Developing and Testing a 2D Flash Lidar Transit Bus Collision Avoidance Warning System – DCS Technologies, Inc.

Pedestrian Avoidance Safety System (PASS) Description

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. PASS initiates collision avoidance by decelerating the vehicle through a two-step, de-throttle and brake apply, process. Deceleration is performed with consideration of on-board passenger safety.

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 to 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 (see Figure 1).

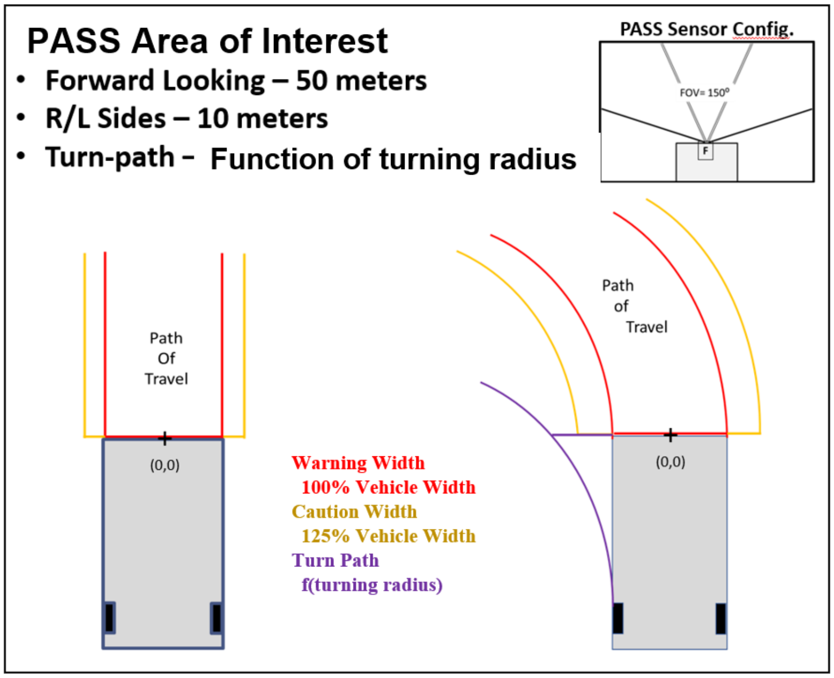

Figure 1 PASS – Detection Area - Area of Interest

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. The PASS object VRU detection system uses an array of three solid state 2D flash light detection and ranging (LiDAR) sensors attached to 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 chosen for PASS due to its inherent durability and cost advantage over oscillating LiDAR systems. Sensor array specifications are shown in Table 1.

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 (ºC)	-40 to 85
Storage Temp (ºC)	-40 to 85
Shock/Vibe	SAE J1455
Sensor Characteristics	
Field of View Horizontal/Vertical (º)	144/3
Technology	2D Flash LiDAR
Wavelength (nm)	905
Accuracy (cm)	± 5
Refresh Rate (Hz)	12

Table 1 Sensor Array Specifications

Figure 2 shows an isometric engineering drawing of the sensor assembly. The assembly is bolted to the support bracket for the folding bicycle rack as shown in Figure 3 mounted to the front of a typical transit bus.

