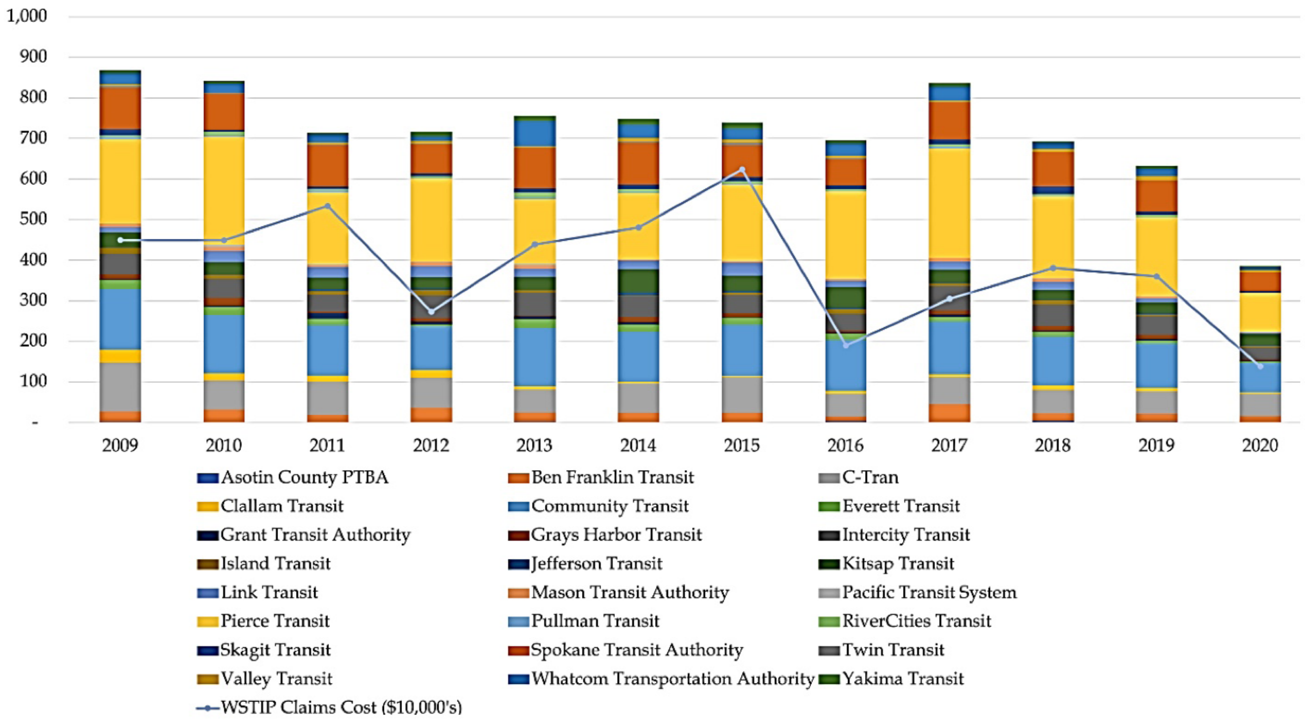

Figure C-3 *WSTIP fixed-route claim count and cost history*

Figure C-4 depicts historical fixed-route miles and claims costs by type for the years 2009 through 2020 for WSTIP. Historically, fixed-route miles remained static, with a slight decrease in 2020. Claims costs by type shows that most expenses have been due to bodily injury. The second largest expense category is property damage, followed by legal costs. Additionally, recovery of claims costs though subrogation or other means has been very minimal since 2015.

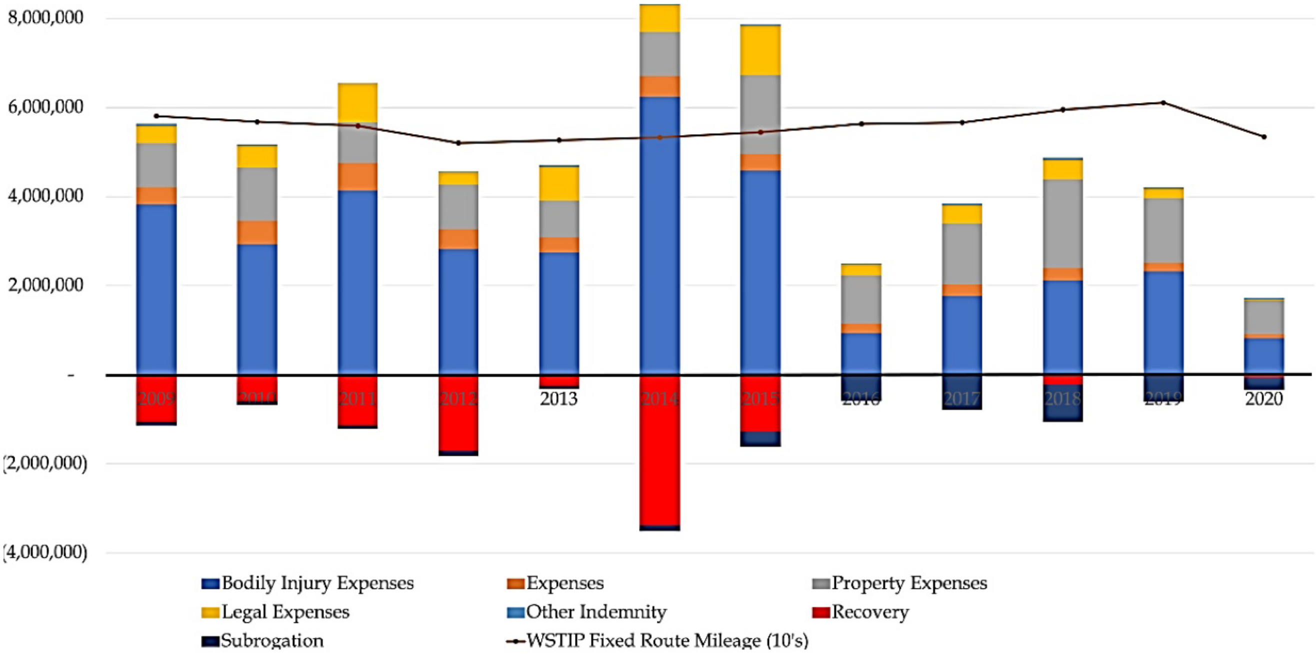

Figure C-4 *WSTIP fixed-route miles and claims costs by type*

After reviewing WSTIP member historical events, the project team found that 25% of WSTIP member claims were technologically impactable by the PASS system and 75% were not impactable by the PASS system, as shown in Figure C-5.

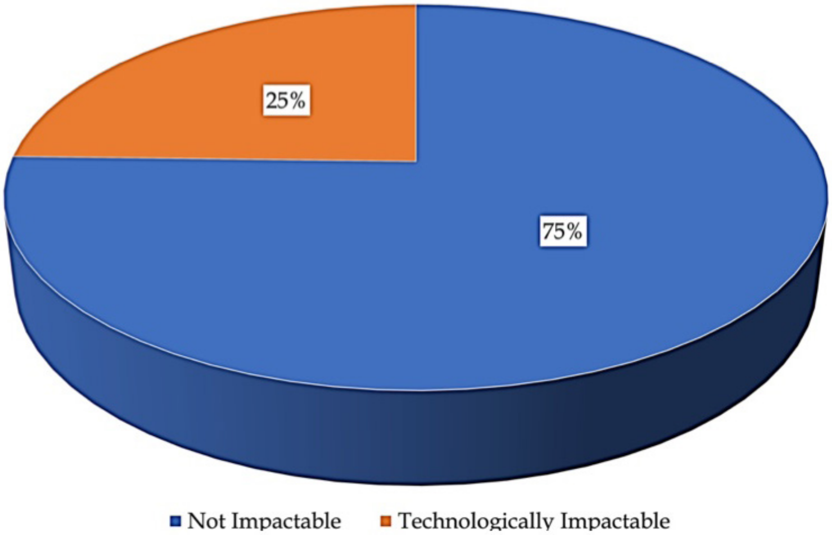

Figure C-5 *WSTIP claims history*

The 25% of claims that were categorized as technologically impactable comprised 45% of the claims and liability expenses incurred by WSTIP members, as shown in Figure C-6.

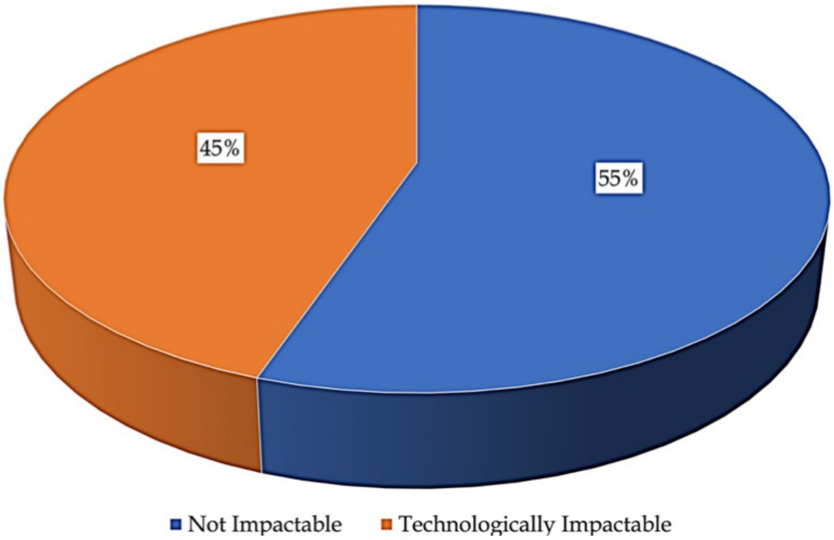

Figure C-6 *WSTIP claims expense history*

For purposes of this report, the project team assumed three levels of efficacy for a fully tested and functional CAWS/AEB system: 25%, 50%, and 75%. Table C-10 summarizes the potential breakeven cost for the acquisition and implementation of the PASS system on WSTIP fixed-route buses based on the technologically impactable events shown in Figure C-6. The PASS system cost per unit was $10,000.

Table C-10 *Return on Investment – Breakeven Cost*

Scenarios	Saved Claims & Liability Expense per Mile	Less Maint. Expense per Mile	Saved Claims & Liability Expense per Mile	System Life Expectancy Miles Needed to Break Even	Breakeven Cost – Assuming 37,080 Miles per Year		
					6 Years – 222,480 miles	8 Years – 296,640 miles	10 Years – 370,800 miles
Scenario 1 - 25% Reduction	$0.008	($0.003)	$0.005	1,902,280	$502	$669	$837
Scenario 2 - 50% Reduction	$0.017	($0.003)	$0.014	739,990	$2,339	$3,119	$3,898
Scenario 3 - 75% Reduction	$0.025	($0.003)	$0.022	459,336	$4,176	$5,568	$6,960
Current Life Expectancy of System							Unknown

Note: The lifetime maintenance expense at the date of this report is unknown. However, for the 30 systems that were installed for 930,091 miles, $3,000 in repairs and maintenance was incurred (i.e., $.003 per mile).

The project team also obtained from the NTD historical safety and security, agency, and operating expense data for transit agencies across the US. The claims and liability expenses tracked within the NTD operating expense data were primarily for premiums. NTD defines C&L expenses as "C&L Costs (5050)," which refers to the expenses a transit agency incurs for loss protection. If a transit agency is liable for a loss, it must report all applicable compensation under this object class. C&L costs include:

- Physical damage insurance premiums
- Recovery of physical damage losses for public liability and property damage insurance premiums
- Insured and uninsured public liability and property damage settlement payouts and recoveries
- Other corporate insurance premiums (e.g., fidelity bonds, business records insurance)
- Self-insurance costs

However, for purposes of this project, WSTIP event-caused claims and liability expenses incurred were compared with what WSTIP members reported to the NTD for C&L costs. This comparison was made to establish a ratio of event-caused claims and liability expenses as a percentage of C&L costs (i.e., event costs as a percentage of insurance premiums). Table C-11 compares WSTIP incurred claims and liability-related expenses with NTD reported C&L costs for the same WSTIP members for 2015–2019. Because the majority of what agencies report to the NTD for C&L costs are for premiums, the project team needed to establish what percentage of premiums could reasonably be calculated as claims and liability expenses, also known as a loss ratio. For the years 2015 through 2019 event-related claims and liability expenses for WSTIP members equaled, on average, 58.52% of the C&L costs reported to the NTD (i.e., 58.52% of premiums).

Table C-11 *WSTIP 2015-2019 Member Claims and Liability Expenses – Comparison of NTD Reported Data to WSTIP Event-Related Expenses*

WSTIP Member	NTD ID	NTD Description	NTD Reported C&L Expense	WSTIP Event-Related C&L Expense	WSTIP % of NTD
Ben Franklin Transit	00018	Ben Franklin Transit	$1,664,348	1,177,663	70.76%
C-Tran	00024	Clark Co. Public Transportation Benefit Area Authority	2,947,212	1,065,746	36.16%
Community Transit	00029	Snohomish Co. Public Transportation Benefit Area Corp.	5,086,942	1,908,752	37.52%
Everett Transit	00005	City of Everett	3,071,811	131,335	4.28%
Intercity Transit	00019	Intercity Transit	2,669,685	1,188,431	44.52%
Kitsap Transit	00020	Kitsap Transit	2,357,258	2,651,061	112.46%
Link Transit	00043	Chelan Douglas PTBA	1,324,886	424,771	32.06%
Pierce Transit	00003	Pierce Co. Transportation Benefit Area Authority	4,673,293	6,699,513	143.36%
Spokane Transit Authority	00002	Spokane Transit Authority	4,986,359	1,360,603	27.29%
Yakima Transit	00006	City of Yakima	445,772	372,407	83.54%
Skagit Transit	00044	Skagit Transit	602,814	486,998	80.79%
Whatcom Transp. Authority	00021	Whatcom Transp. Authority	351,208	195,209	55.58%
Total			$30,181,588	17,662,490	58.52%

Table C-12 similarly summarizes WSTIP incurred claims and liability-related expenses with NTD claims and liability expenses for the same WSTIP members for the years 2015 through 2019. Historically, incurred claims and liability-related expenses equaled 58.52% of NTD reported claims and liability expenses (i.e., premiums).

Table C-12 *WSTIP 2015–2019 Member Claims and Liability Expenses – NTD vs. WSTIP Event-Related Expenses – Annual Totals for WSTIP NTD Reporters*

Year	NTD C&L	WSTIP Event-Related C&L Expense	WSTIP % of NTD
2015	$5,152,659	$6,029,068	117.01%
2016	5,456,661	1,733,817	31.77%
2017	6,141,857	3,075,377	50.07%
2018	5,434,795	3,568,997	65.67%
2019	7,995,616	3,255,231	40.71%
Total	$30,181,588	$17,662,490	58.52%

Table C-13 summarizes the potential claims cost reductions for NTD reporting agencies, assuming that 58.52% of NTD reported C&L costs (i.e., premiums) were equal to the amount of claims and liability expenses that events caused for agencies with service area populations similar to those of WSTIP members (i.e., under 1 million).

Table C-13 *Potential NTD Return on Investment*

Scenarios	Potential Saved C&L Expense per Mile	Less Maint. Expense per Mile	Saved C&L Expense per Mile	System Life Expectancy Miles Needed to Break Even	Breakeven Cost – Assuming 37,080 Miles per Year		
					6 Years – 222,480 miles	8 Years – 296,640 miles	10 Years – 370,800 miles
Scenario 1 – 25% Reduction	$0.017	($0.006)	$0.011	595,301	$3,070	$4,093	$5,116
Scenario 2 – 50% Reduction	$0.034	($0.006)	$0.028	297,651	$6,807	$9,076	$11,345
Scenario 3 – 75% Reduction	$0.050	($0.006)	$0.044	198,434	$10,544	$14,059	$17,574
Current Life Expectancy of System							Unknown

Note: The lifetime maintenance expense at the date of this report is unknown. However, for the 30 systems that were installed for 930,091 miles, $6,000 in repairs and maintenance was incurred (i.e., $.006 per mile).

The project team also reviewed PT internal costs incurred that were connected with small claims such as mirror slaps. Table C-14 summarizes costs incurred that were not captured by NTD or WSTIP loss data.

Table C-14 *PT 2019 Internal Costs – Fixed Route*

Description	Count	Internal Cost Incurred
Fixed-Route Vehicles	356	
Small Claims & Total Expenses	76	$187,945
Head-On	2	$17,489
Other Front Impact	7	$9,750
Other Rear Impact	16	$33,347
Rear-Ending	6	$27,812
Side Impact	8	$32,643
Side Swipe	35	$65,844
Other	2	$1,060

Commercialization Conclusions

The evidence examined in this project suggests the potential for a return on investment for transit agencies if fully tested and functional CAWS/AEB systems were available for retrofit on transit buses. There does not appear to be a "one size fits all" solution. The business case will vary from agency to agency. However, an agency should be able to estimate the potential benefits based on in-house historical data on collisions and expenses and based on costs and performance data provided by vendors. Historical agency averages can be computed for the expected amortization life of the CAWS/AEB system or the expected life of the vehicle. Anticipated savings will depend on the proportion of C&L expenses that result from collisions, and the proportion of those collisions that could be prevented or mitigated by CAWS/AEB.

Appendix D

Developing and Testing a 2D Flash Lidar Transit Bus Collision Avoidance Warning System

Pedestrian Avoidance Safety System Description

The Pedestrian Avoidance Safety System (PASS is a collision avoidance warning system (CAWS) with an automatic vehicle deceleration feature designed to provide a bus operator with collision-avoidance assistance in the form of improved reaction time to mitigate an imminent collision with a pedestrian, cyclist, or vehicle in front of the bus. PASS initiates collision avoidance by decelerating the vehicle through a two-step, de-throttle and brake application, process. Deceleration is performed with consideration of on-board passenger safety. The operator is expected to complete the accident-avoidance process.

To deliver accident avoidance and guard the safety of on-board passengers, PASS must initially assume that the operator is unaware of objects detected by the system. PASS's CAWS/AEB algorithm and automated emergency braking (AEB) activation threshold must account for an unaware driver's reaction time to a CAWS warning to allow for a safe operator response. PASS's instantaneous response, including AEB deceleration, is key to overall system performance and passenger safety.

The PASS object vulnerable road user (VRU) detection system uses an array of three solid state, 2D flash light detection and ranging (lidar) sensors attached to bike rack mounting standoffs at the front of the bus. Flash lidar continually emits light pulses, measures the time for the light to reflect from objects in front of the sensor, and calculates the distance between the object and the sensor. Flash lidar was selected as the object detection sensor technology because of its extremely accurate distance to object measurement capabilities (~5cm), exact relative object location to the bus, and sustained performance in challenging weather and lighting conditions. Sensor array specifications are shown in Table D-1.

Table D-1 *Sensor Array Specifications*

Sensor Array Assembly	
Physical Characteristics	
Dimensions (LxWxH) (cm)	51x13x10
Weight (kg)	9.1
Color	Black
Material	Steel/Aluminum
Electrical Characteristics	
Input Voltage (V)	15-32
Input Current (A)	3.5 max
Power (W)	105 max
Off State Current (A)	0
Environmental Characteristics	
Environmental Rating	IP67
Operating Temp (^{0}C)	-40 to 85
Storage Temp (^{0}C)	-40 to 85
Shock/Vibe	SAE J1455
Sensor Characteristics	
Field of View Horizontal/Vertical (^{0})	144/3
Technology	2D Flash lidar
Wavelength (nm)	905
Accuracy (cm)	± 5
Refresh Rate (Hz)	12

PASS simultaneously detects and tracks up to 32 discrete objects in the vehicle-under-test (VUT) area of interest (AOI). The AOI is forward looking to 50 meters and 10 meters to the right and left sides of the forward path of travel. It can be tuned to transit agency preferences, vehicle response time and deceleration rates, and unique route requirements. The AOI is dynamic, accounting for the VUT path-of-travel in straight path or turning conditions.

