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Technical Report

Enhanced Rail Grade Crossing Safety Using Machine Vision and Trusted V2X Communications

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1 Introduction

1.1 Purpose

The project sought to explore emerging and innovative technologies to improve public safety at railway crossings, with a particular focus on solutions that could enhance the situational awareness of road users approaching at-grade crossings. By implementing these technological advancements, it would be possible to alert road users about their proximity to rail crossings, the presence and speed of oncoming trains, and any potentially hazardous conditions ahead at the crossing.

Testing scenarios involved activating rail crossing safety signals as the test vehicle approached the crossing. C-V2X SPaT messages (detailed in section 3.3.1) were sent to the test vehicle at different distances from the crossing. The goal was to collect data to compare how the test vehicle reacted to the activation of the crossing signals.

Additional testing scenarios included a pedestrian (dummy or adult) or bicyclist in the rail safety zone as the test vehicle approached the crossing. C-V2X PSM messages (detailed in section 3.3.2) were sent to the test vehicle. The goal was to collect data to compare how well thermal cameras detected and classified VRUs in various weather conditions (e.g., rain, snow, fog) and to compare thermal camera performance with LiDAR sensor detection.

Further testing scenarios involved a stopped vehicle or queued traffic in the rail safety zone as the test vehicle approached the crossing. C-V2X TIM messages (detailed in section 3.3.3) were sent to the test vehicle. The goal was to collect data to compare how well RGB cameras detected and classified stopped or queued traffic in various weather conditions, and to compare the performance of thermal cameras versus RGB cameras.

Additional scenarios involved sending combinations of C-V2X messages, either simultaneously or sequentially, as the test vehicle approached the crossing. These messages were received by the test vehicle at different distances from the crossing. The goal was to collect data to compare the order of message receipt (e.g., PSM and SPaT, PSM then SPaT, TIM and SPaT, etc.) and to evaluate the detection and classification capabilities and timing of the infrastructure sensors.

Analysis of message transmission along the C-V2X signal chain (sensor-to-roadside infrastructure, roadside infrastructure-to-vehicle), braking reaction of test vehicle upon receipt of C-V2X messages and test vehicle stopping distance in relation to the designated rail safety zone (described in section 2.5) was conducted on data collected during this testing campaign.

A testing campaign was performed at the Area X.O Private rail crossing facility located in Ottawa.

1.2 Background

There are approximately 14,000 public and 9,000 private grade crossings along over 26,000 miles of federally regulated rail tracks in Canada. From 2012 to 2022, the Transportation Safety Board of Canada (TSB) recorded a total of 11,426 rail accidents [1]. Among these accidents, approximately 16% (1,773 accidents) occurred at-grade crossings, leading to 233 fatalities and 288 serious injuries [1]. This data highlights that grade crossings are the second most hazardous type of rail accident in Canada, surpassed only by train derailments. Consequently, it is crucial to prioritize the enhancement of rail crossing safety to establish a safer rail transportation system.

A grade crossing is an intersection where a road, sidewalk, path or trail crosses railway tracks. Grade crossings are also known as level railway or train crossings.

The emergence of digital and cutting-edge technologies, such as multi-modal vision sensors including color (aka RGB), thermal, Light Detection and Ranging (LiDAR) and Radio Detection and Ranging (RADAR) cameras, sophisticated machine vision algorithms empowered by artificial intelligence (AI) techniques, as well as connected and automated vehicles has started to alter the ground transportation sector. A recent study by Deloitte [2] suggests that within the next 20-to 25 years, vehicles capable of performing most or all driving tasks will become commonplace, with many of them equipped with V2X communication abilities.

A suite of machine visions sensors was deployed at the Area X.O Private rail crossing facility for automatically detection and recognition of vehicles and vulnerable road users (VRUs), as well as identify potentially dangerous situations involving them at or near grade crossings.

1.3 Scope

Testing consisted of twelve scenarios that incorporated the automatic detection and recognition of vehicles and vulnerable road users (VRUs) within a predetermined rail safety zone surrounding a rail crossing. These scenarios also involved the transmission of cellular-vehicle-to-everything (C-V2X) messages to a test vehicle traveling along a designated approach path that intersected with a single rail crossing.

Data was collected from a suite of machine vision sensors, including a thermal camera, two lidar sensors, and an RGB optical camera, installed on a pole adjacent to the private rail crossing facility. Additional data was gathered from a roadside unit (RSU), an onboard unit (OBU), and an instrumented autonomous test vehicle.

For the purpose of testing at the Area X.0 private rail crossing, iterations of the following four use cases were selected:

Use Case 1: This use case scenario, involving pedestrians approaching or waiting at a crossing, was derived from incidents of crossing collisions. It specifically addresses situations where pedestrians approach a grade crossing or wait for trains to clear the crossing. Since nearly all collisions between moving trains and pedestrians result in fatalities or serious injuries, enhancing pedestrians' situational awareness through technological enablers will improve safety at grade crossings.

Use Case 2: The case of pedestrians trespassing onto railway right-of-way involves individuals illegally accessing or crossing railway tracks at a grade crossing when it is configured for rail traffic. This behavior is extremely dangerous and can lead to severe injuries or fatalities.

Use Case 3: Queue buildup on a crossing is a critical issue that can lead to significant safety hazards and traffic inefficiencies. This situation occurs when vehicles form a queue on the crossing surface, which can be particularly dangerous at rail-road intersections. Key points for consideration include:

- **Limited Space:** When there is insufficient space for vehicles to wait before or after the crossing, they may end up queuing on the crossing itself.
- **Long Vehicles:** Articulated buses, trailer trucks, and other long vehicles can exacerbate the problem as they require more space and time to clear the crossing.
- **Traffic Congestion:** High traffic volumes can lead to congestion, causing vehicles to back up onto the crossing.
- **Signal Timing:** Poorly timed traffic signals can contribute to vehicles being unable to clear the crossing in time.

Addressing queue buildup on crossings requires a combination of engineering solutions, policy measures, and public education to ensure the safety and efficiency of both road and rail networks.

Use Case 4: Rail signaling obstructing a crossing is a significant issue that can lead to various safety and operational concerns. According to the Grade Crossing Regulations (GCR), it is prohibited to obstruct a public crossing for more than 5 minutes by leaving railway equipment standing on the crossing when vehicular or pedestrian traffic is waiting to cross. Key points for consideration include:

- **Regulatory Framework Grade Crossing Regulations (GCR):** These regulations are designed to enhance safety at grade crossings by setting standards for the design, construction, and maintenance of crossings. One of the key provisions is the prohibition against obstructing a crossing for more than 5 minutes.
- **Emergency Vehicle Access:** Prolonged obstruction of a crossing can delay emergency vehicles, potentially leading to life-threatening situations.
- **Risky Behavior:** Pedestrians and drivers may attempt to cross the tracks in unsafe ways if they are frustrated by long waits, increasing the risk of accidents.
- **Visibility Issues:** Stationary railway equipment can obstruct the view of oncoming trains, making it difficult for pedestrians and drivers to judge when it is safe to cross.
- **Real-Time Monitoring:** Implementing real-time monitoring systems to detect and address blockages promptly.
- **Communication Systems:** Enhancing communication between rail operators and local traffic management to coordinate and mitigate the impact of blockages.

By addressing the issue of rail signaling obstructing crossings through a combination of regulatory enforcement, operational improvements, infrastructure investments, and public education, it is possible to enhance safety and efficiency at grade crossings.

1.4 Limitations

The results presented in this report represent the as-tested Area X.0 connected and autonomous vehicle platform. It is assumed that the vehicle is representative of other vehicles of the same configuration.

2 Instrumentation and Test Facilities

Area X.O played a crucial role in the installation and commissioning of all equipment used during the testing of Vulnerable Road User (VRU) scenarios. The personnel from Area X.O managed the technology infrastructure, equipment setup, and configuration, with assistance from the National Research Council of Canada (NRC).

The following is an overview of the equipment and its installation locations:

> **Rail Bungalow and Signaling:** A small building near the rail crossing housed rail signaling and communication equipment. The instrumentation installed in a rail bungalow would typically include communication devices, and control systems necessary for monitoring and managing the crossing.
>
> **Infrastructure (Utility) Pole:** Equipment installed on a utility pole adjacent to the rail grade crossing include cameras, sensors, and communication devices. These are used to monitor traffic, detect VRUs, and communicate with other systems.
>
> **Test Vehicle:** Instrumentation within the test vehicle included various sensors, data acquisition systems, and communication devices to collect and transmit data during the testing scenarios.

The collaboration between Area X.O and the NRC ensured that the equipment was properly installed, configured, and tested. This partnership leveraged the expertise of both organizations to achieve the testing objectives.

An overview of the equipment utilized during testing is provided in the following sections.

2.1 Rail Bungalow Instrumentation

2.1.1 Rail Signaling

The active rail signaling installed at the test intersection included several key components designed to enhance safety and effectively manage the interaction between rail and road traffic. Here is a detailed overview of the components:

> **Flashing Red Lights:** These lights are activated when a train is approaching or occupying the crossing. They serve as a visual warning to drivers and pedestrians to stop and not proceed across the tracks. They are typically mounted on poles or crossbucks at the crossing, ensuring they are visible to approaching road users from a distance.
>
> **Bells:** The bells provide an audible warning in addition to the visual signals. This is particularly important for alerting pedestrians and drivers who may not see the flashing lights immediately. The bells start ringing when the train is detected and continue until the train has safely passed the crossing.

Crossbuck with Mounted Lighting: The crossbuck is a standard railroad crossing sign that indicates the presence of a rail crossing. The mounted lighting enhances visibility, especially in low-light conditions. The crossbuck typically features reflective materials and may include additional lighting that activates along with the flashing red lights to draw more attention to the crossing.

Barricades (Gates): The barricades, or gates, lower to physically block the road when a train is approaching or present at the crossing. They provide a strong visual and physical barrier to prevent vehicles and pedestrians from crossing the tracks. The gates are synchronized with the flashing lights and bells, lowering when the train is detected and raising once it has passed and it is safe to cross.

All these components, shown in Figure 1, are synchronized to activate simultaneously when a train is detected. This ensures a comprehensive warning system that maximizes safety for all road users

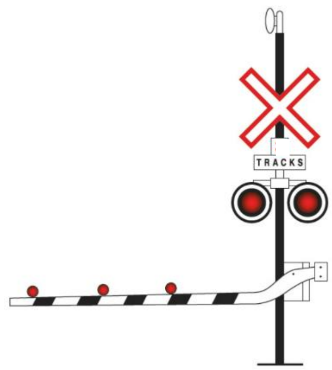

Figure 1: Rail signaling device installed at test intersection

2.1.2 Rail Signaling Control

The rail controller equipment used at the test intersection included advanced systems designed to manage and automate the operation of the rail crossing signals and barriers. Here is a detailed overview of the equipment included a Schneider Electric SCADAPack 535E Remote Programmable Automation Controller and a Siemens SSCC III 40 Amp Crossing Controller.

The SCADAPack 535E is a remote Programmable Automation Controller (PAC) used for monitoring and controlling industrial processes. In the context of a rail crossing, it is used to manage the various signals and barriers based on real-time data and allows for remote access and control of the crossing equipment, enabling operators to monitor the status and make adjustments as needed. The controller can be programmed to execute specific actions based on inputs from sensors and other devices, ensuring that the crossing operates safely and efficiently and is capable of logging data for analysis and troubleshooting.

The Siemens SSCC III is a crossing controller specifically designed for managing the operation of rail crossing signals and gates. It ensures that the crossing signals are activated and deactivated in a timely and coordinated manner. The unit includes built-in safety features to prevent malfunctions and ensure that the crossing signals operate correctly and can be integrated with other control systems and sensors to provide a comprehensive solution for managing the rail crossing.

Both the SCADAPack 535E and the Siemens SSCC III were installed in the rail bungalow, as shown in Figure 2. This location provides a secure and controlled environment for the equipment. The equipment was configured to work together seamlessly, with the SCADAPack 535E handling the overall automation and control logic, and the Siemens SSCC III managing the specific requirements of the crossing signals and gates.

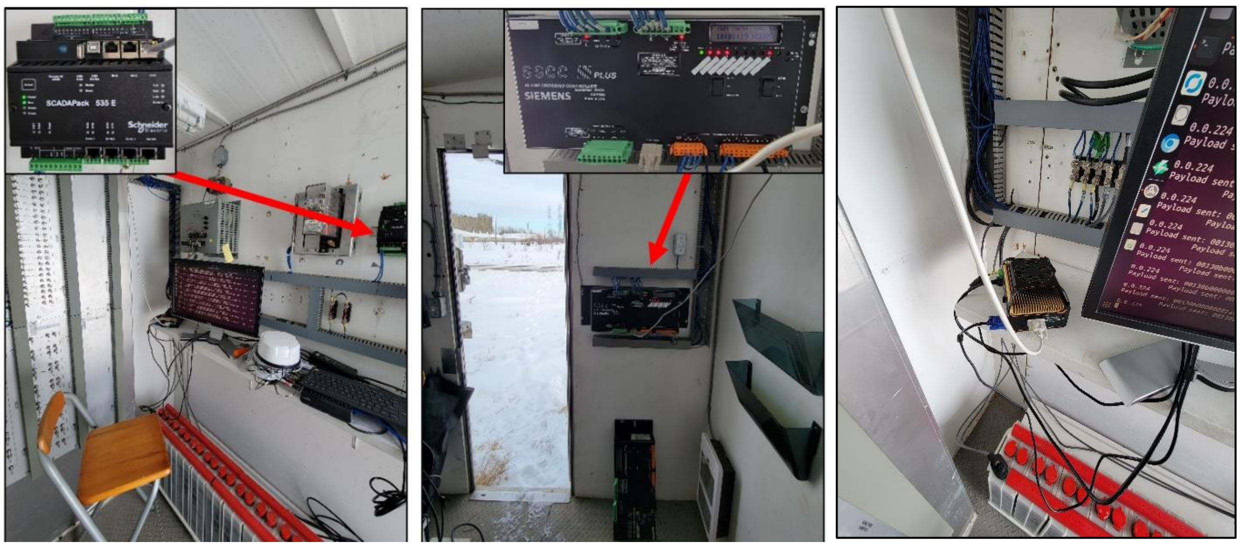

Figure 2: Rail signaling control setup

The Siemens SSCC III controller managed the signaling through three output states, each corresponding to a different phase of the crossing operation:

Inactive Rest State (Output 5): This is the default state when no train is detected, and the crossing is clear for vehicles and pedestrians to pass. Output 5 is active, indicating that the system is in its rest state. In this state, all active signaling components (flashing lights, bells, crossbuck lighting, and barricades) are inactive.

Bells Activated and Crossbuck Mounted Lighting Activated (Output 7): When a train is detected approaching the crossing, the system transitions to this state to provide an initial warning. Output 7 is active, indicating that the bells and crossbuck mounted lighting are activated. Bells start ringing to provide an audible warning and the lights on the crossbuck are activated to enhance visibility and alert drivers and pedestrians.

Barricades Lowering/Lowered (Output 3): As the train gets closer, the system transitions to this state to provide a physical barrier to prevent vehicles and pedestrians from crossing. Output 3 is active, indicating that the barricades are in the process of lowering or are fully lowered. The gates begin to lower and eventually reach the fully lowered position, providing a physical barrier across the road.

The integration of the rail signal controller with Vehicle-to-Everything (V2X) technology at the level-crossing test intersection was a critical step in enhancing the safety and efficiency of the crossing. This integration was performed by a technical representative from Siemens Canada.

2.2 Infrastructure Pole Instrumentation

At the Area X.O. rail crossing test facility intersection, a comprehensive suite of infrastructure sensors was installed on an infrastructure pole, shown in Figure 3, to detect and transmit the positions of VRUs and other traffic vehicles. This setup utilized Cellular Vehicle-to-Everything (C-V2X) technology to enhance safety and communication.

The sensors utilized during this testing campaign included a thermal camera, two lidar sensors and an RGB optical camera.

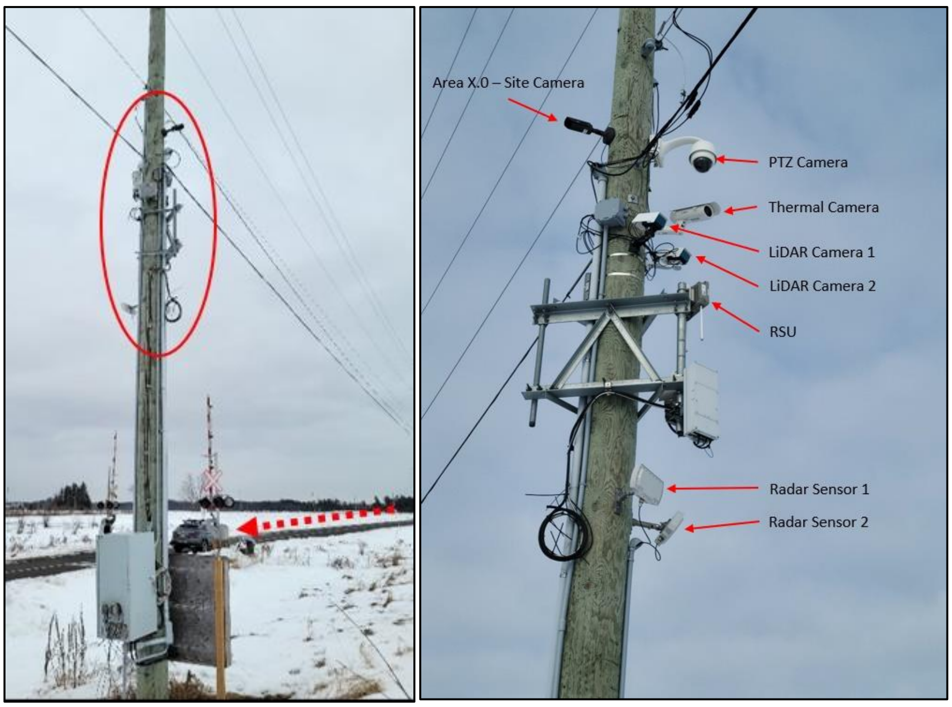

Figure 3: Machine vision and ITS sensors (PTZ RGB camera, thermal camera, lidar, radar) and C-V2X RSU mounted on infrastructure pole adjacent to test intersection

A description of the machine vision and ITS sensors utilized during testing is provided in the following sections.

2.2.1 Roadside Unit (RSU)

A C-V2X RSU platform from Kapsch, model RIS-9360, was installed on the infrastructure pole at the Area X.O. rail crossing test facility intersection, as shown in Figure 3, to support 5.9GHz C-V2X communication. The antennas for C-V2X communication were installed directly on the RSU, ensuring efficient signal transmission and reception.

The RSU facilitated real-time data exchange between the infrastructure and test vehicle, providing critical information such as the status of the rail crossing, presence of VRUs, and traffic conditions. The RSU is equipped with a standards-compliant C-V2X communication stack, supporting deployment in both IEEE wireless access in vehicular environments (WAVE) and Electrical and Electronics Engineers (IEEE) wireless access in vehicular environments (WAVE) and for European Telecommunications Standards Institute (ETSI) ITS G5 based cooperative systems.

The RSU is part of a full end-to-end V2X solution, which includes the V2X Onboard Unit (OBU) platform installed in vehicles. The OBU communicates with the RSU to receive and transmit V2X messages. A representative RSU is shown in Figure 4. C-V2X RSU technical specifications are provided in Table 1.

Figure 4: Kapsch RSU

Table 1: C-V2X RSU technical specifications

ITS communication standards	IEEE 802.11p / IEEE 802.11 C-V2X 3GPP Rel.14 SAE J2735 ETSI ITS-G5 standard set IEEE WAVE standard set
C-V2X radio characteristics	3GPP C-V2X Rel. 14 radio Frequency band: 5.850 to 5.925 GHz LTE B47 10/20 MHz channel spacing, PC5 side link Output power max. 20 dBm

2.2.2 RBG PTZ Optical Camera

A single AXIS Q6315-LE PTZ (pan, tilt, zoom) camera was installed on the infrastructure pole, shown in Figure 3, to perform object detection, tracking and classification. PTZ camera specifications are provided in Table 2. A representative RGB PTZ camera and the camera field of view of the test intersection are shown in Figure 5.

Figure 5: Network camera and representative camera field-of-view of rail crossing test area

Table 2: PTZ Camera specifications

Technical Specification	AXIS Q6315-LE PTZ
Resolution	1920x1080 (HDTV 1080p) to 320x180
Frame rate	Up to 50/60 fps (50/60 Hz) in all resolutions
Image sensor (CMOS)	1/2" progressive scan
Lens Focal Length Horizontal field of view: Vertical field of view	 6.91 – 214.64 mm, F1.36 – F4.6 60.6° – 2.0° 36.5° – 1.1°
Minimum illumination Color B/W Color B/W	 0.06 lux at 30 IRE, F1.36 0.001 lux at 30 IRE, F1.36, 0 lux with IR illumination on 0.09 lux at 50 IRE, F1.36 0.008 lux at 50 IRE, F1.36, 0 lux with IR illumination on
Operating conditions	-50 °C to 50 °C (-58 °F to 122 °F)
Pan/Tilt/Zoom Pan Tilt Zoom	 360° endless 0.05° – 550°/s +20 to -90°, 0.05°-500°/s 31x optical, 12x digital, total 372x zoom

2.2.3 Thermal Camera

A single Bosch DINION IP8000 thermal camera was installed on the infrastructure pole, shown in Figure 3, to perform object detection, tracking and classification. The thermal camera was used to provide both infrared images and video analytics for additional environmental perception. The thermal camera is capable of detection, tracking, and analysis of objects, sending alerts when predefined alarms are triggered, and operating in a variety of weather and lighting conditions. A representative thermal camera and the camera field of view of the test intersection are shown in Figure 6. The thermal camera specifications are provided in Table 3.

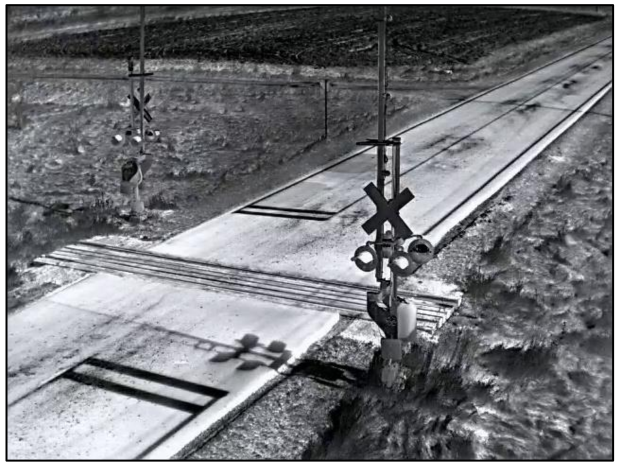

Figure 6: Thermal camera and representative camera field-of-view of rail crossing test area

Table 3: Thermal camera sensor technical specifications

Technical Specification	Values
Model	NHT-8001-F17VF
Lens	16.7 mm VGA
Detection range	315 m (1033 ft) Human, 1450 m (4757 ft) Object
Recognition range	80 m (262 ft) Human, 360 m (1181 ft) Object
Identification range	40 m (131 ft) Human, 180 m (591 ft) Object
FOV	37.5°H x 28°V
Focal distance	9.0 m to ∞
Pixel pitch	17 μm
Laser wavelength	905 nm
Thermal sensitivity	<50 mK
Video resolution	VGA 640 x 480 at 9 fps or 30 fps
Thermal color mapping	12 selectable modes
Operating temperature	-40°C to +55°C
Video content calibration	Automatic based on gyro / accelerometer data and camera height
Lenses option	Narrow field-of-view (NFOV) or wide field-of-view (WFOV)

2.2.4 LiDAR Sensor

Two LiDAR sensors were installed on the infrastructure pole, shown in Figure 3, to perform object detection, tracking and classification.

The LiDAR's were used to perform object detection, tracking and classification. The sensor raw output is a point cloud, which is a collection of thousands of 3D pints in the field of view of the sensor. Point cloud output from each sensor was combined to create a single reference frame for object detection and tracking. Cepton P60 LiDAR sensors are commonly used in automotive applications. The Cepton P60 LiDAR sensor and representative field-of-view of rail crossing test area, are shown in Figure 7. Sensor specifications are provided in Table 4.

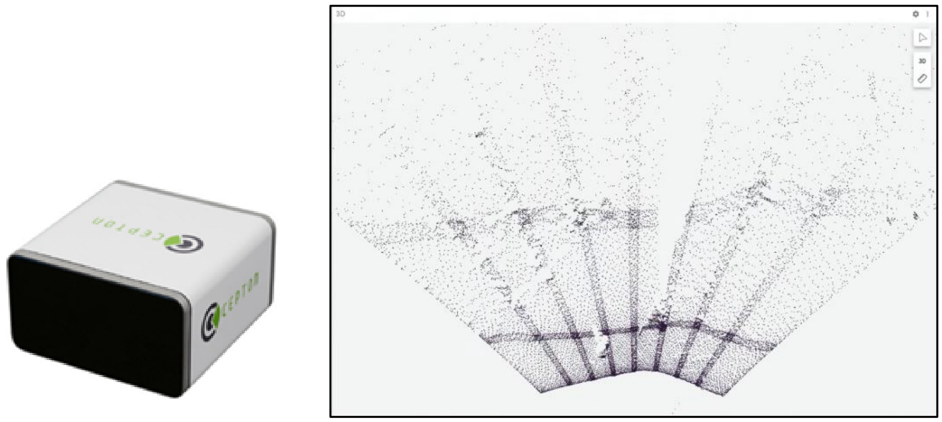

Figure 7. LiDAR sensor and lidar point cloud of rail crossing test area

Table 4: LiDAR sensor technical specifications

Technical Specification	Values
Detection range	200 metres at 30% reflectivity
FOV (HxV)	60° x 24°
Angular resolution (HxV)	0.25° x 0.25°
Frame rate	10 Hz
Range resolution	2 cm (1σ)
Laser wavelength	905 nm
Points per second	~320,000 points/sec (single return)
Date per point	Time stamp, angle (HxV), range, reflectivity
Time synchronization	GPS (pulse per second signal), Ethernet (PTP 802.1AS)
Operating temperature	-40°C to +85°C
Laser safety	Class-1 eye safe

2.2.5 RTMS Radar

Two radar sensors were installed on the infrastructure pole, shown in Figure 3, at the test intersection but were not utilized as they were not within the scope of this testing campaign.

2.2.6 Roadside Sensor Integrator and Edge Computer Node

An edge sensor compute platform, utilized to run real-time algorithms, process sensor data in the field, and provide latency-critical results to the roadside V2X infrastructure and/or in-vehicle C-V2X OBUs was installed in an equipment control cabinet on the infrastructure pole, shown in Figure 3. The MH Corbin Connect:ITS compute platform device is shown in Figure 8.

Figure 8: MH Corbin CONNECT:ITS device

2.3 Connected and Autonomous Vehicle Platform Instrumentation

The test vehicle, a 2020 Lexus RX 450h SUV (with specifications in Table 5), was equipped with numerous localizing systems that were either factory installed or added by Area X.O. The test vehicle and instrumentation installed in the vehicle trunk are shown in Figure 9.

Figure 9: Lexus RX 450h test vehicle and instrumentation installed in the trunk

Table 5: Test vehicle technical specifications

VIN	2T2JGMDA7LC045548
Model year, make, and model	2020 Lexus RX 450h
Length overall	4.77 m /187.8 in
Width (without mirrors)	1.88 m / 74.2 in
Base curb weight	1895 kg /4178 lbs
Powertrain	3.5L V6, hybrid electric, AWD
Tire make and model	Bridgestone 235/55R20

The test vehicle contained a sensor suite consisting of Lexus factory-installed and after-market installed sensors, outlined below, which enabled machine vision perception and localization features required for autonomous driving. The sensor hardware on the Lexus RX 450h test vehicle is shown in Figure 9**.**

Lexus factory-installed sensors:

- Ultrasonic parking sensors
- Lane departure system cameras

Additional after-market installed sensors:

- Spectra sensor compute platform (1)
- Delphi electronically scanning radar (ESR) (1)
- Velodyne Lidar front and rear sensors (2)
- Allied Vision forward-looking cameras (2)
- NovAtel global navigation satellite system (GNSS) positioning solution (1)
- Sierra Wireless mobile long-term evolution (LTE) radar router (1)

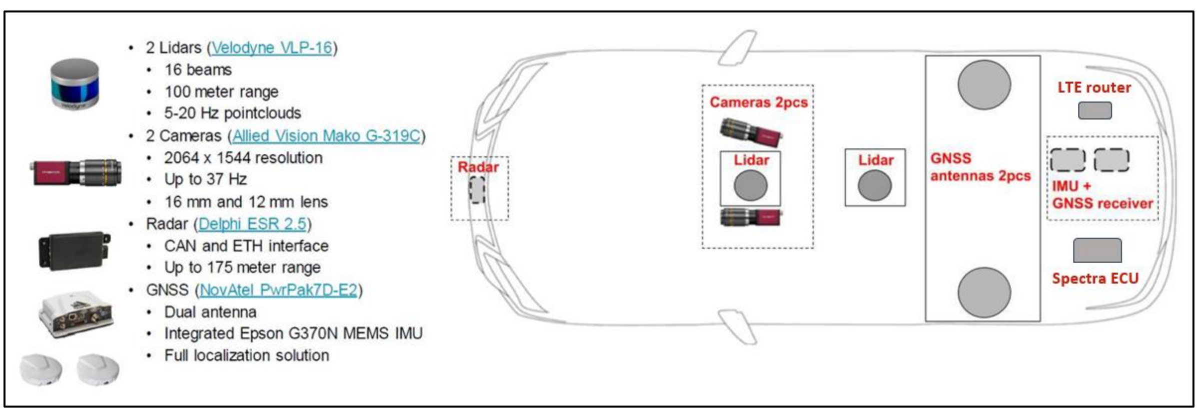

Figure 10: Sensor hardware on the Lexus RX 450h test vehicle

2.3.1 On Board Unit (OBU)

A C-V2X onboard communication unit (OBU) platform from Kapsch was installed in the test vehicle trunk to support 5.9GHz C-V2X communication. The OBU was equipped with a standards compliant C-V2X communication stack for deployment in IEEE WAVE and for ETSI ITS G5 based cooperative systems. As a mobile unit, this C-V2X OBU is part of a full end-to-end V2X solution, consisting of V2X roadside units (RSUs) and the dedicated Connected Mobility Control Center (CMCC) software. The antenna for C-V2X communication was installed on the rooftop of the test vehicle. C-V2X OBU technical specifications are provided in Table 6.