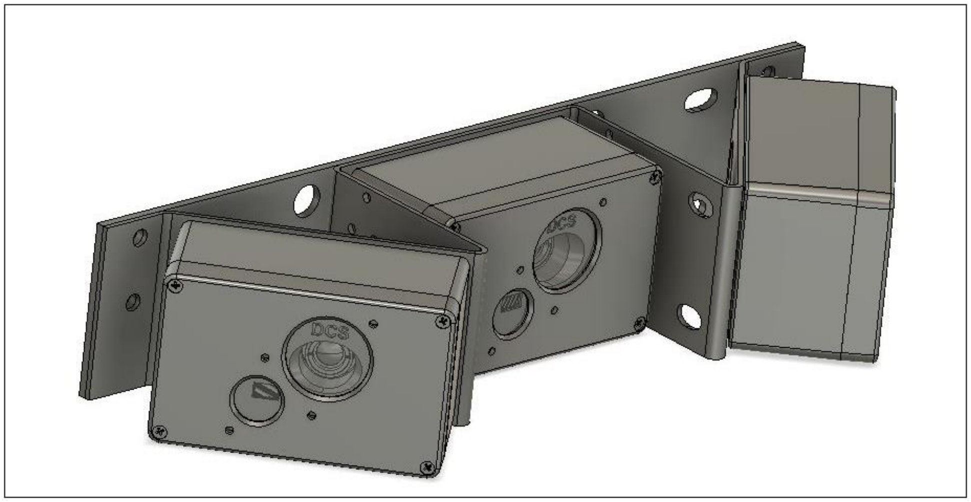

Figure 2 PASS LiDAR Sensor Assembly

Figure 3 PASS Sensor Assembly attached to Pierce Transit Bus #230

PASS Operational Design Domain (ODD)

The CAWS 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 2.

Collision Avoidance Warning System (CAWS)/Automatic Emergency Braking (AEB) Performance Parameters	
Operating/Functional Conditions	
Field of View (FOV)	144º (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]
System Reaction Time[3]	
Dethrottle Response time (s)	0.02
Brake Apply Response time (s)	0.02
Notes 1. Critical Distance based on DCS proprietary algorithms. 2. AEB activation does not interfere with normal ABS and TCS functionality. 3. Vehicle brake system delay not included.	

Table 2 PASS CAWS/AEB Performance Parameters

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 (bus #s 230-233) 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. Data was archived and backed-up for project security.

Table 3 shows a summary of the PASS telematics data set. Each Data Element represents a data column in the PASS Event file. The data elements capture general timing information, vehicle J1939 data, vehicle location, vehicle acceleration, and gyroscopic (turning) data, and PASS Automatic Emergency Braking (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) will begin the collection of the data set, at a 40ms rate, for the duration of the AEB event. Additionally, two seconds of pre-trigger and post-trigger data (40ms rate) were collected with each AEB event.

Source	Data Element	Data Element Description	Measurement Unit	Resolution
Vehicle	Bus Number	Identification number of the bus under test		1
	PASS Event Vehicle Location	GPS longitude/latitude coordinate of a PASS Event	Degrees	0.000001
	Time Stamp	Time stamp of PASS Event	UTC (ms)	1
	Vehicle Heading (GPS)	Vehicle directional heading at the time of the PASS event as reported by the GPS unit (COG)	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		1
	PASS Event ID	Identification code of PASS Event		1
	Object Relative Velocity	The relative velocity of the object (Longitudinal/Latitudinal wrt VUT)	MPH	0.1
	Object Distance	The Object position from the VUT (Longitudinal/Latitudinal wrt VUT)	Feet	1
	Object TTC	Time to Collison of the object	Seconds	0.01

Table 3 SRD Project Data Set

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 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 4.

SYSTEM PROCESSING & DATA LOGGING	
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 (ºC)	-40 to 85
Storage Temp (ºC)	-40 to 85
Communication/Algorithm Characteristics	
Master Controller Clock Speed	64MHz
Algorithm Processing Rate (Hz)	50
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 º/s

Table 4 PASS System Processing and Data Logging Specifications

Alpha Testing

Alpha testing was conducted at Virginia Tech Transportation Institute (VTTI) Smart Road Test Track in Blacksburg, VA. VTTI and DCS jointly developed a test plan for simulating collisions with pedestrians “vulnerable road users” (VRU’s) and forward collisions with vehicles[1]. For collision avoidance with VRU’s, a simulated intersection was constructed to represent one that PT buses regularly traverse. The simulated intersection included lane markings, stop 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 4 shows a drone view and graphical overlay of the test track intersection. Forward collision testing was performed on a high-speed section of the Virginia Smart Road facility.

