Selection and Evaluation of Sensor Technology for Transit Industry Collision Avoidance Systems

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ABSTRACT

According to the Federal Transit Administration's National Transit Database, in 2017, a typical year, transit buses and vans were involved in 4,739 collisions, 16,353 injuries, 98 fatalities, and reported $717 million in casualty and liability expenses. This shows a need for a vulnerable road user collision mitigation system in the transit industry. To accurately assess the applicability of a candidate technology for use in a Collision Avoidance System (CAS) for the transit industry, we must first identify and prioritize the high-level system requirements and lower-level derived requirements. Many sensor technologies are available to measure distance or proximity of various types of objects. Selecting a sensor to meet the CAS requirement set becomes a crucial task. Acting in the role of technology provider/vendor in the FTA SRD project, DCS, after thorough research and evaluation, determined that LiDAR was the appropriate technology for a transit industry collision avoidance system. The CAWS used in the SRD project, Pedestrian Avoidance Safety System (PASS), will be used as an example to provide performance parameters and specifications. At the time of development, the transit industry lacked a VRU CAWS/AEB test protocol. Therefore, a phased test plan was developed to include closed-area and on-the-road evaluation. Throughout the SRD project, various lessons were learned about adapting a VRU collision avoidance system into the transit industry. From the lessons learned about LiDAR in transit, many enhancements can be made to a two-dimensional LiDAR based VRU collision mitigation system.

Keywords: collision avoidance, LiDAR, automated emergency braking, vulnerable road user.

Background

According to the Federal Transit Administration's National Transit Database, in 2017, a typical year, transit buses and vans were involved in 4,739 collisions, 16,353 injuries, 98 fatalities, and reported $717 million in casualty and liability expenses. [1] Evidence from a recent study of $53 million in transit insurance claims indicates that 65% of casualty and liability expenses may be the result of preventable collisions with other vehicles, cyclists, and pedestrians. [2] The transit bus industry does not offer the level of advanced pedestrian detection and avoidance technology that the passenger car market currently produces. In 2017 the Federal Transit Administration (FTA) awarded Pierce Transit of Lakewood, WA a $1.66 million grant for a bus collision avoidance and mitigation safety research and demonstration project to advance collision avoidance technology for transit. As part of this project, DCS Technologies, Inc. (DCS) was tasked to deliver a Collision Avoidance and Warning System (CAWS) equipped with Automatic Emergency Braking (AEB). This paper discusses the requirements for vulnerable road user (VRU) collision mitigation systems in transit, the processes of selecting, characterizing, and implementing a suitable sensor technology for a CAWS, and the application of a Light Detection and Ranging (LiDAR) based VRU collision avoidance system in a transit environment.

Requirements for Collision Avoidance Safety Systems in Transit Bus

To accurately assess the applicability of a candidate technology for use in a Collision Avoidance System (CAS) for the transit industry, we must first identify and prioritize the high-level system requirements and lower-level derived requirements.

For the purpose of this paper, high-level requirements are divided into four (4) areas, Collision Avoidance (external to vehicle), Passenger Safety (internal to vehicle), transit agency (TA) operational impacts, and return on investment.

- Collision Avoidance – The CAS shall assist the bus operator in avoiding and/or reducing the severity of collisions with pedestrians and cyclist (Vulnerable Road User, VRU), vehicles, and static objects.
- Passenger Safety – The CAS system shall prioritize the safety of passengers by avoiding and/or reducing the severity of panic stops (high-g decelerations) while delivering collision avoidance assistance to the bus operator.
- TA Impacts – The CAS system design and functionality shall minimize negative impacts to TA operational and maintenance procedures.
- Return on Investment – The CAS system should provide a positive return on investment.

Collision Avoidance

Collision avoidance begins with object detection. Object detection encompasses the ability to: identify VRUs, vehicles, and static objects; object discrimination; and object tracking. In short, object detection includes the ability to detect objects of interest such that the CAS can assess if system and/or operator action is required to avoid a collision.

Passenger Safety

The ability for a CAS to incorporate and prioritize passenger safety in its functionality is critical. All aspects of object detection must be performed quickly to allow the bus operator (and potentially an Automatic Emergency Braking, AEB system) to respond without requiring a panic stop. The CAS sensor technology detection range and response time must envelope the bus and VRU speed ranges to avoid bus operator panic stops and/or aggressive maneuvers.