PASS has been tested to SAE J1455 vibration profiles (heavy duty applications) and ISO 20653 IP67. The sensor enclosures are designed to mitigate impacts of the environmental, natural, mechanical, and operational transit operating environment.

Figure D-1 shows an isometric engineering drawing of a complete lidar sensor assembly. The sensor assembly was bolted to the support bracket for the folding bicycle rack on all 30 project buses. A sensor assembly is shown in Figure D-2 mounted to the front of Pierce Transit (PT) bus #230.

Figure D-1 *PASS lidar sensor assembly*

Source: DCS

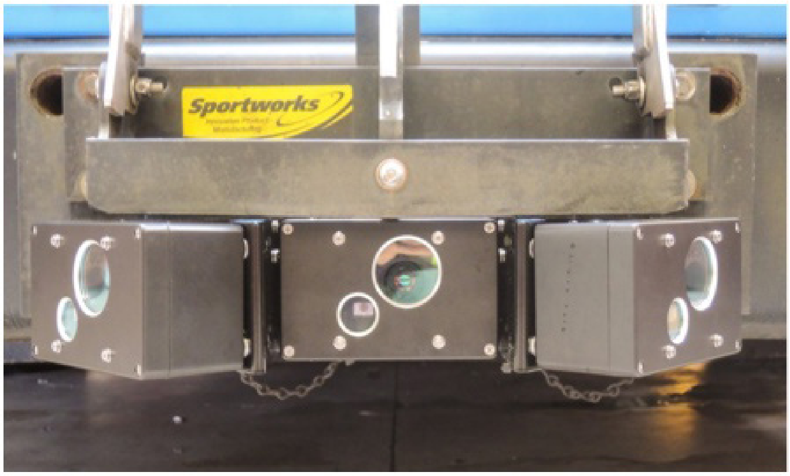

Figure D-2 *PASS sensor assembly attached to PT Bus #230*

Source: DCS

PASS Operational Design Domain (ODD)

The CAWS operational design domain (ODD) seeks to maximize overall collision avoidance performance and safety while balancing the chosen sensor technology's strengths and weaknesses. PASS CAWS and AEB performance parameters or ODD are shown in Table D-2.

Table D-2 *PASS CAWS/AEB Performance Parameters*

CAWS/AEB Performance Parameters	
Operating/Functional Conditions	
Field of View (FOV)	144^0 (Covers A-pillar blind spot)
Lighting Conditions	Day & Night (All)
Rain	Yes
Fog	Yes
Snow	Yes
Object Discrimination	No
Operator Over-ride	Yes
CAWS/AEB Outputs	
Warning/AEB Conditions	Object detected in vehicle Path of Travel (PoT)
	Object detected meets PASS' Critical Distance threshold[1]
Outputs	Red Light Signal (A-pillar & Center Windshield)
	Buzzer/audible signal (Haptic feedback optional)
	Dethrottle Activate AEB[2]
Maximum Deceleration Rate (g)	0.3
System Reaction Time[3]	
Dethrottle Response time (s)	0.02
Brake Apply Response time (s)	0.02

[1] Critical Distance based on DCS proprietary algorithms.

[2] AEB activation does not interfere with normal antilock braking system (ABS) and traction control system (TCS) functionality.

[3] Vehicle brake system delay not included.

PASS Data Logging and Processing

PASS data-loggers automatically collected and transferred vehicle and PASS telematics data to DCS servers. PT provided DCS access to an on-board cellular modem located on each VUT for wireless data transfer. Early beta testing with VUTs (buses 230 through 233) provided an opportunity to exercise the PASS data collection hardware and software, as well as data reduction processes. All 30 project VUTs successfully delivered data files to DCS servers for data processing.

Table D-3 shows a summary of the PASS telematics data set. The data elements capture general timing information, vehicle J1939 data, vehicle location, vehicle acceleration, gyroscopic (turning) data, PASS AEB event data such as object position and trajectory with respect to the VUT, and general modes and settings information. Each PASS warning (AEB event) began the collection of the data set at a 40-ms rate for the duration of the AEB event. Additionally, two seconds of pre-trigger and post-trigger data (40-ms rate) were collected with each AEB event. Project data were delivered to the UW via secure file transfer protocol (SFTP).

Table D-3 *PASS Project Data Set*

Source	Data Element	Data Element Description	Measurement Unit	Resolution
Vehicle	Bus Number	Identification number of bus under test		1
	PASS Event Vehicle Location	GPS longitude/latitude coordinate of PASS Event	deg	0.000001
	Time Stamp	Time stamp of PASS Event	UTC (ms)	1
	Vehicle Heading (GPS)	Vehicle directional heading at time of PASS event as reported by GPS	deg	0.1
	Vehicle Speed (J1939)	Vehicle speed at time of PASS event as reported by J1939 cruise control/ vehicle speed (CCVS) message	mph	0.1
	Vehicle Brake Switch	Vehicle foundation brake application as reported by J1939 CCVS message.		1
	Vehicle Throttle	Vehicle throttle position as reported by J1939 electronic engine controller 2 (EEC2) message	%	1
	Vehicle Longitudinal Acceleration	Measured vehicle acceleration along longitudinal axis	g	0.001
	Vehicle Latitudinal Acceleration	Measured vehicle acceleration along latitudinal axis	g	0.001
	Vehicle Vertical Acceleration	Measured vehicle acceleration along vertical axis	g	0.001
	Vehicle Yaw Rate	Measured vehicle yaw rate	°/s	0.1
PASS	PASS Operating Mode	PASS operating mode		1
	PASS Event ID	Identification code of PASS Event		1
	Object Relative Velocity	Relative velocity of object (longitudinal/ latitudinal WRT VUT)	mph	0.1
	Object Distance	Object position from VUT (longitudinal/ latitudinal WRT VUT)	ft	1
	Object TTC	Time to collison of object	sec	0.01

Data processing and control were managed by a dedicated processor/IO controller. System logging and vehicle dynamics functions were handled by a single board computer with internal measurement unit (IMU) sensors. The entire PASS control and monitoring system was housed in a system enclosure mounted in the electronics/radio cabinet of the bus. The system processing and data logging specifications are shown in Table D-4.

Table D-4 *PASS System Processing and Data Logging Specifications*

Physical Characteristics	
Dimensions (LxWxH) (cm)	27x16x9
Weight (kg)	2.3
Material	Aluminum
Electrical Characteristics	
Input Voltage (V)	15–32
Input Current (A)	10 max
Input Power (W)	320 max
Off State Current (A)	0.001
Environmental Characteristics	
Environmental Rating	IP51
Operating Temp (^{0}C)	-40 to 85
Storage Temp (^{0}C)	-40 to 85
Communication/Algorithm Characteristics	
Master Controller Clock Speed	64MHz
Algorithm Processing Rate (Hz)	50
Controller Area Network (CAN)	SAE-J1939 compliant
Diagnostics	SAE J1939-DM1
	SAE J1939-DM2
	SAE J1939-DM3
Logging Characteristics	
Logger Processor Clock Speed	1GHz
Non-Volatile Memory	32GB
GPS Measurement Rate	1Hz
GPS Accuracy (m)	1.5 max
IMU Measurement Rate (3 axis)	100Hz
IMU Accelerometer Accuracy	1 mg
IMU Gyroscope Accuracy	0.05 ^{0}/s

Alpha Testing

Alpha testing was conducted at the VTTI Smart Road Test Track in Blacksburg, Virginia. VTTI and DCS jointly developed a test plan for simulating collision scenarios with pedestrians, "vulnerable road users" (VRUs), and forward collisions with vehicles.[47] For collision avoidance with VRUs, a simulated intersection was constructed to represent one that PT buses regularly traverse, as shown in Figure D-3. The simulated intersection included lane markings, stop

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[47] DCS Technologies, Inc., and VTTI, "FTA-Pierce Transit Collision Avoidance and Mitigation SRD Project Alpha Test Quicklook Report," March 18, 2019.

lines, a streetlight, a bus stop pad and shelter, a curb parking lane in which a vehicle could be parked to occlude the view of a pedestrian stepping from the curb, and a crosswalk equipped with a computer-controlled belt that could propel a VRU manikin across the crosswalk at walking or running speed.

Figure D-3 shows a drone view and graphical overlay of the test track intersection. The figure shows buses at the three approaches used during testing. A straight approach was applied in the second lane of the six-lane configuration for testing interactions with the VRU on the crosswalk, in addition to tests near the bus stop and parked vehicle for obscuration of a VRU in the crosswalk. Left square and round turns were applied as illustrated in the upper–right corner of the figure. Right turns were applied as illustrated in the upper–left corner of the figure. The VRU path is illustrated as a red dotted line on the crosswalk. Forward collision testing was performed on a high-speed section of the Virginia Smart Road facility.

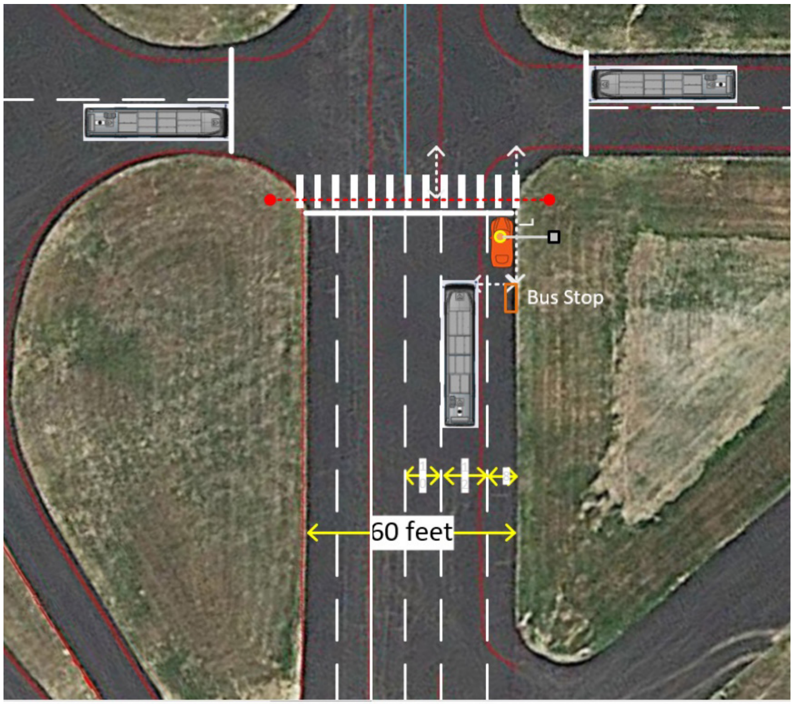

Figure D-3 *Drone view and graphical overlay of bus approaches on test track intersection*

Source: VTTI

Figure D-4 shows a forward collision test using a towed inflatable dummy vehicle. This figure shows the tests performed on the Highway Section of the Virginia Smart Roads to characterize PASS interactions with vehicles in braking scenarios. Figure D-5 shows the bus braking automatically for a VRU at the simulated intersection during a test. The figure shows the test track crosswalk, VRU belt, VRU manikin, and instrumented bus. Markers were placed on the bumper to represent the 0%, 25%, 50%, 75%, and 100% width of the bus. These markings were used to verify roadway and software integrated bumper contact points for the VRU manikin test interactions during straight and left/right turn bus approaches.

Figure D-4 *Forward collision avoidance test*

Photo credit: J Lutin

Figure D-5 *VRU collision avoidance test*

Source: VTTI

Alpha testing consisted of two four-day test sessions at the VTTI Smart Road facility. PT Bus #230, a 40-ft/12.2-m Low Floor (LF) manufactured by New Flyer, was equipped with DCS PASS and Data-Logger units. The test protocol included approximately 150 tailored vehicle-VRU and vehicle-vehicle test scenarios, resulting in approximately 550 test runs. Scenarios were based on the European New Car Assessment Program (NCAP) and SAE J3029 protocols. At the time this testing was performed, Euro-NCAP was used since no comparable US protocol was available for testing collision avoidance for vehicles and VRUs. Test scenarios included day and night, static and dynamic VRU, and rain/fog conditions.

The two test sessions allowed for hardware and software integration and tuning. Additionally, raw sensor data and vehicle telematics were produced for each of the 550 test runs. These data served as a “control” stimulus for offline software-in-the loop (SWIL) PASS tuning and regression testing throughout the project. An informal survey of VTTI and DCS test personnel at the completion of each test day during Session 2 found PASS performance “acceptable” at the “fine-tuning” phase.

Initial PASS calibrations (AEB activation threshold as a function of distance, velocity, and acceleration), at the beginning of Alpha testing, assumed a 0.2-g vehicle deceleration rate during PASS AEB deceleration. A lower actual vehicle deceleration rate of 0.11 g for bus #230 resulted in late PASS activations and driver panic stops. The PASS AEB deceleration rate calibration value was adjusted to match the measured results. Subsequent testing showed improved PASS-driver activation and stopping performance.

PASS performance throughout the Alpha testing showed a high sensitivity to ground noise. The VTTI Smart Road facility utilized raised reflective tape for lane and road markings. The high sensitivity resulted in incidents of false positive (FP) CAWS/AEB triggers. DCS reduced the number of ground noise FPs by adjusting the sensor assembly mounting and CAWS algorithm. At the completion of the Alpha testing, DCS concluded that further ground noise mitigation was required before commencement of the revenue test phase.

The Alpha testing served as a PASS characterization test and a PASS-vehicle-VTTI integration test. Alpha test trials were chosen to exercise the CAWS and AEB systems in real-world scenarios. Integration testing consisted of vetting of the hardware installation procedures, vehicle electrical and mechanical interfaces, and vehicle platform specific response. Additionally, integration with research partner system interfaces and communication was implemented.

During the period of November 5, 2020, to July 31, 2021 (after the final PASS software update), 4,607 log files were collected over 930,091 operational miles from the 30 project vehicles. Table D-5 summarizes high-level fleet metrics (total PASS warning events, estimated bus operating hours or uptime, and warning events per hour) and warning event metrics on a per bus basis for the nine-month period.

Table D-5 *Summary PASS Data Metrics, November 5, 2020–July 31, 2021*

	PASS Warning Events	Bus Uptime (est. hours)	Events/Hour
Fleet Totals	42343	34001.5	1.2
Per-bus Metrics			
Average/Day	9.2	7.4	1.5
Minimum/Day	0.0	0.5	0.0
Maximum/Day	75.0	23.1	18.0

Preliminary decomposition of the full data set is shown in the following graphs. Data measured at the instant of a PASS warning event provided some insight into vehicle operating conditions and operator behavior. During the data collection period, PASS operated in data collection mode only. PASS event signals were logged and sent to the server via telematics. No warnings were provided to drivers, and no automatic deceleration or braking was applied. The following graphs illustrate manual operation of the bus solely by the driver.

Figure D-6 shows the VUT vehicle speed at the time of PASS events for all 30 PASS-equipped project buses. The histogram indicates the presence of two overlapping distributions at 15 mph and 25 mph mean vehicle speed. This may be due to speed limits on the operating routes. A review of the data showed an overall mean vehicle speed of 22.6 mph (36.4 kph), with 50% of measured events occurring between 15 mph and 28 mph (24 kph and 45 kph).

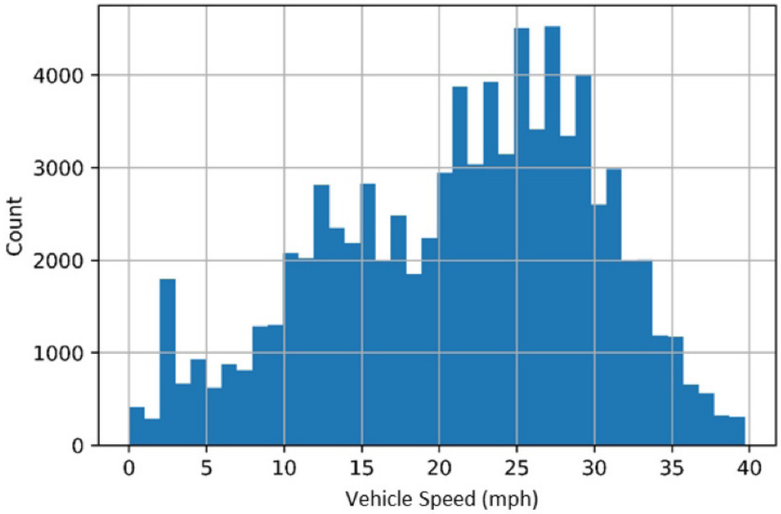

Figure D-6 *Bus speeds at time of PASS warning events*

Figure D-7 shows the VUT throttle% at the time of PASS warning events for all project buses. The histogram shows two peaks at 0% and 100%. The 100% spike may indicate events that occur near bus starts or launches, e.g., stoplights or bus stops. The 0% spike may indicate an aware driver slowing down or stopping under normal operating conditions or perhaps avoiding a dangerous situation.

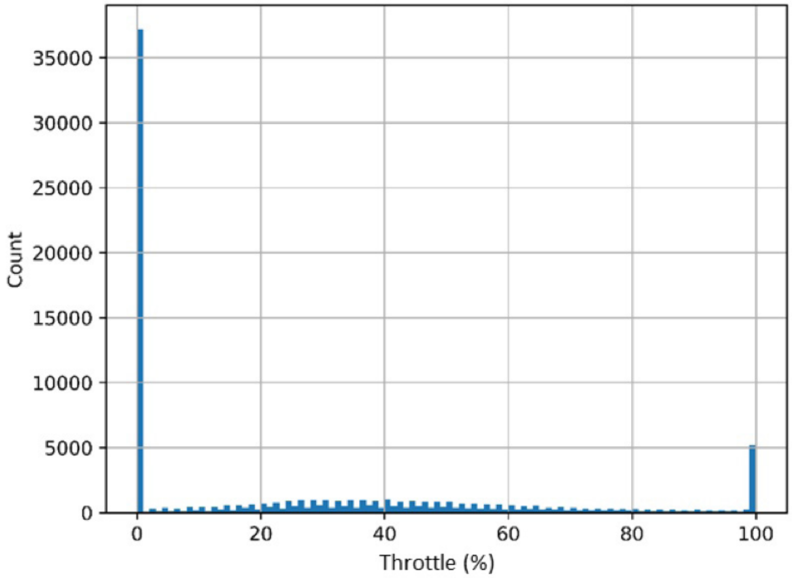

Figure D-7 *Bus throttle percent at time of PASS warning events*

Figure D-8 shows the VUT brake switch at the time of PASS warning events for all project buses. The brake switch signal was a binary (off/on) signal. There was no indication available for percent brake application. Figure D-8 shows that the operator was applying the brake at the time of the PASS warning event during approximately one-third of the PASS events.

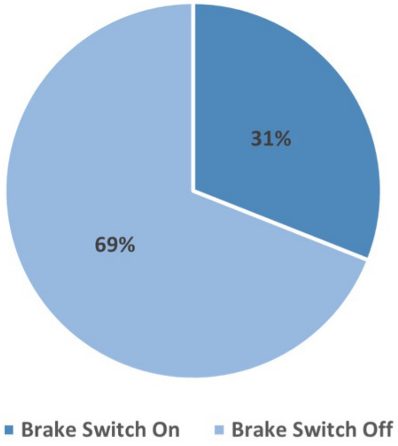

Figure D-8 *Bus brake switch at time of PASS warning events*

Figure D-9 shows VUT forward deceleration at the time of PASS warning events for all project buses. Negative values indicate deceleration. The graph appears to show a higher incidence in distribution for values beyond -0.1 g. It is reasonable to associate these data with brake switch applied events.