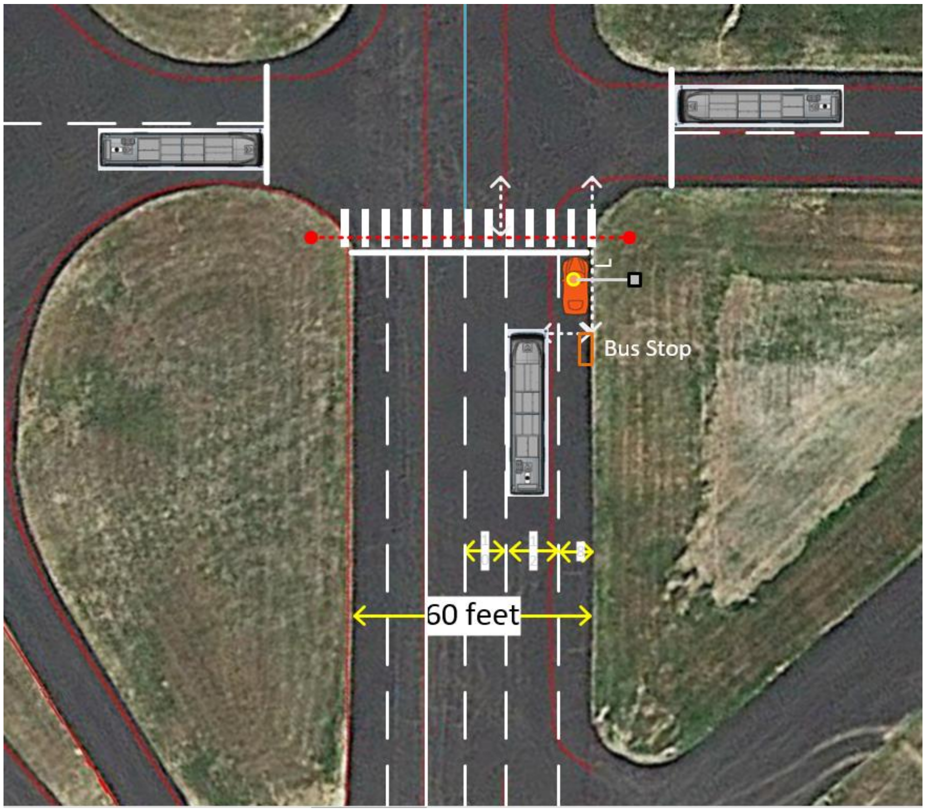

Figure 4 Drone view and graphical overlay of bus approaches on test track intersection Photo credit: VTTI

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

Figure 5 shows a forward collision test using a towed inflatable dummy vehicle. Figure 6 shows the bus braking automatically for the VRU at the simulated intersection during a test.

Figure 5 Forward Collision Avoidance Test Photo Credit J Lutin

Figure 6 VRU Collision avoidance test Photo credit: VTTI

Alpha testing consisted of two (2) four (4) day test sessions at the VTTI Smart Road facility. PT Bus #230, 40ft/12.2m 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 Euro-NCAP and SAE J3029 protocols. Test scenarios included day and night, static and dynamic VRU, and rain/fog conditions.

The two (2) 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. This data served as a "control" stimulus for offline Software in the Loop (SWIL) PASS tuning and regression testing throughout the project. 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.

System Response Time (SRT) represents the summation of PASS and Vehicle Response Time (VRT). VRT is defined as the time between a brake command being sent from PASS and the time when the bus braking system is fully engaged. PASS algorithms use SRT in CAWS/AEB activation calculations. PASS response time is 20ms, typical (40ms, worst-case). Characterization of PT Bus #230 found the Vehicle Response Time (VRT) to be approximately 550ms. Baseline PASS tuning, at the beginning of Alpha testing, assumed a 100ms VRT. The larger actual VRT of bus #230 resulted in late PASS activations and driver panic stops. The PASS VRT calibration value was adjusted to match the measured results. Subsequent testing showed improved PASS-Driver activation and stopping performance.

PASS algorithms utilize the Vehicle Deceleration Rate in CAWS/AEB activation calculations. With passenger safety of utmost importance, DCS ensured PASS deceleration rates below 0.3g. Characterization of PT Bus #230 measured a vehicle deceleration rate during AEB of 0.11g.

Baseline PASS tuning, at the beginning of Alpha testing, assumed a 0.2g vehicle deceleration rate. The lower actual deceleration rate of bus #230 resulted in late PASS activations and driver panic stops. The PASS deceleration rate calibration value was adjusted to match the measured results. Subsequent testing showed improved PASS-Driver activation and stopping performance.