Transit Agency Impacts

The operating environment encompasses all external influences, natural, mechanical, and operational, on the CAS' ability to perform object detection. Natural environment includes weather conditions (rain, snow, fog, sun), temperature range or extremes, and lighting conditions (day, night, shade, tunnels). Mechanical environment includes CAS mounting constraints, shock and vibration, and power sources. Operational environment includes constraints derived by typical TA operations, such as maintenance, repair, passenger on/off-boarding, bus speed ranges, VRU speed ranges, and VRU density. CAS physical design and functional performance must tolerate and/or allow for these environments.

Return on Investment

In general, the system needs have a positive return on investment (ROI). The purchase and installation costs of the VRU collision mitigation system, maintenance costs of the system, and expected lifetime of the system need to be weighed against the expected reduction of liability payouts.

Technology Overview

The primary function of CAS is to assist in the avoidance of collisions with VRUs, vehicles, and static objects (objects). The first step in collision avoidance is to be able to detect, or sense, objects in the path of travel of the bus. Many sensor technologies are available to measure distance or proximity of various types of objects. Selecting a sensor to meet the CAS requirement set becomes a crucial task. An initial set of evaluation criteria was developed to assist with down selecting the technologies best suited for functional and environmental requirements. The selection criteria are as follows:

1. VRU detection confidence – How well does the sensor technology detect VRUs?
2. Vehicle detection confidence – How well does the sensor technology detect other vehicles?
3. Range – How far can the sensor technology see a VRU?
4. Precision – How well does the sensor technology measure VRU distance and location with respect to the front of the bus?
5. Object discrimination – Is the sensor technology capable of distinguishing different types of objects?
6. Robustness – What is the estimated life expectancy within the working environment?
7. Cost – A primary driver of any system design.

The sensor evaluation process was limited to sensor technologies that were readily available (mature products) and being utilized in the transportation industry. The object detection sensor technologies considered for a CAS were radar, ultrasonic, camera (Computer Vision), and LiDAR. Once the evaluation criteria were determined, a method of scoring each technology was developed. A simple low, medium, high technique was used to quickly quantify each criterion per technology. Actual scores were based upon available specifications from various vendors for each of the technologies. The evaluation is summarized in Table 1.

Technology	VRU Detection Confidence	Vehicle Detection Confidence	Range	Precision		Object Discrimination	Robustness	Cost
				Distance	Location			
LiDAR/Flash	High	High	Medium	High	High	Low	Medium	Medium
LiDAR/Scanning	High	High	Medium	High	High	Medium	Medium	High
Radar	Medium	High	High	High	Medium	Low	Medium	Medium
Ultrasonic	High	High	Low	High	Low	Low	High	Low
Vision	High	High	Medium	Low	Low	High	Medium	Medium

Table 1. Sensor Comparison Matrix

Technology Selection and Development

Acting in the role of technology provider/vendor in the FTA SRD project, DCS, after thorough research and evaluation, determined that LiDAR was the appropriate technology for a transit industry collision avoidance system. Radar was found to be unsuitable for detection of most VRUs due to the inability to reliably detect objects with soft tissue. Ultrasonic sensors were found to have inadequate range capability. Vision systems proved more viable than ultrasonic and radar solutions; it could not only detect VRUs but, through various algorithms, are able to discriminate between different objects. For example, Computer Vision can classify an object as a pedestrian, car, and other type of object. However, computer vision lacks high resolution distance and location measurement capability. Two types of LiDAR systems were evaluated: scanning and flash. Scanning LiDAR was discounted early in the evaluation process due to the high cost. Flash LiDAR provided a reasonable price to performance ratio. LiDAR had longer range than ultrasonic, detected VRUs much better than radar, and avoids the distance and location measurement challenges of Computer Vision. Lidar directly measures an objects distance which allows relative velocity of the object to be calculated. The relative velocity, as well as the real measured distance, allows for a more accurate response to dangerous situations.

With the CAS requirements, operating environment, and sensor technology defined, the Theory of Operation and Operating Design Domain (ODD) can now be addressed. The CAWS used in the SRD project, Pedestrian Avoidance Safety System (PASS), will be used as an example to provide performance parameters and specifications.