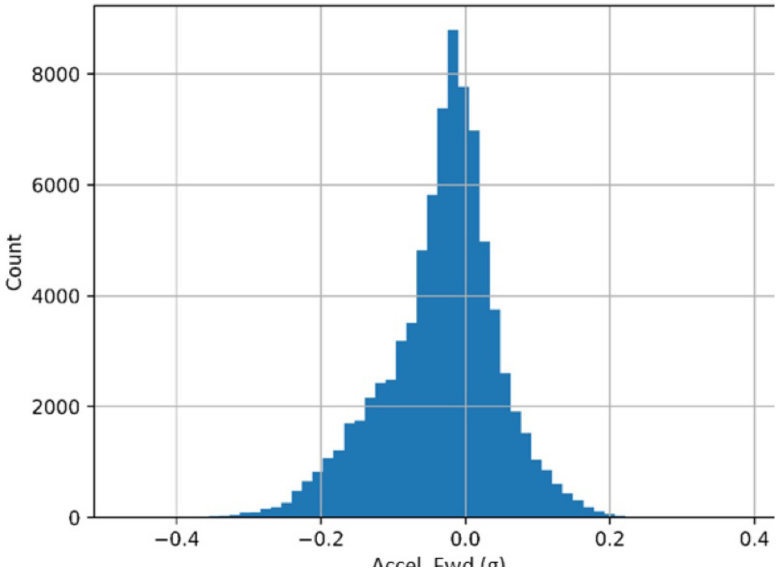

Figure D-9 *Forward deceleration at time of PASS warning events*

Figure D-10 shows the VUT gyro z-axis data (turning maneuvers) at the time of PASS warning events for all project buses. The gyro Z-axis (deg/sec) is shown to provide additional insight into operator/bus maneuvers at the time of the PASS warning event.

Figure D-10 also shows that a greater number of PASS warning events occurred during a left-turn maneuver. Negative (-) deg/sec indicates right turn and (+) indicates left turn. These data can later be evaluated with respect to VUT location data (GPS lat/long) and route data for further study of traffic and or location dependencies.

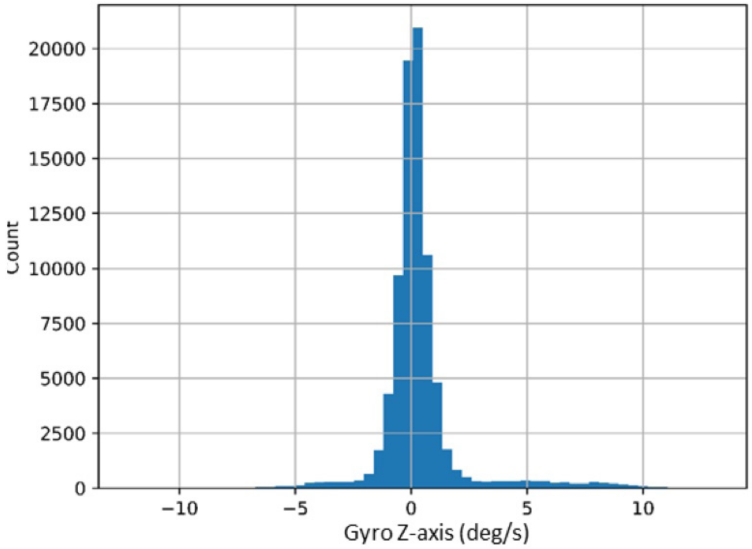

Figure D-10 *Bus VUT turning (Gyro-Z) at time of PASS warning events*

PASS activations should be expected during normal operating conditions. As previously mentioned, the PASS must initially assume an unaware operator and associated reaction time. The PASS algorithm is tuned to maximize safety while minimizing negative impacts to the operator and transit agency operations. The PASS data metrics captured in Table D-5 show an average of 1.2 PASS warning events per bus operation, or one to two events per day. Further analysis of the data in figures 12–15 along with video are necessary to better quantify overall PASS performance.

PASS Functionality and Reliability

In June 2019, buses 230–233 received pre-production PASS units for early PASS system performance evaluation and partner integration testing. PASS systems were installed on 30 New Flyer Low Floor (LF) buses, starting from the initial Alpha system on bus 230 in March 2019 to full fleet installation of production units completed in September 2020. Buses 230–233 then received production upgrades during the full fleet installation phase, completed in September 2020. A PASS software update to address controller area network (CAN) message structure communication to partner systems was distributed to the entire fleet in November 2020. Official data collection for all PASS-equipped buses commenced later that month and continued through July 2021. In April 2020, the PASS logger system received a software update to accommodate a DCS backend server connectivity update. This software update did not affect the collection of PASS system data nor any partner interfaces.

All PASS maintenance items were tracked throughout the project. Table D-6 documents any item that required replacement because of component failure or physical damage. Physical damage included events such as traffic accidents or unavoidable environmental factors (e.g., rock strikes). Out of the nine items listed in Table D-6, five fall into the category of component failure. Three of the component failures were due to logger computer failures traced to original manufacturer defects. The remaining two component failures were lidar sensor failures due to PASS manufacturing defects that allowed moisture into the sensor enclosure.

The PASS was designed and tested to meet a minimum 100,000 miles mean distance between failure (MDBF). The total test fleet vehicle mileage for PASS production equipment was approximately 1 million miles. With the five component failures during the project timeframe, the MDBF calculated to 200,000 miles.

Figure D-6 *PASS Maintenance Events Summary*

Date	Veh #	Item	Description/Cause
October 2020	230	Sensor assembly	Damaged in traffic accident
November 2020	229	System enclosure	Logger computer failure
November 2020	239	System enclosure	Logger computer failure
February 2021	245	Receiver lens	Sensor receiver lens shattered
April 2021	230	Sensor enclosure	Sensor enclosure seal failure
April 2021	231	Sensor enclosure	Sensor enclosure seal failure
April 2021	239	System enclosure	Logger computer failure
July 2021	250	Sensor assembly	Damaged in traffic accident
Unknown*	238	Emitter lens	Sensor Emitter Lens Shattered

*System functional with no indication of failure date through examination of telematics data.

Appendix E

Using CAWS/AEB Data for Hot Spot Mapping

Hot Spot Mapping

The research team developed a method for event hot spot mapping and analysis, shown in Figure E-1. The method has four steps:

- Step 1 – Integrate the collision avoidance system's event data and telematics data; in this case, the two data sources are PASS data and Swiftly data. Event latitudes, longitudes, and route information for the buses are extracted. Then, events are mapped to the bus routes with geographic information system (GIS) functions.
- Step 2 – Apply a density-based clustering algorithm (DBSCAN) that does not require a pre-defined number of clusters to group events on every route and identify clusters. Road information is used to determine the road segment boundary for each high-risk cluster.
- Step 3 – In a parallel task to step 2, apply DBSCAN to spatial clustering for high-risk regions rather than individual road segments.
- Step 4 (optional) – Leverage existing data (e.g., crash, traffic volume, population) to identify high-risk road segments and regions for further validation and exploration.

The proposed method, once implemented, is expected to be beneficial to transit agencies: On the one hand, the method identifies transit-related, high-risk road segments and locations, thereby providing guidance for the design of new safety improvement measures. On the other hand, transit buses have rich data, but those data often come from different sources with barriers for data fusion. This section consists of a data mining and fusion approach for integrating multi-source transit data, which can be applied to hot spot mapping as well as other application scenarios.

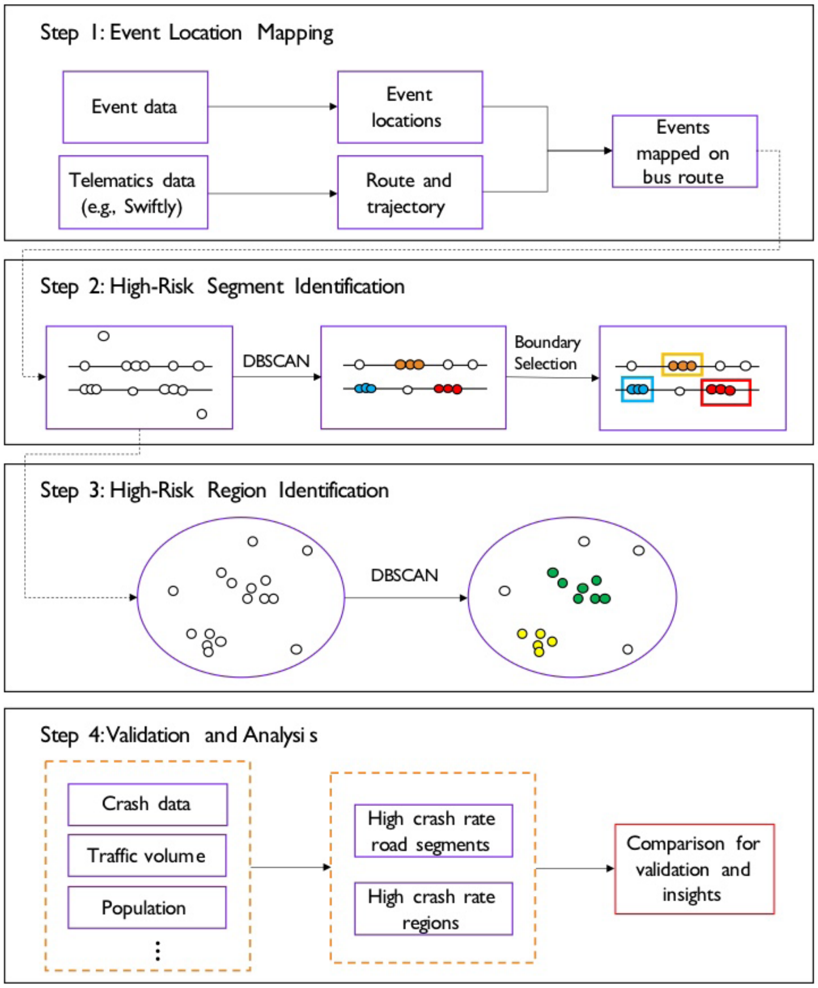

Figure E-1 *Proposed method for crash risk hot spot mapping*

Source: R. Ke

Because of the high share of false positives (FPs) from the system being evaluated (>90%), the research team did not apply the proposed hot spot mapping method to the event data collected to avoid producing possibly misleading findings. Instead, the Transit Event Logging System (TELS) hot spots shown in Figure E-2 are sample point clouds of pedestrian and vehicular events captured from the data logger installed on PT bus 233 during the project.

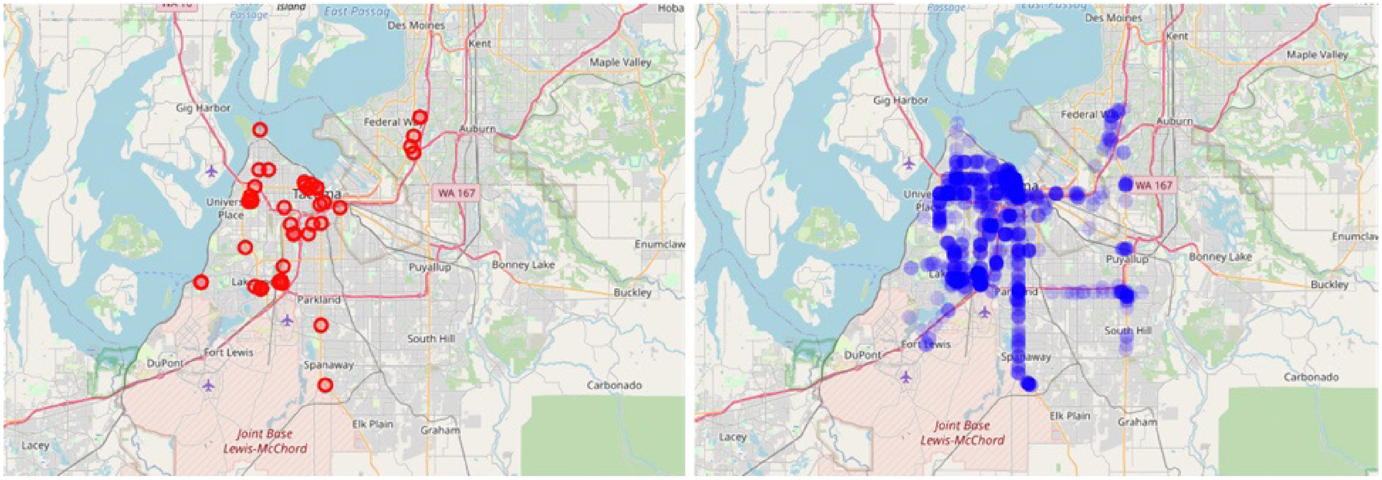

Figure E-2 *Pedestrian (red dots) and vehicular (blue dots) CAWS event point clouds from Bus 233 data logger*

Source: UW

Appendix F

Evaluating the Accuracy of Transit Bus Collision Avoidance Warning Systems

Research Objectives

The primary research objectives of the UW Smart Transportation Applications and Research (STAR) Lab were data collection and evaluation of the collision avoidance warning system (CAWS) technology used in conjunction with automated emergency braking (AEB) for transit buses. The following primary research tasks were conducted:

- Develop a computer-vision based transit event logging system (TELS) for recording and detecting near-miss events (including those with both pedestrians/bikes and vehicles) and install TELS and smart data hubs on four buses.
- Design and implement independent methods and tools based on the selected single board computer, real-time telematics, and lidar sensor data to detect false positives (FPs) and false negatives (FNs).
- Build a smart data hub for efficient data downloading, storage, and analysis of large amounts of video and telematics data for CAWS and Pedestrian Avoidance Safety System (PASS) evaluation. Collect and transmit the telematics data using Pierce Transit's (PT's) existing service channel to the data server. Create a database of incidences of FPs and FNs by route and vehicle.
- Design and implement a data communication protocol with DCS to collect DCS devices' event data for the on-board Smart Data Hub from 30 PASS-equipped buses.
- Develop a methodology for geo-locating and mapping high-risk areas.

Transit Event Logging System (TELS)

The TELS is a system mounted on buses that receives forward facing video camera imagery, detects potential collisions, fuses video with other data, and transmits fused event data to a cloud server.

Real-time video for on-board near crash detection was obtained from existing forward-looking Apollo cameras installed on four project buses. The Apollo system is an Internet Protocol (IP) camera system for on-board bus surveillance and video recording. Providing real-time video feed required Apollo software reconfiguration to the Real-Time Streaming Protocol (RTSP).

The Apollo camera feed was converted through the Apollo high-definition recorder to readable signals sent to the Nvidia Jetson boards via Internet cable. To read and integrate the camera feed into the code on the Jetson, the OpenCV video capture function was used to read the RTSP link. Because there was only one ethernet port on the Jetson, they could not connect to two ethernet cables with different functions. This was addressed by configuring an internet switch to allow the Jetson device to access both the Internet and Apollo camera feed at the same time without conflict.

TELS Edge Computing System Architecture

The UW selected the Nvidia Jetson TX2, which was one of the most advanced edge computers for robotics, computer vision, and deep learning applications available at the time. The Nvidia Jetson incorporated the TensorRT software development kit for high-performance deep learning inference. It included a deep learning inference optimizer and run time that delivered low latency and high throughput for deep learning inference applications. The TensorRT optimized deep neural networks on Nvidia devices and allowed standard deep learning models for object detection to be quantized and run in real time on the Jetson TX2, enabling real-time, on-board video processing, data fusion, and data abstraction.

The TELS system architecture on the edge computing platform is shown in Figure F-1. The two major functions of the system were near-crash detection and data collection. Given the real-time operation requirement for both functions, the design needed to be simple enough to be highly efficient and sophisticated enough to use the Nvidia Jetson's computational power for greater accuracy and reliability. The near-crash detection method also was insensitive to camera parameters to accommodate large-scale deployments.

The TELS system was implemented in a multi-thread manner. Four different threads operated simultaneously: 1) the main thread, 2) a data transmission thread, 3) a video frame reading thread, and 4) the controller area network (CAN) thread. The proposed near-crash detection method was implemented in the main thread. When near-crash events were detected, a trigger was sent to the data transmission thread, which recorded and transmitted video frames from a queue (a global variable) and other data associated with the near-crash event to the project server. The third thread for video frame reading kept the latest video frame captured from the camera in another queue and dumped previous frames when the capturing speed was faster than the main thread's frame processing speed. The CAN thread provided additional information for each near-crash event, including vehicle-under-test (VUT) speed, throttle%, brake application state, and acceleration/deceleration rate.

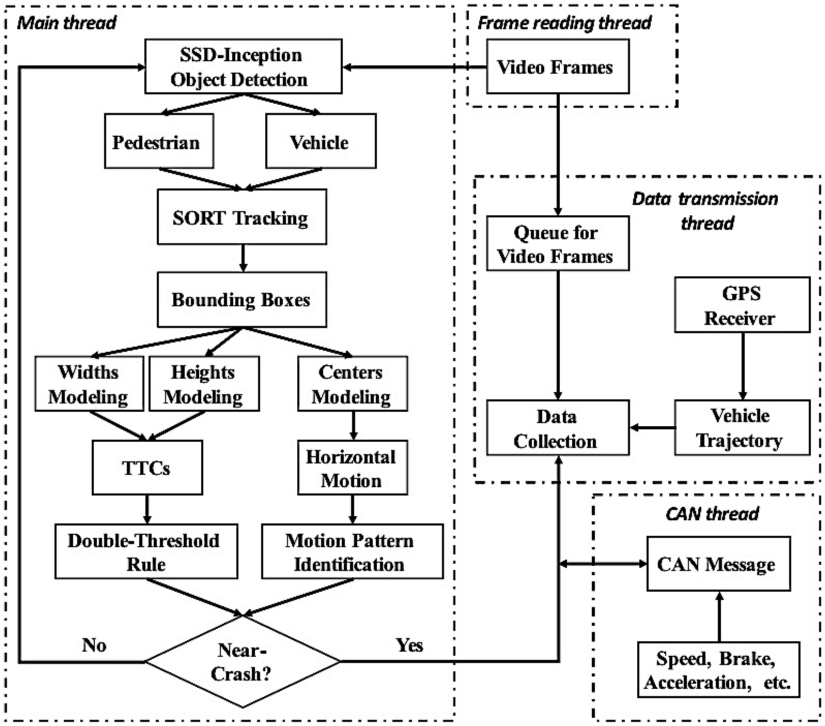

Figure F-1 *TELS system architecture for edge computing on bus*

The architecture provided low system latency. The frame reading thread ensured that the main thread read the latest frame captured by the camera by not accumulating frames. The data transmission thread was designed as an individual thread to handle data transmission so that the main thread operation was not affected by network bandwidth. The CAN thread was for additional information collection. It was separated as an individual thread to allow for extension of TELS functionality and communications with other vehicle systems via the CAN without affecting the performance of the other threads used for the TELS.

Real-Time Camera-Parameter-Free Near-Crash Detection Algorithm

Deep-Learning-Based Road User Detection and Tracking

The main thread started with applying a deep-learning-based object detector to every video frame. Deep-learning-based object detection could simultaneously localize and classify objects with high accuracy. However, deep-learning-based inference required high-power computing, which could limit its deployment for certain applications. The Nvidia Jetson TX2 ran deep object detectors in real time with TensorRT-optimized inference neural networks. Single Shot

Detector (SSD)-Inception, a real-time detector on the Jetson TX2 with a nearly 30 frames-per-second (FPS) speed, was chosen for object detection. Object detection created bounding boxes and identified the types of road users that were within the pre-defined region of interest in each video frame. (Bounding boxes around a pedestrian and a vehicle are shown in Figure F-4.)