PASS performance throughout Alpha testing showed 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 CAWS/AEB triggers. DCS reduced the number of ground noise False Positives through adjustments to sensor assembly mounting and CAWS algorithm changes. At the completion of Alpha testing, DCS concluded that further ground noise mitigation was required prior to commencement of the revenue test phase.

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

PASS Telematics Analysis

During the period November 5, 2020, to July 31, 2021 (after the final PASS software update) a total of 4,607 log files were collected over 930,000 operational miles from the 30 project vehicles. **Table *5*** summarizes high-level metrics (Total PASS Warning Events, Estimated Bus Operating Hours or Uptime, Warning Events per hour, and Operating Miles) for the nine-month period.

	PASS Warning Events	**Estimated Bus Operating Hours**	**Average Events/Hour**	**Operating Miles**

Totals	**42,343**	**34001.5**	**1.2**	**930,000**
Average/Day	9.2	7.4	1.5	
Min/Day	0.0	0.5	0.0	
Max/Day	75.0	23.1	18.0	

Table 5 Summary PASS Data Metrics (November 5, 2020, - July 31, 2021)

Preliminary decomposition of the full data set is shown in the following graphs. Data measured at the instant of a PASS warning event provides some insight into vehicle operating conditions and operator behavior. During the data collection period, PASS was 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.

Error! Reference source not found. Figure 7 shows the VUT vehicle speed at PASS events for all 30 PASS-equipped project buses. The histogram indicates the presence of two overlapping distributions at 15mph and 25mph 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 22.6mph (36.4kph), with 50 percent of measured events occurring between 15mph and 28mph (24kkph and 45kph).

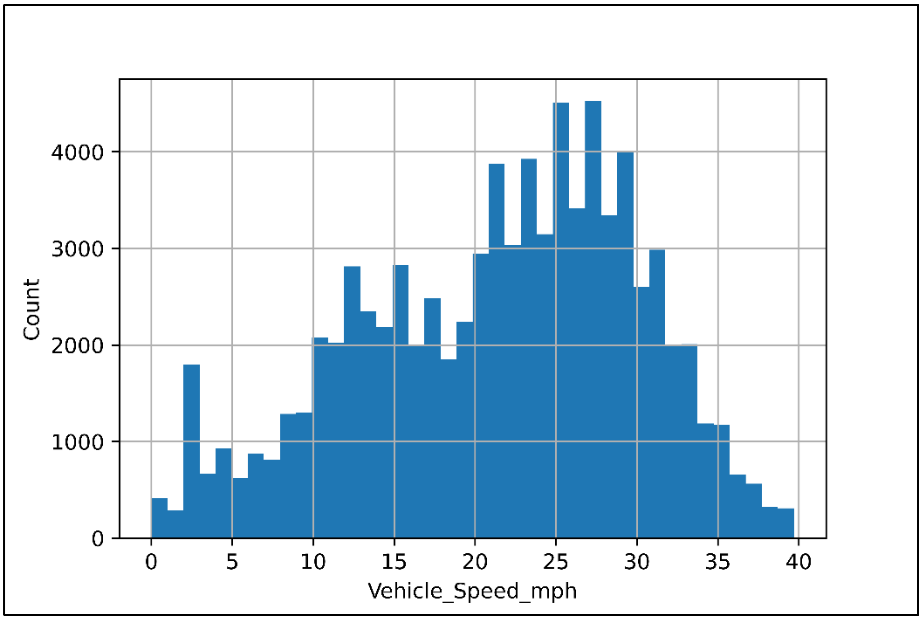

Figure 7 Bus Speeds at PASS Warning Events

Error! Reference source not found.Figure 8 shows the VUT throttle percent at PASS warning events for all project buses. The histogram shows two peaks at zero percent and 100 percent. The 100 percent spike may be indicative of events occurring near bus launching. The zero percent spike may indicate an aware driver responding to, slowing down and or stopping, in normal operating conditions.

Figure 9 shows the VUT Brake Switch at PASS Warning events for all project buses. **Error! Reference source not found.**The Brake Switch signal is a binary (off/on) signal. There was no indication available for percent brake application. **Error! Reference source not found. Figure**

9 shows that the operator was applying the brake at the time of the PASS warning event during approximately one-third of the PASS events. Viewing these results with those in **Error! Reference source not found. Figure 8** may reinforce the idea that zero percent throttle events do indicate an operator responding to, or preventing, a dangerous event. This theory ties the two events, Throttle lift (0%) and Brake Switch (ON), together as an indication of the 2-step, throttle-lift + brake-apply, deceleration process.