PASS Theory of Operation

PASS is a Collision Avoidance Warning System (CAWS) with an automatic vehicle deceleration feature designed to provide a bus operator 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. Simply stated, PASS initiates collision avoidance by decelerating the vehicle through a two (2) step, de-throttle & brake apply, process. Deceleration is performed with every consideration of on-board passenger safety.

PASS simultaneously detects and tracks up to twenty-four (24) discrete objects in the vehicle/bus Area of Interest (AOI). The AOI is tuned to transit agency preferences, vehicle response time and deceleration rates, and unique route requirements. The AOI is dynamic, accounting for the bus path-of-travel in straight path or turning conditions (see Figure 1).

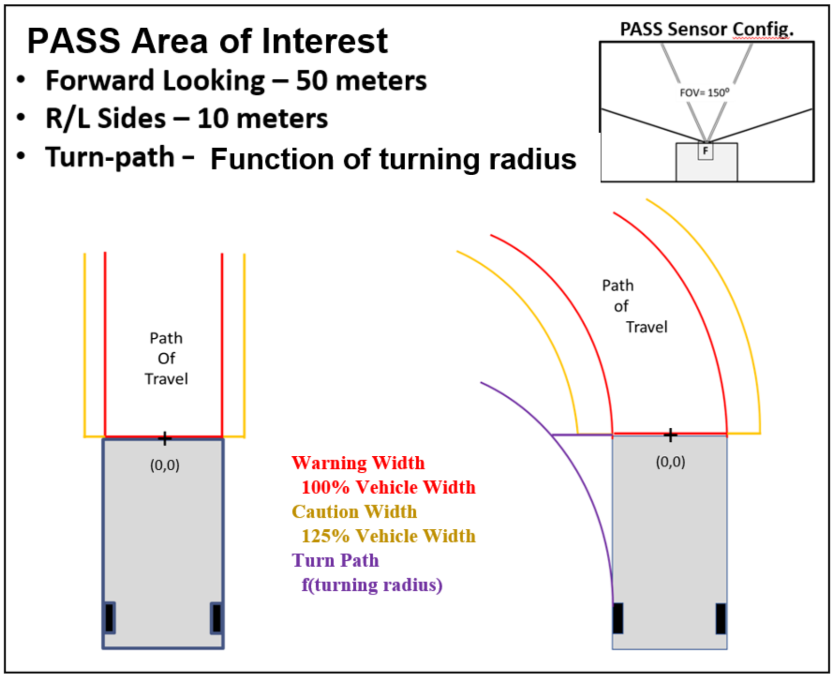

Figure 1 PASS – Detection Area - Area of Interest – AOI

PASS also can be outfitted with the telematics data logging system. This system acts like a black box and records telematics and CAWS event data. This data is used to monitor the performance of the PASS system and to be used in reconstructing events of interest after they occur.

PASS is designed to be robust and easily mountable to various vehicle platforms. Furthermore, PASS has been tested to the SAE J1455 vibration profiles (heavy duty applications), and to ISO 20653 IP67. The sensor enclosures are designed to mitigate impacts of the transit operating environment, natural, mechanical, and operational. The final design of the PASS LiDAR sensor enclosures that comprise the PASS sensor assembly is shown in Figure 2**Error! Reference source not found.**.