Relative Motion Patterns in Camera for Near-Crashes

Relative motion between a VUT and other road users can provide cues for near-crash detection using a single camera. Relative motion patterns between two road users vary from case to case. Roadway geometry, road user behavior, relative position, and traffic scenarios are all factors that may affect relative motion patterns. For example, from the VUT perspective, its motion relative to a vehicle it is overtaking in a neighboring lane differs from its relative motion to a vehicle it is overtaking in the same lane.

Relative motion that has the potential to develop into a crash/near-crash is characterized from the VUT's perspective as the target road user moving toward it. Figure F-2 shows the top view of the relative motions. Two vehicles and one pedestrian are given as examples. For each of the three road users, a solid red arrow shows the motion toward the VUT, a dotted yellow arrow shows motion that could result in conflict, and a green dotted arrow shows motion away from the line of sight. Figure F-2 shows this kind of relative motion as motion vectors of target road users, depicted as solid red arrows moving vertically toward the bottom of the camera view. In the real-world top view, shown in Figure F-2, the three solid red arrows represent the relative motions among the VUT and each of three road users (a pick-up truck, a car, and a pedestrian). Each of the three camera sight lines aligns with a relative motion vector (Z2, Z4, and Z7). In the camera view, the lines of sight are shown as vertical bands. The relative motion vectors for near-crashes in the top view correspond to vectors moving toward the bottom in the camera view aligning with Z2, Z4, and Z7.

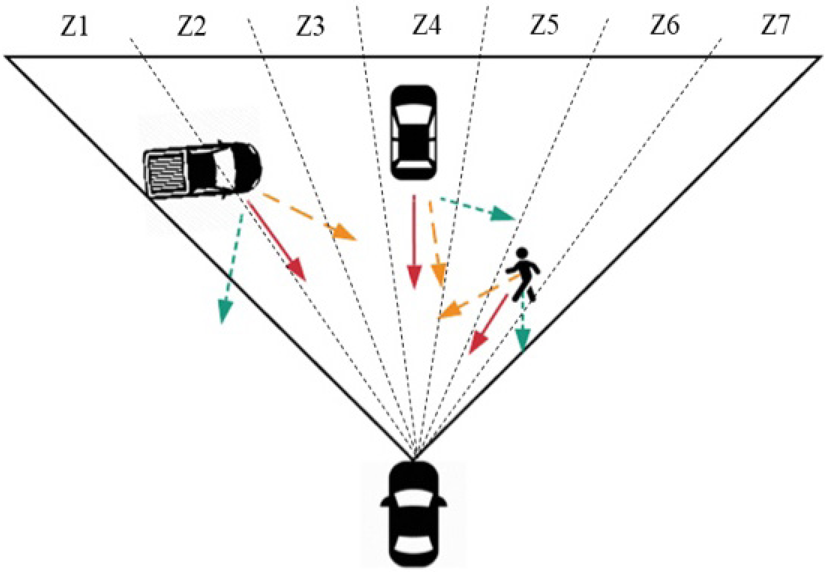

Figure F-2 *Top view – relative motions, locations, and lines of sight to three target road users*

Source: R. Ke

Two road users may have relative motion at any time. A target road user may move toward the VUT, move away from the VUT, or stay at the same distance from the VUT. These changes in road user position can be identified as object image size changes in the camera, which is the basis for our approach. Image size decreasing or remaining the same would not indicate a potential crash or near-crash. Three classifications are used for image size increases, as shown in Figure F-3:

- Potential Crashes – shown as solid red arrows.
- Warning Cases – shown as dotted orange arrows, in which the relative motion is toward the center line of sight of the camera (the pick-up truck and the pedestrian), and relative motion, which is slightly different from the solid red arrow while the target road user is at the center line of sight (the car). These classifications could develop into crashes if there were slight changes in speeds or headings of either the target or the VUT,
- Safety Cases – in which object images are moving away from the center line of sight, shown as dotted green arrows.

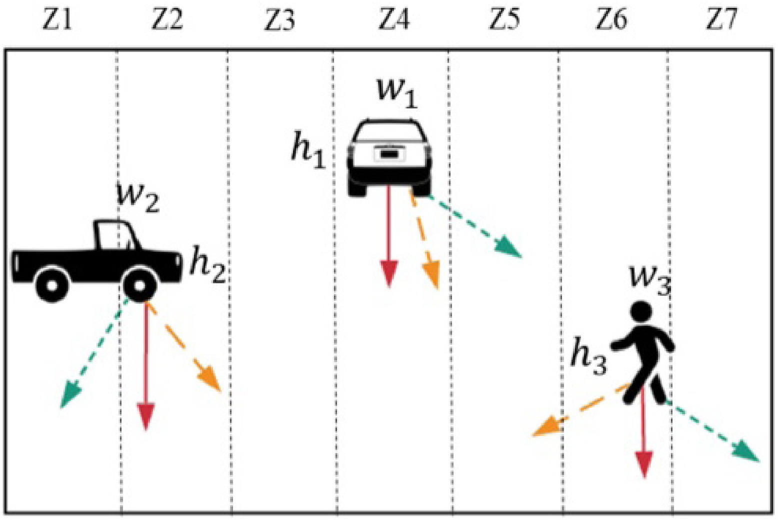

Figure F-3 *Camera view – relative motions, locations, and lines of sight to three target road users*

Source: R. Ke

Object tracking follows object detection and associates the information from each frame to determine each road user's movement by using the Simple Online and Real-Time Tracking (SORT) algorithm. SORT is a recent benchmark for object tracking online and in real time performance. It achieves good tracking accuracy without the need for complicated features, and it only uses bounding box information. It also can eliminate some FPs and FNs that are generated in the detection phase.

An object appears larger in the camera view as it approaches the camera, and smaller as distance from the camera increases. Mobileye researchers published a paper in 2004 to show that it was possible to determine time to collision (TTC) using image size changes. [48]

Modeling Bounding Boxes for Camera-Parameter-Free TTC Estimation

Bounding boxes approximate object size and are not used for accurate determinations. Figure F-4 shows green bounding boxes around a parked car and a pedestrian standing on the sidewalk. Size changes of an object in two consecutive frames may be subtle; and in many cases, size change is unobservable because of noise in bounding box generation. Inaccurate size change detection also results from short time durations between consecutive frames. At a video frame rate of 24 FPS, the next frame is captured in less than

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[48] E. Dagan, E., O. Mano, G. P. Stein, and A. Shashua, "Forward Collision Warning with A Single Camera," *IEEE Intell. Veh. Symp. Proc.*, 2004, 37-42.

0.05 seconds. For size change detection we use more frames to compensate for the noise in each frame and increase the time interval for the detection. Linear regression is used to estimate bounding box heights or widths over a group of consecutive frames. We found that 10 to 15 frames are enough to compensate for noise, and the time associated with 10 to 15 frames is still short enough (about 0.5 second) to assume that the road user's motion is consistent. Therefore, the input to the first linear regression is a list of heights or widths extracted from the bounding boxes, and the output by the regression will be the estimated TTC. Another linear regression takes the bounding boxes' centers and outputs the slope value as the estimated horizontal motion of the road users. TTCs and the slopes of horizontal motions jointly determine near-crash events.

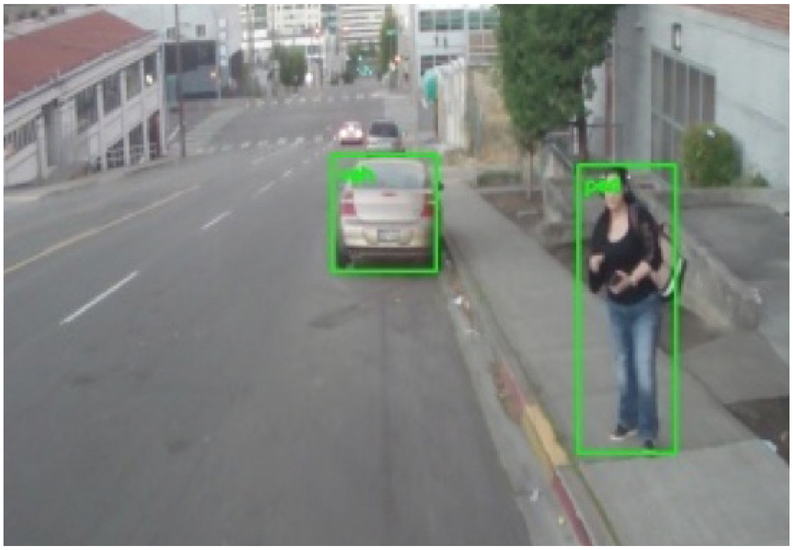


Figure F-4 *Bounding boxes around car and pedestrian*

Source: UW

A sample near-crash detection result is shown in Figure F-5, which is a vehicle-pedestrian near-crash. The bounding boxes turned red to indicate an identified near-crash, while another detected road user (a vehicle) had green bounding boxes.

Figure F-5 *Sample TELS detection of near-crash*

Source: UW

TELS Parameter Settings

Several key parameters needed to be appropriately set—SSD detector confidence threshold, the number of frames for size regression, the number of frames for center regression, TTC threshold δ, TTC threshold φ, horizontal motion threshold α, horizontal motion threshold β, and Jetson power mode. Given that the SSD detector tended to have fewer false positives than false negatives, some false-positives could be filtered out at the tracking step, and more false positives (if any) would be filtered out by the near-crash detection algorithm. We set the detection confidence threshold to be 0.3–0.5.

For the number of frames for size regression, we suggested setting them around 10–15 frames. This range was large enough to compensate for the bounding box noises and small enough to assume that the target's motion was consistent. The number of frames for center regression could be a little larger to capture the horizontal motion better, and the suggested number was in the range of 15–20. For δ and φ, as defined by many previous studies, the TTC threshold for a near-crash was around 2–3 seconds, which was our suggested value for δ. And we found that setting φ to about 2–2.5 times δ worked well. We suggested setting α to the range of [-1, -0.5] and β to [0.02, 0.1]. The Jetson power mode was recommended to be set as Max-N to use its computational power fully, although our system still operated in real time (but lower FPS) with Max-Q mode.

For operation of the TELS on the four PT buses 230–233, the thresholds were set to be much looser than the suggested thresholds. This was to ensure that we collected as many video clips as possible that might contain near-crash events of interest. But even with the loose settings, the video data reduction effect was still impressive. In comparison to collecting all raw videos, the total number of video clips that the four TELS collected was less than 3% with a rough estimation.

Data Collection

On-Board Data Communication

The TELS and PASS communicated on board via the CAN to collect event data for evaluation. When one system detected an event, it sent a pre-defined event code via the CAN to trigger other systems for joint data collection. Therefore, for every single event that previously could be captured by only one system, a comprehensive dataset for the event was recorded to enrich the event data.

The UW and DCS synchronized the event detection status transmission rate between PASS and the TELS at 10 Hz via the CAN. When all sensors were inactive, PASS and the TELS both periodically transmitted their status and identification codes to indicate they were awake. When a message associated with the PASS ID indicated an event, the TELS data transmission thread was triggered, and data (including video clips and other data) were collected and transmitted via the intra-bus network to the UW server to record the PASS event. PASS event codes contained warning indication, caution indication, and identification of which sensor(s) were active for a particular event.

Data Reception and Processing on the Server

Three types of data were collected at the UW project server:

1. Data and videos from the TELS on four buses in real time using the cellular network, which transmitted the data wirelessly from the bus to the server – The TELS was connected to the bus cellular network modem via cable connection to an intra-bus Ethernet network. Whenever a TELS event, PASS event, or a randomly sampled event was captured, the data transmission thread was triggered, and the data and video frames associated with the event were transmitted to the project server in real time. A global queue temporarily stored the immediate past video frames in memory. When triggered, the data transmission thread called the global queue and uploaded the frames to the cloud server. This design ensured that the video transmission took place in real time but did not interrupt the main thread operation.
2. Bus operation data from the Swiftly API – Swiftly is a platform that collects transit system data, including real-time bus locations for reporting and analysis. Swiftly data were collected every 5 seconds, creating 17,280 data files in the JSON format every day. The JSON files

were combined into one CSV file, ordered by bus ID and time, both in ascending order. The primary columns included bus ID, route ID, head sign, vehicle type, direction, latitude, longitude, time, bus speed, and bus heading. In addition, two data features were added to the file: one was the "distance" feature calculated from two consecutive GPS points, and another was the local Pacific Time Zone time converted from Unix time.

3. Event data containing PASS and TELS events – Data fusion and transmission were completed on board the bus in real time. Later, the data were shared from the DCS server to the project server at the UW via file transfer protocol (FTP) transmission. Event data included brake switch, throttle, accelerations (in X, Y, and Z directions), gyro, time/location, and sensor data recording objects tracked by the PASS lidar sensors. Each of the three PASS sensors could track up to eight different objects, which produced eight different column groups for each sensor consisting of object distance, object speed, and time-to-collision.

All data went through a quality control process to check completeness, consistency, orderliness, timeliness, and uniqueness. This process also included converting Swiftly data from raw JSON format files to one aggregated CSV file per day for each bus. After the data quality control and conversion, and missing and erroneous values had been filtered out, the data were in a much more user-friendly format. Each day 17,280 data files were converted to a single file with organized rows and columns. In this format, all JSON data were integrated into the database on the server.

The UW STAR Lab project server was a Dell PowerEdge R740XD server with high-end configuration. It ran during the project period to support six major tasks, including four programs for receiving video frames and data in real time from TELS devices on buses 230, 231, 232, and 233; a secure FTP server for receiving PASS data from the DCS server; and a program for Swiftly data collection. The server also supported multiple computation and visualization functions for data analysis.

The Microsoft SQL Server database and PostgreSQL database were installed on the UW STAR Lab project server. Raw event log data, processed data, and video frames data were stored on this server. The database structure is diagramed in Figure F-6. The research team utilized an MS SQL Server to store the metadata for the detected events, including attributes such as the event occurrence time, the GPS location, event type, and the system by which the event was detected. The original data uploaded by the TELS and PASS were in CSV format, as well as the converted Swiftly data. The uploaded CSV and Swiftly data were processed and formatted for further analysis. TELS videos were stored in folders ordered by bus number and date. Each video had a unique ID with the exact time of the event.

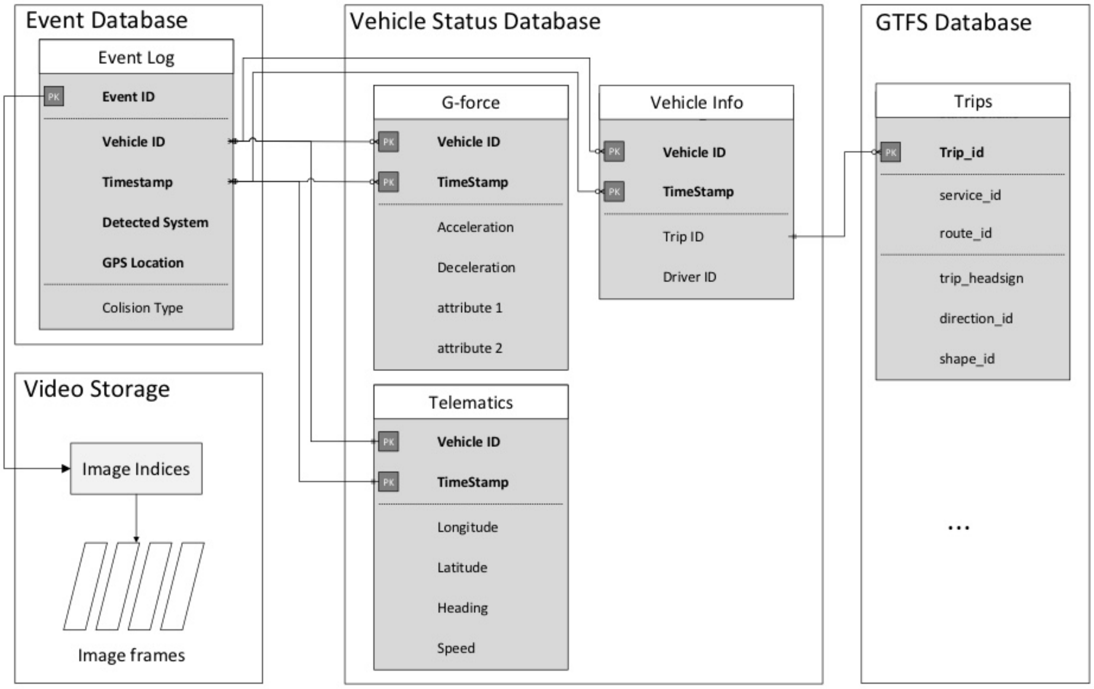


Figure F-6 *Design of databases and file systems for hosting project data*

Event Data Collection Summary

Monthly and project totals for data collected from each of the four TELS-equipped buses are summarized in Table F-1, including pedestrian warning events, vehicle warning events, randomly sampled events, total events, and video file sizes. The number of PASS data files collected in the UW server via FTP for all 30 project buses is shown in Table F-2.

Table F-1 *TELS Data Collection Summary for Buses 230, 231, 232, and 233, 8/25/20–7/31/21*

Veh #	Pedestrian events	Vehicle events	Random events	Total events	Video (GB)
230*	156	1619	5499	7274	44.39
231**	157	2547	6440	9174	55.74
232	273	3632	10477	14382	86.96
233***	205	3572	9793	13596	79.89
Total	791	11370	32209	44426	266.98

*Bus #230 data collection interruptions: 2/5–28/21 due to Arduino board malfunction; 3/1–10/21 and 3/22–31/21 due to Arduino board malfunction; 4/1–12/21 and 4/16–28/21 due to Arduino board malfunction

**Bus #231 data collection interruptions: 2/10–28/21 due to Apollo camera feed interruption; 3/1–31/21 due to Apollo camera feed interruption; 4/1–28/21 due to Apollo camera feed interruption

***Bus #233 Data collection interruptions: 3/6–31/21 due to loose connection to on-board power supply; 4/1–30/21 due to loose connection to on-board power supply

Table F-2 *PASS Data Files Received at UW Project Server*

Veh #	Files	Veh #	Files	Veh #	Files
221	1	231	233	241	47
222	124	232	199	242	153
223	2	233	238	243	166
224	133	234	152	244	245
225	127	235	146	245	206
226	216	236	240	246	213
227	178	237	123	247	245
228	223	238	223	248	193
229	227	239	136	249	169
230	216	240	207	250	93
Total files for 30 buses = 5,074					

Four databases were designed for hosting the project data (as shown in Figure F-6). First, the event database contained an event log with event ID, vehicle ID, timestamp, detected system, GPS location, and collision type. Second, the vehicle status database contained g-force data, vehicle information, and telematics data; vehicle ID and timestamp was included for all three types of data in the vehicle status database. Third, the General Transit Feed Specification (GTFS) database contained bus trip information. Fourth, the video storage database stored video image indices and image frames.

FP and FN Analysis

FP Identification Method and Summary Statistics

An FP was a PASS recorded event in which a warning signal was transmitted, but on later inspection, the associated data did not indicate the presence of a collision path trajectory between the VUT and a detected object. A suspected FP would be initially extracted when a PASS event trigger was received by the TELS and the vehicle speed was found to be greater than zero. The TELS then determined whether the tracked object's trajectory was projected to be within the VUT's path of travel. If the TELS showed that the object was not within the VUT's path of travel during the recorded period, then the TELS would indicate that no conflict existed, and the event was classified as an FP.