Table 6. C-V2X OBU technical specifications

ITS communication standards	C-V2X 3GPP Rel.14 SAE J2735 ETSI ITS-G5 standard set IEEE WAVE standard set
C-V2X radio characteristics	3GPP C-V2X Rel. 14 radio Frequency band: 5.850 to 5.925 GHz 10/20 MHz channel spacing LTE-V2X PC5 side link

2.4 VRU Test Platform

Official static Euro NCAP pedestrian and cyclist targets (EPTa and EBTa) were used during VRU testing [3]. VRUs included an adult male as specified in ISO 19206-2:2018, and an adult male on a standard European utility bike as specified in ISO 192064:2020. VRU testing targets utilized during testing are shown in Figure 11.

Figure 11: Static adult pedestrian (EPTa), and adult cyclist (EBTa) VRU targets

VRU targets were controlled by a 4activeSB system, the official Euro NCAP propulsion system used for all VRU testing. The 4activeSB system was manually triggered by an Area X.0 representative positioned near the test intersection. The Oxford Technical Solutions Ltd (OxTS) RT3000 RTK GNSS-aided inertial measurement system installed in the test vehicle was not activated or used for triggering the 4activeSB system. EPTa pedestrian targets are recognizable by mono and stereo cameras, as well as radar (24 to 77 GHz), lidar, and infrared systems (50% reflectivity between 850 nm and 910 nm). Representative adult VRU transversal start position outside and entering the rail safety zone is shown in Figure 12.Figure 12: Pedestrian VRU start position outside of rail safety zone. Travel path of VRU utilized during transversal PSM scenario testing.

Figure 12: Pedestrian VRU start position outside of rail safety zone. Travel path of VRU utilized during transversal PSM scenario testing.

The positions of a representative adult bicyclist VRU, both outside and entering the rail safety zone, is shown in Figure 13. The presented images were captured from screenshots of recorded infrastructure RGB (left frames) and thermal cameras (right frames).

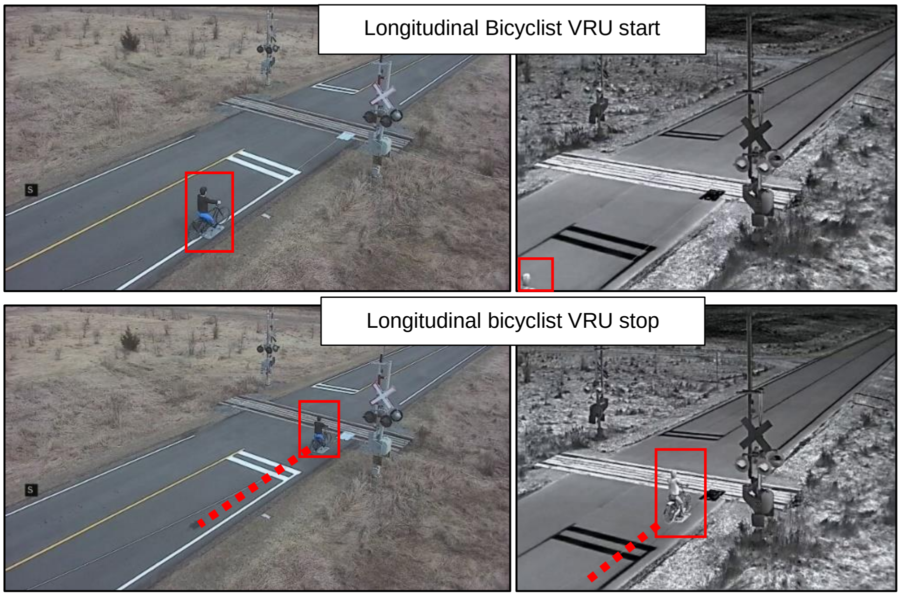

Figure 13: Bicyclist VRU start position outside of rail safety zone (A) and end position inside the rail safety zone (B).

2.5 Test Facilities

Testing was conducted on a two-lane roadway that intersects with a representative at-grade rail crossing. This rail crossing is considered representative because it consists of a single 39-foot length of track, as shown in Figure 14 (right image). The rail crossing is located at the Area X.O advanced mobility test facility at 1740 Woodroffe Avenue in Ottawa, Ontario. The test intersection is depicted in Figure 14.

The roadway surface had lane markings and had recently been resurfaced with asphalt. The level crossing test intersection did not have marked pedestrian crossings or adjacent sidewalk elements. The intersection included rail signaling with railway crossbucks, red flashing lights, and barricades with flashing red lights.

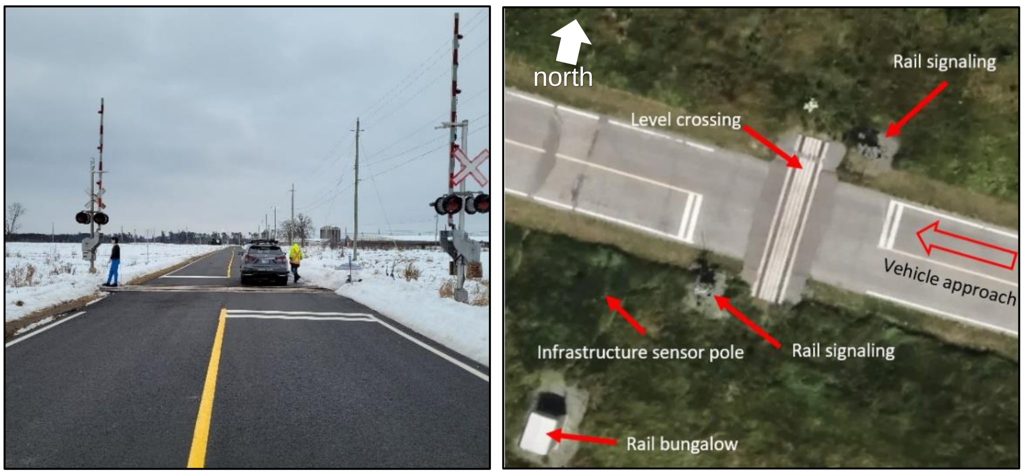

Figure 14: Area X.O level crossing test intersection

The test vehicle's start position was approximately 425 meters from the roadway level crossing intersection. The approach path consisted of a 140-meter straight run heading north, followed by a left-hand curve with a radius of approximately 35 meters, and a final 250-meter straight run heading west towards the level crossing, as shown in Figure 15. The designated rail safety zone, measuring approximately 13 meters by 7.25 meters, was delineated by the roadway stop line markings and the far edge of the tarmac surface, as shown in Figure 15.

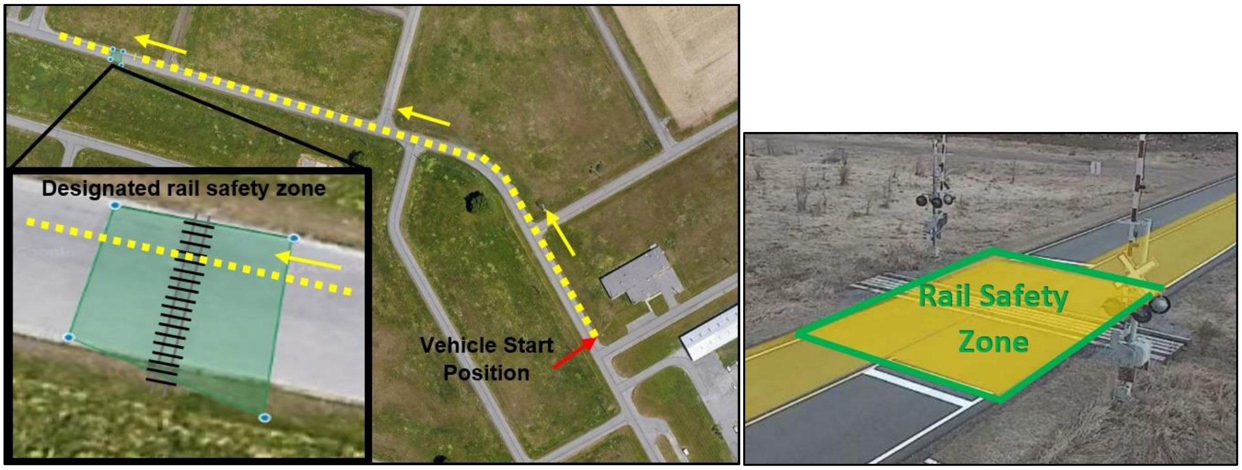

Figure 15: Aerial view of the Area X.O rail crossing test facility and vehicle under test approach path

2.6 Time synchronization of instrumentation

Time synchronization of the various sensors and equipment was necessary to ensure accurate analysis of the numerous recorded data sets for each test scenario. The National Research Council network time protocol (NTP) server and GPS were used for this purpose. The synchronization times differed by less than 20 ms between the two sources. The specific time synchronization used for each piece of instrumentation during testing is detailed in Table 7.

Table 7: Official time sources used to for facilitation of synchronisation of instrumentation

Equipment / Sensor	Official time synchronization source
Golden top computer, rail arms log (rail activation)	NRC NTP server
Lexus rosbag	NRC NTP server
Kapsch (DLVP)	NRC NTP server
RSU	GPS time (which can be synchronized with Lexus rosbag time)
Infrastructure sensors (PTS, thermal and LiDAR)	Feed directly recordings: 4 hours and 20 seconds ahead of Lexus rosbag time (varied between 4 hr 15 sec and 4 hr and 22 sec)

To avoid false positive triggering, a three-second delay was programmed into the LiDAR detection software; a PSM message is sent three seconds after a pedestrian is detected. For the Kapsch DLVP, a two-second delay begins once the vehicle enters the rail safety (danger) zone. In contrast, the LiDAR's three-second delay starts as soon as a pedestrian is detected, regardless of whether they are in the rail safety (danger) zone or not.

2.7 Weather and Roadway Conditions

Environmental data was recorded at the Ottawa International Airport, the closest available location on the Environment Canada website. The airport is approximately seven km east of the test track. The temperature ranged from -9.4 to 15.0 °C for the duration of the test campaign.

The ambient environmental conditions were recorded from the Environment Canada website and are presented in Appendix D.

The roadway condition in the testing area during testing included partly snow covered, bare and dry, and bare and wet. Representative roadway conditions are shown in Appendix D.

3 Standardized Test Procedures

All testing utilized the Area X.O Lexus RX 450h platform operating in autonomous mode. The minimum risk maneuver (MRM) performed by the test vehicle, which involved braking to stop the vehicle, was programmed to be triggered only upon the successful receipt of V2X safety messages inside the vehicle. Although the machine vision sensors on board the test vehicle may have detected VRUs and other traffic activity in certain test scenarios, the vehicle's programmed logic relied solely on valid V2X safety messages to decelerate and avoid potential collisions with VRU targets or lowered rail safety barricades. The raw data collected inside the vehicle was used to validate VRU visibility from the vehicle sensors' perspective. However, to demonstrate the advanced warning delivery to the test vehicle, the control modality for the vehicle's dynamic driving task (DDT) in autonomous mode was based exclusively on V2X communications.

3.1 Implementation of VRU targets

During some testing scenarios, a VRU dummy target (adult or bicyclist) or an adult pedestrian was utilized to simulate dynamic (traveling through rail safety zone[1]) and static (stopped in rail safety zone[2]) pedestrian movement. The VRU near-side approach corresponds to the test vehicle's right side (curbside) and the far side corresponds to the test vehicle's left side (street centre), as defined in the Euro NCAP test protocol AEB VRU systems V3.0.2.

3.2 Implementation of other traffic vehicles

In certain testing scenarios, other vehicles were used to simulate both dynamic (traveling through rail safety zone) and static (stopped in rail safety zone) traffic. The other traffic vehicles were positioned centrally within their designated driving lanes to mimic legal traffic maneuvers. For example, this included scenarios such as an immobilized tractor-trailer[3], school bus[4], or snow grader[5] unintentionally stopped in the rail safety zone, as well as vehicles halted in the rail safety zone due to traffic queueing.

3.3 V2X messages tested

Testing incorporated SAE Standard J2735 which specifies a message set, and its data frames and data elements for V2X communications systems.

A brief description of the V2X communication variables tested are outlined in the following sections.

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[1] TSB investigation report R19T0191 / TSB (link) [16]

[2] TSB investigation reports R18V0127 and R16M0026 / TSB (link, link) [17, 10]

[3] TSB investigation reports R08T0158, R07D0111, R02T0149, R99T0298, R99H0009 and R05E0008 / TSB (link, link, link, link, link, link) [12, 13, 15, 7, 8, 14]

[4] TSB investigation report R17H0015 / TSB (link) [9]

[5] TSB investigation report R13E0015 / TSB (link) [11]

3.3.1 Signal Phase and Timing (SPaT)

Signal Phase and Timing (SPaT) refers to the current signal state of an intersection and the duration for which that state will persist for each lane. For a vehicle approaching a level crossing intersection to interpret SPaT messages being broadcast, its systems must have a reference to determine the approach (or signal phase) that the rail signal controller is following, thereby understanding the current signaling. All SPaT messages are linked to SAE J2735 MAP messages, which provide intersection map geometry such as complex intersection descriptions, high speed curve outlines and segment of roadways. This linkage conveys roadway details and connects the signal controller phases to the appropriate set of lanes. The MAP message is not created in real-time but is a static description of the intersection's geometries and vectors describing the approaches. The vehicle systems will compare GPS location readings against the MAP message to determine the vehicle's approach.

Triggering of rail signaling equipment (SPaT V2X message) was conducted by an Area X.0 representative during testing.

3.3.2 Personal Safety Message (PSM)

A Personal Safety Message (PSM) is a type of communication used to enhance the safety of VRUs such as pedestrians, cyclists, and road workers. The PSM broadcasts real-time safety data about the kinematic state (e.g., position, speed, direction) of these VRUs to nearby vehicles and infrastructure. This information helps vehicles and traffic management systems to better detect and respond to the presence and movements of VRUs, thereby reducing the risk of accidents and improving overall road safety

Triggering of VRU movement (PSM V2X message) into the rail safety zone was conducted by an Area X.0 representative during testing.

3.3.3 Traveler Information Message (TIM)

A Traveler Information Message (TIM) is a type of communication used in intelligent transportation systems to provide important information to travelers. TIMs can include a wide range of data, such as: traffic conditions (Information about current traffic flow, congestion, and incidents), road conditions (updates on road closures, construction zones, and detours), weather conditions (alerts about adverse weather conditions that could affect travel), safety alerts (warnings about hazards, such as accidents or dangerous road conditions) and event information (notifications about events that could impact traffic, such as parades or sports events).

TIMs are typically broadcast to vehicles and mobile devices using various communication technologies, including C-V2X and Dedicated Short-Range Communications (DSRC). The goal of TIMs is to enhance situational awareness for drivers and travelers, helping them make informed decisions and improving overall traffic safety and efficiency

During testing, TIM messages were programmed to inform about queued traffic and stopped vehicles in the designated rail safety zone at the test intersection. The triggering of other traffic movement (TIM V2X message) into the rail safety zone was conducted by an Area X.0 representative during testing.

Representative images of PSM, TIM and SPaT triggering at the test intersection are shown in Figure 16.

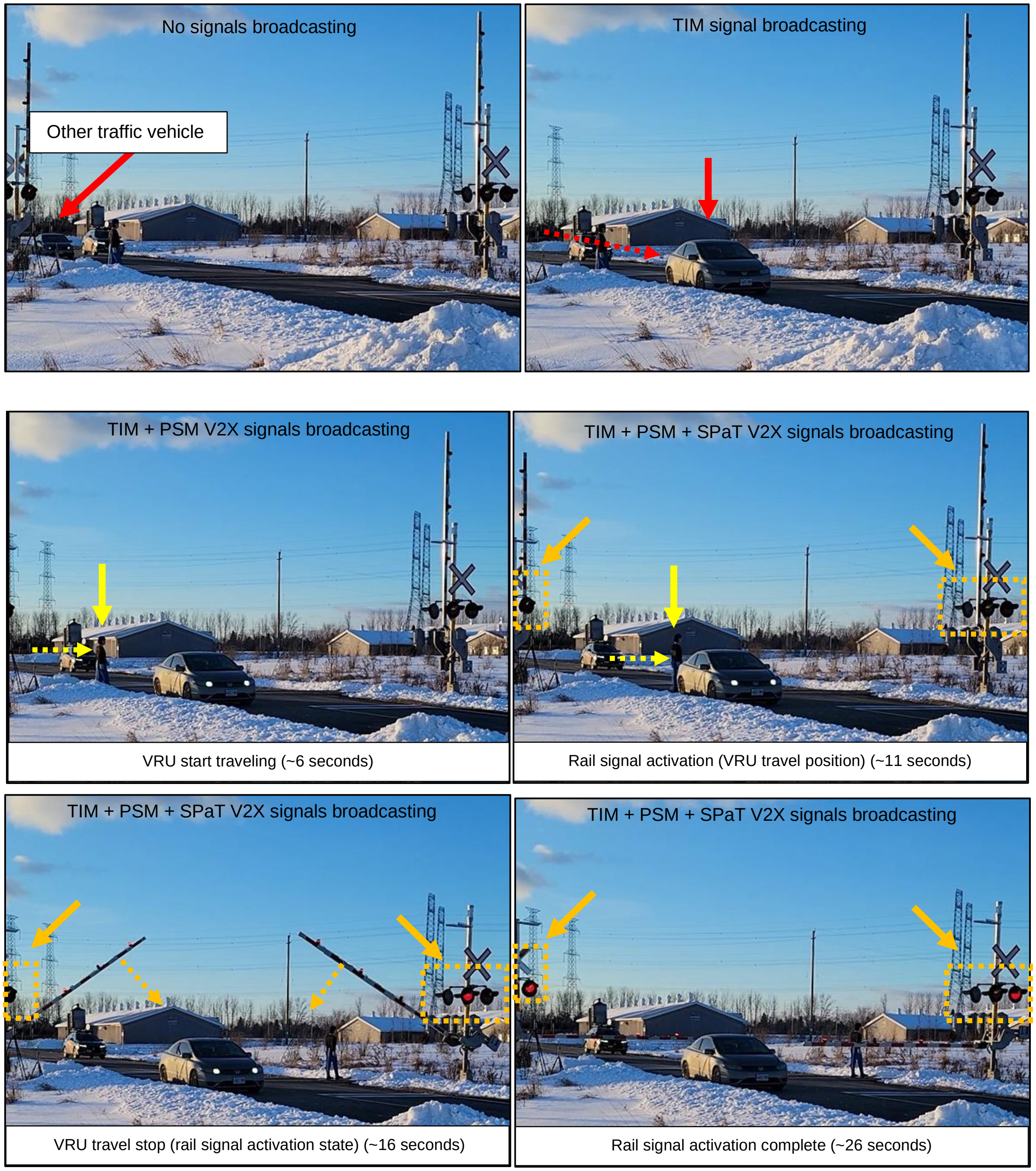

Figure 16: Representative sequence of signaling and positioning of VRU and other traffic vehicle during testing of scenario 11 (TIM / PSM / SPAT)

3.4 Determination of V2X trigger positions along test route

Triggering of C-V2X messages was calculated to ensure messages were received at the appropriate time,corresponding to specific test vehicle distances from the designated rail safety zone. Transport Canada's rail safety Guide for Road Authorities and Railway companies [4] documentation was used for guidance in the determination of appropriate level crossing C-V2X trigger distances (minimum sightline).

The term "road crossing design speed" refers to the motor vehicle speed that corresponds to the current design of the grade crossing. The Stopping Sight Distance (SSD) is the minimum sight distance required along the road approach for a crossing user to react to approaching railway equipment.

When calculating a level crossing's minimum sightline, several factors must be considered: the design vehicle and its dimensions (passenger car, truck, bus), road crossing design speed (km/h), railway design speed (km/h), road approach gradient (%), stopping sight distance (m), and the rail crossing clearance distance.

The Lexus SUV used during testing falls within the passenger car design vehicle class. A test vehicle approach speed of 60 km/h was utilized during testing. A rail crossing speed was not a determining factor as there was no train present during testing. The test intersection road approach gradient was approximately zero percent. Using the above-stated variables and referencing the Transport Canada Rail stopping sight distance table shown in Table 9, a stopping distance of 85 meters was determined.

Table 8: Determine SSD for Passenger Car Class [4]

Road Crossing Design Speed	Passenger Class Car Stopping Sight Distance (SSD) (m)										
	Road Approach Gradient										
	-5%	-4%	-3%	-2%	-1%	0%	1%	2%	3%	4%	5%
10 km/h	8	8	8	8	8	8	8	8	8	8	8
20 km/h	21	20	20	20	20	20	20	20	20	20	20
30 km/h	31	31	31	30	30	30	30	30	29	29	29
40 km/h	48	47	46	46	45	45	45	44	44	43	43
50 km/h	70	69	68	67	66	65	64	63	63	62	61
60 km/h	93	91	89	88	**86**	**85**	**84**	83	81	80	79
70 km/h	122	119	117	114	112	110	108	106	105	103	101
80 km/h	157	153	149	146	143	140	137	135	132	130	128
90 km/h	191	186	182	178	174	170	167	163	160	157	155
100 km/h	238	232	226	220	215	210	205	201	197	194	190
110 km/h	287	278	270	263	256	250	244	239	234	229	224

Four triggering distances, defined as the distance of the test vehicle from the perimeter of the designated rail safety zone, were selected for testing. A test vehicle distance of 85 m from the designated rail safety zone corresponded to a 100% trigger, 63.75 m corresponded to a 75% trigger, 42.5 m corresponded to a 50% trigger, and 21.25 m corresponded to a 25% trigger.

Due to system latencies and the need for manual C-V2X triggering, as described in section 3.5, the triggering of C-V2X messages had to occur at distances greater than those corresponding to the four triggers. For example, for the test vehicle to receive a C-V2X TIM message at the correct time corresponding to its designated distance from the rail safety zone (trigger distance), the initiation of the TIM message had to occur 8 seconds prior. Numerous trial runs were performed with the test vehicle before the commencement of official testing to confirm the necessary test vehicle distances from the rail safety zone to accurately and repeatedly trigger C-V2X messages at the four triggering distances.

Test vehicle trigger distances for triggering the activation of rail signaling (SPaT), VRU movement (PSM), and other traffic to enter the rail safety zone (TIM) are provided in Table 9.

Table 9: Distance of test vehicle from rail crossing for initiation of triggering of activation of rail signaling (Spat), VRU movement (PSM) and other traffic to enter rail safety zone (TIM)

Scenario	Date	Vehicle State	Category	Trigger (m)					
				5%	15%	25%	50%	75%	100%
1	Jan 24	Traveling	SPaT	-	-	95	117	138	160
2	Feb 2	Traveling	PSM	-	-	202	225	245	260
			SPaT	-	-	95	117	138	160
3	Feb 2	Traveling	PSM	-	-	166	197	218	237
4	Feb 16	Traveling	TIM	-	-	303	314	326	342
5	Feb 15	Traveling	TIM	-	-	303	314	326	342
			SPaT	-	-	95	117	138	160
6	March 13	Traveling	PSM	-	-	202	225	245	260
			SPaT	-	-	95	117	138	160
7	March 12	Stopped	TIM			303	314	326	342
			SPaT			95	117	138	160
8	March 27	Traveling	PSM	-	-	202	225	245	260
			SPaT	-	-	95	117	138	160
9	March 11	Queued	TIM	-	-	303	314	326	342
			SPaT	-	-	95	117	138	160
10	March 15	Queued	TIM	-	-	303	314	326	342
			SPaT	-	-	95	117	138	160
11	April 3	Traveling	TIM	-	-	303	314	326	342
			PSM	-	-	202	225	245	260
			SPAT	-	-	95	117	138	160
12	April 3	Traveling	TIM	-	-	303	314	326	342
			SPAT	-	-	95	117	138	160
			PSM	-	-	202	225	245	260

3.5 Triggering of V2X messages

Due to project time constraints, the GPS position of the test vehicle as it traveled along the test route was not available for use in the automated triggering of the VRU dummy, other traffic vehicles, or the rail signaling infrastructure during scenario testing. As a result, manual triggering was required. This involved the coordinated actions of several individuals: the test vehicle driver (or NRC personnel seated in the rear seat), a person positioned at the test intersection outside the rail safety zone operating a tablet to control the 4Active VRU platform controller, a person located in the Area X.0 control room (or seated in the test vehicle passenger seat) to control the activation of the rail signaling, and one or more individuals operating the other traffic vehicles to initiate movement into the rail safety zone. Communication between these individuals was facilitated through a cellular conference call.

Four triggering distances, defined as the distance of the test vehicle from the perimeter of the designated rail safety zone, were selected (25%, 50%, 75%, and 100%).

Within the test vehicle, an Area X.0 or NRC representative monitored the vehicle's position using a computer monitor attached to the rear of the passenger seat. During a cellular conference call, the representative called out "rail" when "Trigger Rail Arms Now" appeared on the screen, signaling the designated person to activate the rail signaling. Similarly, they called out "car" when "Trigger Car Now" appeared, prompting the other traffic vehicle(s) to begin moving into the rail safety zone, and "dummy" when "Trigger Dummy Now" appeared, instructing the designated person to activate the 4Active VRU platform for dummy movement into the rail safety zone. Representative images of the trigger messages shown on the test vehicle's rear computer monitor are displayed in Figure 17.

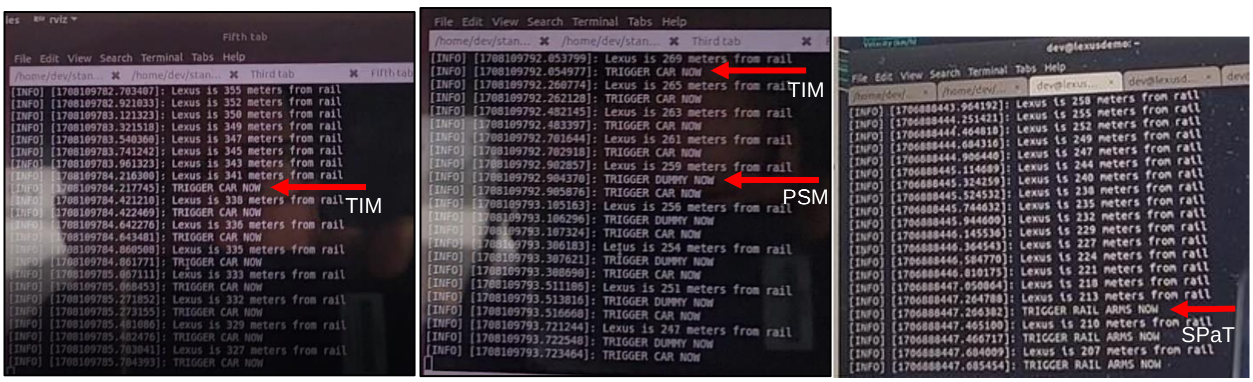

Figure 17: Representative manual triggering scripts indicating test vehicle distance from the rail safety zone and V2X trigger for call out

3.6 Test Scenarios

Area X.O and the NRC developed the testing scenario matrix with guidance from a literature review of published and publicly available reports on grade crossing collisions, including a total of 54 investigation reports published by the Transportation Safety Board of Canada (TSB) since 1994. The literature review focused solely on publicly available investigation reports on grade crossing collisions from the TSB, as well as publicly available Notices and Orders issued by Transport Canada (TC) concerning safety at grade crossings.