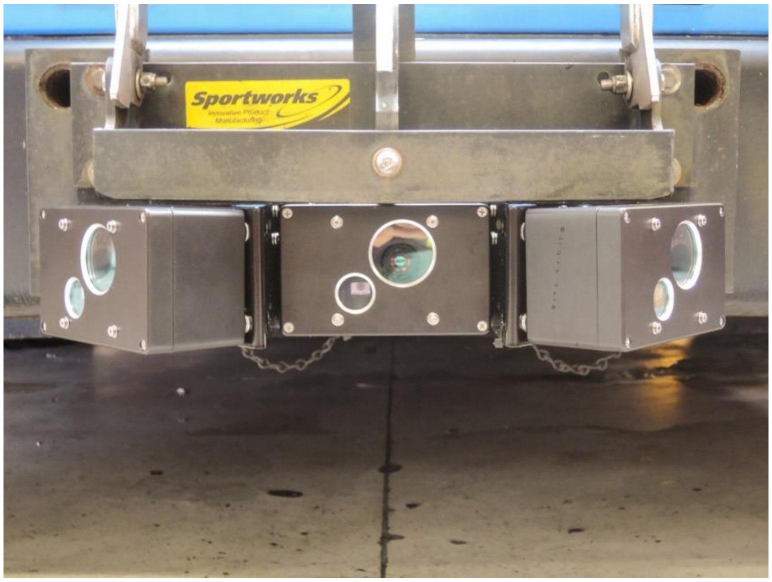

Figure 2 PASS LiDAR Sensor Assembly

Operational Design Domain

Again, DCS' PASS will be used as an example. The CAWS ODD seeks to maximize overall collision avoidance performance while balancing the chosen sensor technology's strengths and weaknesses. The PASS CAWS and AEB performance parameters or ODD are captured below. See Table 2 and Table 3.

Table 2 PASS CAWS Performance Parameters

Collision Avoidance Warning System (CAWS) Performance Parameters	
Operating/Functional Conditions[1]	
Lighting	Day & Night (All)
Rain	Yes[2]
Fog	Yes[2]
Snow	Yes[2]
Object Discrimination	No[3]
Area of Interest/Detection	
Frontal	144º FOV - Covers A-pillar blind spot
Side (Left/Right)	TBD[4]
CAWS Outputs/Conditions[5]	
Caution	
Condition	Object detected near vehicle PoT + meets Warning/AEB condition.
	Object detected in vehicle PoT + approaching Warning/AEB condition.
Output	
	Yellow Light Signal (A-pillar & Center Windshield)
Warning	
Condition	Object detected in vehicle PoT + meets Warning/AEB condition.
Output	
	Red Light Signal (A-pillar & Center Windshield)
	Buzzer/audible signal
Notes	
1. Increased risk of panic stops above 25mph.	
2. Performance may be degraded if conditions are heavy.	
3. Object(s) must be in projected vehicle Path-of-Travel (PoT).	
4. Optional addition to meet customer requirements.	
5. Tunable to meet customer requirements.	

Table 3 PASS AEB Performance Parameters

Automatic Emergency Braking (AEB) Performance Parameters	
Operating/Functional Conditions[1]	
Lighting	Day & Night (All)
Rain	Yes[2]
Fog	Yes[2]
Snow	Yes[2]
Operator Over-ride	Yes
AEB Functions[4]	
Dethrottle	
Response time (s)	0.02
Brake Apply	
Response time (s)	0.02
AEB Outputs/Conditions[5]	
Warning/AEB	
Condition	Object detected in vehicle PoT
	Object detected meets PASS' Critical Distance threshold.[6]
Output	
	Red Light Signal (A-pillar & Center Windshield)
	Buzzer/audible signal
	Activate AEB function
Notes	
1. Increased risk of panic stops above 25mph.	
2. AEB activation does not interfere with normal ABS and TCS functionality.	
3. Object(s) must be in projected vehicle Path-of-Travel (PoT).	
4. Vehicle electro-mechanical delay not included.	
5. Tunable to meet customer requirements.	
6. Critical Distance based on DCS proprietary algorithms.	

Federal Transit Administration (FTA) Safety, Research, and Demonstration (SRD) Project: Technology Application

DCS Technologies, Inc. was selected as the CAWS/AEB vendor utilizing the Pedestrian Avoidance Safety System (PASS) as the VRU detection (CAWS) and AEB system. The AEB portion of PASS had been developed and fielded prior to the SRD grant award. As part of the grant, a LiDAR based CAWS system would be developed as the trigger source for the AEB system. The complete PASS package of CAWS and AEB was fielded on 30 Pierce Transit buses for evaluation. Testing of the PASS was the first portion of the SRD project.

At the time of development, the transit industry lacked a VRU CAWS/AEB test protocol. Therefore, a phased test plan was developed to include closed-area and on-the-road evaluation. In preparation for closed-area testing, Alpha testing, DCS tailored two (2) existing protocols, Euro-NCAP [3] and SAE J3029 [4], to capture transit VRU and vehicle-to-vehicle scenarios. Alpha testing was performed over two (2) weeks at the Virginia Tech Transportation Institute (VTTI) Smart Road facility. The test bus, a 40ft LF New Flyer provided by Pierce Transit, 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. Test scenarios included day and night, static and dynamic VRU, and rain/fog conditions with examples shown in Figure 3. Additionally, raw sensor data and vehicle telematics were captured for each of the 550 test runs. This data now serves as a "control" stimulus for offline Software in the Loop (SWIL) PASS tuning and regression testing. An example of typical CAWS-AEB data captured during Alpha testing is shown in Figure 4**Error! Reference source not found.**. The plot shows the decomposition of the CAWS detection and response, AEB activation, and bus operator induced deceleration.