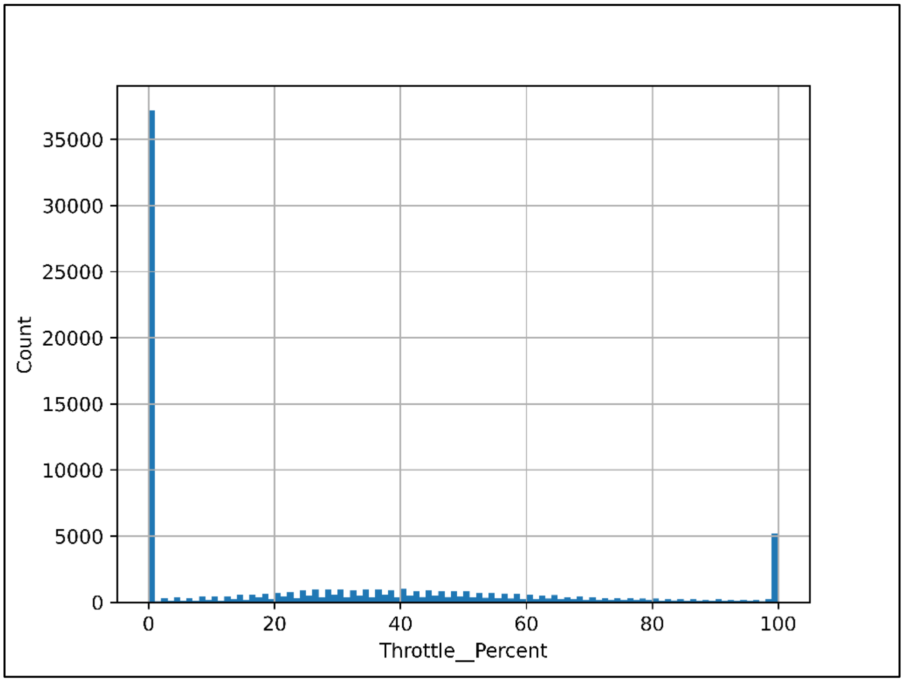

Figure 8 Bus Throttle Percent at PASS Warning Events

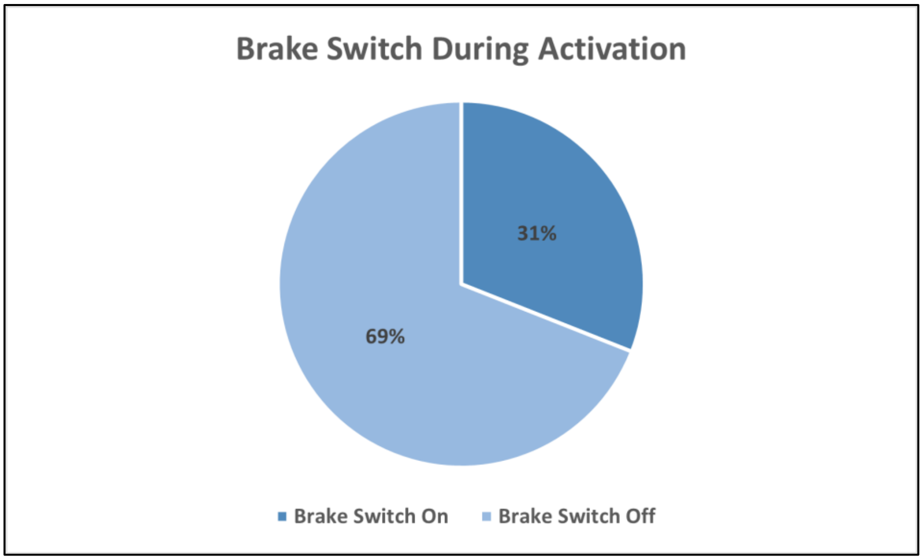

Figure 9 Bus Brake Switch at PASS Warning Events

Taking the theory of evidence of a two-step deceleration process further, **Error! Reference source not found.** Figure 10 shows VUT forward deceleration at PASS warning events for all project buses. Negative values indicate deceleration. The graph appears to show higher incidence in distribution for values beyond -0.1 g. It is reasonable to associate these data with Brake Switch Applied events, subject to further analysis.