If the VUT speed was greater than zero, then its acceleration/deceleration was examined to determine whether there were high g moments during the event. If a high g event occurred, one more step was to determine a theoretical deceleration value by using distance to the object and relative speed. If the TELS estimated that the bus could decelerate at a value below a 0.3-g threshold and still avoid the conflict, then hard braking behavior would not have been necessary, and the event was considered to be a FP as well. Final verification was conducted by using event video clips collected by the TELS.

Figure F-7 shows that the FP identification pipeline started with determining whether vehicle speed was greater than 0 at event code 16, which was the PASS event warning signal. If yes, it checked whether an object was projected to be within the path of travel at event code 16. If yes, it checked whether the bus was turning or accelerating dangerously. If yes, it checked whether the driver could have decelerated at a lower g level and still avoided a collision. If no to any of the judgments above, then the event would be an FP

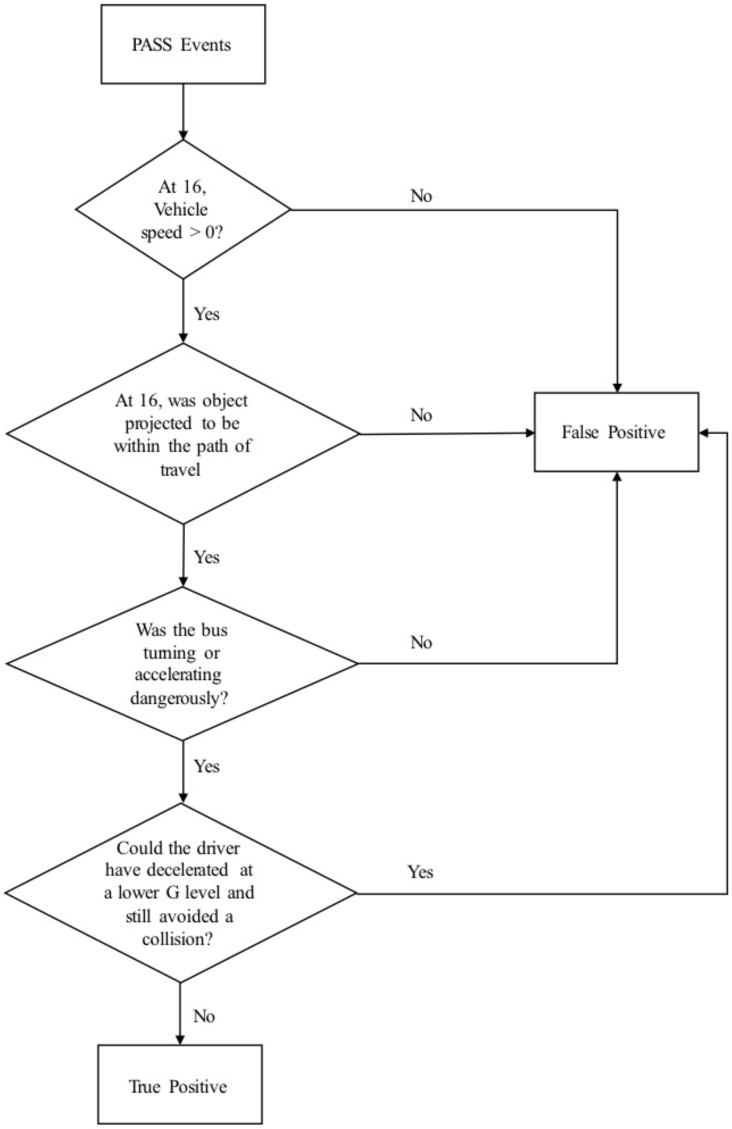


Figure F-7 *FP identification pipeline*

FP Examples

Several representative examples of FPs are presented, showing typical patterns.

Example #1

The PASS event shown in Figure F-8 was a forward collision warning at 16:37:57 on May 7, 2021, on bus 230. PASS was triggered by a red pick-up truck in front of the bus. Acceleration values indicated there was not a dangerous situation. The highest deceleration value was 0.185 g (below the 0.3-g threshold) during the event window, so it was classified as an FP.

Figure F-8 *FP example #1 – Deceleration rate below threshold*

Source: UW

Example #2

This example, as shown in Figure F-9, occurred on a snowy day at 09:53:49 PST on February 13, 2021, on bus 232. The bus was starting off at an intersection and turning left. PASS triggered a warning, and after verification with the video and detailed PASS data, no road users or objects were observed. The brake switch was off, and the throttle was on. Detailed data indicated that the trajectory of the tracked object was abnormal, and the “object” stayed very close (within 120 cm) to the bus during the event. No object of conflict was observed in the entire video clip. The object’s relative position to the bus was [-20 cm, 40 cm], and the TTC was less than 1 second. We did not observe this pattern of FP on non-snowy days. A possible cause of this FP was that the lidar was triggered by snow in front of the sensor (e.g., snow on the bike rack).

Figure F-9 *FP example #2 – Unique FP on snowy day*

Source: UW

Example #3

Another pattern of FPs was found in the evaluation: PASS was sensitive to traffic drums and traffic cones. Figure F-10 shows an example of this FP pattern. The cause was that traffic drums/cones had reflective surfaces, so they could trigger a warning based on lidar sensitivity to reflected light.

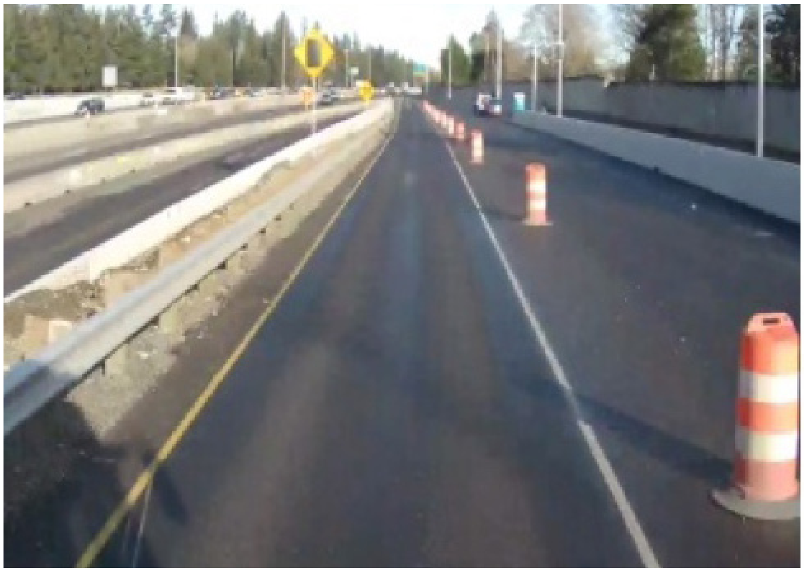


Figure F-10 *FP example #3 – FPs triggered by traffic drums or cones*

Source: UW

FP Summary Statistics

For each of the four buses equipped with the TELS, three months of data (5/1/2021–7/31/2021) collected after the final project PASS update were used for evaluation. Results are shown in Table F-3. The overall share of PASS events that were FPs was 93.5%. Nearly 60% of the FP events were attributed to finding no actual high g event, and nearly 40% of FPs were attributed to the object not being on the path of travel of the VUT. A few (less than 3%) FPs were attributed to the potential for the VUT to decelerate at a rate below 0.3 g. In nearly 60% of the FP events, objects were detected as having potential conflicts with the VUT, although in some cases the objects did not pose a risk to the bus. (e.g., snow on the bike rack). None of the PASS or TELS incidents logged was associated with an actual vehicular or pedestrian collision.

Table F-3 *Summary Using PASS Events, May–July 2021*

Vehicle #	PASS Events	FPs	Share of FP
Bus 230	445	417	93.7%
Bus 231	669	603	90.1%
Bus 232	582	553	95.0%
Bus 233	785	747	95.2%
Total	2,481	2,320	93.5%

False Negative Identification Method

An FN is an event that does not trigger a PASS signal when 1) an object is within the path of travel or 2) a high g moment is observed. The total number of events included PASS events, TELS events, and randomly sampled events. Note that the random events were qualitatively evaluated by using the TELS videos. The FN detection pipeline is shown in Figure F-11. The pipeline started with searching for event code 241 or 242, which were events generated by the TELS. These events were filtered by using TTC and horizontal motion as threshold criteria. Tracked trajectories of objects were then used to determine whether the object was projected to be within the vehicle's path for every data point within that event window. High g events were identified by using g values in the X and Y directions. A high g event was identified when the vector addition of the two g values appeared to exceed the 0.3-g threshold. Tracked trajectories of objects were then used to determine whether the object was projected to be within the vehicle's path at 85 cm for any data point within that event window. The 85-cm threshold accounted for the length of the bike rack.

Z-axis acceleration was not used in the vector addition of g value calculation because:

- It was constant most of the time (around 1 g) and did not contribute to the deceleration/ acceleration parallel to the ground (X-Y plane).
- The small change in Z direction was not always identifiable as an actual Z-axis value change or a measurement error.
- The data provided did not contain roadway geometry (e.g., slope) information for accurate integration of Z-axis acceleration.

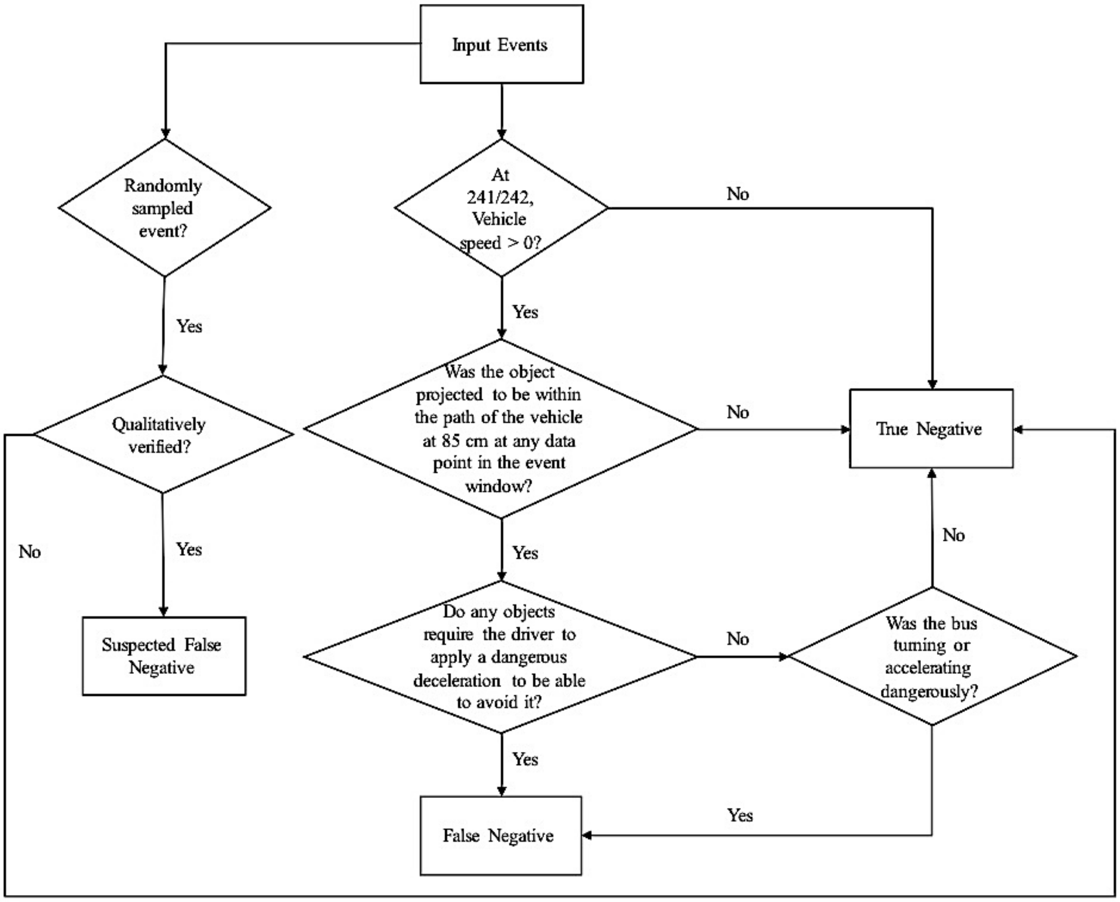


Figure F-11 *FN identification pipeline*

False Negative Examples

Several representative examples of FNs are presented. Detailed parameters, such as bus speed, TTC, and deceleration are available for each event. Given the space constraint, one video frame and one type of parameter are displayed for one event.

Example #1

This event occurred on bus 233 at 10:09:04 AM on May 31, 2021, as shown in Figure F-12. The bus was approaching an intersection when a pedestrian was crossing the street. The relative movement between the pedestrian and the bus posed a conflict with the path of the bus, and the maximum deceleration rate of the bus was over 0.3 g during the event window. The TTC value was about 2 seconds. PASS did track this pedestrian but did not issue a warning.

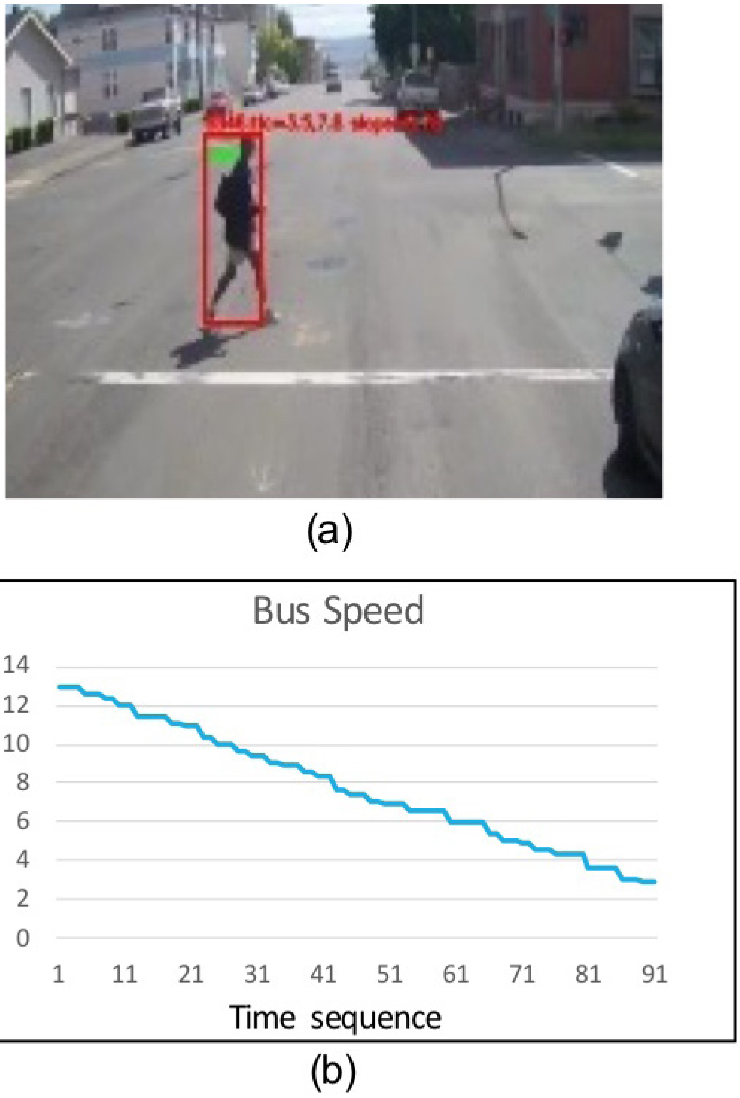
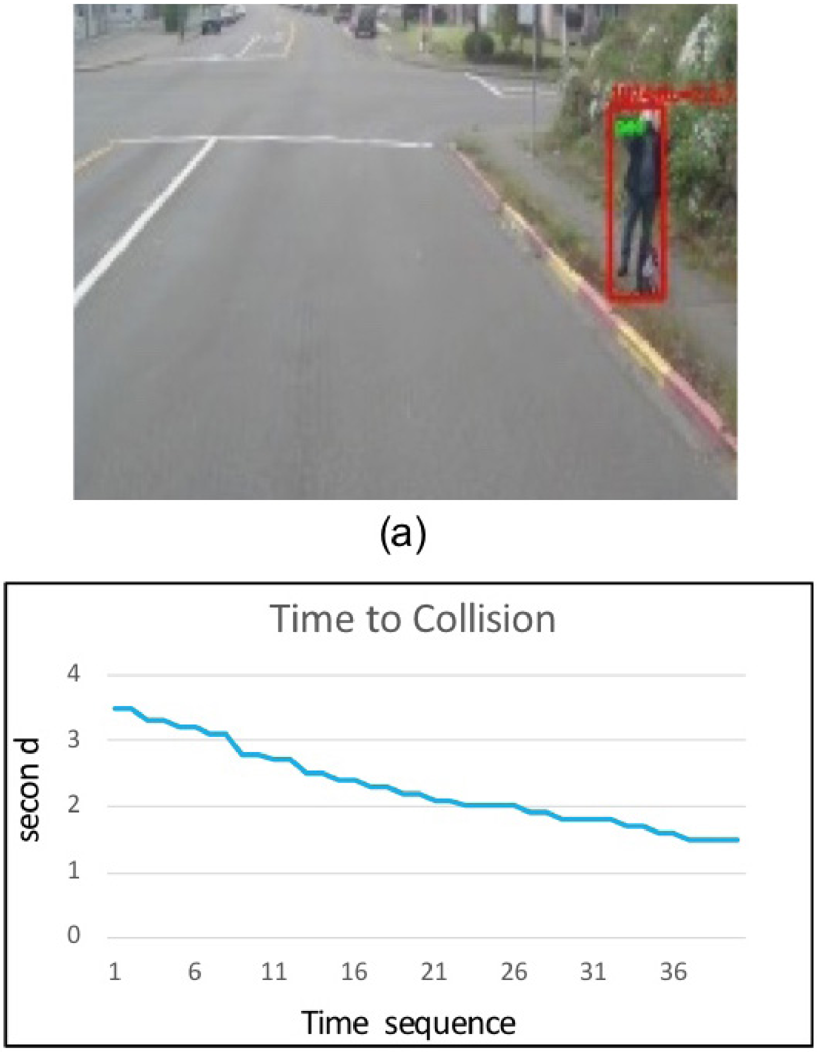


Figure F-12 *False negative example #1 – Missed conflict event with pedestrian crossing street*

Source: UW

Example #2

This event, shown in Figure F-13, occurred when bus 230 was approaching a bus stop at 8:02:30 AM on May 1, 2021. A person, shown with a red bounding box, was waiting at the sidewalk. PASS did not generate a warning. The trajectory showed that there was a conflict between the pedestrian and the front face of the bus. The bus was decelerating over 0.3 g within the event window and could not decelerate at a lower g to avoid collision. The TTC also kept decreasing and reached 1.4 seconds. At the conflict data point, the path of the bus would bring it over the curb. According to the proposed pipeline, this event was classified as an FN.



(a)

(b)

Figure F-13 *FN example #2 – Missed conflict event with pedestrian at bus stop*

Source: UW

Example #3

This representative FN event occurred at 6:02:31 AM on July 28, 2021, on bus 230, as shown in Figure F-14. The deceleration rate in this event was constantly greater than 0.3 g the entire time, which indicated very hard braking. The TTC was 1.8 seconds, and the SUV, shown with a red bounding box, had a conflict with the path of the bus. In the detailed data file, we found only five discrete rows that corresponded to this SUV based on the relative location. A well-tracked object would be represented by continuous rows in the data file. Since the vehicle was not well tracked, PASS failed to trigger a warning.