Figure 3 Test Run Samples

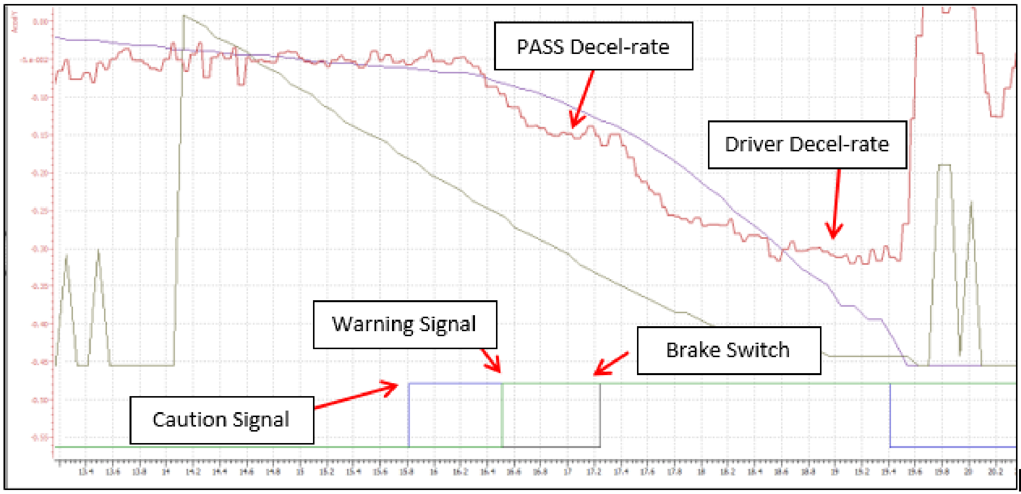

Figure 4 ALPHA Test CAWS-AEB Event Decomposition

After successful execution of Alpha testing, the test PASS equipped test bus was returned to the Pierce Transit fleet in support of Beta testing. The goal of Beta testing was to prepare for potential revenue service with the PASS system fully activated. Beta testing included the equipping an additional three (3) 40ft LF New Flyer buses with DCS' PASS and Data-logging units. The testing included exercises of the Telematics data collection processes, necessary hardware and software updates, and system monitoring/maintenance. Verbose data was collected during Beta engineering trials. Each engineering trial allowed DCS engineers to collect a full suite of vehicle and PASS telematics with accompanying video. Further SWIL data was captured during beta as well.

After Beta testing was concluded, the AEB portion of PASS was decided to not be enabled. Pierce Transit's readiness for active revenue service operation was dependent on gaining OEM technical approval of the PASS-Vehicle integration. Unfortunately, impacted by the COVID-19 pandemic, the OEM was not able to allocate resources to this effort. However, DCS further improved the PASS system and installed PASS on thirty (30) buses at Pierce Transit. Then, non-revenue and stealth mode, testing began. During this phase of the project, data was collected (Table 4) on each of the project buses that included location data, vehicle dynamics data, and object tracking data of the PASS system.

Source	Data Element	Data Element Description	Measurement Unit	Resolution
Vehicle	Bus Number	Identification number of the bus under test		1
	PASS Event ID	Identification code of PASS Event.		1
	PASS Event Vehicle Location	GPS longitude/latitude coordinate of a PASS Event	Degrees	0.000001
	Time Stamp	Time stamp of PASS Event synchronized to GPS UTC	UTC (ms)	1
	Vehicle Heading (GPS)	Vehicle directional heading at the time of the PASS event as reported by the GPS unit	Degrees	0.1
	Vehicle Speed (J1939)	The vehicle speed at the time of the PASS event as reported by the J1939 CCVS message.	MPH	0.1
	Vehicle Brake Switch	The Vehicle foundation brake application state as reported by the J1939 CCVS message.		1
	Vehicle Throttle	The Vehicle throttle position as reported by the J1939 EEC2 message.	%	1
	Vehicle Longitudinal Acceleration	Measured vehicle acceleration along the longitudinal axis.	g	0.001
	Vehicle Latitudinal Acceleration	Measured vehicle acceleration along the latitudinal axis.	g	0.001
	Vehicle Vertical Acceleration	Measured vehicle acceleration along the vertical axis.	g	0.001
	Vehicle Yaw Rate	Measured vehicle Yaw rate.	°/s	0.1
PASS	PASS Operating Mode	PASS operating mode: Stealth CAWS Only CAWS + AEB Faulted/Non-Op		
	Object Relative Velocity	The relative velocity of the object at the indication of a Collision Warning	MPH	0.1
	Object Distance	The distance from the vehicle collision point and the object at the indication of a Collision Warning	Feet	1
	Object TTC	Time to Collison of the object	Seconds	0.01