By examining the TSB crossing collision scenarios and the hazardous conditions observed at grade crossings, the primary instances of risky situations and potentially dangerous actions exhibited by motorists, cyclists, and pedestrians as they traversed railway crossings were identified. This analysis mirrors actual rail safety concerns in the real world, shaping the rail safety use cases and establishing the basis for data collection, analysis, and assessment undertaken in this project.

Six rail safety use cases were developed, highlighting how various technology enablers, including secure V2X communications, advanced train detection, and AI-empowered machine vision sensors deployed on roadside infrastructure at grade crossings, could reduce collision risks, increase situational awareness of road users, and thereby enhance safety at grade crossings.

Testing involved the use of an adult and bicyclist VRU target, an adult male pedestrian, as well as passenger and light-duty commercial vehicles. The test vehicle approach speed to the level crossing was 60 km/h during all scenarios. Higher test vehicle approach speed runs were attempted but it was found that the available road network around the Area X.O rail crossing did not provide enough permissible road length to reach safe and consistent speeds. The test vehicle approach speed was selected for two reasons: to match typical traffic speeds within an urban area and due to the test vehicle being unable to achieve a faster steady-state approach speed.

Area X.O personnel controlled the test vehicle during all test scenarios with an NRC representative sitting in the vehicle's backseat, monitoring data on a display mounted on the rear of the passenger seat and taking field testing notes.

Each test scenario consisted of a minimum of three test runs. Some scenarios required more than three to obtain three clean test runs with data collection.

Testing was performed over 10 days (January 24, February 2,15, and 16, March 11, 12, 13, 15 and 27, and April 3 of 2024) at the Area X.O private test track facility.

A total of 12 test scenarios, outlined in Table 10, were performed.

Table 10: V2X scenarios tested at rail crossing intersection

Scenario	Test Date	Vehicle State	Infrastructure Sensor	Trigger (%)	Infrastructure Sensor Utilized for Detection
1	2024-01-24	Traveling	SPaT	25, 50, 75, 100	
2	2024-02-02	Traveling	PSM / SPaT	25, 50, 75, 100	LiDAR (PSM)
3	2024-02-02	Traveling	PSM	25, 50, 75, 100	LiDAR
4	2024-02-16	Traveling	TIM	25, 50, 75, 100	PTZ and Thermal
5	2024-02-15	Traveling	TIM / SPaT	25, 50, 75, 100	PTZ and Thermal (TIM)
6	2024-03-13	Traveling	PSM / SPaT	75, 100	LiDAR (PSM)
7	2024-03-12	Stopped	TIM / SPaT	5, 15, 25, 50, 75, 100	DLVP (TIM)
8	2024-03-27	Traveling	PSM / SPaT	25, 50	LiDAR (PSM)
9	2024-03-11	Queued	TIM / SPaT	100	DLVP (TIM)
10	2024-03-15	Queued	TIM / SPaT	25, 50, 75	DLVP (TIM)
11	2024-04-03	Traveling	TIM / PSM / SPaT	100	DLVP (TIM) / LiDAR (PSM)
12	2024-04-03	Traveling	TIM / SPaT / PSM	100	DLVP (TIM) / Thermal (PSM)

The sequence of V2X messages transmitted, the test vehicle distance from the rail safety zone at the time at the trigger time of V2X messages, the VRU target and travel path, additional vehicle traffic used, and which infrastructure sensor(s) data was utilized for V2X detection for the test scenario is provided in the following sections.

3.6.1 Test Scenario 1 - SPaT

This scenario was conducted to represent a vehicle approaching a rail crossing, receiving a SpaT C-V2X message indicating activation of a level crossing warning signaling and then braking to a stop at a position located outside of the designated rail safety zone. Screenshots of this testing sequence are provided in Appendix A.

A rail safety zone scenario was conducted using the autonomous test vehicle and the following characteristics:

- Sequence of V2X messages: SPaT message only.
- Trigger distances: 25%, 50%, 75% and 100%.
- Rail signaling activated: yes.
- VRU target and travel path: no VRU present.
- Additional traffic: no other traffic was present.
- Test vehicle action during test: Upon receipt of SPaT message, the test vehicle comes to controlled stop outside of the designated rail safety zone. The test vehicle remains stopped until rail signaling resets and C-V2X SPaT messaging terminates. Test vehicle continues to travel through rail safety zone.
- Testing performed: January 24, 2024.

No infrastructure data was recorded. The Area X.0 Python trigger script was included in a separate file and not included in the Lexus rosbag.

3.6.2 Test Scenario 2 – PSM then SPaT

This scenario was conducted to represent a vehicle approaching a rail crossing, simultaneously receiving a PSM C-V2X message indicating the presence of a pedestrian with the designated rail safety zone and a SPaT C-V2X message indicating activation of a level crossing warning signaling and then braking to a stop at a position located outside of the designated rail safety zone. Screenshots of this testing sequence are provided in Appendix A.

A rail safety zone scenario was conducted using the autonomous test vehicle and the following characteristics:

- Sequence of V2X messages: PSM message followed by SPaT message (synchronous transmission).
- Trigger distances: 25%, 50%, 75% and 100%.
- Rail signaling activated: yes.
- VRU target and travel path: nearside adult.
- Additional traffic: no other traffic was present.
- Infrastructure sensor(s) data analyzed: LiDAR was used for detection of VRU (PSM)
- Test vehicle action during the test: Upon receipt of PSM/SPaT messages the test vehicle comes to a controlled stop outside of the designated rail safety zone. The test vehicle remains stopped until rail signaling resets, VRU clears the rails safety zone and C-V2X SPaT and PSM messaging terminates. Test vehicle continues to travel through the rail safety zone.
  Testing performed: February 2, 2024.

3.6.3 Test Scenario 3 – PSM

This scenario was conducted to represent a vehicle approaching a rail crossing, receiving a PSM C-V2X message indicating the presence of a pedestrian with the designated rail safety zone and then braking to a stop at a position located outside of the designated rail safety zone. Screenshots of this testing sequence are provided in Appendix A.

A rail safety zone scenario was conducted using the autonomous test vehicle and the following characteristics:

- Sequence of V2X messages: PSM message only.
- Trigger distances: 25%, 50%, 75% and 100%.
- Rail signaling activated:
- VRU target and travel path: adult dummy, transverse nearside approach entering rail safety zone from the north. VRU travel path is centered between the rails.
- Additional traffic: no other traffic was present.
- Infrastructure sensor(s) data analyzed: LiDAR was used for detection and creation of VRU (PSM) message.
- Test vehicle action during the test: Upon receipt of PSM messages the test vehicle comes to a controlled stop outside of the designated rail safety zone. The test vehicle remains stopped until the VRU clears the rails safety zone and C-V2X PSM messaging terminates. The test vehicle continues to travel through the rail safety zone.
- Testing performed: February 2, 2024.

The dummy started outside of the detection box. The Area X.0 Python trigger script was included in the Lexus rosbag.

3.6.4 Test Scenario 4 – TIM

This scenario was conducted to represent a vehicle approaching a rail crossing, receiving a TIM C-V2X message indicating the presence of another vehicle positioned with the designated rail safety zone and then braking to a stop at a position located outside of the designated rail safety zone. Screenshots of this testing sequence are provided in Appendix A.

A rail safety zone scenario was conducted using the autonomous test vehicle and the following characteristics:

- Sequence of V2X messages: TIM message only.
- Trigger distances: 25%, 50%, 75% and 100%.
- Rail signaling activated:
- VRU target and travel path: no VRU present.
- Additional traffic: passenger vehicle (sedan).
- Additional traffic position(s): opposing lane of traffic - approach to level crossing then stop in rail safety zone.
- Infrastructure sensor(s) data analyzed: PTZ and thermal camera used for detection of stopped other traffic vehicle (TIM). V2X message was created using Kapsch DLVP.
- Test vehicle action during test: Upon receipt of TIM messages the test vehicle comes to a controlled stop outside of the designated rail safety zone. The test vehicle remains stopped until the other traffic clears the rails safety zone and C-V2X TIM messaging terminates. The test vehicle continues to travel through the rail safety zone.
- Testing performed: February 16, 2024.

3.6.5 Test Scenario 5 – TIM then SPaT

This scenario was conducted to represent a vehicle approaching a rail crossing, simultaneously receiving a TIM C-V2X message indicating the presence of another vehicle positioned with the designated rail safety zone and a SPaT C-V2X message indicating activation of a level crossing warning signaling and then braking to a stop at a position located outside of the designated rail safety zone. Screenshots of this testing sequence are provided in Appendix A.

A rail safety zone scenario was conducted using the autonomous test vehicle and the following characteristics:

- Sequence of V2X messages: TIM message followed by SPaT message (synchronous transmission).
- Trigger distances: 25%, 50%, 75% and 100%.
- Rail signaling activated:
- VRU target and travel path: no VRU present.
- Additional traffic: passenger vehicle (sedan).
- Additional traffic position(s): opposing lane of traffic - approach level crossing then stop in rail safety zone.
- Infrastructure sensor(s) data analyzed: PTZ and thermal camera used for detection of stopped other traffic vehicle (TIM).
- Test vehicle action during the test: Upon receipt of TIM/SPaT messages the test vehicle comes to a controlled stop outside of the designated rail safety zone. The test vehicle remains stopped until rail signaling resets, the other traffic clears the rails safety zone and C-V2X TIM/SPaT messaging terminates. The test vehicle continues to travel through the rail safety zone.
- Testing performed: February 15, 2024.

3.6.6 Test Scenario 6 – PSM then SPaT

This scenario was conducted to represent a vehicle approaching a rail crossing, receiving a PSM C-V2X message indicating the presence of a pedestrian with the designated rail safety zone followed by a SPaT C-V2X message indicating activation of a level crossing warning signaling, then braking to a stop at a position located outside of the designated rail safety zone. Screenshots of this testing sequence are provided in Appendix A.

A rail safety zone scenario was conducted using the autonomous test vehicle and the following characteristics:

- Sequence of V2X messages: PSM message followed by SPaT message (asynchronous transmission, staggered).
- Trigger distances: 75% and 100%.
- Rail signaling activated: yes.
- VRU target and travel path: adult dummy, transverse nearside approach entering rail safety zone from the north.
- Additional traffic: no other traffic was present.
- Infrastructure sensor(s) data analyzed: LiDAR was used for detection of VRU (PSM).
- Test vehicle action during the test: Upon receipt of PSM/SPaT messages the test vehicle comes to a controlled stop outside of the designated rail safety zone. The test vehicle remains stopped

until rail signaling resets, the VRU clears the rails safety zone and C-V2X PSM/SPaT messaging terminates. The test vehicle continues to travel through rail safety zone.
- Testing performed: March 13, 2024.

3.6.7 Test Scenario 7 - TIM then SPaT (stopped vehicle)

This scenario was conducted to represent a vehicle approaching a rail crossing, receiving a TIM C-V2X message indicating the presence of another vehicle positioned (stopped) with the designated rail safety zone followed by a SPaT C-V2X message indicating activation of a level crossing warning signaling, then braking to a stop at a position located outside of the designated rail safety zone. Screenshots of this testing sequence are provided in Appendix A.

A rail safety zone scenario was conducted using the autonomous test vehicle and the following characteristics:

- Sequence of V2X messages: TIM message followed by SPaT message (asynchronous transmission, staggered).
- Trigger distances: 5%, 15%, 25%, 50%, 75% and 100%.
- Rail signaling activated: yes.
- VRU target and travel path: no VRU present.
- Additional traffic: medium-duty truck (box truck).
- Additional traffic position(s): opposing lane of traffic - approach level crossing, stop in rail safety zone then depart rail safety zone.
- Infrastructure sensor(s) data analyzed: PTZ (DLVP) used for detection of stopped other traffic vehicle (TIM).
- Test vehicle action during test: A large truck was positioned outside of the infrastructure sensor frame (FOV), in the opposing lane of traffic. The truck quickly enters the rail safety zone and stops inside the danger zone. The test vehicle approaches the rail intersection, receives a C-V2X TIM message and comes to a stop outside of the rail safety zone. The truck then exits the rail safety zone and continues to travel past the stopped test vehicle. The rail signaling is then activated with a corresponding C-V2X SPaT message. The test vehicle remains stopped until rail signaling resets then continues to travel through rail safety zone.
- Testing performed: March 12, 2024.

3.6.8 Test Scenario 8 – PSM then SPaT

This scenario was conducted to represent a vehicle approaching a rail crossing, receiving a PSM C-V2X message indicating the presence of a pedestrian with the designated rail safety zone followed by a SPaT C-V2X message indicating activation of a level crossing warning signaling, then braking to a stop at a position located outside of the designated rail safety zone. Screenshots of this testing sequence are provided in Appendix A.

A rail safety zone scenario was conducted using the autonomous test vehicle and the following characteristics:

- Sequence of V2X messages: PSM message followed by SPaT message (asynchronous transmission, staggered).
- Trigger distances: 25% and 50%.

- Rail signaling activated: yes.
- VRU target and travel path: adult bicyclist dummy, longitudinal approach in opposing lane of traffic entering rail safety zone from the west. The start position is out of the frame of infrastructure sensors.
- Additional traffic: no other traffic was present.
- Infrastructure sensor(s) data analyzed: LiDAR was used for detection of VRU (PSM)
- Test vehicle action during the test: Upon receipt of PSM message the test vehicle comes to controlled stop outside of the designated rail safety zone. The test vehicle remains stopped as the VRU target is reset (pulled back) to its initial position outside the frame of the infrastructure sensors. The rail signaling is triggered (SPaT) and test vehicle remains stopped. The rail signaling completes its cycle and SPaT messaging terminates. The test vehicle then continues to travel through the rail safety zone.
- Testing performed: March 27, 2024.

3.6.9 Test Scenario 9 – TIM then SPaT (queued vehicle)

This scenario was conducted to represent a vehicle approaching a rail crossing, receiving a TIM C-V2X message indicating the presence of other traffic positioned (queued) with the designated rail safety zone followed by a SPaT C-V2X message indicating activation of a level crossing warning signaling and then braking to a stop at a position located outside of the designated rail safety zone. Screenshots of this testing sequence are provided in Appendix A.

A rail safety zone scenario was conducted using the autonomous test vehicle and the following characteristics:

- Sequence of V2X messages: TIM message followed by SPaT message (asynchronous transmission, staggered).
- Trigger distances: 100%.
- Rail signaling activated: yes.
- VRU target and travel path: no VRU present.
- Additional traffic: passenger vehicle (sedan), passenger vehicle (hatchback).
- Additional traffic position(s): same lane of traffic – begin stopped at designated roadway stop line (east) approach at the level crossing (sedan leading with hatchback queued behind), both vehicles travel forwards entering and then travelling through the rail safety zone, both vehicles stop outside the rail safety zone (rear bumper of hatchback at the edge of rail safety zone), after test vehicle approaches and then stops (upon successful receipt of TIM V2X message) at the designed roadway stop line the sedan and hatchback travel forwards.
- Infrastructure sensor(s) data analyzed: PTZ (DLVP) used for detection of stopped other traffic vehicle (TIM).
- Test vehicle action during test: Upon receipt of TIM/SPaT messages the test vehicle comes to a controlled stop outside of the designated rail safety zone. The test vehicle remains stopped until rail signaling resets, the other traffic clears the rails safety zone and C-V2X TIM/SPaT messaging terminates. The test vehicle continues to travel through the rail safety zone.
- Testing performed: March 11, 2024.

3.6.10 Test Scenario 10 – TIM then SPaT (queued vehicle)

This scenario was conducted to represent a vehicle approaching a rail crossing, receiving a TIM C-V2X message indicating the presence of other traffic positioned (queued) with the designated rail safety zone followed by a SPaT C-V2X message indicating activation of a level crossing warning signaling and then braking to a stop at a position located outside of the designated rail safety zone. Screenshots of this testing sequence are provided in Appendix A.

A rail safety zone scenario was conducted using the autonomous test vehicle and the following characteristics:

- Sequence of V2X messages: TIM message followed by SPaT message (asynchronous transmission, staggered)
- Trigger distances: 25%, 50% and 75%
- Rail signaling activated: yes
- VRU target and travel path: no VRU present
- Additional traffic: medium-duty truck (box truck), passenger vehicle (sedan)
- Additional traffic position(s): opposing lane of traffic – begin stopped at designated roadway stop line (west) approach at level crossing (box truck leading with sedan queued behind), both vehicles travel forwards entering and stopping in the rail safety zone, after test vehicle approaches and then stops (upon successful receipt of TIM V2X message) at the designed roadway stop line the box truck and sedan travel forwards clearing the designed rail safety zone
- Infrastructure sensor(s) data analyzed: PTZ (DLVP) used for detection of stopped other traffic vehicle (TIM)
- Test vehicle action during the test: Upon receipt of TIM/SPaT messages the test vehicle comes to a controlled stop outside of the designated rail safety zone. The test vehicle remains stopped until rail signaling resets, the other traffic clears the rails safety zone and C-V2X TIM/SPaT messaging terminates. The test vehicle continues to travel through the rail safety zone.
- Testing performed: March 15, 2024.

3.6.11 Test Scenario 11 – TIM then PSM then SPaT

This scenario was conducted to represent a vehicle approaching a rail crossing, receiving a TIM C-V2X message indicating the presence of other traffic positioned with the designated rail safety zone followed by a PSM C-V2X message indicating the presence of a pedestrian with the designated rail safety zone followed by a SPaT C-V2X message indicating activation of a level crossing warning signaling and then braking to a stop at a position located outside of the designated rail safety zone. Screenshots of this testing sequence are provided in Appendix A.

A rail safety zone scenario was conducted using the autonomous test vehicle and the following characteristics:

- Sequence of V2X messages: TIM message followed by PSM message followed by SPaT message (asynchronous transmission, staggered).
- Trigger distances: 100%.
- Rail signaling activated: yes.

- VRU target and travel path: adult male (not a VRU dummy), walking longitudinal direction approach in opposing lane of traffic entering the rail safety zone from the west and stopping behind stopped additional traffic (truck), walking longitudinal in the west direction to position outside rail safety zone.
- Additional traffic: passenger vehicle (sedan), medium-duty truck (box truck)
- Additional traffic position(s): opposing lane of traffic – begin stopped at designated roadway stop line (west) approach at the level crossing (box truck leading with sedan queued behind), both vehicles travel forwards entering and stopping in the rail safety zone, after test vehicle approaches and then stops (upon successful receipt of TIM V2X message) at the designed roadway stop line the box truck and sedan travel forwards clearing the designed rail safety zone
- Infrastructure sensor(s) data analyzed: PTZ (DLVP) was used for the detection of stopped other traffic vehicle (TIM), LiDAR was used for the detection of VRU (PSM).
- Test vehicle action during test: Upon receipt of TIM/PSM/SPaT messages the test vehicle comes to controlled stop outside of designated rail safety zone. The test vehicle remains stopped until rail signaling resets, the VRU clears the rails safety zone, the other traffic clears the rails safety zone and C-V2X TIM/SPaT messaging terminates. Test vehicle continues travel through rail safety zone.
- Testing performed: April 3, 2024.

3.6.12 Test Scenario 12 – TIM then SPaT then PSM (thermal)

This scenario was conducted to represent a vehicle approaching a rail crossing, receiving a TIM C-V2X message indicating the presence of other traffic positioned with the designated rail safety zone followed by a SPaT C-V2X message indicating activation of a level crossing warning signaling followed by a PSM C-V2X message indicating the presence of a pedestrian with the designated rail safety zone and then braking to a stop at a position located outside of the designated rail safety zone. Screenshots of this testing sequence are provided in Appendix A.

A rail safety zone scenario was conducted using the autonomous test vehicle and the following characteristics:

- Sequence of V2X messages: TIM message followed by SPaT message followed by PSM message (asynchronous transmission, staggered).
- Trigger distances: 100%.
- Rail signaling activated: yes.
- VRU target and travel path: adult male (not a VRU dummy), walking longitudinal direction approach in opposing lane of traffic entering the rail safety zone from the west and stopping behind stopped additional traffic (truck), walking longitudinal in the west direction to position outside rail safety zone.
- Additional traffic: passenger vehicle (sedan), medium-duty truck (box truck).
- Additional traffic position(s): opposing lane of traffic – begin stopped at designated roadway stop line (west) approach at level crossing (box truck leading with sedan queued behind), both vehicles travel forwards entering and stopping in the rail safety zone, after test vehicle approaches and then stops (upon successful receipt of TIM V2X message) at the designed roadway stop line the box truck and sedan travel forwards clearing the designed rail safety zone

- Infrastructure sensor(s) data analyzed: PTZ (DLVP) used for the detection of stopped other traffic vehicle (TIM), LiDAR was used for the detection of VRU (PSM).
- Test vehicle action during test: Upon receipt of TIM/SPaT/PSM messages the test vehicle comes to controlled stop outside of designated rail safety zone. The test vehicle remains stopped until rail signaling resets, the VRU clears the rails safety zone, the other traffic clears the rails safety zone and C-V2X TIM/SPaT/PSM messaging terminates. Test vehicle continues travel through rail safety zone.
- Testing performed: April 3, 2024.

4 Data Analysis

The following sections summarize the analysis conducted on data collected from the infrastructure sensors (thermal camera, LiDAR, RGB camera), C-V2X technology (RSU, OBU), rail signaling technology (Siemens controller), VRU control platform (dummy), DLVP technology (JSON logs), the test vehicle (bag files), and screen capture and video recordings of the testing.

A summary of data analyzed is outlined in Table 11.

Table 11: Summary of test runs and infrastructure data analysed

Scenario	V2X Message Sequence (Detecting Infrastructure Sensor)	Trigger Samples Tested (%)						Test Runs Analyzed (quantity)		SPaT	PSM (Lidar)	PSM (Thermal)	TIM (non-DLVP)	TIM (DLVP)
		100	75	50	25	15	5	Lexus	Infrastructure					
1	**SPaT Only**	Yes	Yes	Yes	Yes			3/3/3/3	3/3/3/3	Yes				
2	**PSM and SPaT** PSM (transversal lidar)	Yes	Yes	Yes	Yes			3/3/3/3	3/3/3/3	Yes	Yes			
3	**PSM Only** PSM (transversal lidar)	Yes	Yes	Yes	Yes			3/3/3/3	0/0/3/3		Yes			
4	**TIM Only** TIM (PTZ/thermal)	Yes	Yes	Yes	Yes			3/3/3/3	0/3/3/3				Yes	
5	**TIM and SPaT** TIM (PTZ/thermal)	Yes	Yes	Yes	Yes			3/3/3/3	3/3/3/3	Yes			Yes	
6	**PSM then SPaT** PSM (longitudinal lidar)	Yes	Yes					3/3	3/3	Yes	Yes			
7	**TIM (stopped) then SPaT** TIM (dlvp)	Yes	Yes	Yes	Yes	Yes	Yes	3/3/3/3/1/1	3/3/3/3/1/1	Yes				Yes
8	**PSM then SPaT** PSM (longitudinal lidar)			Yes	Yes			3/3	3/3	Yes	Yes			
9	**TIM (queued) then SPaT** TIM (dlvp)	Yes						3	3	Yes				Yes
10	**TIM (queued) then SPaT** TIM (dlvp)		Yes	Yes	Yes			3/3/3	3/3/3	Yes				Yes
11	**TIM then PSM then SPaT** TIM (dlvp), PSM (longitudinal lidar)	Yes						3	3	Yes	Yes			Yes
12	**TIM then SPaT then PSM** TIM (dlvp), PSM (longitudinal lidar)	Yes						3	3	Yes		Yes		Yes

4.1 Data parameters analyzed

Table 12 provides an outline of the key data parameters analyzed, including a brief description of each parameter, the source of the data, and its output format.

Table 12: Data parameters utilized in timing sequence of infrastructure calculations

Parameter	Description of parameter	Data Source
DLVP, TIM, Stopped vehicle (Camera time)	Infrastructure RGB camera time feed into Kapsch message.	stopped_vehicle_blue.jsonl, congestion.jsonl
DLVP, TIM, Stopped vehicle (OS time)	Kapsch operating system time.	stopped_vehicle_blue.jsonl, congestion.jsonl
Lexus Brakes Applied	Initial application of the test vehicle brakes (autonomous) after receipt of V2X message along designated test route	Lexus BAG: /pacmod/as_rx/brake_cmd, /gps/fix.latitude, /gps/fix.longitude
Lexus Stopped	Stop position of the test vehicle (autonomous) after receipt of V2X message and application of brakes	Lexus BAG: /pacmod/as_tx/vehicle_speed.data, /gps/fix.latitude, /gps/fix.longitude
LiDAR, PSM (Start)	Infrastructure LiDAR detected first movement of the VRU dummy	LiDAR Bag: /capton/point
LiDAR, PSM (Stop)	Infrastructure LiDAR detected final movement of the VRU dummy	LiDAR Bag: /capton/points
OBU, PSM, Activated	OBU receipt time of RSU broadcast PSM V2X message	Lexus BAG: /v2x/personal_safety_message/
OBU, SPaT (yellow), Activated	OBU receipt time of RSU broadcast SPaT V2X message	Lexus BAG: /v2x/signal_phase_and_timing/ (state 7 permissive clearance, state 3 stop and remain)
OBU, TIM, Activated	OBU receipt time of RSU broadcast TIM V2X message	Lexus BAG: /v2x/traveler_information_message/
RSU, PSM, Activated	RSU broadcast of PSM V2X message	RSU csv
RSU, SPaT (yellow), Activated	RSU broadcast of SPaT V2X message	RSU csv
RSU, TIM, Activated	RSU broadcast of TIM V2X message	RSU csv
Siemens Controller, Rail Signal, Activated	Activation time of Siemens rail controller (activation of rail warning bells and lights, gates lowered)	Siemens controller csv
Siemens, Controller, Rail Signal, Deactivated	Deactivation time of Siemens rail controller (deactivation of rail warning bells and lights, gates raised)	Siemens controller csv
SPaT (Green)	Initial SPaT message received by test vehicle as it traverses along the designated test approach route to the level crossing	Lexus BAG: /v2x/signal_phase_and_timing/ (state 5 permissive movement allowed)

The following sections describe the data analysis methodology.

4.2 Lexus test vehicle

The test vehicle utilizes Autoware.AI, an open-source software stack for self-driving vehicles built on the Robot Operating System (ROS). It includes all the necessary functions to drive an autonomous vehicle from localization and object detection to route planning and control and was created to enable open innovations in autonomous delivering technology.

Parameters from the test vehicle were saved into a ROSBag bag file. In ROS, all topic messages are subscribed to and time-stamped into a bag file, a ROS-specific format that allows logging information to be serialized for data extraction, visualization and/or playback. This file can be used from replaying the messages on RViz (an ROS-based visualization tool for data and software status). ROS enables efficient analysis and debugging of robotic systems where it is difficult to synchronize and analyze the interactions of multiple sensors simultaneously.

The ROS platform is designed to allow user control of AutonomousStuff-supported vehicles with PACMod drive-by-wire system. PACMod provides throttle and brake-by-wire control as well as steer- and shift-by-wire control. The PACMod interface uses the ROS application programing interfaces (APIs) to monitor and control the test vehicle using publish and subscribe topics. The PACMod system publishes numerous vehicle data parameters (topics). ROSBag topics used during analysis of the rail crossing scenario testing data are provided in Appendix E.

Each PACMod topic includes a header field with a time stamp provided by a Linux computer. The timestamps indicate when each message was published into the system. The clock used for this timestamp in informally called ROS time, which is the system time of the Linux operating system.

Platform actuation and control (PAC) components to enable safe navigation of the CAV based on sensor feedback and planning. Platform actuation and control module (PACMod) control and feedback components are outlined below.

PACMod control

- Control throttle, brake, steering, gear positions
  Ultrasonic parking sensors

PACMod feedback

- Control throttle, brake, steering, gear positions
- Manual input
- Wheel speeds
- Auxiliary reports (e.g., horn, turn signals, headlights, etc.)

4.3 DLVP

A deep learning video platform (DLVP) provided by Kapsch TrafficCom [5] technology and powered by artificial intelligence was utilized during testing. DLVP uses RGB cameras for automatic detection of vehicles, pedestrians, and queues on railway tracks and adjacent roads, while also informing transportation services to enhance safety and mobility. Data was output in JSON format and imported into Microsoft Excel for analysis. Analyzed data parameters are provided in Table 13. Representative Kapsch DLVP views of the test intersection during testing of queued traffic and rail signaling activation are shown in Figure 18 and Figure 19, respectively.