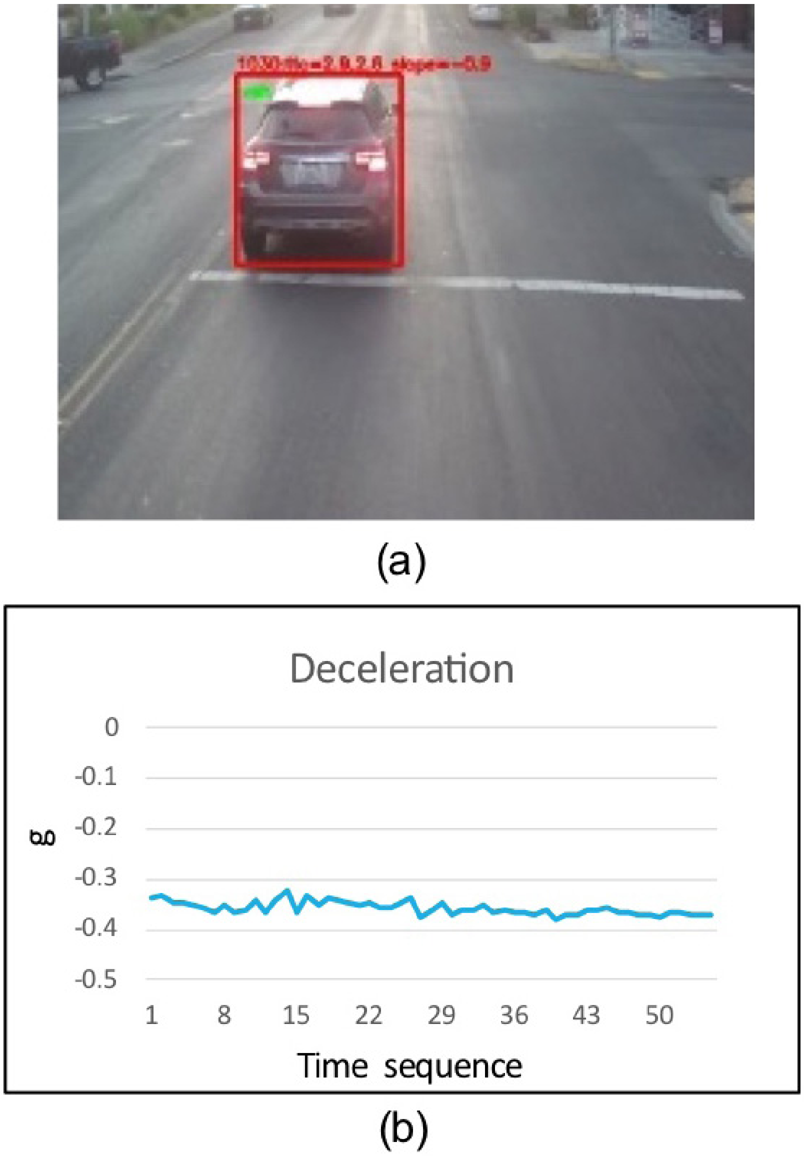


Figure F-14 *FN example #3 – Missed conflict event with vehicle at intersection*

Source: UW

False Negative Summary Statistics

The FN statistics for the four TELS-equipped buses from 5/1/2021 to 7/31/2021 are presented in Table F-4 and Table F-5. Within the 441 FNs, 16 were pedestrian-related events, and 425 were vehicle-related events. These events were classified according to which of the three PASS sensors triggered the event. The center PASS sensor triggered 283 signals, the left sensor triggered 134, and the right sensor triggered 24 signals. There were 150 FNs recorded when bus speed was low (0 to 10 mph), and nearly half of the events (203) occurred between 10 mph and 20 mph, 60 occurred between 20 and 30 mph, and 28 occurred over 30 mph. Overall, 69 of the events occurred in the morning between 5:00 and 9:00 AM, 192 were from 10:00 AM to 2:00 PM, 167 were between 3:00 and 7:00 PM, and only 13 occurred in the evening after 7:00 PM. None of the PASS or TELS false negative incidents logged was associated with actual vehicular or pedestrian collisions. Two of the PASS-equipped buses experienced collisions in which other vehicles struck the buses. Neither of those collisions occurred within the PASS operational design domain.

Table F-4 *FN Statistics, May–July 2021*

Vehicle #	Total Events	False Negatives	False Negative %
Bus 230	3,854	95	2.5%
Bus 231	2,854	93	3.3%
Bus 232	4,850	79	1.6%
Bus 233	5,627	174	3.1%
Total	17,185	441	2.6%

Table F-5 *FN Events Summary*

Type	Pedestrian 16, vehicle 425
Position	Front 283, left 134, right 24
Speed	0–10 mph 150, 10–20 mph 203, 20–30 mph 60, >30 mph 28
Time of Day	5–9am 69, 10am–2pm 192, 3–7pm 167, >7pm 13
Total	441

Evaluating the Accuracy of CAWS Conclusions

This section described the design, development, and implementation of an evaluation process for the PASS system. The TELS system design, algorithm design, data collection, and the judgment pipelines were documented. The FP and FN identification pipelines relied on PASS data and TELS video. The TELS system was fine-tuned to enable real-time, on-board event processing, which not only filtered out most of the raw videos to save network and cloud resources but also kept as many as possible potential near-miss events for post-evaluation.

Regarding the evaluation of PASS, the share of FP (FP events/total PASS events) was found to be 93.5%, and the FN% (FN events/total events evaluated) was 2.6%. Example FPs and FNs as well as associated analyses were described in the section. Additional information on the instrumentation, analysis methods, and data developed for this project can be found in Wang et al.[49]

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[49] Wang et al., "Evaluating the Accuracy of Transit Bus Collision Avoidance Warning Systems Technical Report #1," FTA/Pierce Transit Automated Collision Avoidance and Mitigation Safety Project, University of Washington, 2021, http://www.uwstarlab.org/research/highlights/20211113_PT_FinalReport_TELS_Publish.pdf.

Appendix G

Analyzing Unrestrained Passenger Motion During Transit Bus Braking

Introduction and Methodology

Deceleration, which is also referred to as negative acceleration, is the rate at which speed is reduced, and jerk, which is the rate of change in acceleration, must be closely controlled on transit buses. While collision avoidance and emergency braking systems have been successfully developed for trucks and autos and are in widespread use, none has yet been deployed for transit buses. Unlike auto and truck passengers, most transit bus passengers are unrestrained and may be standing. However, some passengers with disabilities may use a wheelchair and therefore may be required to have their wheelchair secured to the bus. Consequently, automation and driver-assisted braking for transit buses must be designed to avoid injuring passengers who maintain standing and seated postures and where a vast majority of passengers are unrestrained during deceleration.

The focus of this investigation was to understand the baseline profiles of manual braking and passenger postures. VTTI developed a passenger motion capture system that recorded signals from the PASS system via the bus's controller area network (CAN), the motion behaviors of passengers, and obscured video of passenger motion.

The research team was tasked with collecting and measuring passenger motion by using data acquisition systems designed to collect naturalistic field data on two PT buses while the buses were being used to perform typical revenue operations. This document describes the data collection set-up and collection activities, the ingestion of data from hard drives (HDs), identification of vehicle events, filtering of vehicle files in which braking maneuvers and resulting passenger motion measures could be observed, and the post-collection production of passenger motion behaviors. The approach to this novel analysis and the method are also examined.

Data Collection

VTTI designed the passenger motion capture system to record passenger motion based on signal triggering of a Pedestrian Avoidance Safety System (PASS) warning indication via the bus's CAN from five seconds preceding the PASS warning until five seconds following the PASS warning for a total of ten seconds surrounding each PASS warning activation. Video images of the interior passenger bus compartment were blurred to protect individual privacy. This protocol was reviewed by the Virginia Tech (VT) Human Research Protection Program and was approved by the VT Institutional Review Board.

Passenger motion on a transit bus may occur for multiple reasons. A passenger may choose to change posture, change seats, transition from standing to sitting or from sitting to standing, or manipulate a personal article or assist other passengers (e.g., children). A passenger may also move as a result of the bus's motion because of a bus operator's control action (e.g., brake pedal) or driver-assisted technology activation (e.g., automated emergency braking (AEB)). It is difficult to determine the intent of each passenger. However, it is valuable to observe and measure the resulting motion of individual passengers near events of brake pedal activation to instruct future bus braking automation systems that may be developed to reduce collision events outside the bus while reducing unintended consequences inside the bus.

Passenger motions were recorded by using stereovision, a technology that collects three-dimensional information on objects within its field of view. The video collection unit included two cameras offset at a fixed distance. The separation in camera positions allowed the system to measure the position and change in position of objects over time. A StereoLabs ZED 2.2 K stereo camera was used for video collection. This model collected high resolution and frame rate data with a depth perception of up to 20 meters. For the purposes of this study, the camera was configured to collect video at 720 p and 15 Hz.

Data Acquisition System

The data acquisition system (DAS) used software developed by VTTI running on a Neuosys Technologies Nuvo in-vehicle computer with an Nvidia graphics card to collect data. The NuvoDAS collected the following data elements for two field buses on 2-terabyte (TB) HDs: passenger motion stereovision measured in the Robot Operating System (ROS) bag (.bag) file format, blurred interior passenger compartment video (for motion verification) at 15 Hz, full¬–resolution forward camera video (scenario context: vehicle, pedestrian, or other) at 15 Hz, vehicle status (e.g., brake status, vehicle speed) on the vehicle CAN at 10 Hz, vehicle inertial measurement unit motion (i.e., accelerometers) at 20 Hz, vehicle location (i.e., GPS) at 5 Hz, PASS warning Indication on the vehicle CAN (i.e., forward collision warning) at 10 Hz, and PASS caution indication on the vehicle CAN (i.e., forward collision caution) at 10 Hz.

Installation

Figure G-1 shows the NuvoDAS as installed in the Pierce bus video cabinet where it could be secured. Nvidia Jetson embedded systems provided by the UW were also installed in the cabinet along with standard Pierce Transit (PT) radio and computer-aided dispatch/automatic vehicle location (CAD/AVL) equipment. The connection to the CAN bus network was also made on cables available in the video box. Figure G-2 shows the two interior rearview blurred cameras, one mounted above the passenger compartment on each side of the bus. The ZED stereovision camera is also displayed in the image. The external forward-facing camera is identified near the rearview mirror on the windshield in the image. The cell modem extension antenna is identified, and it was mounted behind the video cabinet and attached to the street–side window behind the bus driver.

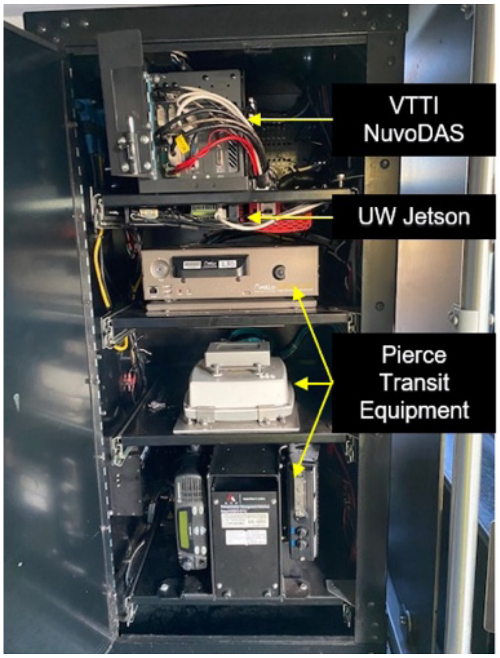

Figure G-1 *Instrumentation of NuvoDAS and UW Jetson in Pierce Transit Bus 230 video cabinet*

Source: VTTI

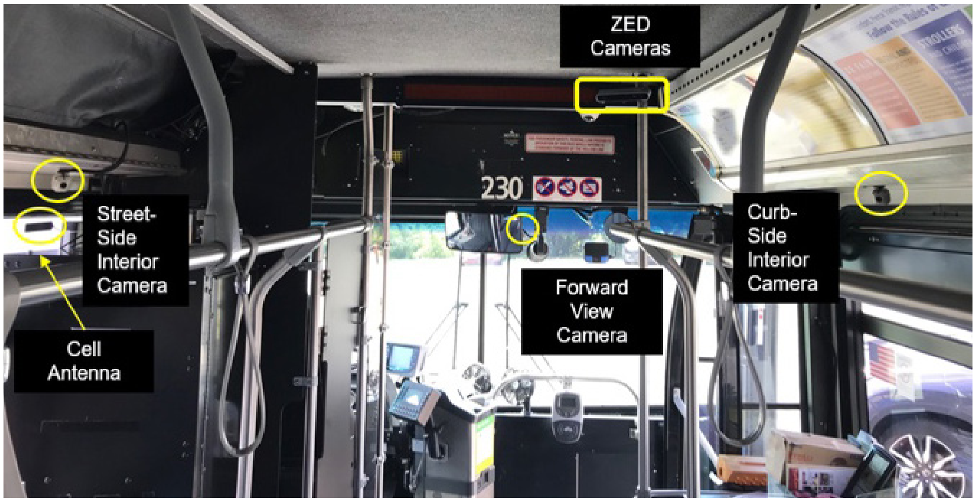

Figure G-2 *Instrumentation of NuvoDAS ZED Stereovision, forward, and interior cameras*

Source: VTTI

Data Ingestion and Field Data Assessment

The status of data collection on each bus was assessed through health checks that were automatically captured by the NuvoDAS at each ignition start. These included still image snapshots of each camera, a GPS location reference, a check of the input signals such as the inertial measurement unit (IMU), cameras, and the vehicle CAN including the PASS signals.

The HDs on the NuvoDAS were swapped once a month to ensure that they did not fill, which could result in lost data. After each swap, the HDs were returned to VTTI. These HDs were ingested, a process which included decrypting the data on each drive and decompressing the video and distributing the camera video, stereo-vision video, CAN, GPS, and IMU variables into the appropriate database format on VTTI data servers.

After ingestion, the decompressed and distributed data were reviewed to confirm the status of each data element. Research team personnel verified the data using the VTTI Hawkeye data visualizer to randomly select files containing video, PASS triggers, passenger motion, vehicle CAN, and NuvoDAS native GPS and IMU variables. The research team also scanned files in the database collection to determine the amount of data collected and number of PASS and passenger motion events. Summaries of the data collection were shared with the entire research team on a regular basis.

Equipment and Software Issue Summary

The collection of data on each bus during the study depended on the status of the NuvoDAS equipment, bus connections, and connections to other research components. The NuvoDAS collection depended on its own system function and the function of other components, including PASS system warning frequency, the stereovision cameras, the exterior and interior video cameras, and connections to the bus power and vehicle CAN. Therefore, updates to software on the PASS system and typical wear and tear on the sensors impacted the amount of vehicle and passenger data collected. The status of the NuvoDAS, a list of issues, and the periods of time that data collection was active or affected by issues are provided for each bus in Table G-1.

Table G-1 *INuvoDAS Data Collection and Issue Summary for Bus 230*

Period	Start Date	Stop Date	Active Days	Issue	Missing Data
1	25-Aug-20	18-Sep-20	24	NA	NA
2	19-Sep-20	11-Oct-20	22	PASS warning and caution signals switched	Warning triggered events
3	12-Oct-20	27-Oct-20	0	Caution signal frequency led to HDs full	Video, vehicle, passenger
4	28-Oct-20	4-Nov-20	7	PASS warning and caution signals switched	Warning triggered events
5	5-Nov-20	6-Jan-21	62	NA	NA
6	7-Jan-21	13-Mar-21	65	PASS warning signal null	Passenger
7	14-Mar-21	30-Apr-21	47	NA	NA
8	1-May-21	19-Jun-21	0	NuvoDAS system failure	Video, vehicle, passenger

Table G-2 *NuvoDAS Data Collection and Issue Summary for Bus 231*

Period	Start Date	Stop Date	Active Days	Issue	Missing Data
1	25-Aug-20	18-Sep-20	24	NA	NA
2	19-Sep-20	11-Oct-20	22	PASS warning and caution signals switched	Warning triggered events
3	12-Oct-20	27-Oct-20	0	Caution signal frequency led to HDs full	video, vehicle, passenger
4	28-Oct-20	4-Nov-20	7	PASS warning and caution signals switched	Warning triggered events
5	5-Nov-20	24-Feb-21	111	NA	NA
6	25-Feb-21	17-Mar-21	0	NuvoDAS video card repair	Video, vehicle, passenger
7	18-Mar-21	19-Jun-21	93	NuvoDAS stereovision failure	Passenger

Vehicle Event Identification

The first operation performed on the data after ingestion was a database query to determine data timeframes, called epochs, which contained driver-initiated brake pedal activation within the 10-second window (± 5 seconds) around the PASS warning trigger. Following this step, research personnel reviewed blurred video to confirm the presence of passengers. The research team also checked when the brake pedal was activated by observing the vehicle CAN brake signal during the passenger file epoch. During this activity, the researchers also identified and noted whether the brake was already depressed at the timeframe of 5 seconds before the PASS warning and whether the brake pedal was depressed at the timeframe of 5 seconds after the warning. This observation served as an exploratory step that would be automated later as a database query to identify vehicle events of interest. Events of interest were collected when the change of passenger motion may have been due to braking activity. Research personnel also identified the number of passengers visible in the video. If video was available for the forward roadway from the front-view camera, the bus motion scenario type and notes on the scenario were described—for example “driving straight” and “car in front braking.”

All identified events of interest were individually reviewed, and the passengers were described according to type, posture, location, and articles being carried. The passenger types were adult or child. A child was subjectively rated as shorter than five feet tall, standing head height.

Passengers were classified into the following postures: seated forward, seated sideways (Americans with Disabilities Act (ADA) seat area), standing forward, standing sideways, seated in a wheelchair, or seated unstable if the passenger was holding a stroller, cane, or walker. Articles being worn, such as shoulder bags, backpacks, or other articles carried by the passenger that appeared to be heavy were also noted. The locations of the passengers in the bus were also identified. An illustration of the locations of passengers is provided Figure G-3. This figure illustrates the 40-foot bus and passenger locations seated and standing (hatched) in front (letters) and mid-bus (numbers) sections. The approximate location of the motion-collection device (ZED/yellow) is illustrated on the front curbside (lower side) of the image. Identification of events of interest was completed for events with passengers present and brake pedal activity during the epoch collected around a PASS warning trigger. A sample of these events was selected for passenger motion production based on verification, as described in the next section of this chapter.

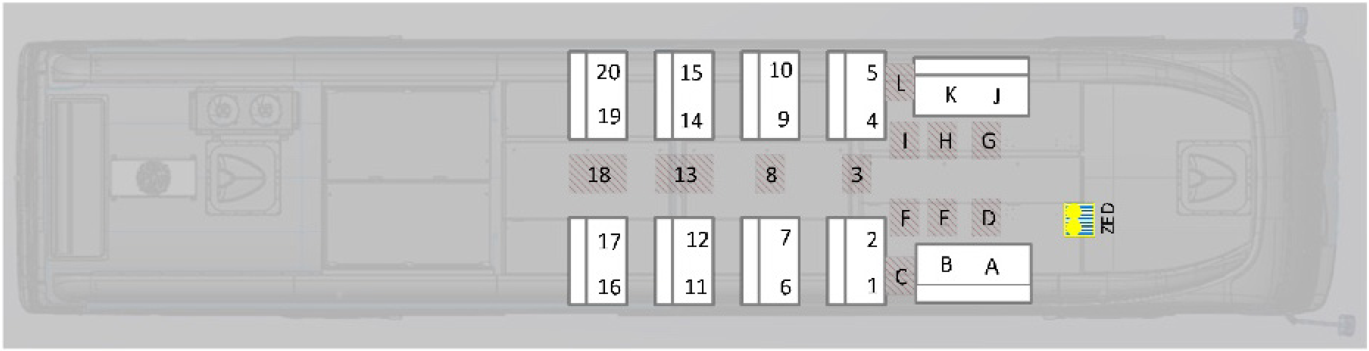

Figure G-3 *Illustration of 40-ft bus and passenger locations for motion tracking*

Source: VTTI

From the passenger verified epochs, a database query was performed to identify files that might be of interest across a range of vehicle braking events along the axis parallel to the length of the bus (i.e., longitudinal axis). During this database query operation, passenger motion epochs that were verified in previous steps to contain brake activation and passengers were queried to determine the level of maximum negative longitudinal acceleration forces, identified as "IMU_Accel X," that occurred while the vehicle speed was greater than 3.1 mph (5.0 kph) and the brake pedal status was "depressed" (combined) for at least 0.1 second. The IMU recorded vehicle motion at 20 Hz every 0.05 seconds, but the maximum negative longitudinal acceleration forces were calculated at 10 Hz every 0.1 seconds, to minimize spurious sensor anomalies possible at a higher data resolution. On the basis of a review of the distribution of maximum accelerations, events were organized into three groups of g-force levels: Level 1 (0.0, -0.1], Level 2 (-0.1, -0.2], and Level 3 (-0.2, -0.3].