Table 4 SRD Project Data Set

Once the data collection process for the PASS systems began, the intrinsic value of the telematics data for generation of data analytics and transit agency fleet management became evident. Therefore, a suite of tools including data repository and customizable analysis (Histograms, box plots, heatmaps, event classifications, and simulated/virtual recreations of events) were developed. Below are some examples of outputs generated from the data.

Figure 5 shows high-level statistics of specific telematics data correlated to PASS activations.

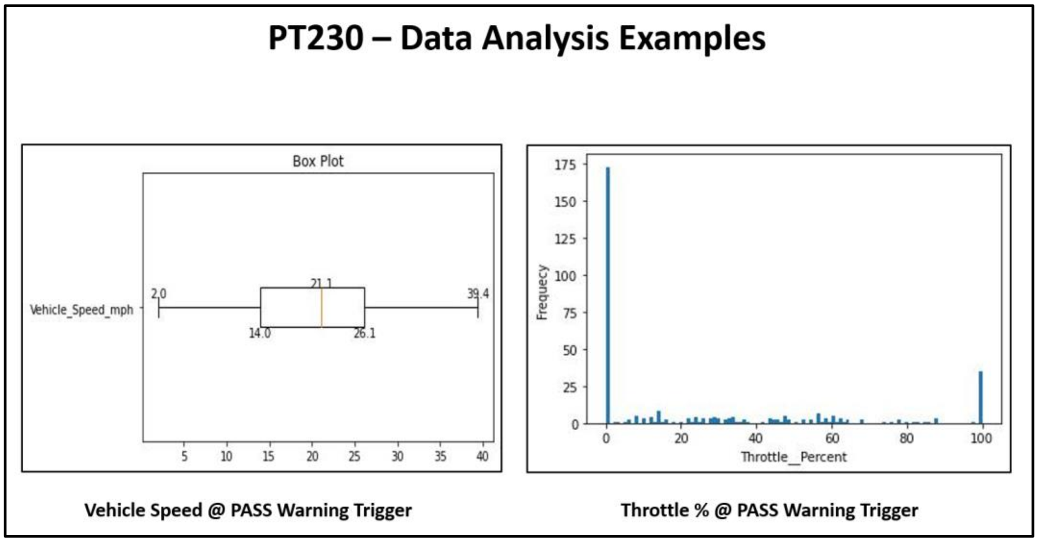

Figure 5 Example SRD Project Data Analysis – Box Plot and Histogram

Figure 6 shows approximately twelve (12) months of PASS activation history in a bus route heat map. Each activation can be uniquely inspected for telematics data at PASS activation.