Figure 11 shows the VUT gyro z-axis data (turning maneuvers) at PASS Warning event for all project buses. Gyro Z-axis (deg/sec) is shown to provide additional insight into operator/bus maneuver at the time of the PASS Warning event.

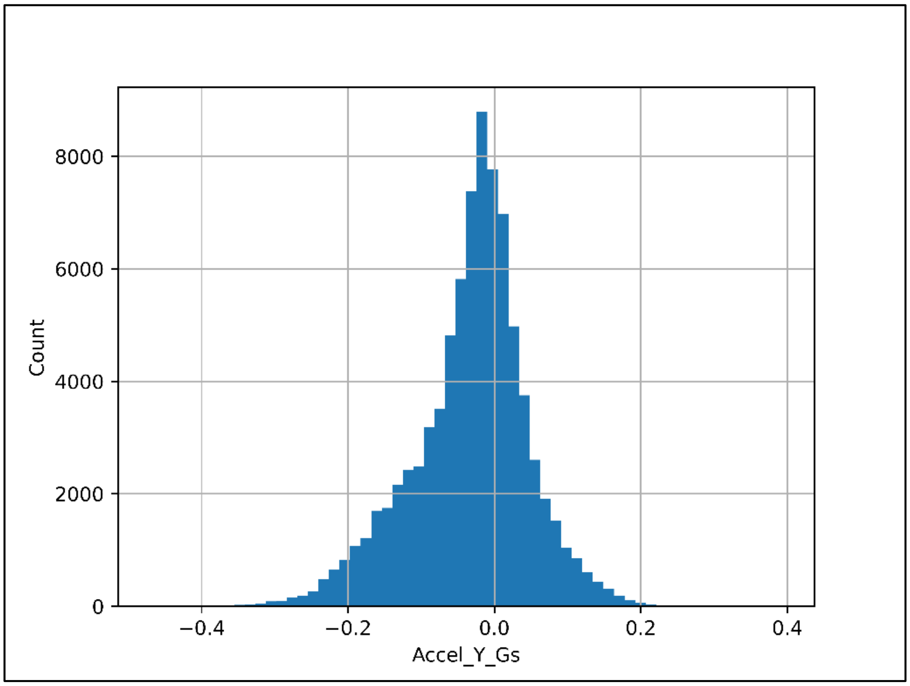

Figure 10 Forward Deceleration at PASS Warning

Figure 11Error! Reference source not found. 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. This 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.

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 a total of 30 New Flyer LF buses from the initial Alpha system on bus 230 in March of 2019 to full fleet installation of production units completed in September of 2020. Buses 230-233 then received production upgrades during the full fleet installation phase completed in September of 2020. A PASS software update to address 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 of 2021. In April of 2020, the PASS logger system received a software update to accommodate a DCS backend server connectivity update. This software update did not affect collection of PASS system data nor any partner interfaces.

All PASS maintenance items were tracked throughout the project**Error! Reference source not found.** documents any item that required replacement due to component failure or physical damage. Physical damage includes events such as traffic accidents or unavoidable environmental factors (e.g., rock strikes). Out of the nine items listed in **Error! Reference source not found.**, 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 allowing moisture into the sensor enclosure.