Table 13: Analyzed DLVP data variables

Data parameter	Description of parameter
Bounding box	xmax, xmin, ymax, ymin (numerical value)
Endpoint name	stoppedObject
Event ID	stopped_object_blue
Object class	Car,
Object class confidence	0 to 1
Object detection confidence	0 to 1
Object track confidence	0 to 1
Position geo	latitude and longitude position
Time stamp camera	yyyy-mm-ddThh:mm:ss.000000
Time stamp OS	yyyy-mm-ddThh:mm:ss.000000

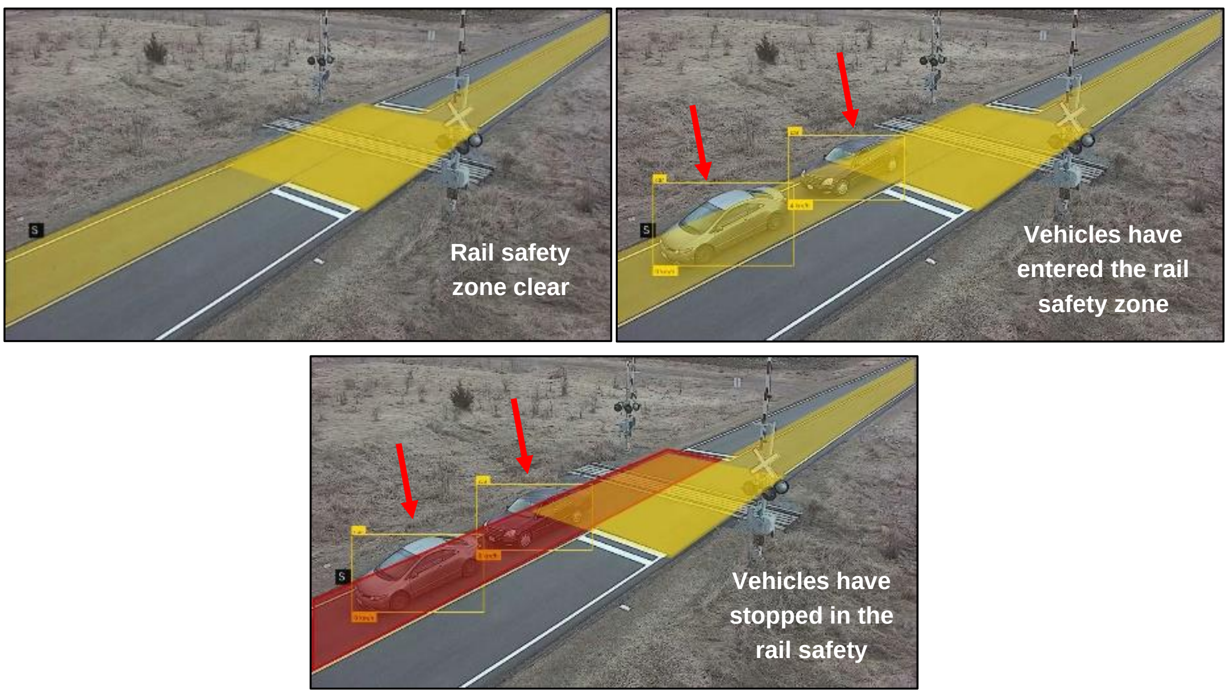

Figure 18: Representative Kapsch DLVP view of clear test intersection (left), beginning of queued traffic (center) and queued traffic (right)

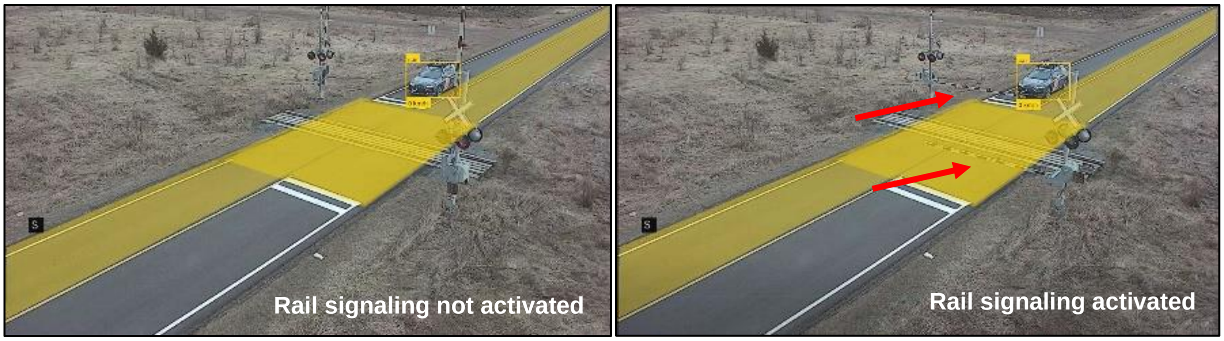

Figure 19: Representative Kapsch DLVP view of rail signaling before (left) and during activation (right)

4.4 Braking application and braking distance

The designed vehicle stop line, two white painted lines on the roadway surface, along the vehicle approach path, shown in Figure 20, at the level crossing test intersection at the Area X.0 facility measured 7.6 meters.

The following test vehicle Bag data parameters were used calculation of braking application and stopping distance: /brake_cmd, /vehicle_speed_rpt, /gps/fix.lattitude and /gps/fix.longitude.

The /brake_cmd parameters indicates the vehicle brake subsystem specific brake pedal position, zero to one, with zero being no brake application and one indicating 100% brake application. The /vehicle_speed_rpt parameter indicates the vehicle's forward speed in meters per seconds (m/s), which is converted to kilometers per hour (km/h) for the purpose of data analysis. The /gps/fix.lattitude and /gps/fix.longitude parameters were fed to the PACMod system from a Novatel global positioning system (GPS) receiver device, which provides high precision GNSS/IMU positioning as well as high accuracy system clock output.

Center of rail crossing, stop line and rail safety zone coordinates positions at the test intersection used for braking calculations are shown in Figure 20 and Figure 21.

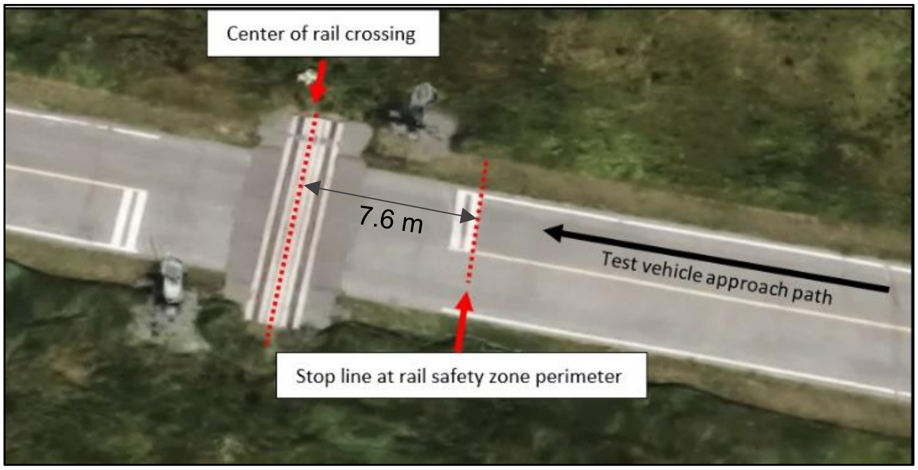

Figure 20: Center of rail crossing and stop line positions at test intersection used for braking calculations

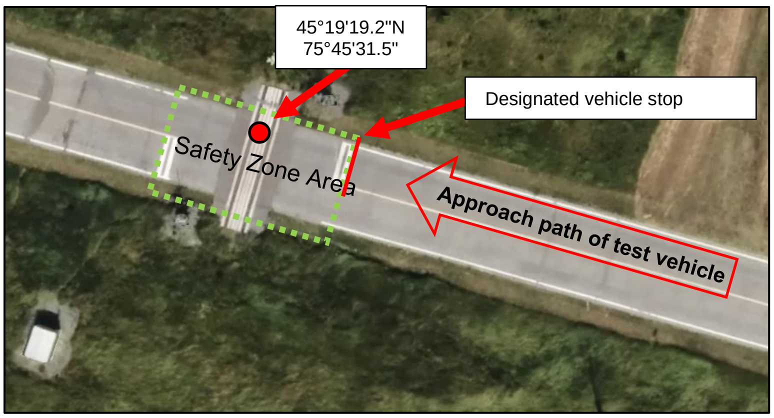

Figure 21: Rail safety zone coordinates used during braking distance calculations

4.5 LiDAR

Determination of VRU position within the rail safety zone was obtained through analysis of rostopic parameter */cepton/points* using open-source software Foxglove Studio 3D visualization panel. A rail safety zone detection box was input into the LiDAR software which matched the ground truth rail safety zone. LiDAR data was output in Bag file format. The LiDAR sensors were connected via a POE ethernet switch to the MH Corbin ITS roadside controller which transferred data to the Kapsch RSU.

Within the Area X.0 control-room the LiDAR and RGB infrastructure live feeds were captured using BandiCam software for assistance in post-data collection analysis. Representative BandiCam screenshots of LiDAR and RBG detection and classification of the VRU dummy outside the designated rail safety zone (A), initial LiDAR classification of the VRU dummy entering the designated rail safety zone (B), continued LiDAR classification of the VRU dummy as it traverses through the designated rail safety zone as well as initial detection of the activation of rail signaling (lowering arms) (C) and termination of LiDAR classification of the VRU dummy as it departs the designated rail safety zone (D) are shown in Figure 22.

The website http://time.is/, which provides official atomic clock time was also included in the BandiCam recordings, upper right corner as a means to accurately sync the LiDAR and RGB video feeds.

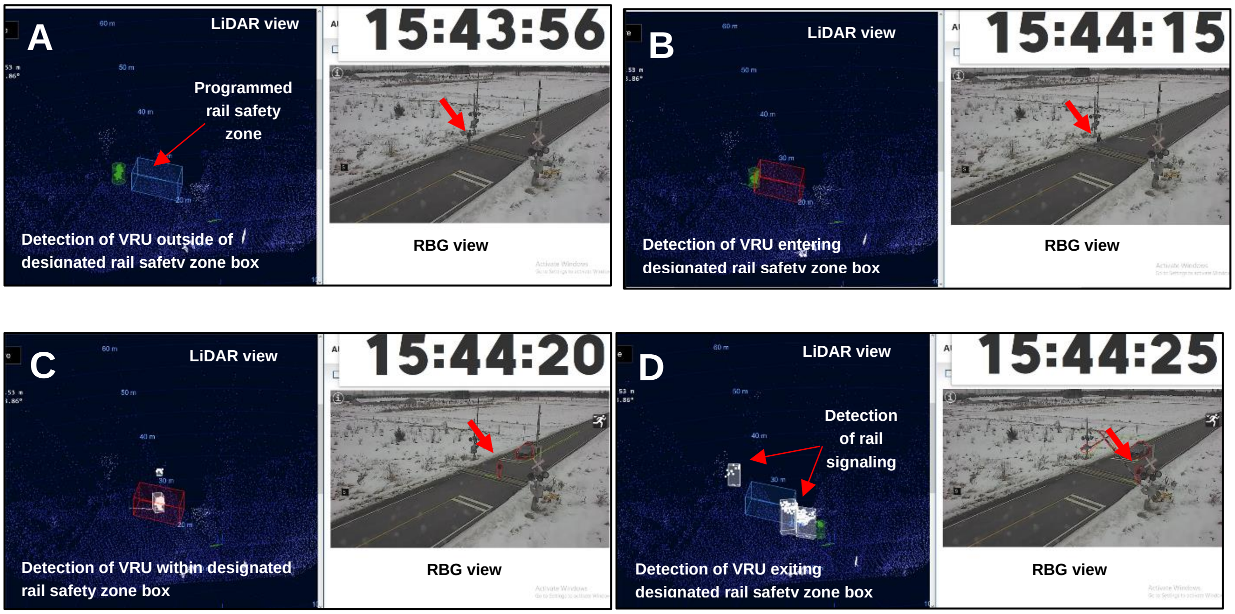

Figure 22: Representative time synchronized LiDAR and RGB infrastructure views. An overlay 3D LiDAR rail safety zone detection box indicates the VRU detection status.

Determination of the initial movement of the VRU target within the rail safety zone was manually resolved through analysis of recorded LiDAR Bag files. At the initiation of a scenario test runs, the VRU target was indicated as a static field within the LiDAR 3D overlay. The LiDAR Bag file was manually progressed frame by frame until dynamic VRU (start of movement) was indicated and the rostopic parameter */cepton/points* time stamp header time was noted. To determine the VRU end of travel time the LiDAR Bag file was manually progressed frame by frame until the VRU target was indicated as a static field within the LiDAR 3D overlay. Again, the rostopic parameter */cepton/points* time stamp header time was noted. Representative 3D overlays of rostopic parameter */cepton/points* illustrating the VRU start and end of movement positions within the rail safety zone are shown in Figure 23.

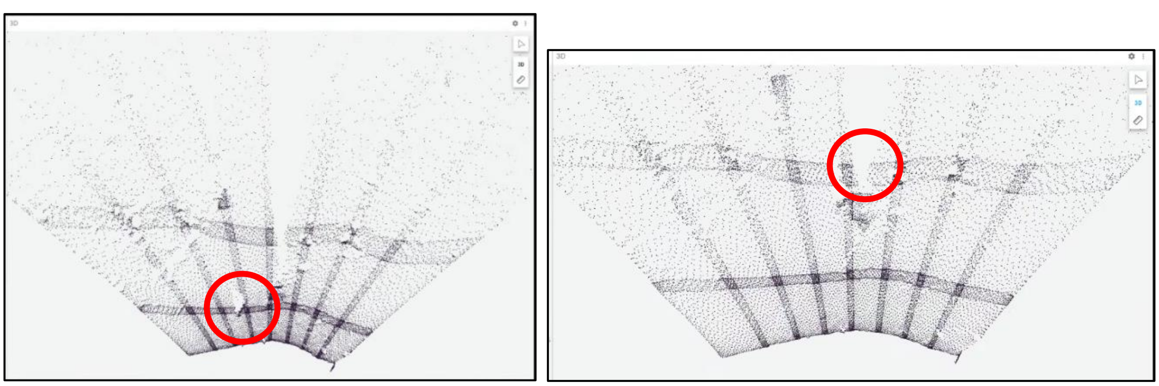

Figure 23: LiDAR initial (left) and final (right) detection of a VRU target position with the rail safety zone

4.6 Thermal camera

As a means to confirm validity of the Lexus test vehicle rosbag file PSM, TIM and SPaT C-V2X trigger times recording of the thermal infrastructure camera records were referenced. The thermal camera was connected via a 26-port POE SFP switch which transferred data to the Kapsch RSU.

The thermal camera infrastructure data was saved as individual folders, each representing 60 seconds of data, and each folder then contained thermal camera images captured approximately every 0.01 seconds as individual jpeg format files. A representative thermal camera image of test intersection is shown in Figure 24.

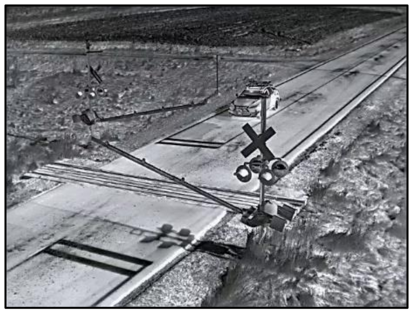

Figure 24: Representative thermal camera image of test intersection

4.7 RGB camera

As a means to confirm validity of the Lexus test vehicle Rosbag file PSM, TIM and SPaT C-V2X trigger times recording of the RBG infrastructure camera records were referenced. The RGB camera sensor was connected via a 26-port POE SFP switch which transferred data to the Kapsch RSU. A representative RGB camera image of test intersection is shown in Figure 25.

Figure 25: Representative RGB camera image of test intersection

4.8 RSU and OBU

Processed RSU data was output as a single daily csv formatted file. TIM and PSM messages were extracted from the daily RSU files and time stamp data of broadcast C-V2X messages were captured. A representation of a small capture of RSU broadcasts of a TIM (stopped vehicle -yellow, queued traffic - green) and PSM (pedestrian – blue) message is shown in Figure 26.

Due to issues experienced during data collection RSU data was not recorded during some test days. The calculated average RSU to OBU transmission time of available RSU data, collected on other testing days, was used as an approximate input during calculations of days which lacked RSU data.

03/12 16:49:37.542 [2841578304] INFO dlvp.processor - Received 1215 DLVP byte(s)
03/12 16:49:37.543 [2841578304] DEBUG dlvp.processor - Trying to parse JSON line: {"boundingBox": {"xmax": 0.7169113582932738, "xmin": 0.5186026818120268, "ymax": 0.46987453505005233, "ymin": 0.20928621694054}, "cameraId": "not set", "endpointName": "**stoppedObject**", "eventId": "**stopped_object_blue**", "laneID": 1, "objectClass": "**car**", "objectClassConfidence": 0.9994661795848329, "objectClassMapped": null, "objectDetectionConfidence": 0.6354349543539328, "objectID": "2d35c5d7-d7d2-4bfc-8757-8ca27d13e38d", "objectMeasurements": {"height": null, "length": null, "width": null}, "objectTrackConfidence": 1.0, "objectTrackDeviation": {"unit": "mm", "value": 1.7737128090269434}, "position": {"unit": "mm", "value": {"x": -66045.27343750001, "y": -279340.8125}}, "positionGeo": {"lat": 45.54444677198282, "lon": -73.53142422829363}, "positionRel": {"x": 0.6177570200526503, "y": 0.46987453505005233}, "speed": {"unit": "kmh", "value": 0.09007484887253495}, "speedVector": {"unit": "kmh", "value": {"x": 0.0, "y": 0.0}}, "state": "ACTIVE", "stationGeoLocation": null, "timestampCamera": {"unit": "ISO8601", "value": "2024-03-12T16:49:36.930420"}, "timestampOS": {"unit": "ISO8601", "value": "2024-03-12T16:49:37.578536"}, "uniqueEventId": "0f4613db-847b-4540-963d-6f77c01ce762", "version": "0.0.11"}
03/12 16:49:37.543 [2841578304] INFO dlvp.processor - Have valid DLVP JSON line...
03/12 16:49:37.543 [2841578304] INFO dlvp.processor - Notifying RSU Processor of valid DLVP data
03/12 16:49:37.543 [2841578304] INFO rsu.processor - ...**built TIM Message** from DLVP data: TIMMessage: Message Id:123456789 Info Type:0 Advisory Code:0 Advisory Text: Path: { } Frames: { FrameType:1**AdvisoryCode:532**, }
03/12 16:49:57.008 [2841578304] INFO dlvp.processor - Received 624 DLVP byte(s)
03/12 16:49:57.008 [2841578304] DEBUG dlvp.processor - Trying to parse JSON line: {"cameraId": "not set", "endpointName": "**congestion**", "eventId": "**congestion**", "laneCentroidPosition": {"unit": "mm", "value": {"x": -56112.48463199198, "y": -278946.99763656344}}, "laneCentroidPositionGeo": {"lat": 45.544545077268936, "lon": -73.53138280379042}, "laneCentroidPositionRel": {"x": 0.763885, "y": 0.29105749999999997}, "laneID": 1, "state": "ACTIVE", "stationGeoLocation": null, "timestampCamera": {"unit": "ISO8601", "value": "2024-03-12T16:49:56.386588"}, "timestampOS": {"unit": "ISO8601", "value": "2024-03-12T16:49:57.044566"}, "uniqueEventId": "befcf097-5090-4ccd-beb4-b3687151b08c", "version": "0.0.8"}
03/12 16:49:57.008 [2841578304] INFO dlvp.processor - Have valid DLVP JSON line...
03/12 16:49:57.008 [2841578304] INFO dlvp.processor - ...continuing with valid endpointName
03/12 16:49:57.008 [2841578304] INFO dlvp.processor - Notifying RSU Processor of valid DLVP data
03/12 16:49:57.009 [2841578304] INFO rsu.processor - ...**built TIM Message** from DLVP data: TIMMessage: Message Id:123456789 Info Type:0 Advisory Code:0 Advisory Text: Path: { } Frames: { FrameType:1**AdvisoryCode:263**, }
03/13 19:48:41.119 [2833189696] INFO dlvp.processor - Have valid DLVP JSON line...
03/13 19:48:41.119 [2833189696] INFO dlvp.processor - Notifying RSU Processor of valid DLVP data
03/13 19:48:41.119 [2833189696] INFO rsu.processor - ...built PersonalSafetyMessage from DLVP data: User Type: 2 Latitude: 45.54442158 Longitude: -73.53143038 Elevation: UNKNOWN TempID: 0x0000010f Speed: 0 Heading: 0
03/13 19:48:41.120 [2833189696] INFO processor.model - **Adding new Pedestrian to the domain** 271

Figure 26: Representative RSU C-V2X TIM (stopped vehicle and congestion) and PSM output messages

4.9 Siemens rail controller

Rail controller data was recorded to a Golden Top computer located in the rail bungalow. The Golden Top computer system time was determined to be approximately two seconds different than the Lexus Rosbag system time. A python trigger script, run from within the test vehicle during testing, was created by Area X.0 for control of the Siemens rail controller activation but was not integrated into the Lexus rosbag during all testing scenarios. A representative Siemens rail control output during a rail crossing signaling activation cycle is shown in Figure 27.

	Payload sent: 00130b00000001e531000000100**5** 2024-03-26T15:44:43.934019943	**State 5** - rest state
	Payload sent: 00130b00000001e5310000001005 2024-03-26T15:44:44.934331820 toIP: /10.70.0.224	
Signaling activated	Payload sent: 00130b00000001e631000000100**7** 2024-03-26T15:44:44.934331820	**State 7** - bells activated
	Payload sent: 00130b00000001e6310000001007 2024-03-26T15:44:45.365840641 toIP: /10.70.0.224	
	Payload sent: 00130b00000001e7310000001007 2024-03-26T15:44:45.365840641	
	Payload sent: 00130b00000001e7310000001007 2024-03-26T15:44:47.942150734 toIP: /10.70.0.224	
	Payload sent: 00130b00000001e8310000001007 2024-03-26T15:44:47.942150734	
	Payload sent: 00130b00000001e8310000001007 2024-03-26T15:44:48.942449689 toIP: /10.70.0.224	
	Payload sent: 00130b00000001e931000000100**3** 2024-03-26T15:44:48.942449689	**State 3** - barricades lowereing
	...	
	Payload sent: 00130b0000000180310000000100**3** 2024-03-26T15:45:13.966990144	**State 3** - barricades raising
	Payload sent: 00130b00000001803100000001003 2024-03-26T15:45:14.967345538 toIP: /10.70.0.224	
	Payload sent: 00130b0000000181310000000100**7** 2024-03-26T15:45:14.967345538	**State 7** - bells deactivating
	Payload sent: 00130b00000001813100000001007 2024-03-26T15:45:15.624014002 toIP: /10.70.0.224	
	Payload sent: 00130b00000001823100000001007 2024-03-26T15:45:15.624014002	
	Payload sent: 00130b00000001823100000001007 2024-03-26T15:45:17.967845648 toIP: /10.70.0.224	
	Payload sent: 00130b00000001833100000001007 2024-03-26T15:45:17.967845648	
	Payload sent: 00130b00000001833100000001007 2024-03-26T15:45:18.968155698 toIP: /10.70.0.224	
	Payload sent: 00130b00000001843100000001007 2024-03-26T15:45:18.968155698	
	Payload sent: 00130b00000001843100000001007 2024-03-26T15:45:19.968459197 toIP: /10.70.0.224	
	Payload sent: 00130b00000001853100000001007 2024-03-26T15:45:19.968459197	
	Payload sent: 00130b00000001853100000001007 2024-03-26T15:45:20.969027053 toIP: /10.70.0.224	
	Payload sent: 00130b00000001863100000001007 2024-03-26T15:45:20.969027053	
	Payload sent: 00130b00000001863100000001007 2024-03-26T15:45:21.969400844 toIP: /10.70.0.224	
Signaling deactivated	Payload sent: 00130b0000000187310000000100**5** 2024-03-26T15:45:21.969400844	**State 5** - rest state
	Payload sent: 00130b00000001873100000001005 2024-03-26T15:45:22.595287751 toIP: /10.70.0.224	

Figure 27: Representative Siemens rail control output during rail crossing signaling activation

5 Results

In the following sub-sections, results of automated detection and recognition of vehicles and VRUs at, through, and around one at-grade crossing during scenario testing conducted at the Area X.0 private rail crossing test facility are presented.

5.1 Timing sequence of infrastructure sensor detection to test vehicle message receipt

A common time delineation data signal used for indication of a start of signal chain analysis was *SPaT Activated Green.* The SPaT Activated Green indicates the first SPaT message received by the test vehicle as it traveled along the rest route. As shown in section 5.2, the SPaT Green signal is not received at a uniform position along the rest route but was received prior to the test vehicle exiting the left hand turn along the test route during all testing scenarios. The *SPaT Activated Green* position is time zero, meaning each subsequent data signal analyzed along the signal chain is in reference to this time.

A description of the data variables analyzed along the infrastructure sensor to C-V2X to test vehicle signal chain are outlined in Table 14.

Table 14: Infrastructure sensor - C-V2X - test vehicle signal chain data variables analyzed

Data variable	Description of data variable
C-V2X PSM Activated	C-V2X (OBU)PSM message received by Lexus test vehicle
C-V2X SPaT Activated	C-V2X (OBU) SPaT activation message received by Lexus test vehicle
C-V2X SPaT Deactivated	C-V2X (OBU) SPaT deactivation message received by Lexus test vehicle
C-V2X TIM Activated	C-V2X (OBU) TIM activation message received by Lexus test vehicle
Lexus Brake Application	Lexus test vehicle brake application after receipt of C-V2X message
Lexus Stopped Position	Lexus test vehicle at a complete stop after reaction to received C-V2X message
LiDAR PSM Detection Start	Infrstrucuture LiDAR first detection of PSM movement within designated rail safety zone
LiDAR PSM Detection End	Infrstrucuture LiDAR final detection of PSM movement within designated rail safety zone
RSU PSM Activated	C-V2X (RSU)PSM message transmitted
RSU SPaT Activated	C-V2X (RSU) SPaT message transmitted
RSU TIM Activated	C-V2X (RSU) TIM message transmitted
Siemens Data (areaxo.xls)	Siemens rail controller data output indication of rail signaling activation
SPaT Activated (green)	First C-V2X (OBU) SPaT message received by Lexus test vehicle, not an indication of rail signaling activation
TIM Congestion DLVP (OS)	Initial DLVP data indication of TIM message - operating system time stamp
TIM Congestion DLVP (Camera)	Initial DLVP data indication of TIM message - camera time stamp

Analysis of *data along the infrastructure sensor to C-V2X to test vehicle* signal chain for each of the tested scenarios is provided in Table 15 through Table 26. Data unavailable (not recorded) for analysis are indicated by blank cells.

Results of individual test runs for each test scenario are provided in Appendix C.