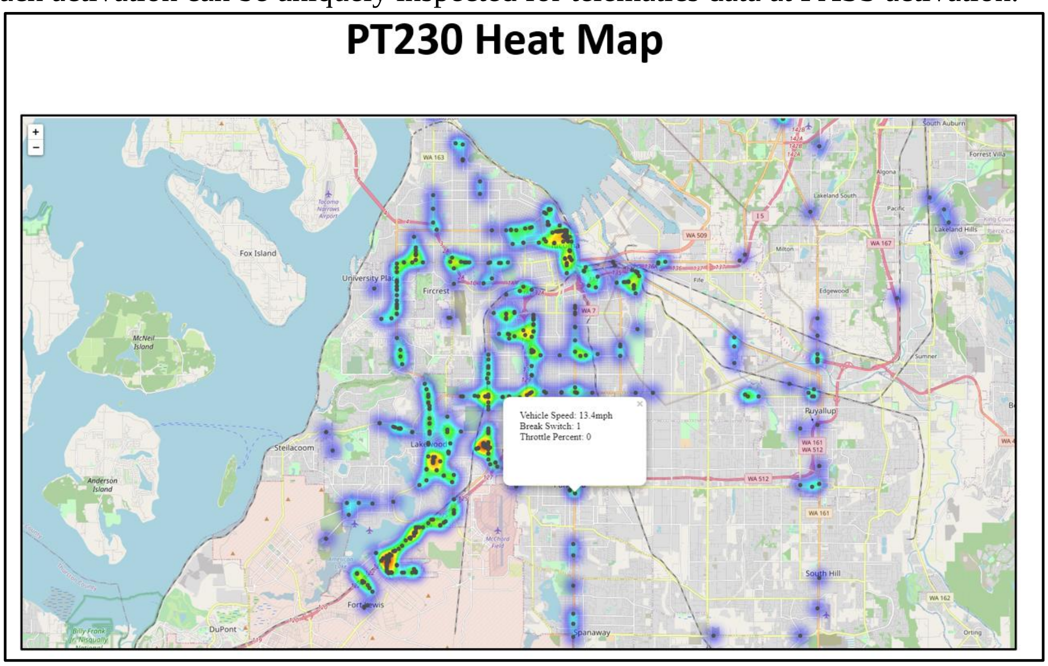

Figure 6 Example SRD Project Data Analysis - Heat Map

Figure 7 shows a single frame of a PASS event window video simulation/play-back. The play-back feature provides visual post-processing of raw telematics data at/during each PASS activation.

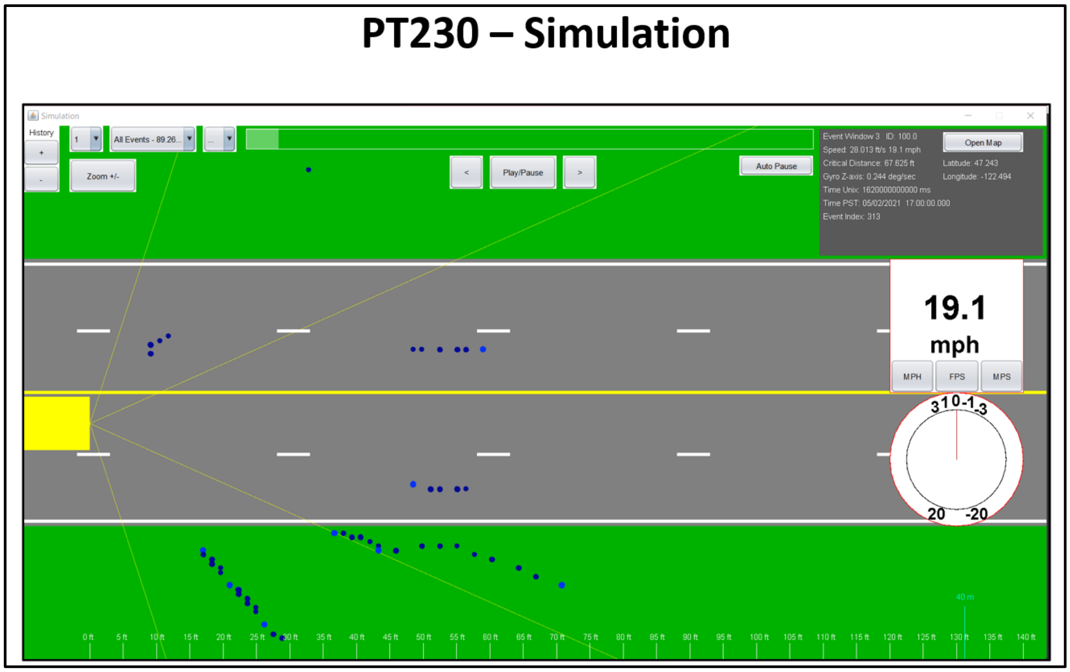

Figure 7 Example SRD Project Data Analysis - Event Simulation/Playback

Lessons Learned

Throughout the SRD project, various lessons were learned about adapting a VRU collision avoidance system into the transit industry. The lessons can be categorized into technology driven lessons and non-technology driven lessons. Technologically speaking, the cons of a solely 2D LiDAR based system became evident. Firstly, reflective objects, such as road signs, reflective tape, and raised road reflectors, became obvious generators of false positives or noise. These types of objects saturated the sensors and made the objects seem larger that they are. A system that utilizes Computer Vision would ignore these objects because their shapes, more often than not, do not resemble the shapes of VRUs. Furthermore, the location of 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 the bike rack and bikes on the bike rack, can create interference for certain mounting locations. Other mounting locations, like the mirrors, have a higher potential to collide with objects in the environment, like tree branches, as compared to other mounting locations.