Another operation was performed to remove vehicle maneuvers that were not of interest. The first feature of this operation was to verify that the brake pedal was not already depressed at the beginning of the passenger motion epoch. The second feature of the query filtered out events with angular acceleration greater than 10 degrees per second. On the basis of these operations, the parameters of transit bus events of interest were defined and classified as vehicle maneuver events (VMEs) as follows

- PASS warning activated
- Brake pedal pressed after start of passenger motion epoch
- Passengers present on bus
- Vehicle speed greater than 3.1 mph (5.0 kph)
- Vehicle yaw less than or equal to 10 degrees per second

Individual Passenger Motion Profile Production

Once VMEs were selected, passenger motion needed to be produced from the 10–second recording clips captured by the stereo-vision cameras, illustrated in Figure G-4.

A VME in the bus would cause passengers' heads to move forward and backward with respect to their seated or standing reference point in the bus. The kinematics experienced by the passengers during the VMEs are called passenger motion profiles (PMPs). A PMP was defined as the resulting negative and positive displacement, speed, and acceleration experienced by an unrestrained passenger due at least in part to transit bus braking.

Figure G-4 illustrates a sample of collected point clouds of surfaces on objects that were both static (i.e., seats and bars) and moving (i.e., passengers) from the field collection bus 231 (File ID: 10462) recorded with VTTI's stereovision motion production tool. This figure also illustrates objects or surfaces in gray that were not measured because they were either too far away from the stereovision cameras or out of the field of view angle. The image shows the information recorded by the NuvoDAS's ZED cameras of two static objects in the bus and passengers moving with the vehicle's braking motion. Passenger 1 was seated facing sideways on the front (ADA area) curbside, and passenger 2 was seated facing forward on the third-row street side. Static object 1 was the sidewall of the bus body between the windows near the front (ADA area) on the curb-side, and static object 2 was a seat in the front row on the street side.

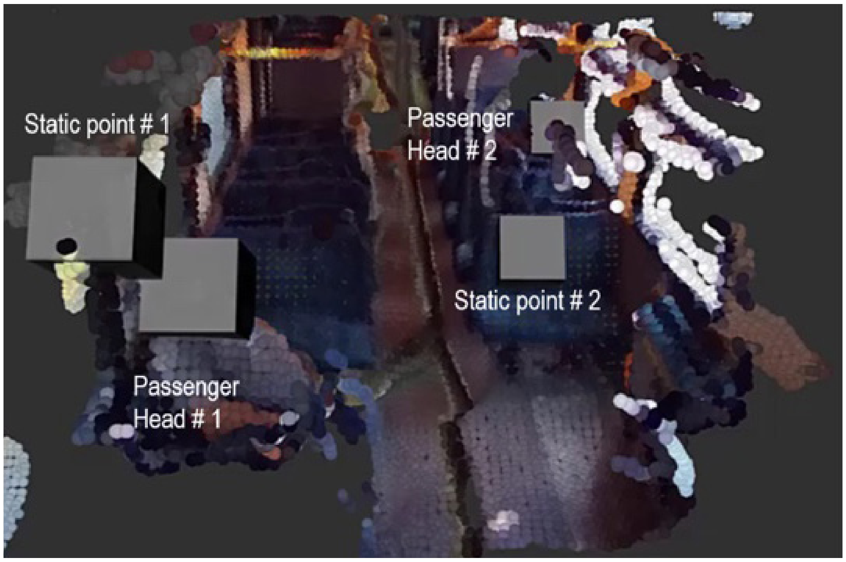

Figure G-4 *Sample image of transit bus passenger data from field collection*

Source: VTTI

This software method was used to obtain non-contact measures of individual passenger displacement (m), velocity (m/s), and acceleration g–force [(m/s^2)/ 9.81 m/s2] in comparison to fixed objects in the field of view on the bus (e.g., floor-to-ceiling mounted handrails). Measurement of passenger motion jerk was attempted but included too much noise to be useful. A sample of passenger motion measures collected during a VME from bus 230 (File ID: 464599) is provided in Figure G-5. The two columns represent the two passenger heads used to produce passenger motion.

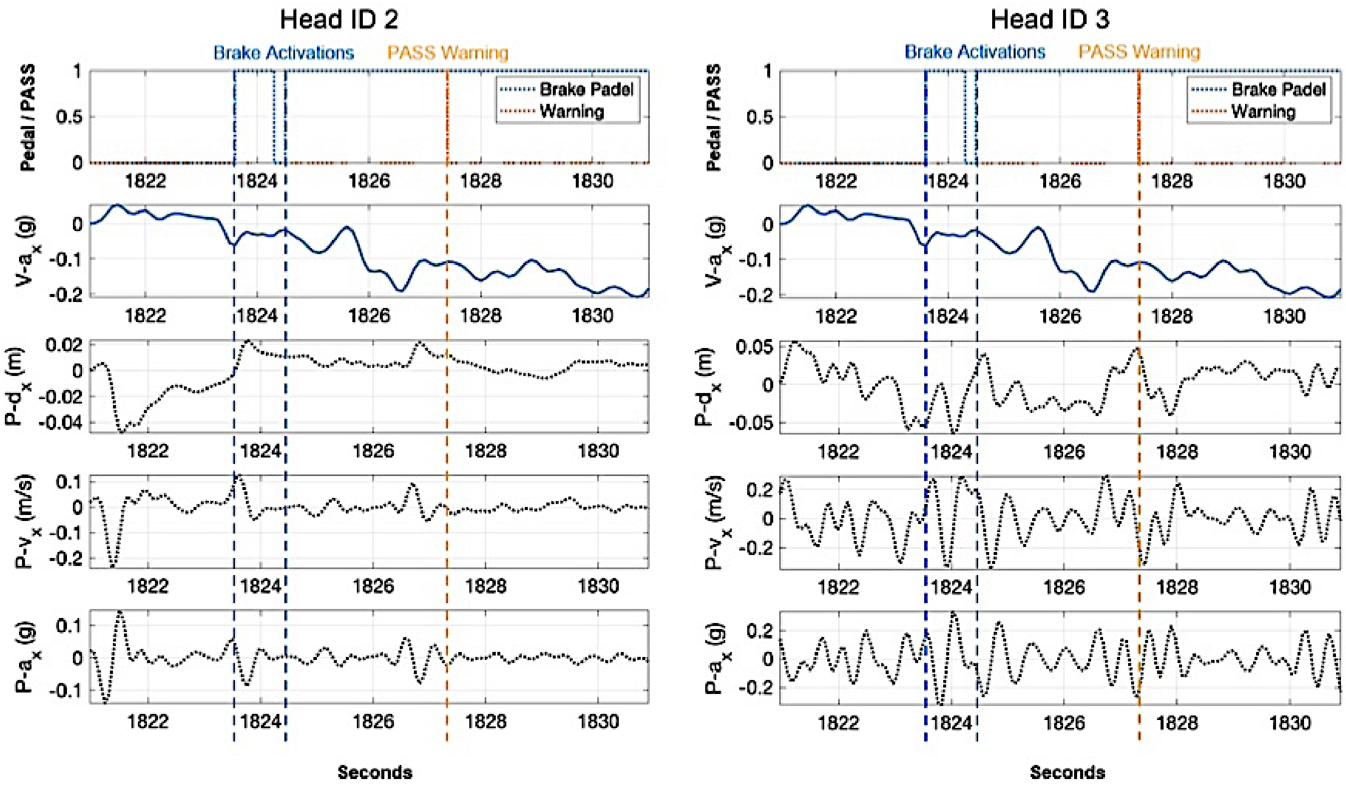

Figure G-5 *Sample of two PMP measures collected during VME from Bus 230*

Source: VTTI

The brake pedal was activated before a PASS warning trigger and after the start of passenger motion stereovision collection. The first two rows of graphs are vehicle variables (brake pedal and vehicle acceleration g–force), duplicated for comparison with passenger motion metrics for each passenger in the graphs below them. The third graph in each column represents passenger position longitudinal "x" displacement. The fourth and fifth graphs in each column represent the longitudinal velocity and the longitudinal g–force acceleration of the passenger.

Analysis Approach

Assumptions inherent in field collection activities of this study that affected the analysis approach included the following. First, the research team did not track drivers during the collection. Therefore, all files collected across both PT buses may have been driven by a few or by many different bus drivers, each with their own approach to braking the bus during their daily operations. Second, the research team did not seek to identify or track which passengers were present on the bus. Therefore, some passengers may have been recorded many times or only once within the collection and selection of VMEs and PMPs.

To accurately and efficiently explore how passengers moved during bus braking activities, the research team sought to develop PMPs of passengers seated, as well as in other postures including standing, seated in a wheelchair, and seated unstable (i.e., holding strollers, walkers, or other objects that might affect seated balance). Therefore, all VMEs containing passengers in postures other than seated only were selected. However, because of the significant number of seated–only passengers present during the VMEs, a process of selection was chosen to maximize the access to the most PMPs. First, VMEs were selected across the three levels of braking, targeting a minimum of 30 VMEs in each level (levels 1, 2, and 3). VMEs were also selected by attempting to evenly balance the number between the two installed PT buses. If there were not enough VMEs on one of the two buses at a specific level, then more VMEs were selected from the other bus to arrive at a minimum of 30 per level. Second, VMEs with the highest number of passengers present on the bus were selected. This process helped to produce the most PMPs possible while limiting the run times for passenger motion production, which was a manual and time-intensive process.

Passengers may choose to move independently inside the bus. They may choose to assist another passenger, get up out of their seat when nearing their bus stop, or merely adjust their seated or standing position while remaining in the same place. These choices were noted by researchers when producing the PMPs; however, a passenger's intent was not always obvious during the passenger motion production of the 10–second measurement epoch until the PMP displacement measures were reviewed. On the basis of a review of the results of the passenger displacement measures, "maximum value backward displacement" and "maximum value forward displacement" PMPs that exceeded 1 meter in the positive or negative direction ($x < -1.0$; $x > 1.0$) were excluded from the analysis.

The measurements produced for analysis on PMPs across braking levels and postures were as follows:

- Maximum value backward displacement of passenger head
- Maximum value forward displacement of passenger head
- Total movement of passenger head in x direction
- Total movement of passenger head during 2 seconds of braking initiation
- Backward speed of passenger head
- Forward speed of passenger head
- Backward acceleration of passenger head
- Forward acceleration of passenger head

Analysis Method

The final analysis data set was examined in multiple ways to better understand the data and the impact of acceleration level and passenger posture on various passenger movement variables. The analysis included calculating the average and standard deviation for each passenger movement variable by passenger posture and level. In the tables, the average calculation across all sampled passenger profiles is represented by the symbol $\bar{x}$; the standard deviation is represented by the symbol s.

For each variable, figures were developed to compare the average value for all passenger postures and levels within one graph. The figures serve as visual references for how average values changed by level within a passenger's posture.

In addition, the final analysis dataset was further assessed by using a mixed-effect linear regression Type III model. Three research questions were investigated using corresponding models:

- How does the passenger movement variable change across braking levels within the seated passenger posture?
- How does the passenger movement variable change by seated passenger posture and wheelchair passenger posture?
- How does the passenger movement variable change by seated passenger posture and seated unstable passenger posture?

Results of Passenger Motion Profile Analysis

The results are organized below into sections according to the stages of collection and procedures of data filtering. The following section provides an overview of all the data collected during the field study of passenger motion on two transit buses. The "Event-Based Passenger Data Summary" section provides a summary of the VMEs that were selected through filtering to identify events that met criteria for longitudinal braking maneuvers and the PMPs that were produced for the passengers on the bus during those events. A final filter was applied to those PMPs to sort out motions that were obstructed by other passengers or that designated intent to move independent of the bus braking effects. The final VME and PMP counts are provided in the section labeled "Counts of VMEs and PMPs for Analysis."

Vehicle Data Summary

Table G-3 describes the raw data and the number of events that were verified in which the brake pedal was simultaneously used during the event window and passengers were present on the bus. Events classified as "other postures" included at least one passenger in a standing, wheelchair seated, or seated unstable posture. The total data column contains continuous video, passenger motion data, and vehicle data—which are not separated in Table G-3. The verified events are not the same as the filtered vehicle events or the VMEs applied to produce the PMPs.

Table G-3 *Overview of All NuvoDAS Field Data Collected on Two PT Buses*

Vehicle #	Total Data (TB	Continuous Video Data (TB)	Passenger Motion Data (TB)	Raw Passenger Motion Events	Verified Brake & Passenger Events	Verified Seated Only Events	Verified Other Postures Events
Bus 230	11.98	4.35	5.26	2,224	859	671	181
Bus 231	12.56	4.96	6.04	2,775	730	553	160
Totals	24.54	9.32	11.30	4,999	1,589	1,224	341

Event-Based Passenger Motion Data

Three operations were performed on the verified brake events to arrive at the set that was processed into PMPs. The first two—brake pedal pressed after the start of the passenger motion epoch and vehicle yaw less than or equal to 10 degrees per second—were verified in data handling steps described previously in this report. The third involved sampling of PMPs from VMEs in which all remaining vehicle events containing passenger "other postures" were kept along with a sample of "seated only" postures. These events were classified as VMEs, and passengers present during these events produced PMPs for analysis that were organized according to the braking levels for "seated only" posture and across all levels for the "seated only" and "standing," "wheelchair," and "seated unstable" postures. VMEs that existed when all passengers were only seated and not unstable or in a wheelchair were listed as "seated only." The VMEs observed to include passengers in the "standing," "wheelchair," and "seated unstable" postures often contained passengers who were in the "seated only" posture in addition to passengers who were in these other postures.

The research team observed that very few passengers were standing during the period of collection. This is likely due to the low volume of passengers present on the buses and routes, which may have been influenced by the pandemic.

Counts of VMEs and PMPs for Analysis

The counts of VMEs and PMPs that were applied to measures of passenger motion are listed in the following tables. As discussed in the analysis approach, PMPs were excluded from analysis if displacement measures "maximum value backward displacement" and "maximum value forward displacement" exceeded 1 meter in the positive or negative direction ($x < -1.0$; $x > 1.0$). These PMPs were observed to carry intentional motion by the passenger being measured or obstructions due to a change of other posture by another passenger in the bus measurement scene.

Table G-4 presents, for each passenger posture, the total VMEs with that posture and the number of VMEs by level. The final analysis data set included 167 VMEs with seated (seated only) passenger profiles, nine VMEs with standing passenger profiles, 14 VMEs with seated unstable passenger profiles, and 36 VMEs with wheelchair passenger profiles.

Table G-4 *Counts of Vehicle Maneuver Event by Passenger Posture and Acceleration Level*

Passenger Posture	Total VME Count	Level 1 Count (%)	Level 2 Count (%)	Level 3 Count (%)
Seated	167	44 (26.35%)	80 (47.90%)	43 (25.75%)
Standing	9	3 (33.33%)	3 (33.33%)	3 (33.33%)
Unstable	14	6 (40.00%)	2 (20.00%)	6 (40.00%)
Wheelchair	36	14 (38.89%)	18 (50.00%)	4 (11.11%)

Multiple passenger profiles were sampled per VME. Included in Table G-5 is the number of passenger profiles per passenger posture, further broken down by level. Seated passenger posture was observed in 584 passenger profiles, which made it the most observed passenger posture in the analysis dataset. The final analysis dataset also included nine standing passenger profiles, 16 seated unstable passenger profiles, and 40 wheelchair passenger profiles.

Table G-5 *Counts of Passenger Profiles by Passenger Posture and Acceleration Level*

Passenger Posture	Total Passenger Profiles	Level 1 Count (%)	Level 2 Count (%)	Level 3 Count (%)
Seated	584	134 (22.95%)	289 (49.49%)	161 (27.57%)
Standing	9	3 (33.33%)	3 (33.33%)	3 (33.33%)
Unstable	16	7 (43.75%)	3 (18.75%)	6 (37.50%)
Wheelchair	40	15 (37.50%)	19 (47.50%)	6 (15.00%)

Analysis of Passenger Motion Profile Measures

Eight measures were examined to describe the PMPs that were produced based on passenger postures and braking levels. Descriptive statistics were used to investigate the range of motions experienced by passengers to determine whether the levels of braking could be observed across seated only passengers and whether any levels of braking affected some postures more than others. For these PMPs, descriptive statistics are illustrated for seated only, standing, seated unstable, and wheelchair postures. Additionally, a Type III mixed-effect model approach was used to compare the effects of braking for seated only passengers, across all braking levels, and between seated only and wheelchair postures, and between seated only and seated unstable postures. However, because of the limited number of standing posture PMPs (n = 9), a mixed-effect model was not applied to test for significance between standing and seated only PMPs. For this report, total movement of heads in the X (longitudinal) direction was chosen to illustrate the analysis of PMP measures. Analysis of all eight PMP measures can be found in Krum et al., 2021.[50]

Total Movement of Heads in X Direction During Event

Descriptive Statistics

Total movement of heads in the X direction during event by level and passenger posture is explored through the descriptive statistics presented in Table G-6. The seated passenger posture had an average total movement of heads in the X direction during events of 0.1932 m in Level 1, 0.2495 m in Level 2, and 0.2355 m in Level 3. The standing passenger posture had average values of 0.0619 in Level 1, 0.2173 in Level 2, and 0.2336 in Level 3. For the seated unstable passenger posture, the average calculations were 0.3317 m in Level 1, 0.2089 m in Level 2, and 0.2709 m in Level 3. The wheelchair passenger posture had average values of 0.1449 m in Level 1, 0.2693 m in Level 2, and 0.1762 m in Level 3.

Table G-6 *Descriptive Statistics of Total Movement of Heads in X Direction during Events, by Level and Passenger Posture*

Level	Passenger Posture	Count	Total Movement in X Direction during Event $\bar{x}$ (m)	Total Movement in X Direction during Event s (m)
1	Seated	134	0.1932	0.2447
1	Standing	3	0.0619	0.0492
1	Seated Unstable	7	0.3317	0.3115
1	Wheelchair	15	0.1449	0.1196
2	Seated	289	0.2495	0.2367
2	Standing	3	0.2173	0.1737
2	Seated Unstable	3	0.2089	0.0307
2	Wheelchair	19	0.2693	0.1683
3	Seated	161	0.2355	0.2141
3	Standing	3	0.2336	0.2805
3	Seated Unstable	6	0.2709	0.1276
3	Wheelchair	6	0.1762	0.1526

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[50] Krum, A., et al., "Analyzing Unrestrained Passenger Motion During Transit Bus Braking," Technical Report, FTA/Pierce Transit Automated Collision Avoidance and Mitigation Safety Research and Demonstration Project, Virginia Tech Transportation Institute, 2021.