Table 15: Scenario 1 – Average timing sequence of infrastructure sensors, transmission and receipt of C-V2X signals and test vehicle braking and stop actions

Scenario	C-V2X Sequence	Trigger %	SPaT Activated (green)	Siemens Data (areaxo.xls)	RSU SPaT Activated	C-V2X SPaT Activated	Lexus Brake Application	Lexus Stopped Position	C-V2X SPaT Deactivated
1	SPAT	25	0.000	17.614		18.135	18.477	28.313	56.097
		50	0.000	13.009		13.203	13.440	27.671	50.765
		75	0.000	22.694		22.916	23.465	39.488	60.308
		100	0.000	14.455		14.982	15.978	31.943	52.353

Table 16: Scenario 2 - Average timing sequence of infrastructure sensors, transmission and receipt of C-V2X signals and test vehicle braking and stop actions

Scenario	C-V2X Sequence	Trigger %	SPaT Activated (green)	RSU PSM Activated	C-V2X PSM Activated	Lexus Brake Application	Siemens Data (areaxo.xls)	C-V2X SPaT Activated	Lexus Stopped Position	C-V2X SPaT Deactivated
2	PSM then SPAT	25	0.000		21.886	22.213	22.473	22.903	29.861	60.370
		50	0.000		19.671	19.948	20.305	21.090	34.901	58.437
		75	0.000		14.452	14.753	14.960	15.505	30.754	52.941
		100	0.000		21.925	22.248	22.984	23.578	39.888	61.016

Table 17: Scenario 3 - Average timing sequence of infrastructure sensors, transmission and receipt of C-V2X signals and test vehicle braking and stop actions

Scenario	C-V2X Sequence	Trigger %	SPaT Activated (green)	LiDAR PSM Detection Start	LiDAR PSM Detection End	RSU PSM Activated	C-V2X PSM Activated	Lexus Brake Application	Lexus Stopped Position
3	PSM	25	0.000				21.649	21.974	
		50	0.000				23.637	23.938	32.613
		75	0.000				16.769	17.067	35.513
		100	0.000				15.962	16.322	32.968

Table 18: Scenario 4 - Average timing sequence of infrastructure sensors, transmission and receipt of C-V2X signals and test vehicle braking and stop actions

Scenario	C-V2X Sequence	Trigger %	SPaT Activated (green)	C-V2X SPaT Activated	TIM Congestion DLVP (Camera)	TIM Congestion DLVP (OS)	RSU Data Status	C-V2X TIM Activated	Lexus Brake Application	Lexus Stopped Position
4	TIM	25	0.000					23.141	23.466	35.153
		50	0.000					24.398	24.683	37.726
		75	0.000					15.592	15.958	32.914
		100	0.000					14.932	15.899	33.229

Table 19: Scenario 5 - Average timing sequence of infrastructure sensors, transmission and receipt of C-V2X signals and test vehicle braking and stop actions

Scenario	C-V2X Sequence	Trigger %	SPaT Activated (green)	TIM Congestion DLVP (Camera)	TIM Congestion DLVP (OS)	RSU TIM Activated	C-V2X TIM Activated	Siemens Data (areaxo.xls)	C-V2X SPaT Activated	RSU SPaT Activated	Lexus Brake Application	Lexus Stopped Position	C-V2X SPaT Deactivated
5	TIM the SPaT	25	0.000				22.532	23.298	23.767		22.793	34.859	61.122
		50	0.000				24.810	24.575	25.464		25.144	37.958	62.896
		75	0.000				21.584	20.574	21.084		21.398	36.651	58.520
		100	0.000				13.611	13.931	14.140		13.939	31.244	51.603

Table 20: Scenario 6 - Average timing sequence of infrastructure sensors, transmission and receipt of C-V2X signals and test vehicle braking and stop actions

Scenario	C-V2X Sequence	Trigger %	SPaT Activated (green)	LiDAR PSM Detection Start	LiDAR PSM Detection End	RSU PSM Activated	C-V2X PSM Activated	Lexus Brake Application	Lexus Stopped Position	Siemens Data (areaxo.xls)	RSU SPaT Activated	C-V2X SPaT Activated	C-V2X SPaT Deactivated
6	PSM then SPaT	75	0.000	10.207	16.729	17.998	18.022	18.346	35.905	60.578		60.573	98.046
		100	0.000	7.442	13.726	15.212	15.241	16.256	33.222	61.463		61.458	98.861

Table 21: Scenario 7 - Average timing sequence of infrastructure sensors, transmission and receipt of C-V2X signals and test vehicle braking and stop actions

Scenario	C-V2X Sequence	Trigger %	SPaT Activated (green)	TIM Congestion DLVP (Camera)	TIM Congestion DLVP (OS)	RSU TIM Activated	C-V2X TIM Activated	Lexus Brake Application	Lexus Stopped Position	Siemens Data (areaxo.xls)	RSU TIM Activated	C-V2X SPaT Activated	C-V2X SPaT Deactivated
7	TIM then SPaT	5	0.000	14.087	14.537	14.489	14.580	14.896	22.703	42.991		43.414	80.831
		15	0.000	13.541	14.005	13.963	14.054	14.332	26.954	47.011		47.633	85.206
		25	0.000	23.810	24.266	24.099	24.319	24.583	37.769	57.686		58.520	95.917
		50	0.000	16.122	16.253		16.312	16.683	30.773	48.676		49.274	87.511
		75	0.000	16.592	17.143		16.189	16.483	33.949	50.325		50.805	87.955
		100	0.000	9.649	10.096		10.176	11.513	29.190	44.645		45.110	83.299

Table 22: Scenario 8 - Average timing sequence of infrastructure sensors, transmission and receipt of C-V2X signals and test vehicle braking and stop actions

Scenario	C-V2X Sequence	Trigger %	SPaT Activated (green)	LiDAR PSM Detection Start	LiDAR PSM Detection End	RSU PSM Activated	C-V2X PSM Activated	Lexus Brake Application	Lexus Stopped Position	Siemens Data (areaxo.xls)	RSU SPaT Activated	C-V2X SPaT Activated	C-V2X SPaT Deactivated
8	PSM then SPaT	25	0.000	7.103	15.740	15.450	15.503	15.854	27.358	53.558		53.573	90.923
		50	0.000	12.136	19.393	19.988	20.053	20.365	36.359	58.309		58.325	95.676

Table 23: Scenario 9 - Average timing sequence of infrastructure sensors, transmission and receipt of C-V2X signals and test vehicle braking and stop actions

Scenario	C-V2X Sequence	Trigger %	SPaT Activated (green)	TIM Congestion DLVP (Camera)	TIM Congestion DLVP (OS)	RSU TIM Activated	C-V2X TIM Activated	Lexus Brake Application	Lexus Stopped Position	Siemens Data (areaxo.xls)	RSU SPaT Activated	C-V2X SPaT Activated	C-V2X SPaT Deactivated
9	TIM then SPaT	100	0.000	18.100	18.687		18.720	19.412	37.209	60.960		60.996	98.454

Table 24: Scenario 10 - Average timing sequence of infrastructure sensors, transmission and receipt of C-V2X signals and test vehicle braking and stop actions

Scenario	C-V2X Sequence	Trigger %	SPaT Activated (green)	TIM Congestion DLVP (Camera)	TIM Congestion DLVP (OS)	RSU TIM Activated	C-V2X TIM Activated	Lexus Brake Application	Lexus Stopped Position	Siemens Data (areaxo.xls)	RSU SPaT Activated	C-V2X SPaT Activated	C-V2X SPaT Deactivated
10	TIM then SPaT	25	0.000	14.566	15.118	15.093	15.209	15.510	27.193	49.997		50.617	88.093
		50	0.000	9.918	10.516		10.584	10.968	28.283	64.692		65.393	102.851
		75	0.000	11.692	12.275	12.737	12.314	12.636	28.740	52.055		52.749	90.238

Table 25: Scenario 11 - Average timing sequence of infrastructure sensors, transmission and receipt of C-V2X signals and test vehicle braking and stop actions

Scenario	C-V2X Sequence	Trigger %	SPaT Activated (green)	TIM Congestion DLVP (Camera)	TIM Congestion DLVP (OS)	RSU TIM Activated	C-V2X TIM Activated	LiDAR PSM Detection Start	Lexus Brake Application	LiDAR PSM Detection End	RSU PSM Activated	C-V2X PSM Activated	Lexus Stopped Position	Siemens Data (areaxo.xls)	RSU SPaT Activated	C-V2X SPaT Activated	C-V2X SPaT Deactivated
11	TIM then PSM then SPaT	100	0.000	5.666	5.716		5.820	2.543	13.150	36.617		27.041	31.648	48.299		49.085	86.476

Table 26: Scenario 12 - Average timing sequence of infrastructure sensors, transmission and receipt of C-V2X signals and test vehicle braking and stop actions

Scenario	C-V2X Sequence	Trigger %	SPaT Activated (green)	TIM Congestion DLVP (Camera)	TIM Congestion DLVP (OS)	RSU TIM Activated	C-V2X TIM Activated	Lexus Brake Application	Lexus Stopped Position	Siemens Data (areaxo.xls)	RSU SPaT Activated	C-V2X SPaT Activated	RSU PSM Activated	C-V2X PSM Activated	C-V2X SPaT Deactivated
12	TIM then SPAT then PSM	100	0.000	3.480	3.940	3.402	4.665	11.334	29.710	46.549		47.243	63.074	63.216	84.134

Representative time-synchronized images of the bicyclist VRU (red outline) and rail signaling (blue outline) captured by the infrastructure RGB camera (top left), thermal camera (top center), 2D LiDAR (top right), and 3D LiDAR (bottom) are shown in Figure 28.

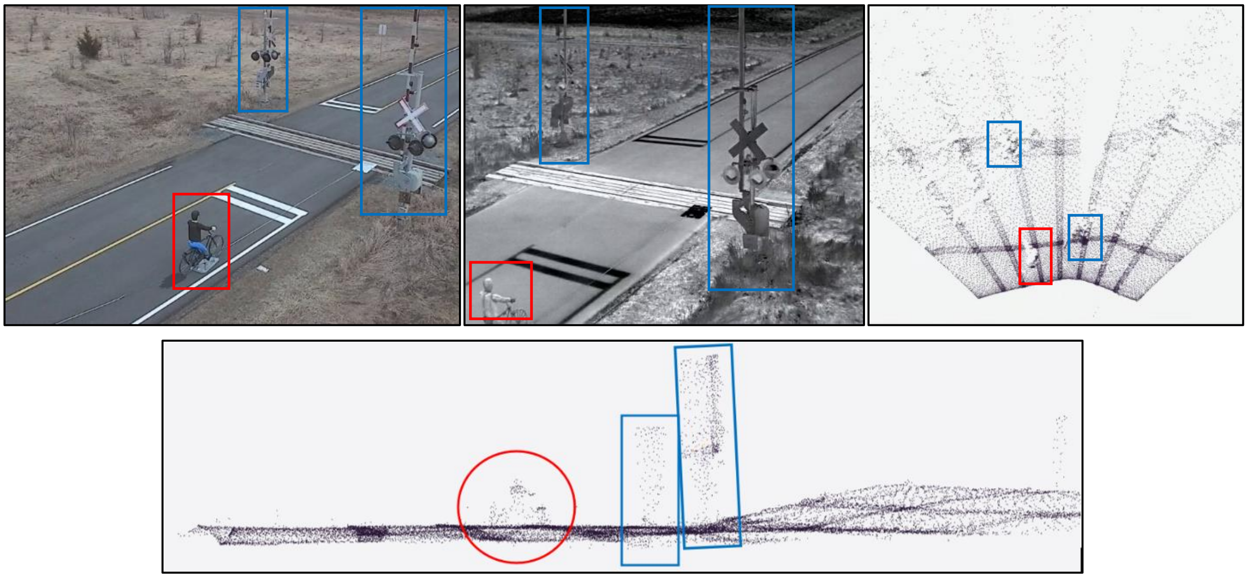

Figure 28: Representative images of the bicyclist VRU and rail signaling captured by the infrastructure LiDAR, RGB and thermal cameras sensors

5.2 Position of test vehicle at time of V2X message receipt

The position of the test vehicle, as it traveled along the test route approaching the rail crossing, at the time of receipt of C-V2X messages (PSM, TIM, SPaT) is indicated in Figure 29 to Figure 39. Images were not available for scenario 6. Trigger distances (25%, 50%, 75%, 100%) are separated into individual image panes with each test run iteration indicated.

- Green dots represent the test vehicle position at the first instance of a C-V2X SPaT message (rail signaling value 5 - rest state) being received.
- Yellow dots represent the test vehicle position upon receipt of a C-V2X SPaT message indicating the rail signaling activation (rail signaling value 7 - bells activated).
- Blue dots represent the test vehicle position upon receipt of a C-V2X PSM message indicating detection of a VRU inside the rail safety zone.
- Red dots represent the test vehicle position upon receipt of a C-V2X TIM message indicating detection of a vehicle inside the rail safety zone.
- The rail crossing position within each image is indicated by a light blue rectangle.

During testing, the initial C-V2X SPaT message (rail signaling value 5 - rest state) was not received at a uniform position as the vehicle traveled along the approach route. However, it was always received before the test vehicle completed the left-hand turn along the test route, at a distance greater than 250 meters from the rail safety zone perimeter. The variance in the receipt of the initial C-V2X SPaT message was, in some instances, due to the test vehicle's line of sight to the RSU being blocked by a building.

Further analysis would be required to determine if other factors potentially affected the test vehicle's initial receipt position of the C-V2X SPaT message. During testing, the initial C-V2X SPaT message (rail signaling value 5 - rest state) was not received at a uniform position as the vehicle traveled along the approach route. However, it was always received before the test vehicle completed the left-hand turn along the test route, at a distance greater than 250 meters from the rail safety zone perimeter. The variance in the receipt of the initial C-V2X SPaT message was, in some instances, due to the test vehicle's line of sight to the RSU being blocked by a building. Further analysis would be required to determine if other factors potentially affected the test vehicle's initial receipt position of C-V2X SPaT messages.

Due to the minimal number of test runs conducted for each trigger distance (3 to 5 runs), quantification of outlier data—such as the significant distance noted between the test vehicle's receipt of C-V2X SPaT messages during testing in scenario 2 with a 50% trigger—would require additional testing. Some variances in the test vehicle's receipt of C-V2X messages (PSM, TIM, SPaT) relative to the distance from the rail safety zone are due to the manual triggering, as described in Section 3.5.

Graphs of test vehicle distance from center of rail crossing at receipt time of V2X messages, at instance of brake application and test vehicle stop position distance from the center of the rail crossing and distance travelled during braking for each of the tested scenarios is provided in Appendix C.

Figure 29: Test vehicle position at time of receipt of V2X SPaT messages during testing of scenario 1 (triggers: 25%, top left, 50% top right, 75% bottom left and 100% bottom right)

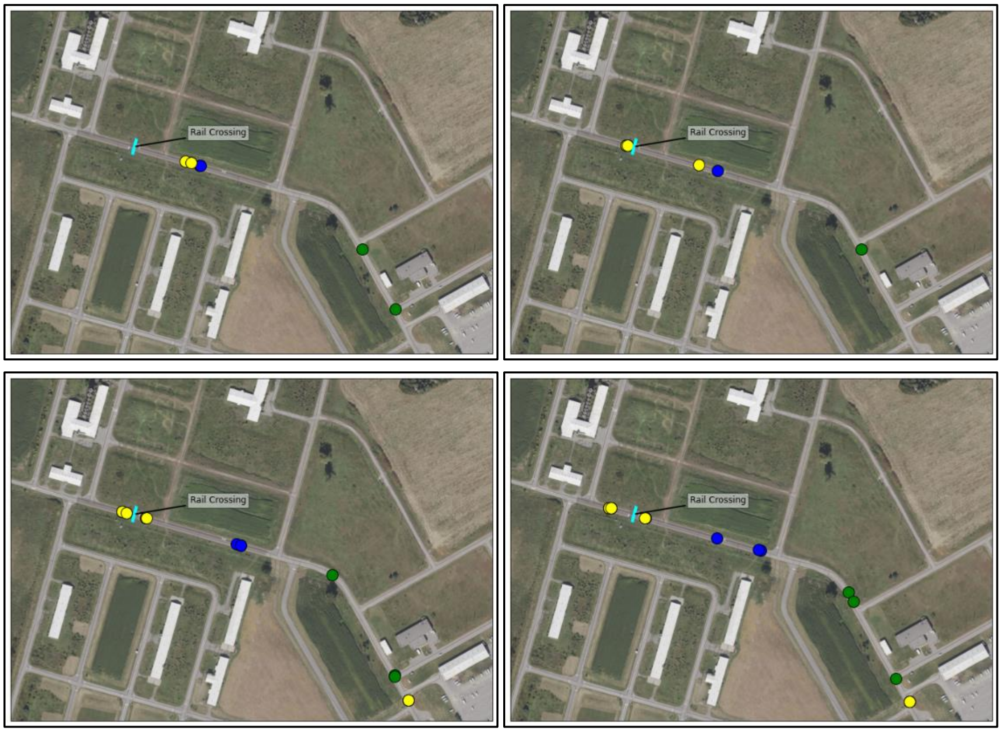

Figure 30: Test vehicle position at time of receipt of V2X PSM then SPaT messages during testing of scenario 2 (triggers: 25%, top left, 50% top right, 75% bottom left and 100% bottom right)

Figure 31: Test vehicle position at time of receipt of V2X PSM messages during testing of scenario 3 (triggers: 50% top right, 75% bottom left and 100% bottom right)

Figure 32: Test vehicle position at time of receipt of V2X TIM messages during testing of scenario 4 (triggers: 50% top right, 75% bottom left and 100% bottom right)

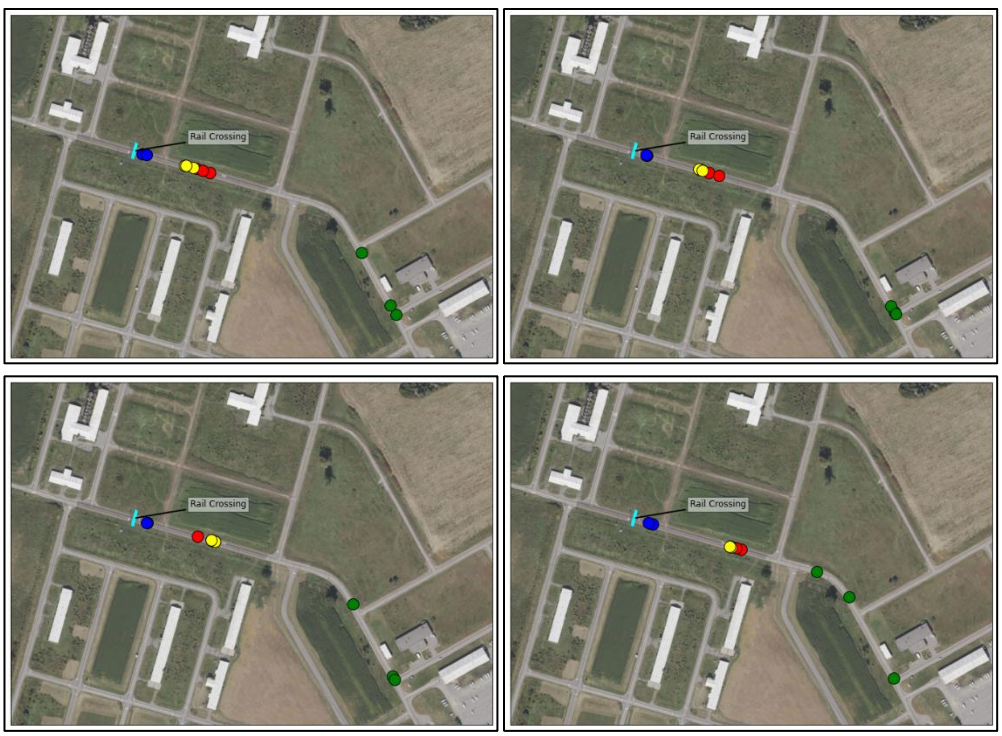

Figure 33: Test vehicle position at time of receipt of V2X TIM then SPaT messages during testing of scenario 5 (triggers: 25%, top left, 50% top right, 75% bottom left and 100% bottom right)

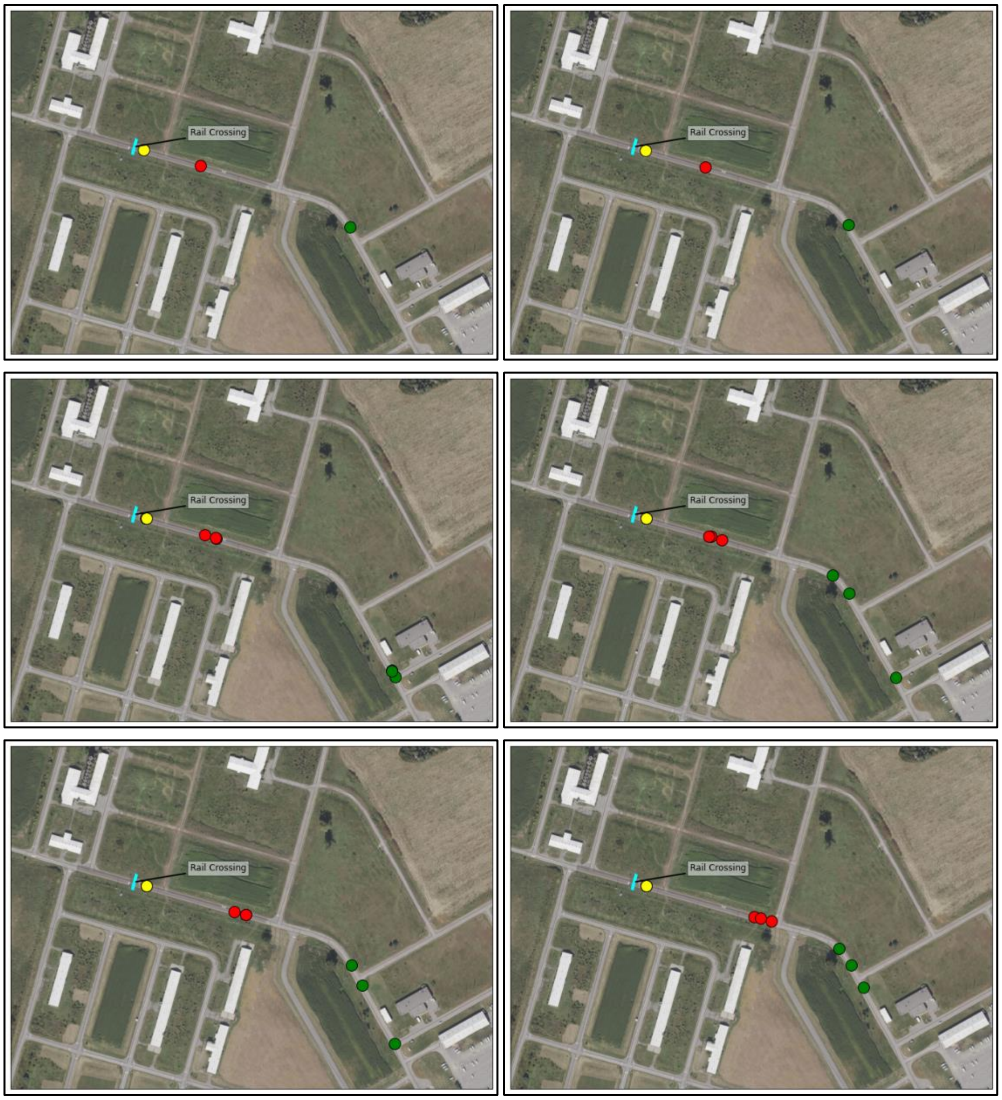

Figure 34: Test vehicle position at time of receipt of V2X TIM then SPaT messages (stopped vehicle) during testing of scenario 7 (triggers: 5% top left, 15% top right, 25% middle left, 50% middle right, 75% bottom left, 100% bottom right)

Figure 35: Test vehicle position at time of receipt of V2X PSM then SPaT messages during testing of scenario 8 (triggers: 25% left, 50% right)

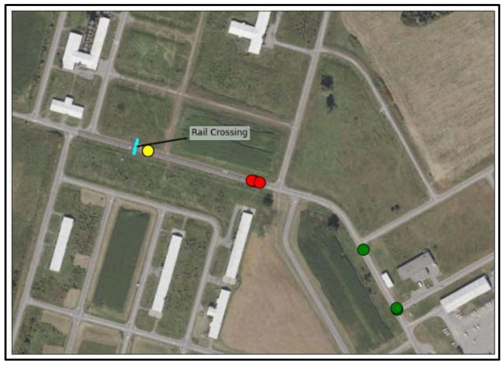

Figure 36: Test vehicle position at time of receipt of V2X TIM then SPaT messages during testing of scenario 9 (queued vehicle) (trigger: 100%)

Figure 37: Test vehicle position at time of receipt of V2X TIM then SPaT messages during testing of scenario 10 (queued vehicle) (triggers: 25% top left, 50% top right, 75% bottom)

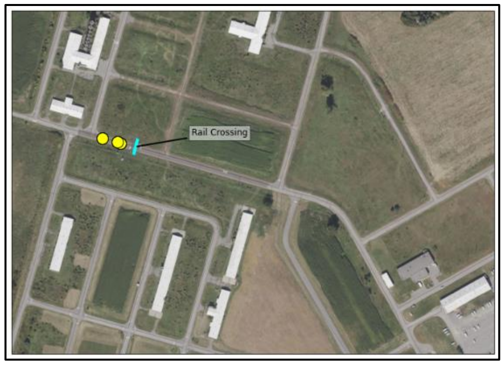

Figure 38: Test vehicle position at time of receipt of V2X TIM then PSM then SPaT messages during testing of scenario 11 (trigger: 100%)

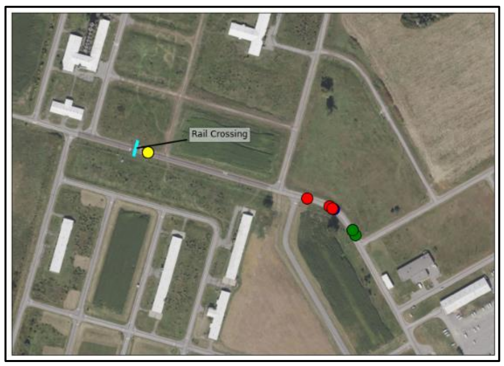

Figure 39: Test vehicle position at time of receipt of V2X TIM then SPaT then PSM messages during testing of scenario 12 (trigger: 100%)

5.3 RSU to OBU transmission time

The time delay of C-V2X message transmission, RSU transmission time to OBU installed in test vehicle receipt time, was calculated. The methodology utilized for calculation of transmission time is outlined in section 4.8. Slight deviations were noted in C-V2X message transmission times but no direct correlation of signal delay to test vehicle reaction was apparent within the data.

If RSU data had been available for all testing scenarios, a correlation between test vehicle reaction and C-V2X message transmission times may have been apparent. Additional testing would be necessary to confirm this. Calculated RSU to OBU transmission times of available data for analysis are provided in Figure 40.

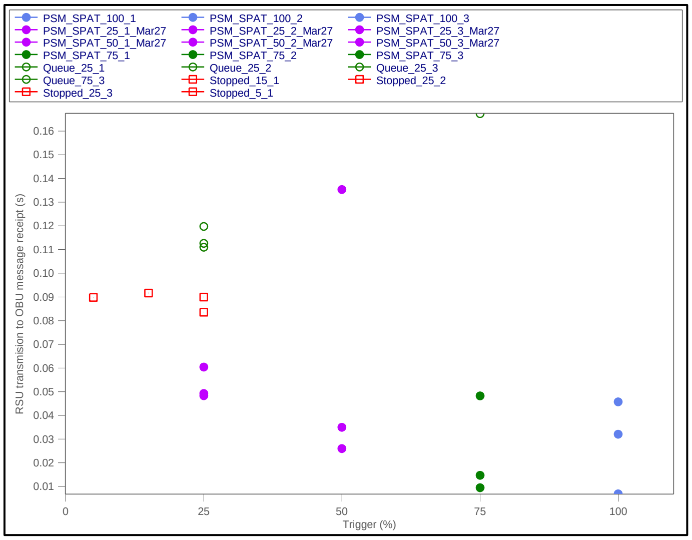

Figure 40: Time delay of transmitted RSU V2X message to test vehicle receipt of OBU V2X message

5.4 LiDAR detection of PSM movement to OBU V2X message receipt

LiDAR detection of PSM movement data analysis was conducted for PSM then SPaT test scenarios 6 and 8. The methodology utilized for the calculation of LiDAR detection to OBU C-V2X PSM message receipt time delay is outlined in section 4.5. Delay time was consistent for all trigger distances with a slight increase noted during 25% trigger distance testing. The calculated delay times are shown in Figure 41.

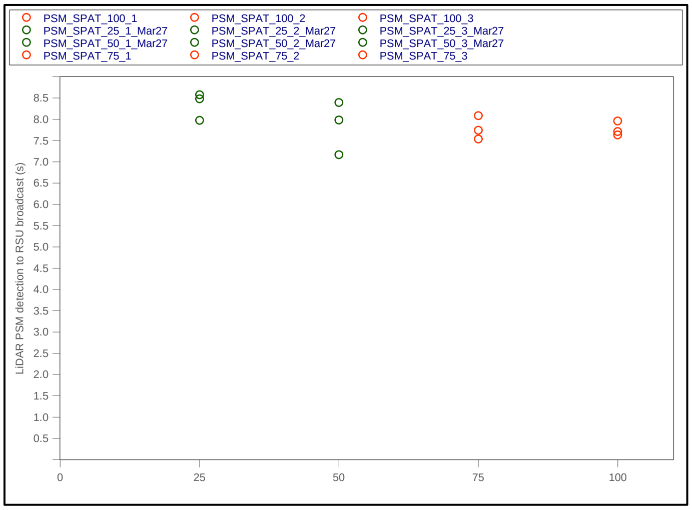

Figure 41: Time delay of LiDAR detection of PSM movement to test vehicle receipt of OBU V2X message for PSM/SPAT scenarios 6 and 8

5.5 DLVP (TIM) object confidence

DLVP data parameters avaible for TIM analysis included object class, object detection and object tracking confidence as well as classification of the detected object. Object class confidence was consistently high during all testing scenario trigger distances, varying between 79 and 100%. Object class confidence was consistent during all testing scenario trigger distances, varying between 59 and 73%. A direct correlation between an increasing or decreasing object class confidence and the trigger distance was not apparent in the data. Object tracking confidence was consistently high during all testing scenario trigger distances, varying between 79 and 100%. The NRC was provided DLVP data by Area X.0 for analysis of test scenarios 7, 11 and 12. Tabulated DLVP TIM data, showing data parameters at the instance of C-V2X classification, are provided in Table 27.