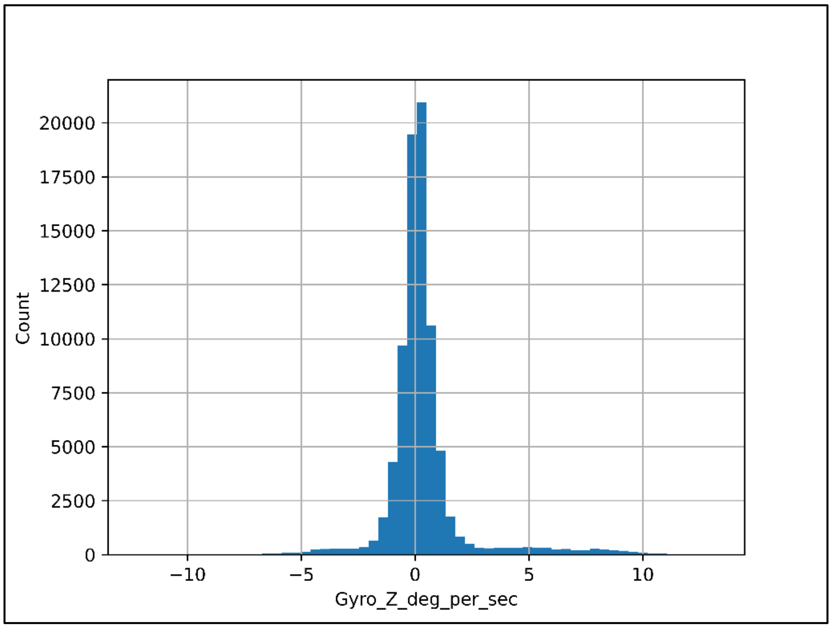

Figure 11 Bus VUT Turning (Gyro-Z) at PASS Warning

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PASS was designed and tested to meet a minimum 100,000 Mean Distance (miles) Between Failure (MDBF). The total test fleet vehicle mileage for PASS production equipment was approximately one million miles. With the five component failures during the project timeframe, MDBF calculates to 200,000 MDBF.

PASS Maintenance Events			
Date	**Bus #**	**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.

Table 6 PASS Maintenance Summary

Lessons Learned

Throughout the SRD project, various technical lessons were learned about adapting a VRU collision avoidance system into the transit industry.

1. Sensing Technology Limitations
    - **2D vs. 3D Flash LiDAR:** 2D flash LiDAR was selected as the object detection sensor system primarily for its cost to performance ratio relative ease of integration with the existing PASS AEB system. The 2D sensor technology provides measurement resolution in distance to object and in the horizontal plane. The vertical plane does not provide any distinction within the entire vertical field of view of the sensor. This is problematic when determining an object's vertical location. Think overhead traffic sign versus a pedestrian.
    - **Highly Reflective Objects:** LiDAR utilizes the time of flight for a light pulse to reflect off an object to precisely measure the object's distance from the sensor. As so, the

LiDAR light detectors are extremely sensitive. This sensitivity can be overwhelmed by highly reflective objects causing temporary inaccuracies in the exact location of an object with respect to the sensor. This can "trick" PASS to think that an object is in the path of the vehicle.

- **Restricted Sensor Mounting Locations:** LiDAR is a line-of-site distance measurement technology. This means there can be no objection between the LiDAR sensor and the object(s) being measured, including windshield glass. By looking at the front of a transit bus, the claim space available to mount an array of LiDAR sensors is extremely restricted. In a perfect world, the sensor array would be mounted in the center of the front of the bus about 3 feet off the ground. Right where the bike rack/bikes reside. The only location left was below the bike rack about 18 inches off the ground. Combined with the lack of vertical resolution of the 2D LiDAR sensors, a precise mounting alignment needed to be developed to prevent visual interference from the ground ahead of the bus and the lower edge of a lower bike rack.
- **Object Discrimination:** LiDAR technology provides extremely accurate distance to object measurements on the order of centi-meters. However, with the 2D systems used for this project, the type of object could not be determined by the tracking algorithms. If the CAWS algorithms "know" the type of object that is being tracked by the LiDAR sensors, better decisions can be made as to what is considered a VRU

2. Expanded Closed/Controlled Area Testing
   - **Beta Evaluation:** The Alpha testing at VTTI was crucial to technically evaluate a new technology in very specific test scenarios. Many of the results of Alpha testing were rolled into early system improvements. As part of introducing a new technology into transit, evaluation and feedback from professional bus operators via extended closed/controlled-area evaluation. Professional operators provide a unique perspective on "acceptable" system performance. Additionally, early involvement in the process may increase driver acceptance of the technology.
3. Project Terminology and Definitions
   - **Terminology Consensus Prior to Data Collection:** One of the difficulties in this project, was to establish a consensus of terminologies and definitive definitions of key performance metrics and evaluation criteria for transit specific 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. Below is a list of key terms that DCS feels best defines the metrics to evaluate a transit CAWS/AEB system.
     - 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." [1]
- 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.