The major non-technological lesson learned was that of transit specific performance evaluation criteria for collision avoidance systems. For example, there are many ways to determine system accuracy and early agreement on the definitions, terms, and metrics to determine system accuracy is critical.

Key terms:
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.

False Positive (FP) – A CAWS Warning event which cannot be correlated to a Dangerous Condition/Event through review of objective evidence.

False Positive Rate (FP_rate) – Number of FP CAWS Warning events, per a given metric, which are determined to be False Positive events (FP_rate = #FP/metric). FP_rate can be calculated against several metrics (e.g. miles, hours, CAWS_Warning_Events, Objects_detected). Each FP_rate calculation captures a unique measure of system performance. Transit agency policy and/or operational environment will determine which FP_rate (metric) is most critical or informative.

Near Miss Event – "A near-miss incident is defined as an unintentional unsafe occurrence in a traffic incident management area or work zone that could have resulted in an injury, fatality, or property damage. Only a fortunate break in the chain of events prevented an injury, fatality, or damage. Any time traffic control devices near the crash scene or work area are struck, a near-miss event should be recorded." [5]

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. 0.3g) as a result of a panic stop or evasive maneuver. External: bus and 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 Negative (FN) – An external Dangerous Condition/Event which 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, per a given metric (FN_rate = #FN/metric). FN_rate can be calculated against several metrics (e.g. miles, hours, Objects_detected). Each FN_rate calculation captures a unique measure of system performance. Transit agency policy and/or operational environment will determine which FN_rate (metric) is a most critical or informative.

CAWS/AEB System Accuracy – AEB systems have the primary function of automatically decelerating the vehicle safely. Accuracy is primarily a measure of the CAWS system. CAWS systems have two (2) primary functions regarding accuracy: 1) Object detection and 2) Imminent Collision determination (respond or ignore). Accuracy of a CAWS/AEB system is the measure of how well a system performs these primary functions. The Key Terms and Definitions above can be used to calculate or measure a system's Accuracy.

When the terms and definitions are clearly defined as above, comprehensive accuracy calculations and descriptions can be generated. Without such terms being defined appropriately, a system cannot be objectively shown to be accurate or inaccurate.

A secondary non-technological lesson learned involved execution of closed-area testing. Introduction of new technology can be aided by including professional bus operators in closed-area testing. Professional operators provide a unique perspective on "acceptable" system performance. Additionally, early involvement in the process may increase driver acceptance of the technology.

Future Enhancements

From the lessons learned about LiDAR in transit, many enhancements can be made to a 2D LiDAR based VRU collision mitigation system to help drive down the False Positive Rate due to detected object discrimination. Many False Positive triggers are driven by detections of objects that do not pose a VRU collision threat such as highly reflective objects, such as road reflectors and street signs off the side of the road. One way to address object discrimination would be to utilize a 3D LiDAR sensor. The point cloud generated from a 3D LiDAR sensor generates a better representation of objects than the single point plane of a 2D LiDAR sensor, allowing for categorizing objects in the environment. Another solution to the lack of object discrimination in a 2D LiDAR system could be the addition of Computer Vision fused with the LiDAR system. The addition of radar sensors could also be added to improve the highway vehicle-to-vehicle performance of a LiDAR based system. Further, as requirements for VRU collision mitigation systems become refined, detection algorithms can be updated to improve to achieve an improved balance of system accuracy (FP/FN) and TA impacts (driver acceptance).

Summary

This paper provided high-level requirements and objective criteria for the selection of sensor technology for CAWS/AEB systems in the transit industry. Extensive testing was performed and discussed. Additionally, key lessons-learned and viable future enhancements were introduced. To thoroughly characterize a LiDAR based system in transit AEB functionality would need to be activated. Furthermore, improved closed area testing would allow for a comprehensive, controlled analysis of a VRU collision avoidance system’s accuracy.

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