Table 27: Recorded DLVP TIM data for scenarios 7, 11 and 12

Scenario	Test	Trigger	TIM Congestion DLVP (timestampCamera)	Object Class Confidenc	Object	Object Detection Confidenc	Object Tracking Confidenc	Bounding Box			
								Xmax	Xmin	Ymax	Ymin
7	TIM /SPAT(Stopped)	5	1710263032.169	1.000	car	0.633	1.000	0.704	0.518	0.476	0.230
			Average	**1.000**		**0.633**	**1.000**	**0.704**	**0.518**	**0.476**	**0.230**
	TIM /SPAT(Stopped)	15	1710262702.185	1.000	car	0.635	1.000	0.749	0.560	0.467	0.210
			Average	**1.000**		**0.635**	**1.000**	**0.749**	**0.560**	**0.467**	**0.210**
	TIM /SPAT(Stopped)	25	1710261875.518	0.975	car	0.636	0.997	0.710	0.530	0.471	0.229
			1710262175.034	0.999	car	0.646	1.000	0.710	0.527	0.468	0.225
			1710262431.371	0.990	car	0.617	1.000	0.726	0.535	0.470	0.222
			Average	**0.995**		**0.631**	**1.000**	**0.715**	**0.531**	**0.470**	**0.226**
	TIM /SPAT(Stopped)	50	1710260927.227	0.864	car	0.590	1.000	0.723	0.535	0.477	0.229
			1710261193.363	0.946	car	0.603	0.994	0.732	0.559	0.472	0.226
			1710261545.513	0.984	car	0.624	0.993	0.709	0.534	0.478	0.234
			Average	**0.965**		**0.614**	**0.993**	**0.721**	**0.543**	**0.476**	**0.230**
	TIM /SPAT(Stopped)	75	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
			1710260347.592	0.965	car	0.600	1.000	0.712	0.526	0.470	0.230
			1710260624.734	0.905	car	0.619	1.000	0.752	0.556	0.465	0.213
			Average	**0.935**		**0.609**	**1.000**	**0.732**	**0.541**	**0.468**	**0.222**
	TIM /SPAT(Stopped)	100	1707756603.009	1.000	car	0.617	1.000	0.758	0.567	0.443	0.197
			1710259418.390	0.881	car	0.632	1.000	0.688	0.504	0.480	0.235
			1710259801.259	0.882	car	0.627	1.000	0.699	0.513	0.485	0.224
			Average	**0.882**		**0.629**	**1.000**	**0.715**	**0.528**	**0.469**	**0.219**
11	TIM / PSM / SPAT	100	1712163866.305	0.904	Truck	0.576	0.793	0.783	0.649	0.407	0.173
			1712164245.413	0.960	Truck	0.625	0.990	0.788	0.651	0.377	0.154
			1712164565.030	0.779	Truck	0.557	0.823	0.788	0.627	0.419	0.142
			Average	**0.869**		**0.591**	**0.906**	**0.787**	**0.643**	**0.401**	**0.156**
12	TIM / SPAT / PSM	100	1712165610.411	1.000	Car	0.737	0.997	0.685	0.588	0.472	0.357
			1712166030.224	0.793	Truck	0.567	0.980	0.791	0.668	0.408	0.153
			1712166457.149	0.828	Truck	0.525	0.922	0.789	0.647	0.433	0.167
			Average	**0.811**		**0.546**	**0.951**	**0.755**	**0.634**	**0.438**	**0.226**

The time delay between DLVP reported camera time data and OBU V2X signal receipt time data, was consistant (averaging ~0.60 seconds) during testing with exception to testing during scenario 12 (TIM/SPAT/PSM thermal), conducted on April 3rd during rain, when the time delay varied between 0.584 and 1.627 seconds (averaging 1.185 seconds). Further testing would be required to confirm potential atmospheric interference.

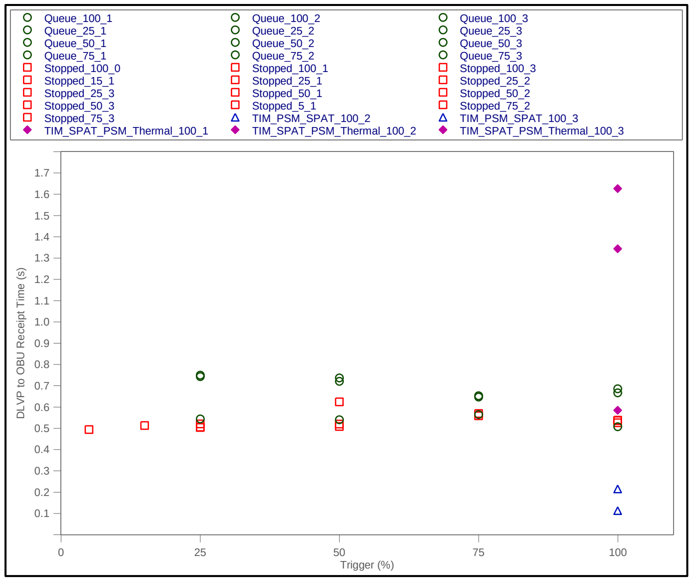

Figure 42: Time delay of reported DLVP data representing 'stopped vehicle blue' (timestampcamera) and RSU V2X TIM message broadcast transmission time (scenario 9 queue, scenario 7 stopped, scenario 11 TIM/PSM/SPaT and scenario 12 TIM/SPaT/PSM thermal)

5.6 Brake application to stop position distance from rail safety zone

The methodology utilized for calculation of braking distance is outlined in section 4.4.

The test vehicle came to a controlled stop outside of the designated rail safety zone during all testing scenarios with exception to scenario 3 (PSM) 25% trigger distance where the test vehicle did initiate braking, upon receipt of a PSM C-V2X message, but failed to come to a stop and travelled into and through the rail safety zone.

Other than scenario 3 (PSM) 25% trigger, the test vehicle final stop position after receipt of C-V2X message(s) and braking application was consistent during all testing scenarios, in reference to the designated rail safety zone perimeter, varying between 5.3 m and 11.0 m. The test vehicle final stop position after receipt of C-V2X message(s) and braking application varied between 11 m and 19 m, in reference to the centre of the rail crossing.

A slight decrease in the stop distance from the rail safety zone was noted as the trigger distance deceased but overall, the distances remained similar.

Test vehicle average stop position distances from start of the rail safety zone are provided in Table 28. Test vehicle average stop position distances from center of the rail crossing are provided in Table 29.

Table 28: Test vehicle average stop position distance from start of rail safety zone

Scenario	Date	Vehicle State	Category	Trigger					
				100% (m)	75% (m)	50% (m)	25% (m)	15% (m)	5% (m)
1	24-Jan	Traveling	SPaT	11.0	10.1	10.5	7.9		
2	02-Feb	Traveling	PSM / SPaT	8.9	8.7	8.8	8.7		
3	02-Feb	Traveling	PSM	9.0	3.5	5.8	no stop		
4	16-Feb	Traveling	TIM	9.0	8.9	7.1	7.8		
5	15-Feb	Traveling	TIM / SPaT	8.8	8.6	8.8	6.7		
6	13-Mar	Traveling	PSM / SPaT	8.9	8.7				
7	12-Mar	Stopped	TIM / SPaT	8.9	9.0	8.5	8.3	7.4	5.3
8	27-Mar	Traveling	PSM / SPaT			8.8	7.6		
9	11-Mar	Queued	TIM / SPaT	8.9					
10	15-Mar	Queued	TIM / SPaT		8.8	8.9	6.3		
11	03-Apr	Traveling	TIM / PSM / SPaT	5.8					
12	03-Apr	Traveling	TIM/ SPaT / PSM	8.8					

Table 29: Test vehicle average stop position distance from center of rail crossing

Scenario	Date	Vehicle State	Category	Trigger					
				100% (m)	75% (m)	50% (m)	25% (m)	15% (m)	5% (m)
1	24-Jan	Traveling	SPaT	18.6	17.7	18.1	15.5		
2	02-Feb	Traveling	PSM / SPaT	16.5	16.3	16.4	16.3		
3	02-Feb	Traveling	PSM	16.6	11.1	13.4	no stop		
4	16-Feb	Traveling	TIM	16.6	16.5	14.7	15.4		
5	15-Feb	Traveling	TIM / SPaT	16.4	16.2	16.4	14.3		
6	13-Mar	Traveling	PSM / SPaT	16.5	16.3				
7	12-Mar	Stopped	TIM / SPaT	16.5	16.6	16.1	15.9	15.0	12.9
8	27-Mar	Traveling	PSM / SPaT			16.4	15.2		
9	11-Mar	Queued	TIM / SPaT	16.5					
10	15-Mar	Queued	TIM / SPaT		16.4	16.5	13.9		
11	03-Apr	Traveling	TIM / PSM / SPaT	13.4					
12	03-Apr	Traveling	TIM/ SPaT / PSM	16.4					

The average distance travelled by the test vehicle after receipt of a C-V2X message to the position at which the test vehicle came to a complete stop was calculated. The average test vehicle braking distance for all trigger distances (i.e. 25, 50, 75, 100%) for each test scenario is provided in Table 30.

Table 30: Test vehicle average brake application to stop position distance

Scenario	Date	Vehicle State	Category	Trigger					
				100% (m)	75% (m)	50% (m)	25% (m)	15% (m)	5% (m)
1	24-Jan	Traveling	SPaT	129.7	118.0	114.1	72.0		
2	02-Feb	Traveling	PSM / SPaT	132.9	113.9	89.7	67.3		
3	02-Feb	Traveling	PSM	112.1	105.0	70.1	no stop		
4	16-Feb	Traveling	TIM	30.2	125.9	73.6	73.2		
5	15-Feb	Traveling	TIM / SPaT	111.8	87.2	79.4	67.7		
6	13-Mar	Traveling	PSM / SPaT	116.8	120.2				
7	12-Mar	Stopped	TIM / SPaT	134.4	123.1	86.1	84.7	71.3	75.0
8	27-Mar	Traveling	PSM / SPaT			103.5	73.2		
9	11-Mar	Queued	TIM / SPaT	132.8					
10	15-Mar	Queued	TIM / SPaT		100.9	120.9	77.3		
11	03-Apr	Traveling	TIM / PSM / SPaT	29.9					
12	03-Apr	Traveling	TIM/ SPaT / PSM	133.6					

Table 31 provides the average test vehicle distances from the rail safety zone perimeter upon receipt of C-V2X SPaT, TIM and PSM messages, the average test vehicle distance from the rail safety zone perimeter at the time of brake application, the average test vehicle stop distance from the center of the rail crossing and the average test vehicle braking distance (test vehicle position at time of receipt of C-V2X message to test vehicle at a complete stop).

Table 31: Calculated average braking distances

Test	Test Date	Scenario	Infrastructure Sensor	Trigger	Spat V2X (m)	TIM V2X (m)	PSM V2X (m)	Brakes Applied (m)	Stop Position (m)	Braking Distance (m)
1	2024-01-24	PTZ and Thermal	SPaT Only	25	93.6	n/a	n/a	87.7	15.5	72.2
				50	125.7	n/a	n/a	121.9	18.1	103.8
				75	147.6	n/a	n/a	139.1	17.7	121.4
				100	165.4	n/a	n/a	148.8	18.6	130.2
2	2024-02-02	LiDAR (PSM)	PSM then SPAT	25	72.3	n/a	89.0	82.8	16.4	66.5
				50	35.6	n/a	44.0	105.9	16.4	89.5
				75	152.3	n/a	152.3	118.1	16.3	101.9
				100	165.8	n/a	165.8	148.2	16.5	131.8
3	2024-02-02	LiDAR	PSM Only	25	n/a	n/a	72.5	60.9	16.7	51.7
				50	n/a	n/a	87.7	83.2	13.4	69.8
				75	n/a	n/a	120.9	115.8	15.8	105.7
				100	n/a	n/a	144.5	137.9	16.6	121.3
4	2024-02-16	PTZ and Thermal	TIM Only	25	n/a	94.7	n/a	89.4	15.4	74.0
				50	n/a	107.3	n/a	102.4	15.7	86.7
				75	n/a	142.3	n/a	136.1	16.5	119.7
				100	n/a	163.5	n/a	147.8	16.6	131.2
5	2024-02-15	PTZ and Thermal (TIM)	TIM then SPaT	25	72.0	92.2	14.5	88.0	14.3	73.7
				50	90.0	101.2	16.8	95.4	16.4	79.0
				75	106.8	98.6	17.1	101.8	16.2	85.7
				100	130.3	138.6	22.1	133.5	16.4	117.2
6	2024-03-13	LiDAR (PSM)	PSM then SPaT	75	15.6	n/a	141.9	136.5	16.3	120.2
				100	15.1	-	150.1	133.2	16.5	116.8
7	2024-03-12	DLVP (TIM)	TIM then SPaT (stopped)	5	13.0	89.1	n/a	84.2	12.9	71.3
				15	15.7	95.6	n/a	90.6	15.7	75.0
				25	16.0	105.0	n/a	100.6	15.9	84.7
				50	16.0	107.9	n/a	102.2	16.1	86.1
				75	16.1	145.2	n/a	139.7	16.6	123.1
				100	16.1	172.7	n/a	150.9	16.5	134.4
8	2024-03-27	LiDAR (PSM)	PSM then SPaT	25	15.2	n/a	93.8	88.3	15.2	73.2
				50	16.1	n/a	124.8	119.8	16.4	103.5
10	2024-03-15	DLVP (TIM)	TIM then SPaT (Queued)	25	13.2	96.1	n/a	91.1	13.9	77.3
				50	15.4	143.8	n/a	137.3	16.5	120.9
				75	15.3	122.8	n/a	117.3	16.4	100.9
9	2024-03-11			100	16.1	160.7	n/a	149.2	16.5	132.8
11	2024-04-03	DLVP (TIM) / LiDAR (PSM)	TIM then PSM then SPaT	100	27.1	260.9	59.0	29.9	16.4	46.2
12	2024-04-03	DLVP (TIM) / LiDAR (PSM)	TIM then SPaT then PSM (Thermal)	100	16.1	253.0	100.0	150.8	16.4	134.4

The autonomous braking control system node parsing sequence was as follows: /pacmod node data transfer to /twistgate node data transfer to /ssc/interface node. The order sequence of braking data variables analyzed was /pacmod variable *as_rx/brake_cmd.command*, /pacmod variable *parsed_tx/brake_rpt.command*, /twistgate variable */vehicle_cmd.brake_cmd.brake* and /ssc/interface variable */ssc/brake_feedback.brake_pedal*. The delay time between braking data variables recorded during testing is shown in Figure 43.

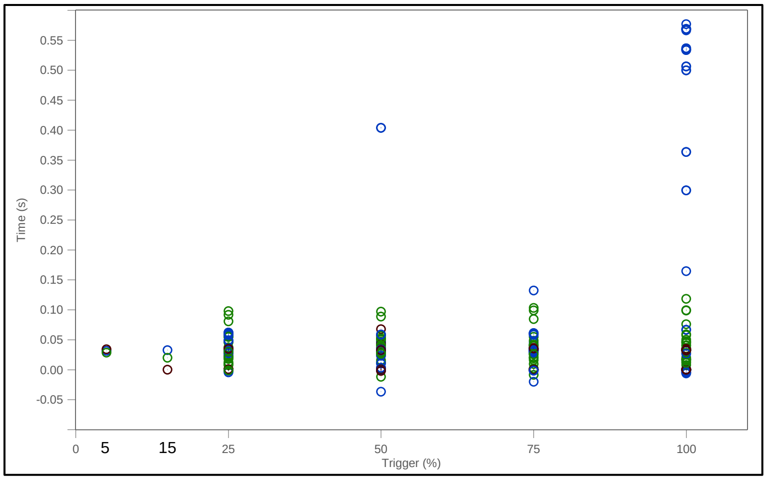

Figure 43: Time delay between autonomous system braking parameters (/pacmod node to /ssc/ node) analyzed from recorded Bag file data

6 Key Findings and Recommendations

This section presents a consolidated summary of the key findings and lessons learned in this project.

6.1 Key findings

The key findings that emerged from the collection, processing and analysis of data are summarized as follows:

- Test vehicle reaction to the receipt of C-V2X messages was consistent during testing.
- Weather did not appear to affect testing. Although, inclement weather (light/moderate rain) was only experienced during testing of scenarios 11 and 12 on April 3rd. As a caveat, testing was conducted during winter but minimal ground accumulation of snow was present and no snowfall was experienced testing.
- Potential opportunities to reduce the likelihood of grade crossing collisions using emerging machine vision technology was confirmed.
- The analysis of real-world data collected from a public grade crossing validated the rail safety use case scenarios studied in this project.

6.2 Recommendations

The following section outlines recommended additional testing for greater qualification of rail crossing C-V2X infrastructure sensor performance and potential C-V2x interference.

- All testing scenarios during this testing campaign were conducted during daylight hours. It is recommended additional testing be performed during various illumination conditions (dusk, night, etc.).
- A comparison of potential environmental conditions' effect on sensor and test vehicle actions would require repeatable testing of individual scenarios on a clear day and during an inclement weather day (heavy snow/rain, fog). The TSB have noted that accident rates increase by 61% in winter months versus summer months (for non-vacation months) and has recently announced a Safety Issue Investigation, R20H0082, looking broadly into the factors contributing to seasonal variations[6].
- The test vehicle approach speed during this testing campaign remained constant, at 60 km/h. Higher approach speeds and speed variation (accelerating upon rail crossing approach versus steady state speed) are recommended.
- A significant dataset of machine vision suite and C-V2X data was collected during this test campaign. Due to project time and cost considerations, a full in-depth analysis of the collected dataset was not possible. Additional analysis of the collected dataset is recommended.

[6] Rail Transportation Safety Issue Investigation R20H0082 - Transportation Safety Board (tsb.gc.ca) / TSB (link) [18]

Acronyms and Abbreviations

AI	artificial intelligence
CMCC	Connected Mobility Control Center
C-V2X	cellular vehicle-to-everything
DDT	dynamic driving task
DLVP	deep learning video platform
ETSI	European Telecommunications Standards Institute
fps	frames per second
GNSS	global navigation satellite system
GPS	global positioning system
IEEE	Institute of Electrical and Electronics Engineers
ITS	intelligent transportation systems
LiDAR	Light Detection and Ranging
NCAP	new car assessment programs
NFOV	narrow field-of-view
NRC	National Research Council
OBU	onboard communication unit
PAC	platform actuation and control
PACMod	platform actuation and control module
PSM	personal safety message
PTZ	pan, tilt, zoom
RADAR	radio detection and ranging
RGB	red, green, blue
ROS	robot operating system
rPAC	remote programmable automation controller
RSU	roadside unit
SAE	Society of Automotive Engineers
SPaT	signal phase and timing
SSD	stopping sight distance
TIM	traveler information message
TC	Transport Canada
TSB	Transportation Safety Board of Canada
V2X	vehicle-to-everything
VRU	vulnerable road user
WAVE	wireless access in vehicular environments

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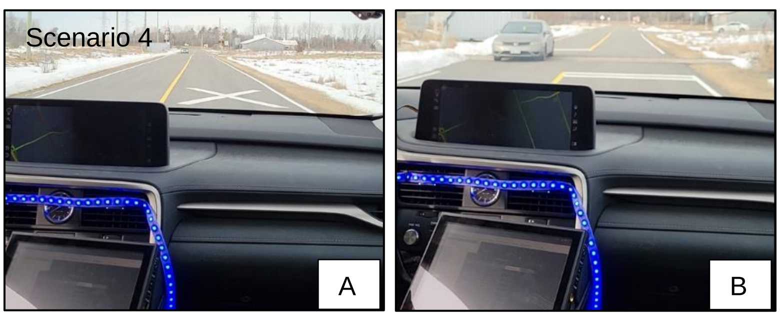
Appendix A – Description of tested scenarios

Scenario 1 (SPAT only) testing sequence: test vehicle approaching grade crossing as SPAT activated (A), stopped at designed stop line location during sequence of SPAT signaling (B) and departing grade crossing upon termination of SPAT activation (C). Presented images were captured from screen shots of the recorded onboard forwarding facing windshield mounted video cameras.

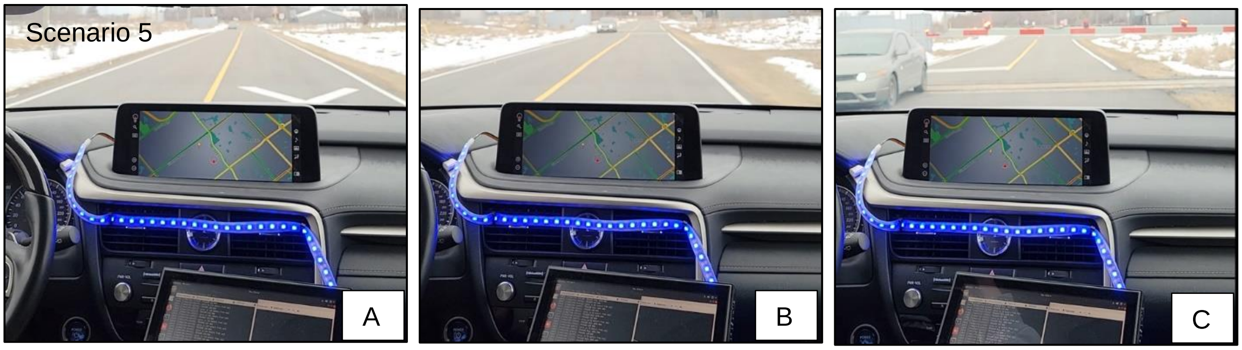
Scenario 2 (PSM then SPAT) testing sequence: test vehicle approaching grade crossing as PSM activated with VRU dummy shown in initial position (A), test vehicle continuing to approach the level crossing as SPAT activated with VRU dummy shown traversing across the rail tracks (B), stopped at designed stop line location during sequence of SPAT signaling (as barriers are in the process of lowering into position) (C), remained stopped at designed stop line location during continued sequence of SPAT signaling (barriers in lowered position)(D) and departing grade crossing upon termination of SPAT activation (E). Presented images were captured from screen shots of the recorded onboard forwarding facing windshield mounted video cameras.

Scenario 3 (PSM only) testing sequence: test vehicle approaching grade crossing as PSM activated with VRU dummy shown in initial position (A), test vehicle continuing to approach the level crossing with VRU dummy shown traversing across the rail tracks (B), and stopped at the designed stop line location during final PSM V2X sequence (VRU dummy just out of frame to the left) (C). Presented images were captured from screen shots of the recorded onboard forwarding facing windshield mounted video cameras.

Scenario 4 (TIM only) testing sequence: test vehicle approaching grade crossing as TIM activated with other traffic vehicle shown in it stopped positioned on the tracks in the opposing lane of traffic (A), test vehicle continues to approach the grade crossing as other traffic vehicle remains stopped positioned on the track in the opposing traffic lane before coming to a stop at the designated stop line (B). Presented images were obtained from a cell phone video recorded from within the vehicle.



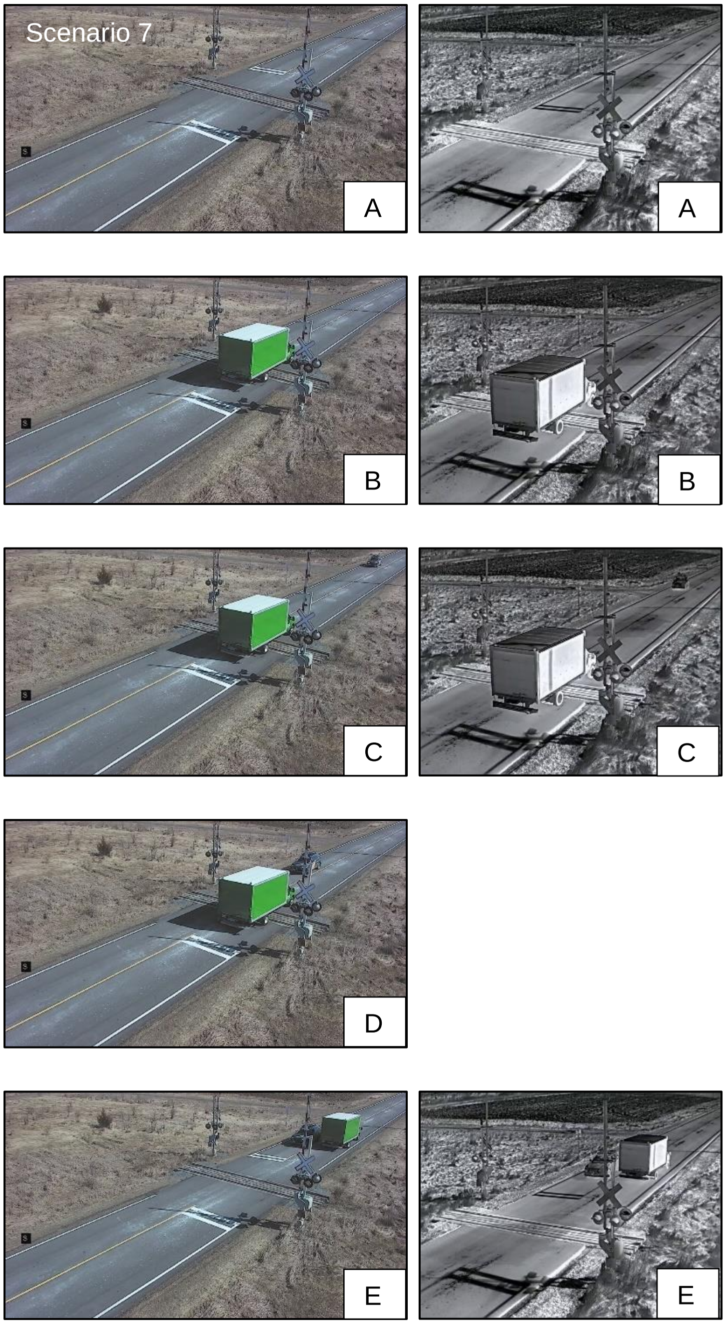
Scenario 5 (TIM then SPAT) testing sequence: test vehicle approaching grade crossing as TIM activated with other traffic vehicle shown in it stopped positioned on the tracks in the opposing lane of traffic (A), test vehicle continued approach to the grade crossing as SPAT activated with other traffic vehicle shown continued to be stopped positioned on the tracks in the opposing lane of traffic (B), and stopped at the designed stop line location during final SPAT V2X sequence (C). Presented images were obtained from a cell phone video recorded from within the vehicle.

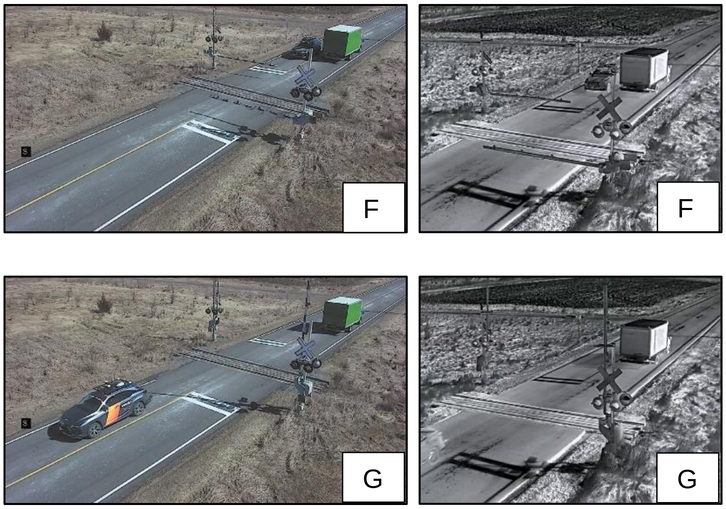


Scenario 6 (PSM then SPAT) testing sequence: test vehicle approaching grade crossing as PSM V2X message received (A), test vehicle stopped at the designed stop line location as VRU dummy begins to exit designed safety zone (B), test vehicle remained stopped at the designed stop line location with VRU dummy exit outside of the designed safety zone and as SPAT V2X message received (C), remained stopped at the designed stop line location during final SPAT V2X sequence (D) and departing the grade crossing upon termination of SPAT activation. Presented images were captured from screen shots of the recorded onboard forwarding facing windshield mounted video camera.