4. Defining CAWS/AEB System Accuracy in Transit

Accuracy of a CAWS/AEB system is primarily a measure of the CAWS system. The AEB system has the primary function of automatically decelerating the vehicle safely. 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. Over-emphasis on FP/FN counts creates obstacles to collision avoidance technology acceptance into the transit industry.

Before examining this assertion, it is appropriate to offer the reader a baseline for the transit industry's collision avoidance goals and objectives.

- Goal: Maximize VRU and vehicle safety while minimizing negative impacts to business operations.
- Objective: Provide the operator a warning and active response in the event of an imminent collision with VRUs and vehicles so to

  - assist operator collision avoidance while preventing injury to transit passengers (avoid high-g decelerations, g > 0.3g)
  - and not create obstacles to operator's execution of duties, safely running routes on schedule.
- In order to achieve operator assistance objective 1, the system must:
  - detect objects of interest
  - identify imminent collisions (respond or ignore)
  - initiate AEB to increase an operator's ability to safely avoid a collision (visual/audible warning and reduced vehicle speed).
- In order to achieve objective 2, the system must:
  - identify imminent collisions in lock-step with an aware operator with respect to timing and risk assessment.

Accepting this baseline, we can now address the assertion – Over-emphasis on FP/FN counts creates obstacles to collision avoidance technology acceptance into the transit industry. Focus on FP/FN counts creates an expectation of zero FP/FNs as a CAWS/AEB transit industry acceptance threshold, ignoring industry Goals and Objectives.

CAWS/AEB telematics data captured in the PASS Telematics Analysis section of this report**Error! Reference source not found.**, provide insight of a system's (PASS') performance with respect to the above goal and objective. Although further analysis of SRD project data is required, it is clear that FP/FN metrics alone fail to capture critical aspects of collision avoidance system performance. FP/FNs should be expected but managed with respect transit industry goals and objectives.

- False Positives should be expected but managed. A CAWS/AEB must initially assume an unaware operator. This initial assumption will generate FPs. Early and long duration activations may create obstacles to operator's execution of duties, safely running routes on schedule. Late activations may negatively impact a system's ability to assist operator collision avoidance while preventing injury to transit passengers (avoid high-g decelerations, g > 0.3g). Therefore, collision avoidance system FP evaluation should incorporate operator acceptance and a measure, possibly time based, of the system's ability identify imminent collisions in lock-step with an aware operator with respect to timing and risk assessment. CAWS/AEB telematics suitable for this evaluation should be identified prior to beginning an evaluation.

- False Negatives must be held as close to zero as possible. FN metrics are inherently difficult to capture accurately. An authoritative source of truth is required to objectively identify a FN through data collection. The sole definitive evidence of a FN is the occurrence of an accident within the operational domain of the system without a CAWS/AEB warning. System evaluation in CAWS (passive) or CAWS/AEB (active) would allow for operator experience data to be collected.

AEB in Revenue Service

One of the main project goals was to evaluate AEB as a feasible safety feature to the transit industry. Early in the project, PASS AEB functionality was installed as a retrofit system, tested, refined, and demonstrated successfully during the Alpha test phase. However, AEB was removed from scope for the remainder of the project due to lack of bus OEM involvement early in the project. Follow-on research is needed and introduction of AEB to transit should remain a primary goal. For successful execution:

1. It is paramount that the executing transit agency works closely with the bus OEM(s) early in the project to evaluate AEB control hardware integration with existing bus systems.
2. Perform additional closed/restricted area evaluation by professional operators to gain crucial feedback of system functionality and affect on day-to-day operations.
3. Perform extended system evaluation in a non-revenue environment on real routes to include real world system responses.

Technology Advancement

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 achieve an improved balance of system accuracy (FP/FN) and TA impacts (driver acceptance).

Rensel, E., Arva, E., Yorks, C., Schofield, T., & Ulp, G. (2013). *A Framework for Collecting Emergency Responder/Roadside Worker Struck-by/Near-Miss Data.* Transportation Research Board. Retrieved from http://onlinepubs.trb.org/onlinepubs/nchrp/docs/NCHRP20-07(321)_FR.pdf

Works Cited

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