Mixed–Effect Model Test

Results from the mixed-effect regression models are included in Table G-7. No significant difference was found in total movement of heads in the X direction during events between levels in the seated passenger profiles ($p = 0.1196$). No significant difference was observed between seated passenger profiles and wheelchair ($p = 0.5839$) or seated unstable passenger profiles ($p = 0.4785$).

Table G-7 *Type III Tests of Fixed Effects from Models of Total Movement of Heads in X Direction during Events*

Comparative Analysis	Effect	Numerator Degrees of Freedom	Denominator Degrees of Freedom	*F*-Value	*p*-value
Levels for seated passenger PMPs	Level	2	417	2.13	0.1196
Seated to wheelchair passenger PMPs	Posture	1	454	0.30	0.5839
Seated to seated unstable PMPs	Posture	1	433	0.50	0.4785

Table G-8 presents the average and standard deviation calculations for total movement of heads during 2 seconds of braking initiation by level and passenger posture. For Level 1 observations, the average total movement of heads during 2 seconds of braking initiation ranged between 0.0494 m (wheelchair passenger posture) to 0.1258 m (seated unstable passenger posture). In Level 2, the average calculations ranged from 0.0779 m (seated unstable) to 0.1061 m (wheelchair). In Level 3, the average calculations included 0.0640 m (wheelchair) through 0.1192 m (seated unstable).

Table G-8 *Descriptive Statistics of Total Movement of Heads during 2 Seconds of Braking Initiation, by Level and Passenger Posture*

Level	Passenger Posture	Count	Total Movement of Head during 2 Secs of Braking Initiation $\bar{x}$ (m)	Total Movement of Head during 2 Secs of Braking Initiation s (m)
1	Seated	134	0.0780	0.1227
1	Standing	3	0.0619	0.0492
1	Seated Unstable	7	0.1258	0.1303
1	Wheelchair	15	0.0494	0.0321
2	Seated	289	0.0787	0.0799
2	Standing	3	0.0909	0.0429
2	Seated Unstable	3	0.0779	0.0142
2	Wheelchair	19	0.1061	0.1027
3	Seated	161	0.0777	0.0724
3	Standing	3	0.0961	0.0751
3	Seated Unstable	6	0.1192	0.0704
3	Wheelchair	6	0.0640	0.0805

Table G-9 presents the results of Type III tests of fixed effects from mixed-effect models. Level of acceleration was not associated with a significant change in total movement of heads during 2 seconds of braking initiation during events for the seated passenger posture ($p = 0.9877$). A comparison of seated passenger profiles to wheelchair passenger profiles found no significant difference in total movement of heads during 2 seconds of braking initiation during events ($p = 0.8802$). As found before, seated and seated unstable passenger postures showed no significant difference in the model ($p = 0.1399$).

Table G-9 *Type III Tests of Fixed Effects from Models of Total Movement of Heads during 2 Seconds of Braking Initiation during Events*

Analysis	Effect	Numerator Degrees of Freedom	Denominator Degrees of Freedom	*F*-Value	*p*-value
Comparing levels for seated passenger profiles	Level	2	417	0.01	0.9877
Comparing seated to UW wheelchair passenger profiles	Passenger Posture	1	454	0.02	0.8802
Comparing seated to seated unstable passenger profiles	Passenger Posture	1	433	2.19	0.1399

Summary of Analysis of Passenger Motion Profile Measures

The measurements provided above are in meters, where a measurement of total movement of head during 2 seconds of braking initiation of 0.078 m at braking level 1 for the seated posture should be understood to mean that the average total measurement of head motion on each of the 134 passengers in the sample was 78.0 millimeters during 2 seconds of braking initiation. The measures of total motion and total motion during 2 seconds of braking initiation were measures of total cyclical motion (e.g., forward, backward, forward again, and backward again) during a selected period.

Only the analysis of total head movement and total head movement during 2 seconds of brake initiation are presented here. However, the analysis of Type III mixed model tests found no significance in the seated only posture PMPs of displacement, speed, and acceleration among the three braking levels. Similarly, there were no significant findings in passenger motion between seated only and seated unstable postures or between seated only and wheelchair postures. The sample of standing postures was not sufficient to perform a mixed model test for significance.

Passenger Motion Conclusions

Bus passengers can choose to move independently of the vehicle's maneuvers. Human judgment is still an important part of any process to analyze passenger motion until behavior models can be developed to classify passenger intended motion vs. the effects of vehicle braking maneuvers. The process of producing PMP displacement, resulting speed, and acceleration force applied within this investigation relied on automated measures of displacement. However, a substantial amount of time was spent by the research team determining the state of passenger posture and behavior before the automation was run.

The measurement process applied in this field investigation was selected primarily because it was non-contact and could attempt to measure natural behavior. Passengers might behave very differently in a controlled lab or test track experimental methodology. However, this collection procedure is novel as was the software developed to post-process the PMPs for each individual passenger. Another strength of this approach was the simultaneous collection of data on multiple passengers and full scenario internal and external data. Although one approach with multiple measures was selected to analyze passenger motion during this investigation, the vehicle and passenger data could be organized in many other ways in the future. This is because of a naturalistic approach that assumed very little at the time of collection but provided full scenario information.

The production of passenger motion is one version that can be modified in the future, given the full scenario collection. A wide range of passenger postures across low to moderate braking maneuvers were analyzed. Two results suggest that the approach and analysis could be improved in future research:

- The levels of bus braking across a large sample of seated posture passengers did not show any significant differences between PMPs for the selected vehicle maneuvers that were evaluated.
- Passengers in postures that may be expected to move less during braking, such as secured and restrained wheelchair passengers, did not differ significantly from movements of other unrestrained, seated, or seated unstable passengers.

This study observed that most transit bus braking maneuvers occurred below 0.3 g. The measured forces—reported elsewhere—on seated passengers during Level 3 braking were 0.10 g in the backward direction and 0.09 g in the forward direction. Previous research on the topic of transit passenger motion and balance sought to determine the limits of forces that passengers may be able to resist to avoid falling. This naturalistic collection of passenger motion found that the total motion and forces acting on passengers in typical transit bus operations did not vary significantly by low to moderate braking level or posture. This finding may be applied to the development of automatic braking assistance features for transit buses.

Discussion

Drivers generally braked the buses of below 0.3 g. The result of this analysis reinforces the current training and natural human driving skill present among transit bus drivers. This finding illustrates that transit bus drivers choose to maneuver buses in a way that is protective of their passengers while still critically responding to the traffic, pedestrians/bicyclists, and environment outside. Future braking assistance and automatic emergency braking systems should imitate driver braking profiles except where a critical and verifiable risk exists for pedestrians or bicyclists outside the bus and aggressive maneuvers are necessary to mitigate or avoid a collision.

Findings based on multiple calculations, including forward, backward, and total displacement, along with speed and acceleration over hundreds of samples of seated passenger motion events, suggest that unrestrained passengers do not move significantly differently between braking levels. The lack of distinction among braking levels for seated passengers may have implications for the development of future driver-assist automation technologies. During the project, the developer of the PASS system was careful to limit the amount of braking force applied across the vehicle during PASS warning activations. This approach is reasonable for new driver assistance features to reduce interference during the driving task, especially as system reliability is under development. However, another consideration of the developer was to limit braking automation to avoid unintended consequences for passengers. These findings suggest that when reliability and the correct balance of sensing and perception are developed in transit bus collision warning systems, passengers will generally react similarly to a range of low to moderate automatic braking assistance levels and vehicle maneuvers.

Finally, for future research activities, it will be useful to recognize that passenger motion behavior is very individual during braking. Intuitive expectations of passenger motion in response to braking may not support the actual behavior or response during low to moderate braking activities. Standing passengers may choose to stand because of confidence in their strength and balance. These passengers may also apply more muscle activity during the trip and remain engaged with the maneuvers of the bus to brake based on traffic or arrival and departure around bus stops. The level of bus loading affects the decision to stand. This consideration about passenger strength and choice to stand will not hold when seats are not available, even for those who may be limited in strength and balance. Also, the assumption that each passenger is stable in any standing or seated posture at any point in time during a trip cannot be made, given the nature of unrestrained passengers on these vehicles.

Abbreviations and Acronyms

ABS	Antilock braking system
ADA	Americans with Disabilities Act
AEB	Automated emergency braking
AOI	Area of interest
API	Application programming interface
APRT	Available perception/reaction time
AVL	Automatic vehicle location
Bag	.bag file extension
CAD	Computer aided dispatch
C&L	Casualty and liability
C&L$	Casualty and liability expenses
CAN	Controller area network
CAWS	Collision Avoidance Warning System
CCVS	Cruise control/vehicle speed
CFI	Comparative Fit Index
CSI	Commuter Stress Index
CSV	Comma separated variables
CUTR	Center for Urban Transportation Research University of South Florida
CV	Computer vision
DAS	Data acquisition system
DBSCAN	Density-Based Clustering Algorithm
DCS	DCS Technologies, Inc.
EEC2	Electronic Engine Controller 2
ET	Everett Transit
Euro-NCAP	European New Car Assessment Program
FAT	Fatalities
FCAM	Forward Collision Avoidance and Mitigation
FMCSA	Federal Motor Carrier Safety Administration
FMVSS	Federal Motor Vehicle Safety Standards
FN	False negative
FP	False positive
FPS	Frames per second
FTA	Federal Transit Administration

FTP	File Transfer Protocol
g	Acceleration due to force of gravity = 9.81 m/s2
GIS	Geographic information system
GPS	Global Positioning System
GTFS	General Transit Feed Specification
HD	High Definition
HD	Hard drive
IDEA	Innovations Deserving Exploratory Analysis
IEEE	Institute of Electronic and Electrical Engineers
IMU	Inertial measurement unit
INJ	Injury
IP	Internet Protocol
IoT	Internet of things
IRB	Institutional Review Board
ISO	International Organization for Standardization
J1939	Society of Automotive Engineers Communications Standard for Bus & Truck
JSON	JavaScript Object Notation
KCM	King County Metro
LF	Low Floor
Lidar	Light detection and ranging
MB	Motor bus
MDBF	Mean distance between failures
MV	Motor vehicle
NB	Negative binomial
NCAP	New Car Assessment Program
NHTSA	National Highway Traffic Safety Administration
NPRT	Needed perception/reaction time
NTD	National Transit Database
NTSB	National Transportation Safety Board
ODD	Operational design domain
OEM	Original equipment manufacturer
PASS	Pedestrian Avoidance Safety System
PMP	Passenger motion profile

PMT	Passenger miles of travel
PoT	Path of travel
PT	Pierce Transit
RCW	Revised Code of Washington
RMSEA	Root mean square error of approximation
ROI	Return on investment
ROS	Robot Operating System
RP	Recommended practice
RTSP	Real-Time Streaming Protocol
S&S	Safety and security
SAE	Society of Automotive Engineers
SEM	Structural equation model
sftp	Secure File Transfer Protocol
SORT	Simple Online and Real-Time Tracking
SQL	Structured Query Language
SRD	Safety Research and Demonstration
STAR Lab	Smart Transportation Applications & Research Laboratory
SRT	System response time
SSD	Single shot detector
SWIL	Software in the loop
TB	Terabyte
TCS	Traction control system
TELS	Transit Event Logging System
TOS	Type of service
TRB	Transportation Research Board
TTC	Time to collision
TTI	Travel Time Index
UMR	Urban Mobility Report
UPT	Unlinked passenger trips
UW	University of Washington
UZA	Urbanized area
VAMS	Vehicles available for maximum service
VDH	Vehicle deadhead hours
VDM	Vehicle deadhead miles

Veritas	Veritas Forensic Accounting and Economics
VME	Vehicle Maneuver Event
VOMS	Vehicles operated in maximum service
VRH	Vehicle revenue hours
VRM	Vehicle revenue miles
VRT	Vehicle response time
VRU	Vulnerable road user
VT	Virginia Tech
VTTI	Virginia Tech Transportation Institute
VUT	Vehicle under test
WSP	Washington State Patrol
WSTIP	Washington State Transit Insurance Pool

References

"2021 NTD Reporting Policy Manual | FTA." https://www.transit.dot.gov/ntd/2021-ntd-reporting-policy-manual.

"2019 NTD Safety & Security Quick Reference Guide – Non-Rail Mode Reporting." Federal Transit Administration, 2019. https://www.transit.dot.gov/sites/fta.dot.gov/files/docs/subdoc/141/2019-ntd-quick-reference-non-rail.pdf.

Dagan, E., O. Mano, G. P. Stein, and A. Shashua, "Forward Collision Warning with a Single Camera," IEEE Intell. Veh. Symp. Proc., 37-42, 2004.

DCS Technologies, Inc., "Pedestrian Avoidance Safety System (PASS)," https://indd.adobe.com/view/3e0a09aa-80d1-47e0-a474-a2794aafddc9.

DCS Technologies, Inc., and VTTI, "FTA-Pierce Transit Collision Avoidance and Mitigation SRD Project Alpha Test Quicklook Report," March 18, 2019.

European New Car Assessment Programme (Euro NCAP) Assessment Protocol – Vulnerable Road User Protection Version 10.0.3, June 2020, Assessment of AEB Vulnerable Road User Systems. https://cdn.euroncap.com/media/58230/euro-ncap-assessment-protocol-vru-v1003.pdfFTA National Transit Database https://www.transit.dot.gov/ntd/ntd-data.

Federal Transit Administration [Docket No. FTA–2015–0017] Z RIN 2132–ZA04, "National Public Transportation Safety Plan," *Federal Register*, 82(11), January 18, 2017, 5628-5636.

Fernando, Jason, "Return on Investment (ROI)," https://www.investopedia.com/terms/r/returnoninvestment.asp.

Gettman, D., J. S. Lott, T. Harrington, "Working Paper #2: Safety Assurance Considerations – Blending Transit and Automotive Safety Analysis Methodologies," National Highway Cooperative Research Program (NCHRP) Project 20-102 (02): Impacts of Laws and Regulations on CV and AV Technology Introduction in Transit Operations, March 2017, http://onlinepubs.trb.org/onlinepubs/nchrp/docs/NCHRP20-102(02)_WP2-Safety_Assurance_Considerations.pdf.

Krum, A., et al., "Analyzing Unrestrained Passenger Motion During Transit Bus Braking," Technical Report, FTA/Pierce Transit Automated Collision Avoidance and Mitigation Safety Research and Demonstration Project, Virginia Tech Transportation Institute, 2021.

Lutin, J. M., A. L. Kornhauser, J. Spears, L. F. Sanders, "A Research Roadmap for Substantially Improving Safety for Transit Buses through Autonomous Braking Assistance for Operators," *Compendium of Papers*, Paper Number 16-1246, 95th Annual Meeting of the Transportation Research Board, Washington, DC, January 12, 2016.

"National Transit Database (NTD) Glossary | FTA," https://www.transit.dot.gov/ntd/national-transit-database-ntd-glossary.

"National Transit Database, Safety and Security Time Series Data," https://www.transit.dot.gov/ntd/data-product/safety-security-time-series-data; "2018 Annual Database Operating Expenses," https://www.transit.dot.gov/ntd/data-product/2018-annual-database-operating-expenses, Federal Transit Administration.

National Transportation Safety Board, "The Use of Forward Collision Avoidance Systems to Prevent and Mitigate Rear-End Crashes." Special Investigation Report NTSB/SIR-15-01. Washington, DC. https://www.ntsb.gov/safety/safety-studies/Documents/SIR1501.pdf.

"Revenue Service (Miles, Hours, and Trips)," National Transit Database (NTD) Glossary, Federal Transit Administration. https://www.transit.dot.gov/ntd/national-transit-database-ntd-glossary#R.

SAE International, https://www.sae.org/standards/content/j1739_200208/.

SAE International, https://www.sae.org/standards/content/j1939_201808/.

SAE International, https://www.sae.org/standards/content/j3029_201510/.

Schrank, D., L. Albert, B. Eisele, and T. Lomax, "Urban Mobility Report," Texas A&M Transportation Institute, June 2021. http://tti.tamu.edu/documents/mobility-report-2021.pdf.

Soule, H., S. Huck, A. Krum, Y. Wang, R. Ke, D. Valadez, D. Sellers, and J. Lutin, "Testing an Automated Collision Avoidance and Emergency Braking System for Buses," *Transportation Research Record,* 2674(4), 66-74.

Soule, Heidi H., Adam Davis, Andrew Krum, Yinhai Wang, Ruimin Ke, Dave Valadez, Dan Sellers, Steve Roberts, Luke Fischer, Jerome M. Lutin, "Risk Mitigation Planning for Revenue Service Testing of Bus Automated Emergency Braking," *Transportation Research Record*, 2675(5), 193-200.

Spears, M. J., J. M. Lutin, Y. Wang, R. Ke, S. M. Clancy, "Active Safety-Collision Warning Pilot in Washington State'" Final Report for Transit IDEA Project 82, Transportation Research Board, May 2017. http://onlinepubs.trb.org/onlinepubs/IDEA/FinalReports/Transit/Transit82.pdf.

Staes, L., J. Godfrey, J. Flynn, M. Spicer, G. Saliceto, R. Yegidis, "TCRP Synthesis 145, Current Practices in the Use of Onboard Technologies to Avoid Transit Bus Incidents and Accidents, a Synthesis of Transit Practice." Center for Urban Transportation Research, University of South Florida. https://www.nap.edu/login.php?action=guest&record_id=25716

U.S. Department of Transportation, Federal Transit Administration, 49 CFR Part 665 [Docket No. FTA–2015–0019] RIN 2132–AB11 Bus Testing: Establishment of Performance Standards, a Bus Model Scoring System, a Pass/Fail Standard and Other Program Updates. Final Rule, *Federal Register*, 81(147), August 1, 2016, Rules and Regulations. https://www.govinfo.gov/content/pkg/FR-2016-08-01/pdf/2016-17889.pdf.

U.S. Department of Transportation, Federal Transit Administration, 49 CFR PART 673—Public Transportation Agency Safety Plans. *Federal Register*, 83(139), July 19, 2018, Rules and Regulations. https://www.govinfo.gov/content/pkg/FR-2018-07-19/pdf/2018-15167.pdf.

U.S. Department of Transportation, "Major Safety Events," Major Safety Events | Department of Transportation – Data Portal.

U.S. Department of Transportation, "National Transportation Statistics 2021." https://www.bts.gov/sites/bts.dot.gov/files/2021-12/NTS-50th-complete-11-30-2021.pdf.

U.S. Department of Transportation, "Preparing for the Future of Transportation, Automated Vehicles 3.0," October 2018. https://www.transportation.gov/av/3.

Washington State Legislature, "Revised Code of Washington (RCW), Title 46, Motor Vehicles," December 16, 2019, update. http://leg.wa.gov/CodeReviser/RCWArchive/Documents/2019/Title%2046%20RCW.pdf.

Wang, Y., R. Ke, S. Yin, Z. Cui, "Quantifying Contributing Factors to Transit Bus Casualty and Liability Expenses Using the National Transit Database," Technical Report #2, FTA/Pierce Transit Automated Collision Avoidance and Mitigation Safety Research and Demonstration Project, University of Washington, 2021. http://www.uwstarlab.org/research/highlights/20211201_PT_FinalReport_NTD_Publish.pdf.

Wang, Y., R. Ke, Z. Cui, S. Yin, and Y. Zhuang, "Evaluating the Accuracy of Transit Bus Collision Avoidance Warning Systems Technical Report #1," FTA/Pierce Transit Automated Collision Avoidance and Mitigation Safety Project, University of Washington, 2021. http://www.uwstarlab.org/research/highlights/20211113_PT_FinalReport_TELS_Publish.pdf.

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