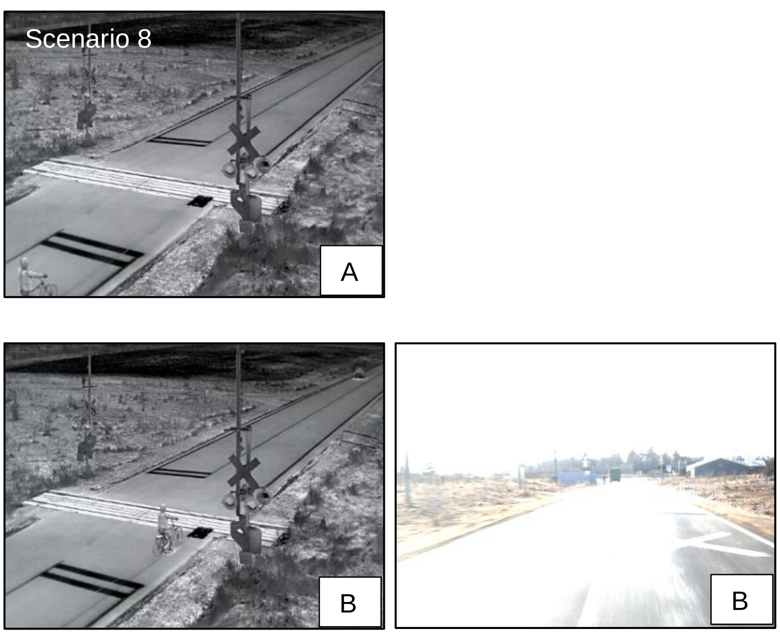
Scenario 7 (TIM then SPAT) stopped vehicle testing sequence: view of level crossing at initiation of test showing absence of stopped vehicles (A), position of the other traffic vehicle after approaching the level crossing and stopping at a positioned on the level crossing in the opposing lane of traffic (B), test vehicle continues to approach the grade crossing as TIM V2X message received as other traffic vehicle remains stopped positioned on the track in the opposing traffic lane (C), test vehicle stopped at the designated stop line location (D), other traffic vehicle exists the designated safety zone while the test vehicle remains stopped at the designed stop lone location and SPAT V2X message received as rail crossing signaling activated (E), test vehicle remains stopped at the designed stop line location as rail crossing signaling

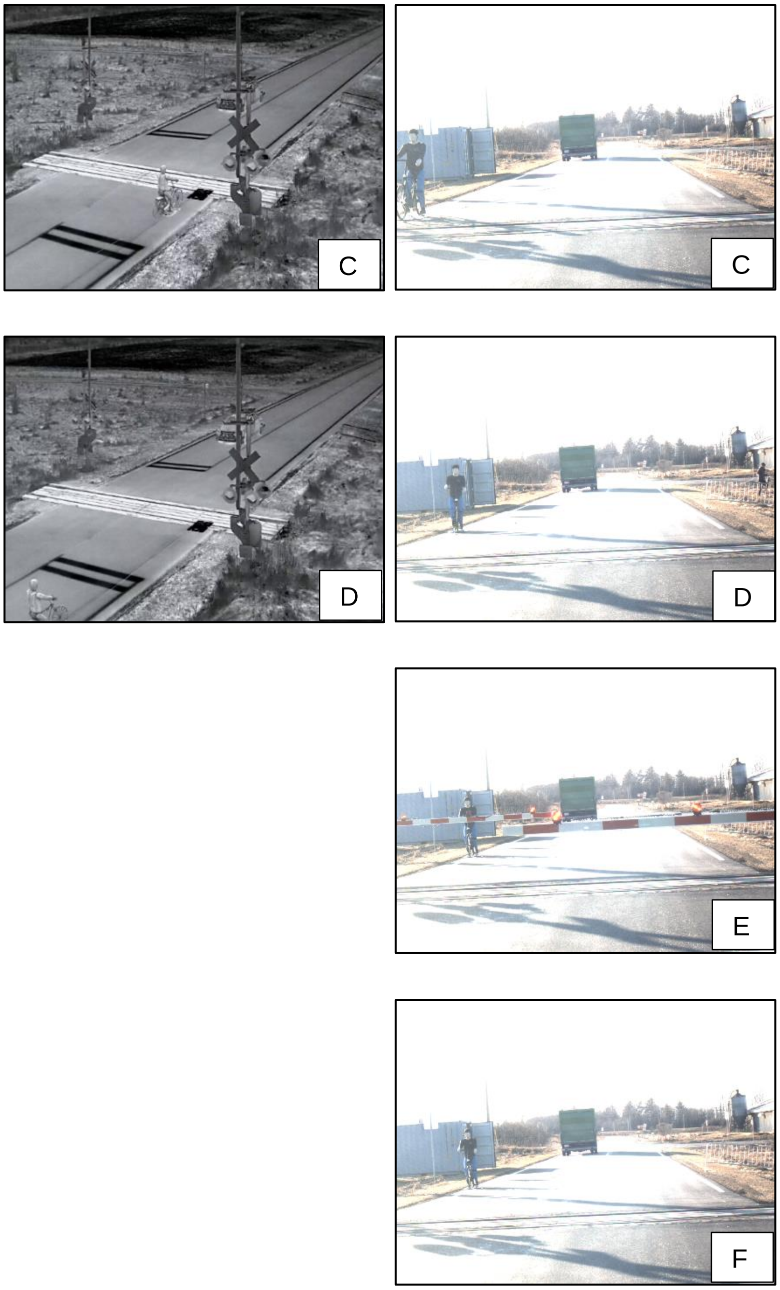
cycles (F), test vehicle travels through the grade crossing safety zone upon termination of the SPAT activation (G). Presented images were captured from screen shots of recorded infrastructure RGB (left frames) and thermal cameras (right frames).





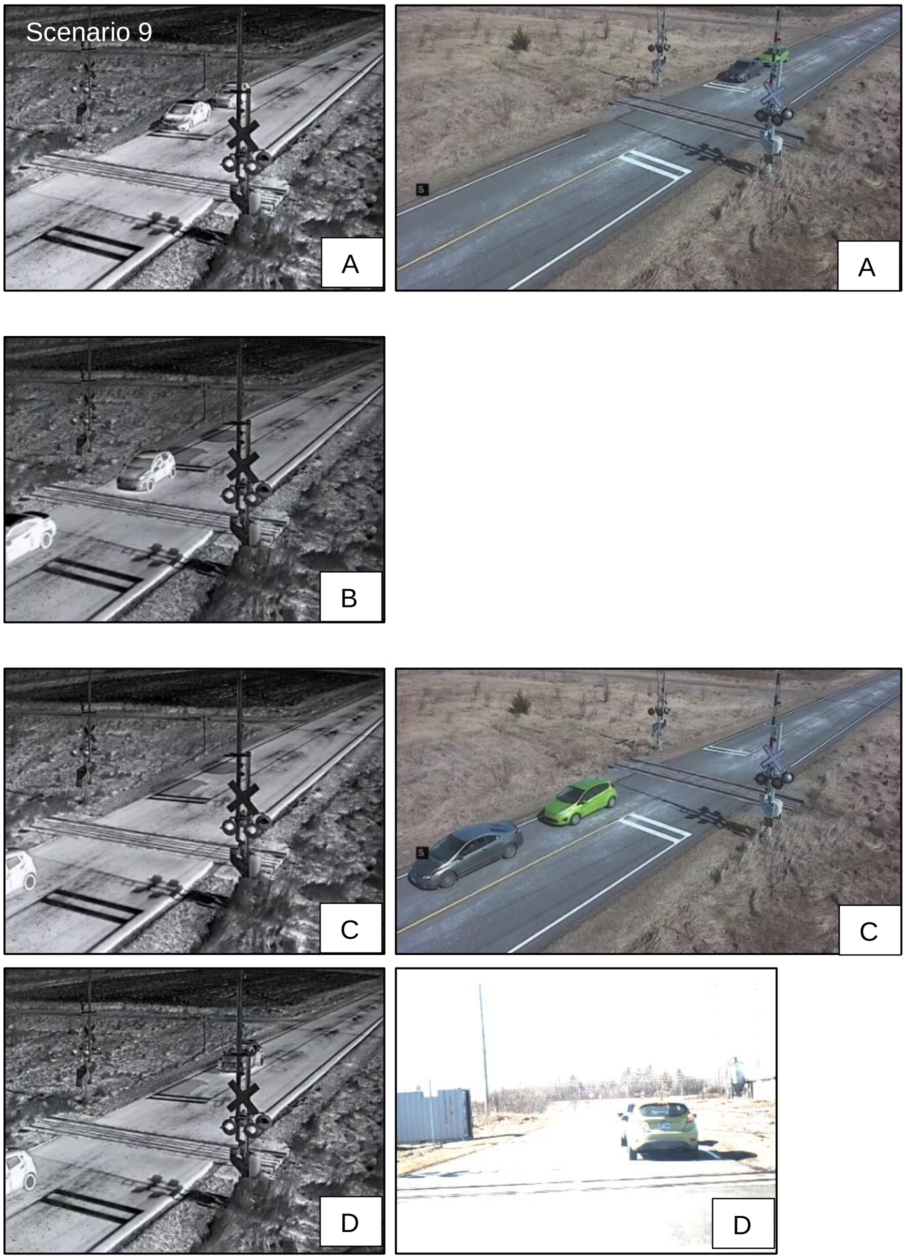
Scenario 8 (PSM then SPAT) testing sequence: view of level crossing at initiation of test showing absence of VRU in rail safety zone (A), VRU dummy (bicyclist) enters the rail safety zone as the test vehicle approaches while receiving a V2X PSM message (B), test vehicle stopped at the designated stop line location as VRU remains in rail safety zone (C), VRU dummy exists the rail safety zone and SPAT V2X message received as rail crossing signaling activated (D), test vehicle remains stopped behind the designated stop line as rail crossing signaling cycles (E), completion of rail crossing signaling and termination of V2X SPAT messaging (F). Presented images were captured from screen shots of recorded infrastructure thermal camera (left frames) and from screen shots of the recorded onboard forwarding facing windshield mounted video cameras (right frames).

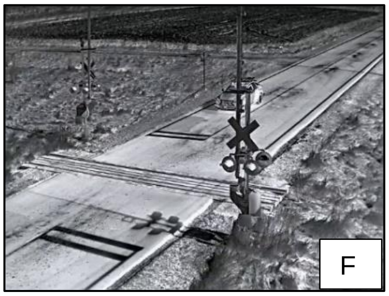




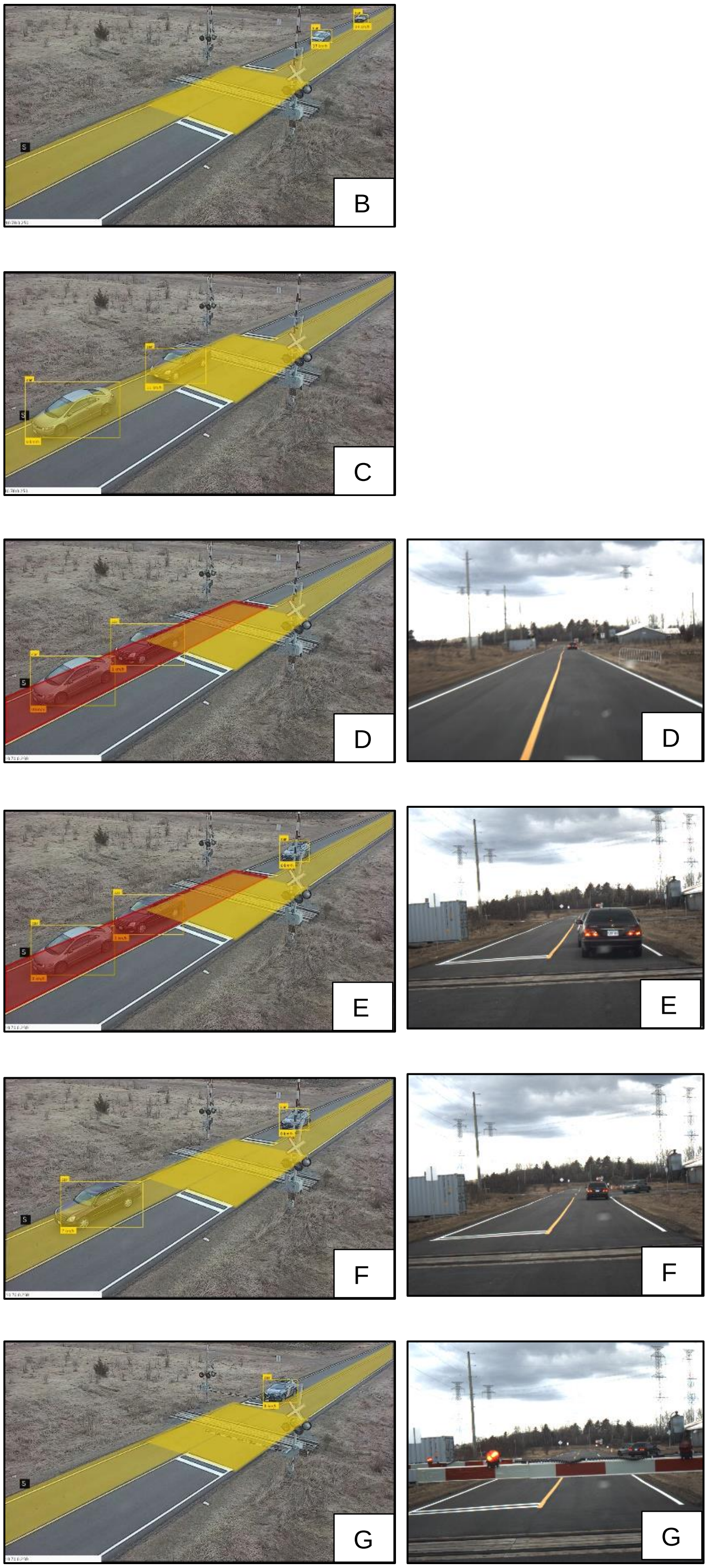
Scenario 9 (TIM then SPAT) queued traffic testing sequence: view of level crossing at initiation of testing showing two other traffic vehicles stopped (queued) at the designated stop line (A), the other traffic vehicles slowly travel forwards through the designated rail safety zone triggering a TIM V2X message (B), the other traffic vehicles continue forwards until the rear of the second other traffic vehicle stops just outside the safety zone as the test vehicle approaches the level crossing (C), the test vehicle stopped outside of the rail safety zone at the designed stop line while the other traffic vehicles remain in their queue positions while rail signaling activated and SPAT V2X message broadcast (D), test vehicle remains stopped behind the designated stop line as rail crossing signaling cycles and the traffic queue clears

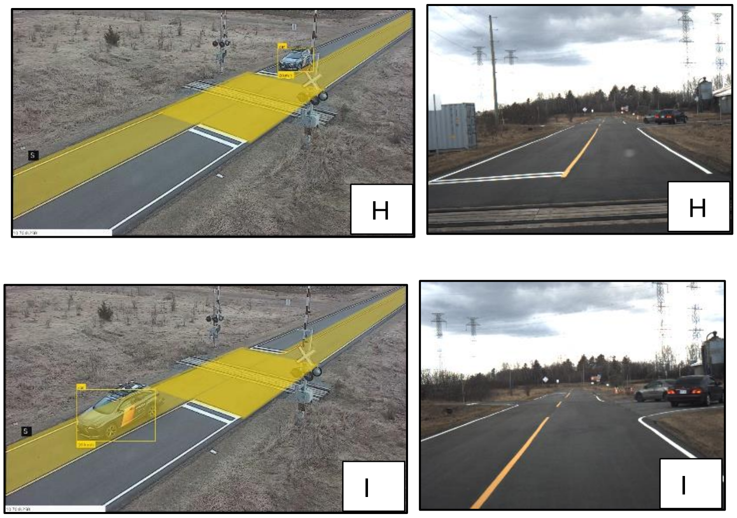
permitting the other traffic vehicles to freely travel forwards (E), and completion of rail crossing signaling and termination of V2X SPAT messaging (F). Presented images were captured from screen shots of recorded infrastructure thermal cameras (left frames) and infrastructure RGB cameras and from screen shots of the recorded onboard forwarding facing windshield mounted video cameras (right frames).



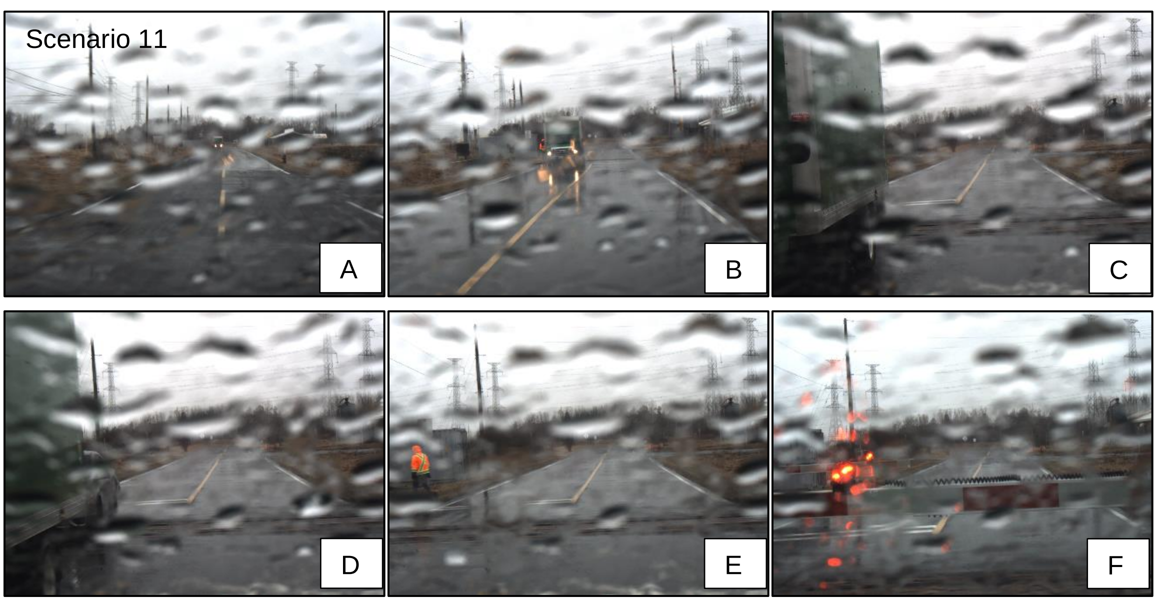


Scenario 10 (TIM then SPAT) queued traffic testing sequence: view of level crossing at initiation of test showing absence of stopped vehicles (A), two other traffic vehicles approach the designated rail safety zone (B), two other traffic vehicles travel through the designated rail safety zone and stop (queued) with the rear of the second other traffic vehicle stopped just outside the safety zone as the test vehicle approaches the level crossing (C), the queued other traffic vehicle trigger a TIM V2X message to the approaching testing vehicle (D), the test vehicle stopped outside of the rail safety zone at the designed stop line while the other traffic vehicles remain in their queue positions while TIM V2X message continues to broadcast (E), the traffic queue clears permitting the other traffic vehicles to freely travel forwards as the rail crossing signaling activates broadcasting at SPAT V2X message (F), the test vehicle stopped outside of the rail safety zone at the designed stop line while the rail crossing signaling cycles (G), completion of rail crossing signaling and termination of V2X SPAT messaging (H), test vehicle travels through the grade crossing safety zone upon termination of the SPAT activation (I). Presented images were captured from screen shots of recorded infrastructure LiDAR (left frames) and from screen shots of the recorded onboard forwarding facing windshield mounted video cameras (right frames).

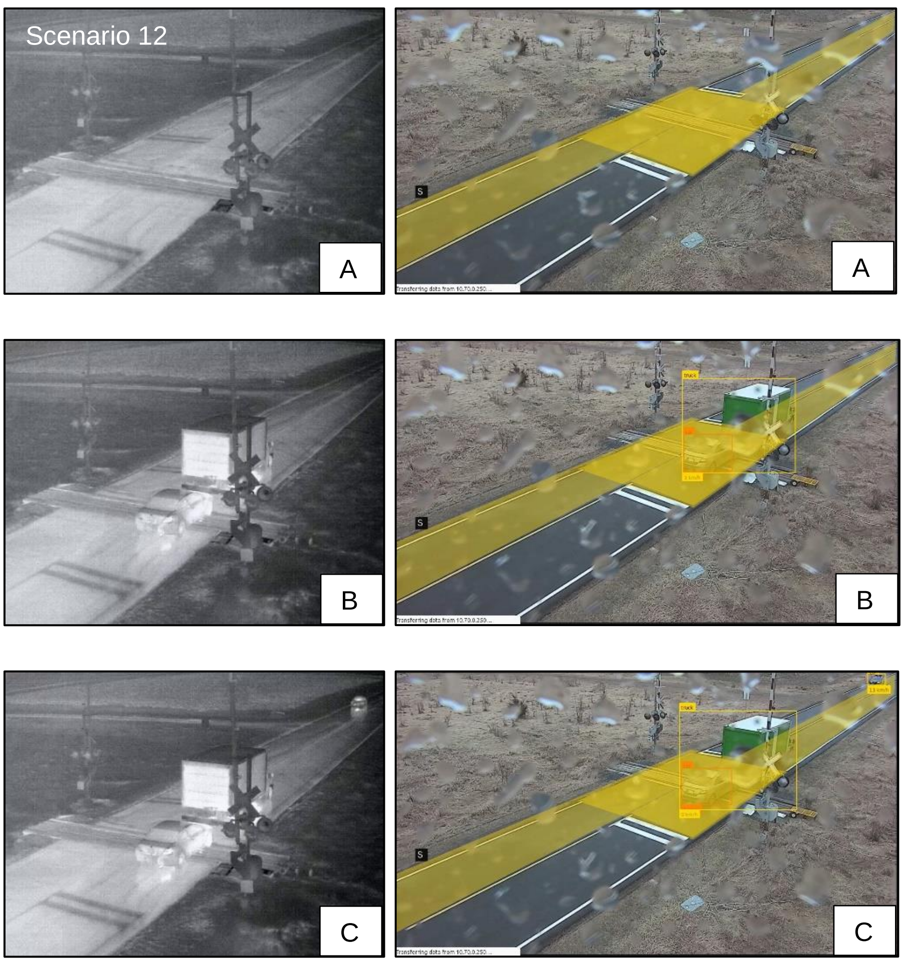

B
C
D
D
E
E
F
F
G
G



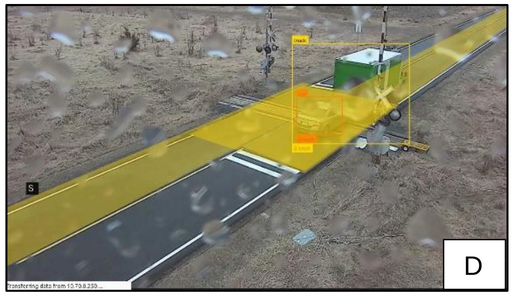
Scenario 11 (TIM then PSM then SPAT) testing sequence: test vehicle approaching the test intersection (A), test vehicle continues to approach the test intersection while other traffic stopped across the rail crossing triggers broadcast of TIM V2X message and a pedestrian approaches but does not enter the rail safety zone (B), a pedestrian enters the rail safety zone triggering a PSM V2X message just prior to the test vehicle slowing to stop at designed stop line (C), other traffic vehicles depart the rail safety zone followed a few seconds later by the pedestrian also exiting the rail safety zone (D and E), the rail crossing signaling activates broadcasting a SPAT V2X message and the test vehicle remains stopped behind the designated stop line as rail crossing signaling cycles (F). Presented images were captured from screen shots of the recorded onboard forwarding facing windshield mounted video cameras (right frames).



Scenario 12 (TIM then SPAT then PSM) testing sequence: view of level crossing at initiation of test showing absence of stopped vehicles (A), two other traffic vehicles travel through the designated rail safety zone and stop (queued) with the second other traffic vehicle stopped across the rail tracks (B), the queued other traffic vehicle trigger a TIM V2X message to the approaching testing vehicle (C), the test vehicle stopped outside of the rail safety zone at the designed stop line while the other traffic vehicles remain in their queue positions while TIM V2X message continues to broadcast (D), two other traffic vehicles travel depart the designated rail safety zone and stop (queued) as the rail crossing signaling activates broadcasting at SPAT V2X message (E), the test vehicle remains stopped outside of the rail safety zone at the designed stop line while the rail crossing signaling cycles. A pedestrian approach but does not enter the rail safety zone (F), the pedestrian enters the rail safety zone triggering a PSM V2X message (G), the pedestrian exits the rail safety zone terminating broadcasting of PSM V2X message which permits the test vehicle to enter and pass through the rail safety zone (H). Presented images were captured from infrastructure thermal and RGB cameras, screen shots of the recorded onboard forwarding facing windshield mounted video cameras (left frames) and from screen shots of recorded infrastructure LiDAR (right frames).




D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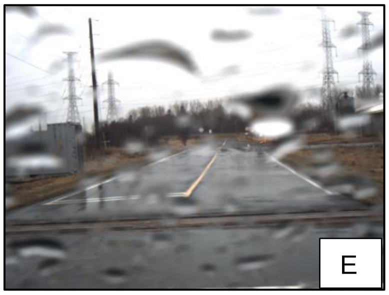
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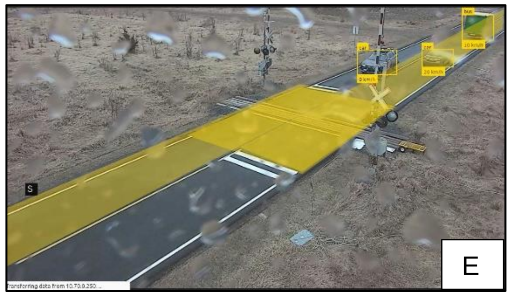
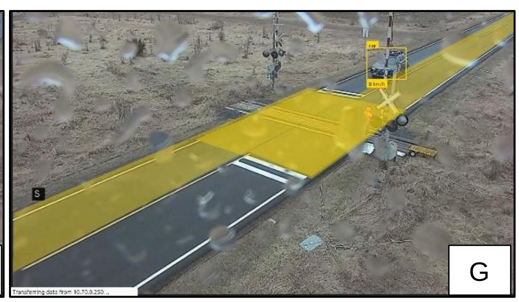

E

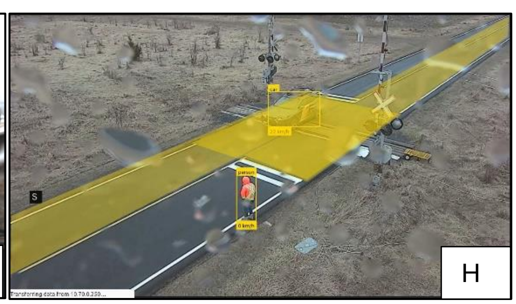

F


F


G


G


H


H

Appendix B - Timing sequence of infrastructure sensors, transmission and receipt of V2X signals and test vehicle braking and stop actions

Scenario 1 - Timing sequence of infrastructure sensors, transmission and receipt of V2X signals and test vehicle braking and stop actions

Scenario	Test Name	Trigger	Run	SPAT (Green)	Siemens Controller Rail Signal Activated	RSU SPaT (yellow) Acivated	OBU SPaT (yellow) Acivated	Lexus Brakes Applied	Lexus Stopped	Siemens Controller Rail Signal Deactivated
1	SPAT Only	25	1	0.000	17.006		17.797	18.225	30.458	55.509
			2	0.000	14.022		14.303	14.622	28.817	51.716
			3	0.000	26.034		26.119	26.383	34.353	63.833
			4	0.000	16.013		16.796	17.130	24.212	not captured
			5	0.000	14.995		15.660	16.024	23.726	53.329
		50	1	0.000	8.008		8.050	8.298	23.689	45.663
			2	0.000	14.014		14.371	14.609	27.407	52.004
			3	0.000	17.004		17.188	17.413	31.916	54.629
		75	1	0.000	23.652		23.666	24.045	39.100	61.201
			2	0.000	23.408		23.426	23.896	38.501	60.700
			3	0.000	21.022		21.657	22.455	40.863	59.023
		100	1	0.000	11.176		11.961	12.834	28.591	49.308
			2	0.000	21.192		21.323	22.299	38.433	58.555
			3	0.000	10.996		11.661	12.800	28.803	49.197

Note: Tigger 25 run 4 Siemens controller data file was stopped prior to the end of the test run

Scenario 2 - Timing sequence of infrastructure sensors, transmission and receipt of V2X signals and test vehicle braking and stop actions

Scenario	Test Name	Trigger	Run	SPAT (Green)	LiDAR PSM (Start)	LiDAR PSM (Stop)	RSU PSM Acivated	OBU PSM Acivated	Lexus Brakes Applied	Siemens Controller Rail Signal Activated	RSU SPaT (yellow) Acivated	OBU SPaT (yellow) Acivated	Lexus Stopped	Siemens Controller Rail Signal Deactivated
2	PSM / SPaT	25	2	0.000	not recorded	not recorded	not recorded	26.063	26.399	26.980		27.320	33.863	64.658
			3	0.000	not recorded	not recorded	not recorded	17.709	18.027	17.967		18.486	25.858	56.081
		50	1	0.000	not recorded	not recorded	not recorded	16.122	16.432	16.949		17.633	31.517	55.104
			2	0.000	not recorded	not recorded	not recorded	18.465	18.785	18.966		19.795	34.077	57.133
			3	0.000	not recorded	not recorded	not recorded	24.425	24.627	25.001		25.840	39.108	63.075
		75	1	0.000	not recorded	not recorded	not recorded	12.632	12.910	13.972		14.418	29.717	51.699
			2	0.000	not recorded	not recorded	not recorded	16.880	17.190	17.962		18.282	34.340	55.693
			3	0.000	not recorded	not recorded	not recorded	13.845	14.158	12.945		13.815	28.205	51.431
		100	1	0.000	not recorded	not recorded	not recorded	22.087	22.497	22.992		23.623	40.414	61.015
			2	0.000	not recorded	not recorded	not recorded	22.424	22.699	22.989		23.949	40.080	61.467
			3	0.000	not recorded	not recorded	not recorded	21.264	21.550	22.972		23.161	39.171	60.565

Scenario 3 - Timing sequence of infrastructure sensors, transmission and receipt of V2X signals and test vehicle braking and stop actions

Scenario	Test Name	Trigger	Run	SPAT (Green)	LiDAR PSM (Start)	LiDAR PSM (Stop)	RSU PSM Acivated	OBU PSM Acivated	Lexus Brakes Applied	Lexus Stopped
3	PSM Only	25	1	0.000	not recorded	not recorded	not recorded	27.997	28.377	no stop
			2	0.000	not recorded	not recorded	not recorded	26.209	26.561	no stop
			3	0.000	not recorded	not recorded	not recorded	10.740	10.983	no stop
		50	1	0.000	not recorded	not recorded	not recorded	26.054	26.409	34.080
			2	0.000	not recorded	not recorded	not recorded	25.357	25.611	33.284
			3	0.000	not recorded	not recorded	not recorded	19.499	19.793	30.475
		75	1	0.000	not recorded	not recorded	not recorded	13.546	13.912	29.819
			2	0.000	not recorded	not recorded	not recorded	11.010	11.202	35.627
			3	0.000	not recorded	not recorded	not recorded	25.749	26.089	41.092
		100	1	0.000	not recorded	not recorded	not recorded	23.295	23.580	39.304
			2	0.000	not recorded	not recorded	not recorded	12.079	12.451	29.853
			3	0.000	not recorded	not recorded	not recorded	12.512	12.935	29.747

Note: During trigger 25 runs 1 to 3 the test vehicle travelled through the rail safety zone and did not come to a complete stop

Scenario 4 - Timing sequence of infrastructure sensors, transmission and receipt of V2X signals and test vehicle braking and stop actions

Scenario	Test Name	Trigger	Run	SPAT (Green)	DLVP TIM Stopped vehicle (Camera time)	DLVP TIM Stopped vehicle (OS time)	RSU TIM Acivated	OBU TIM Acivated	Lexus Brakes Applied	Lexus Stopped
4	TIM Only	25	1	0.000	not recorded	not recorded	not recorded	17.427	17.653	28.497
			2	0.000	not recorded	not recorded	not recorded	24.237	24.567	39.567
			3	0.000	not recorded	not recorded	not recorded	25.799	26.114	39.639
			4	0.000	not recorded	not recorded	not recorded	25.102	25.532	32.909
		50	1	0.000	not recorded	not recorded	not recorded	25.811	26.112	34.079
			2	0.000	not recorded	not recorded	not recorded	24.561	24.884	40.527
			3	0.000	not recorded	not recorded	not recorded	22.822	23.052	38.572
		75	1	0.000	not recorded	not recorded	not recorded	22.500	22.866	40.136
			2	0.000	not recorded	not recorded	not recorded	10.878	11.240	28.496
			3	0.000	not recorded	not recorded	not recorded	13.399	13.768	30.110
		100	1	0.000	not recorded	not recorded	not recorded	13.352	14.016	31.220
			2	0.000	not recorded	not recorded	not recorded	21.443	21.961	39.159
			3	0.000	not recorded	not recorded	not recorded	10.002	11.721	29.308

Scenario 5 - Timing sequence of infrastructure sensors, transmission and receipt of V2X signals and test vehicle braking and stop actions

Scenario	Test Name	Trigger	Run	SPAT (Green)	DLVP TIM Stopped vehicle (Camera time)	DLVP TIM Stopped vehicle (OS time)	RSU TIM Acivated	OBU TIM Acivated	Siemens Controller Rail Signal Activated	RSU SPaT (yellow) Acivated	OBU SPaT (yellow) Acivated	Lexus Brakes Applied	Lexus Stopped	Siemens Controller Rail Signal Deactivated
5	TIM / SPaT	25	1	0.000	not recorded	not recorded	not recorded	26.550	26.937		27.458	26.765	34.234	64.685
			2	0.000	not recorded	not recorded	not recorded	16.703	17.982		18.055	16.996	31.739	55.590
			3	0.000	not recorded	not recorded	not recorded	24.344	24.974		25.788	24.618	38.604	63.092
		50	1	0.000	not recorded	not recorded	not recorded	25.039	24.902		25.700	25.406	40.683	62.959
			2	0.000	not recorded	not recorded	not recorded	24.769	23.891		24.832	25.061	32.566	62.468
			3	0.000	not recorded	not recorded	not recorded	24.623	24.931		25.860	24.963	40.624	63.260
		75	1	0.000	not recorded	not recorded	not recorded	24.317	23.903		24.030	24.327	39.856	61.643
			2	0.000	not recorded	not recorded	not recorded	24.692	23.901		24.606	24.856	40.289	61.929
			3	0.000	not recorded	not recorded	not recorded	15.742	13.917		14.617	15.010	29.808	51.988
		100	1	0.000	not recorded	not recorded	not recorded	22.853	22.946		23.083	23.218	40.726	60.570
			2	0.000	not recorded	not recorded	not recorded	6.467	6.934		7.242	6.772	24.273	44.872
			3	0.000	not recorded	not recorded	not recorded	11.513	11.914		12.096	11.828	28.734	49.366

Scenario 6 - Timing sequence of infrastructure sensors, transmission and receipt of V2X signals and test vehicle braking and stop actions

Scenario	Test Name	Trigger	Run	SPAT (Green)	LiDAR PSM (Start)	LiDAR PSM (Stop)	RSU PSM Acivated	OBU PSM Acivated	Lexus Brakes Applied	Lexus Stopped	Siemens Controller Rail Signal Activated	RSU SPaT (yellow) Acivated	OBU SPaT (yellow) Acivated	Siemens Controller Rail Signal Deactivated
6	PSM / SPaT	75	1	0.000	14.330	20.630	22.420	22.468	22.762	41.055	68.694		68.696	106.104
			2	0.000	15.566	22.424	23.105	23.120	23.407	40.831	64.781		64.772	102.324
			3	0.000	0.725	7.133	8.469	8.479	8.868	25.828	48.258		48.250	85.711
		100	1	0.000	5.524	11.571	13.237	13.244	13.507	30.088	56.840		56.831	94.064
			2	0.000	2.751	9.847	10.713	10.745	12.223	29.398	56.679		56.680	94.259
			3	0.000	14.052	19.761	21.687	21.732	23.037	40.179	70.869		70.863	108.259

Scenario 7 - Timing sequence of infrastructure sensors, transmission and receipt of V2X signals and test vehicle braking and stop actions

Scenario	Test Name	Trigger	Run	SPAT (Green)	DLVP TIM Stopped vehicle (Camera time)	DLVP TIM Stopped vehicle (OS time)	RSU TIM Acivated	OBU TIM Acivated	Lexus Brakes Applied	Lexus Stopped	Siemens Controller Rail Signal Activated	RSU SPaT (yellow) Acivated	OBU SPaT (yellow) Acivated	Siemens Controller Rail Signal Deactivated
7	TIM / SPaT (Stopped)	5	1	0.000	14.087	14.537	14.489	14.580	14.896	22.703	42.991		43.414	80.831
		15	1	0.000	13.541	14.005	13.963	14.054	14.332	26.954	47.011		47.633	85.206
		25	1	0.000	24.080	24.525	not recorded	24.585	24.865	32.993	54.018		54.759	92.122
			2	0.000	24.170	24.618	24.583	24.673	24.939	40.946	61.011		62.000	99.309
			3	0.000	23.179	23.653	23.615	23.699	23.945	39.368	58.027		58.802	96.322
		50	1	0.000	14.059	13.538	not recorded	13.598	13.969	27.406	45.989		46.168	86.119
			2	0.000	23.835	24.284	not recorded	24.336	24.697	40.378	58.040		58.668	95.957
			3	0.000	10.471	10.937	not recorded	11.003	11.382	24.534	41.998		42.986	80.457
		75	1	0.000	not recorded	not recorded	not recorded	14.107	14.432	32.031	47.984		48.401	85.894
			2	0.000	22.242	22.895	not recorded	22.992	23.279	40.123	57.010		57.622	94.855
			3	0.000	10.942	11.391	not recorded	11.469	11.738	29.693	45.981		46.391	83.117
		100	1	0.000	13.017	13.467	not recorded	13.552	14.254	32.057	45.965		46.077	86.113
			2	0.000	6.315	6.768	not recorded	6.842	8.961	26.562	44.986		45.661	82.909
			3	0.000	9.614	10.054	not recorded	10.134	11.325	28.950	42.984		43.591	80.875

Scenario 8 - Timing sequence of infrastructure sensors, transmission and receipt of V2X signals and test vehicle braking and stop actions

Scenario	Test Name	Trigger	Run	SPAT (Green)	LiDAR PSM (Start)	LiDAR PSM (Stop)	RSU PSM Acivated	OBU PSM Acivated	Lexus Brakes Applied	Lexus Stopped	Siemens Controller Rail Signal Activated	RSU SPaT (yellow) Acivated	OBU SPaT (yellow) Acivated	Siemens Controller Rail Signal Deactivated
8	PSM / SPaT	25	1	0.000	5.899	14.688	14.384	14.432	14.849	28.251	55.785		55.801	93.342
			2	0.000	7.170	16.446	15.749	15.798	16.118	29.866	57.192		57.203	94.471
			3	0.000	8.240	16.085	16.218	16.278	16.595	23.958	47.697		47.715	84.954
		50	1	0.000	15.007	23.811	22.993	23.128	23.433	39.565	59.725		59.739	97.059
			2	0.000	4.594	13.946	12.991	13.017	13.336	29.541	52.980		52.992	90.258
			3	0.000	16.809	20.423	23.980	24.015	24.326	39.972	62.222		62.246	99.711

Scenario 9 - Timing sequence of infrastructure sensors, transmission and receipt of V2X signals and test vehicle braking and stop actions

Scenario	Test Name	Trigger	Run	SPAT (Green)	DLVP TIM Stopped vehicle (Camera time)	DLVP TIM Stopped vehicle (OS time)	RSU TIM Acivated	OBU TIM Acivated	Lexus Brakes Applied	Lexus Stopped	Siemens Controller Rail Signal Activated	RSU SPaT (yellow) Acivated	OBU SPaT (yellow) Acivated	Siemens Controller Rail Signal Deactivated
9	TIM / SPaT (Queue)	100	1	0.000	20.931	21.576	not recorded	21.617	22.235	39.853	67.818		67.872	105.390
			2	0.000	12.834	13.466	not recorded	13.500	13.864	31.594	54.575		54.605	91.843
			3	0.000	20.535	21.018	not recorded	21.043	22.137	40.180	60.486		60.511	98.130

Scenario 10 - Timing sequence of infrastructure sensors, transmission and receipt of V2X signals and test vehicle braking and stop actions

Scenario	Test Name	Trigger	Run	SPAT (Green)	DLVP TIM Stopped vehicle (Camera time)	DLVP TIM Stopped vehicle (OS time)	RSU TIM Acivated	OBU TIM Acivated	Lexus Brakes Applied	Lexus Stopped	Siemens Controller Rail Signal Activated	RSU SPaT (yellow) Acivated	OBU SPaT (yellow) Acivated	Siemens Controller Rail Signal Deactivated
10	TIM / SPaT (Queue)	25	1	0.000	14.593	15.246	15.222	15.336	15.696	23.346	43.993		44.633	81.977
			2	0.000	14.539	14.989	14.963	15.083	15.323	31.041	56.000		56.602	94.209
		50	1	0.000	6.517	6.998	not recorded	7.057	7.683	25.130	69.036		69.742	106.999
			2	0.000	12.299	12.953	not recorded	13.020	13.242	29.416	66.027		66.720	104.184
			3	0.000	10.940	11.598	not recorded	11.677	11.978	30.303	59.012		59.716	97.369
		75	1	0.000	13.806	14.459	not recorded	14.452	14.707	30.330	56.119		56.732	94.017
			2	0.000	8.932	9.584	not recorded	9.585	9.873	25.992	52.077		52.717	90.424
			3	0.000	12.340	12.782	12.737	12.904	13.327	29.898	47.970		48.798	86.273

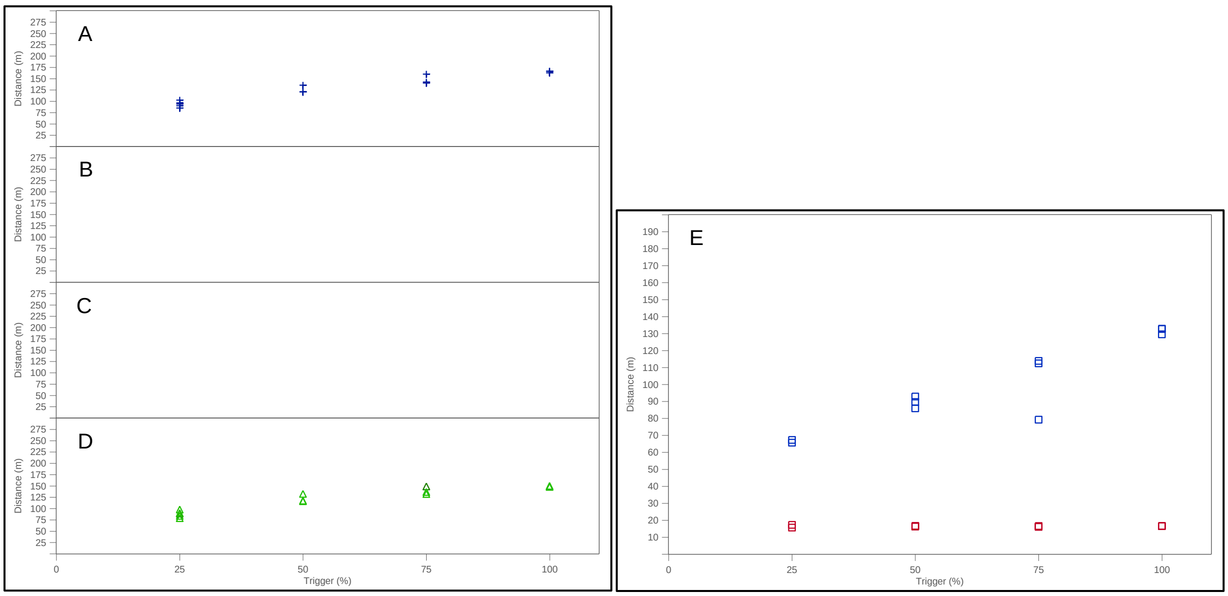
Scenario 11 - Timing sequence of infrastructure sensors, transmission and receipt of V2X signals and test vehicle braking and stop actions

Scenario	Test Name	Trigger	Run	SPAT (Green)	DLVP TIM Stopped vehicle (Camera time)	DLVP TIM Stopped vehicle (OS time)	RSU TIM Acivated	OBU TIM Acivated	LiDAR PSM (Start)	Lexus Brakes Applied	LiDAR PSM (Stop)	RSU PSM Acivated	OBU PSM Acivated	Lexus Stopped	Siemens Controller Rail Signal Activated	RSU SPaT (yellow) Acivated	OBU SPaT (yellow) Acivated	Siemens Controller Rail Signal Deactivated
11	TIM / PSM / SPaT	100	1	0.000	-0.942	-0.870	not recorded	-0.807	11.445	7.045	44.256	not recorded	21.467	24.853	47.973		48.835	86.228
			2	0.000	13.850	13.892	not recorded	13.963	-7.573	21.670	28.151	not recorded	48.362	41.430	54.986		55.734	92.977
			3	0.000	4.089	4.126	not recorded	4.303	3.757	10.735	37.445	not recorded	11.294	28.661	41.938		42.685	80.223

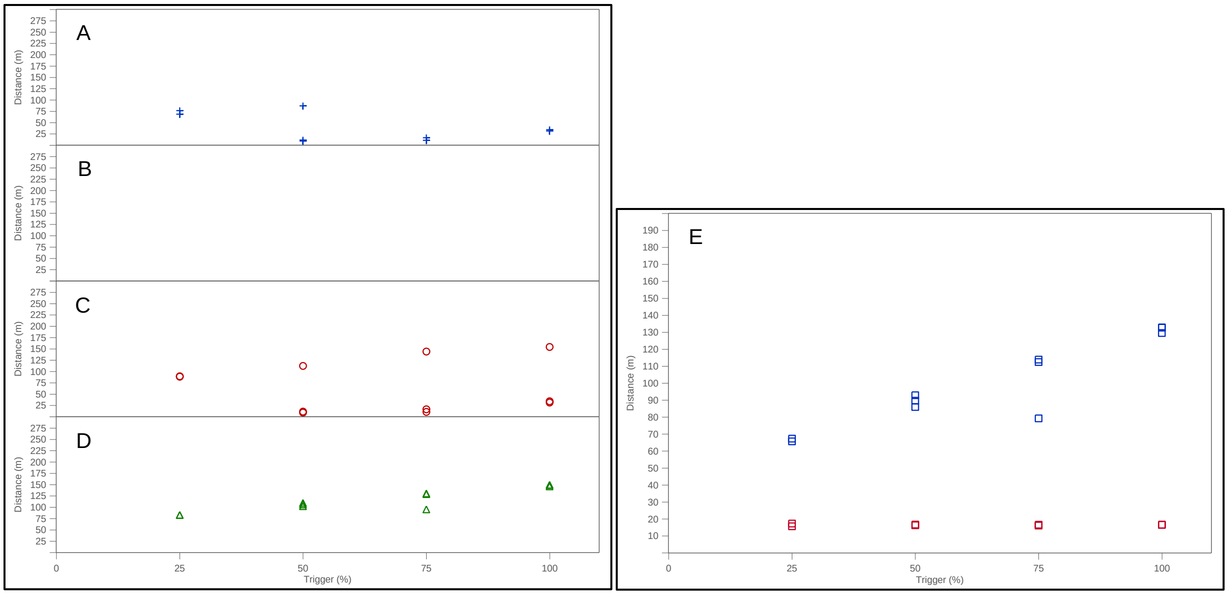
Scenario 12 - Timing sequence of infrastructure sensors, transmission and receipt of V2X signals and test vehicle braking and stop actions

Scenario	Test Name	Trigger	Run	SPAT (Green)	DLVP TIM Stopped vehicle (Camera time)	DLVP TIM Stopped vehicle (OS time)	RSU TIM Acivated	OBU TIM Acivated	Lexus Brakes Applied	Lexus Stopped	Siemens Controller Rail Signal Activated	RSU SPaT (yellow) Acivated	OBU SPaT (yellow) Acivated	LiDAR PSM (Start)	LiDAR PSM (Stop)	RSU PSM Acivated	OBU PSM Acivated	Siemens Controller Rail Signal Deactivated
12	TIM / SPaT / PSM	100	1	0.000	4.516	4.976	not recorded	6.143	11.138	29.206	52.897		53.951	not recorded	not recorded	63.445	63.579	91.459
			2	0.000	3.083	3.541	3.527	4.427	11.735	29.992	44.862		45.466	not recorded	not recorded	52.555	52.731	82.939
			3	0.000	2.840	3.302	3.278	3.424	11.128	29.931	41.887		42.314	not recorded	not recorded	73.221	73.337	78.003

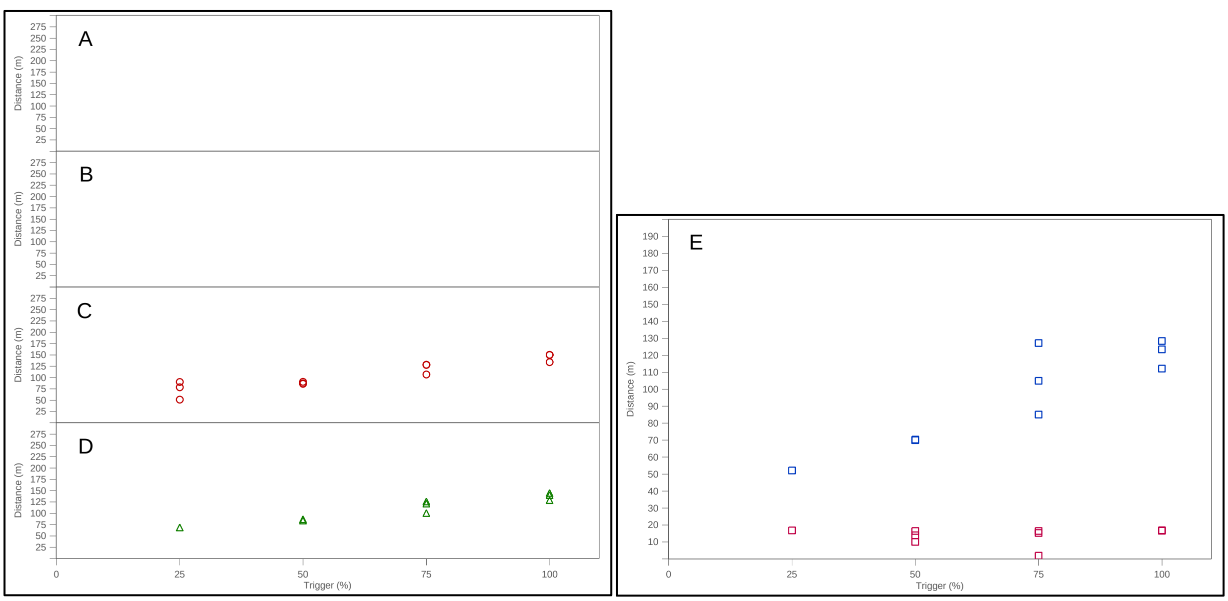
Appendix C - Test vehicle distance from center of rail crossing at receipt time of V2X messages and braking application



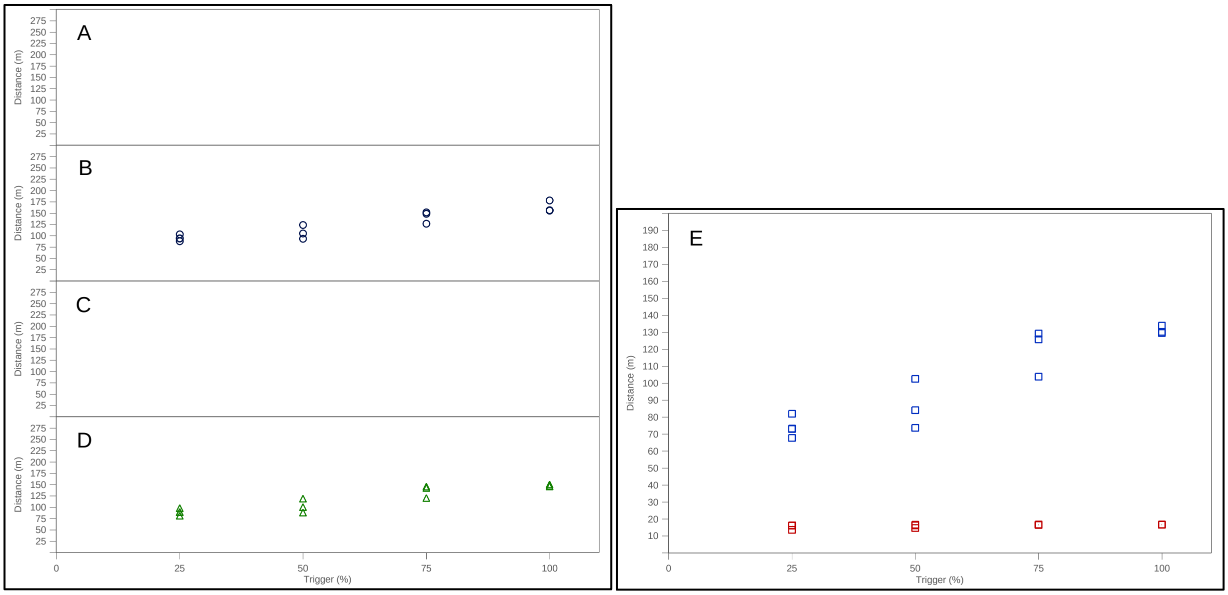
Scenario 1 - Test vehicle distance from center of rail crossing at receipt time of SPaT V2X (A), TIM V2X (B), PSM V2X (C), at instance of brake application (D) and test vehicle stop position distance from the center of the rail crossing (red) and distance travelled during braking (blue) (E)



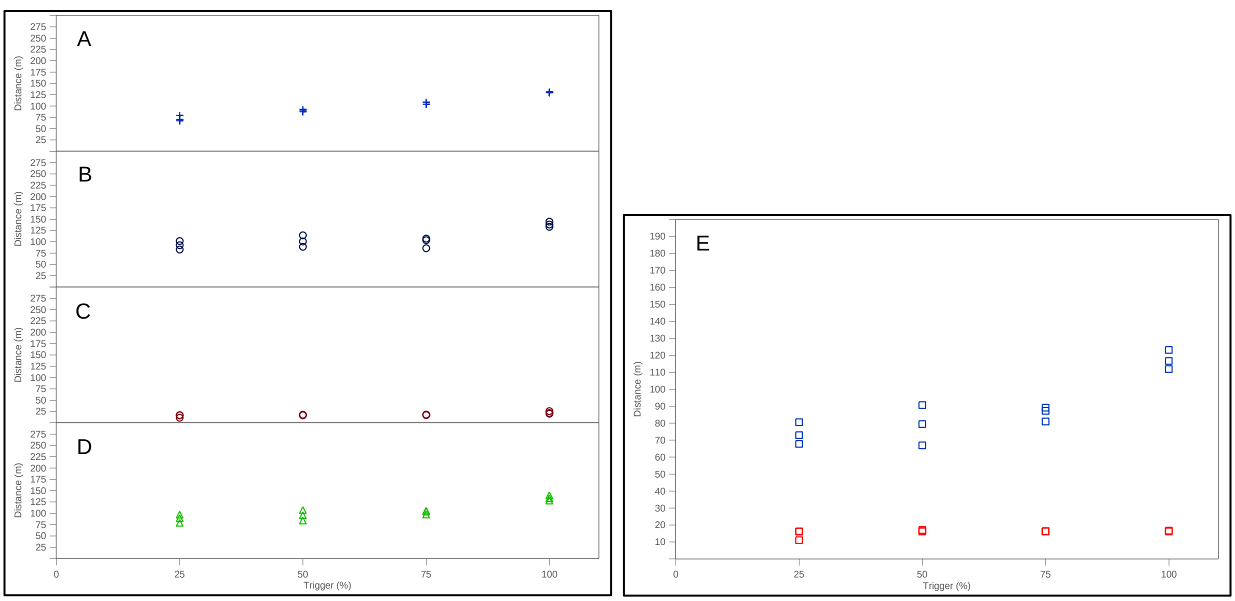
Scenario 2 - Test vehicle distance from center of rail crossing at receipt time of SPaT V2X (A), TIM V2X (B), PSM V2X (C), at instance of brake application (D) and test vehicle stop position distance from the center of the rail crossing (red) and distance travelled during braking (blue) (E)



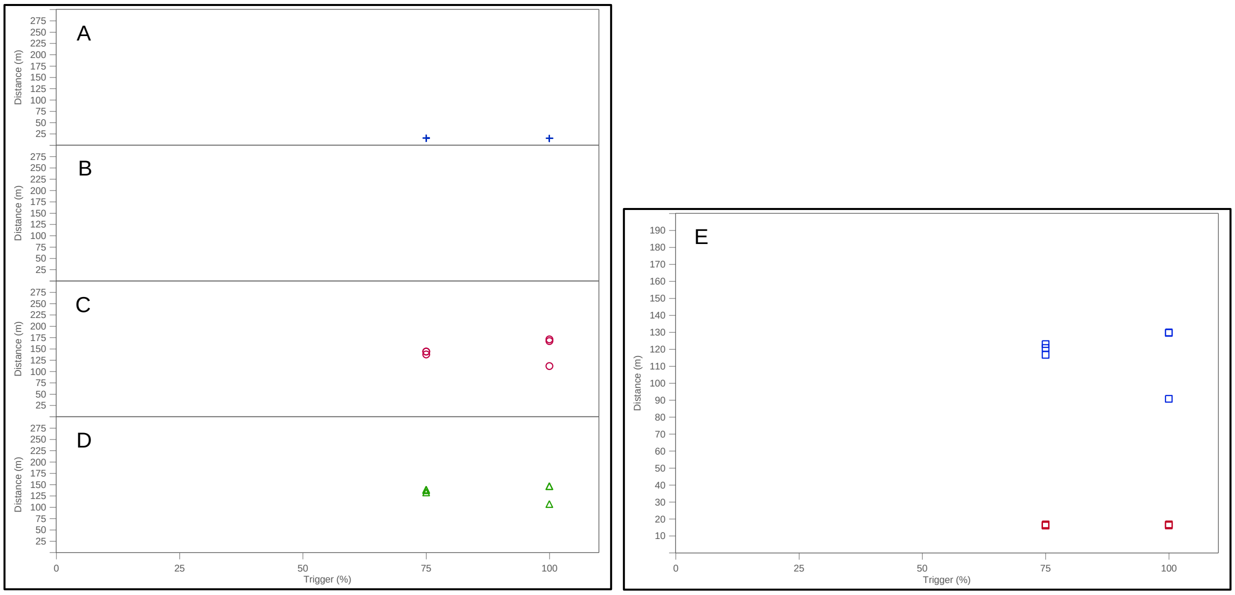
Scenario 3 - Test vehicle distance from center of rail crossing at receipt time of SPaT V2X (A), TIM V2X (B), PSM V2X (C), at instance of brake application (D) and test vehicle stop position distance from the center of the rail crossing (red) and distance travelled during braking (blue) (E)



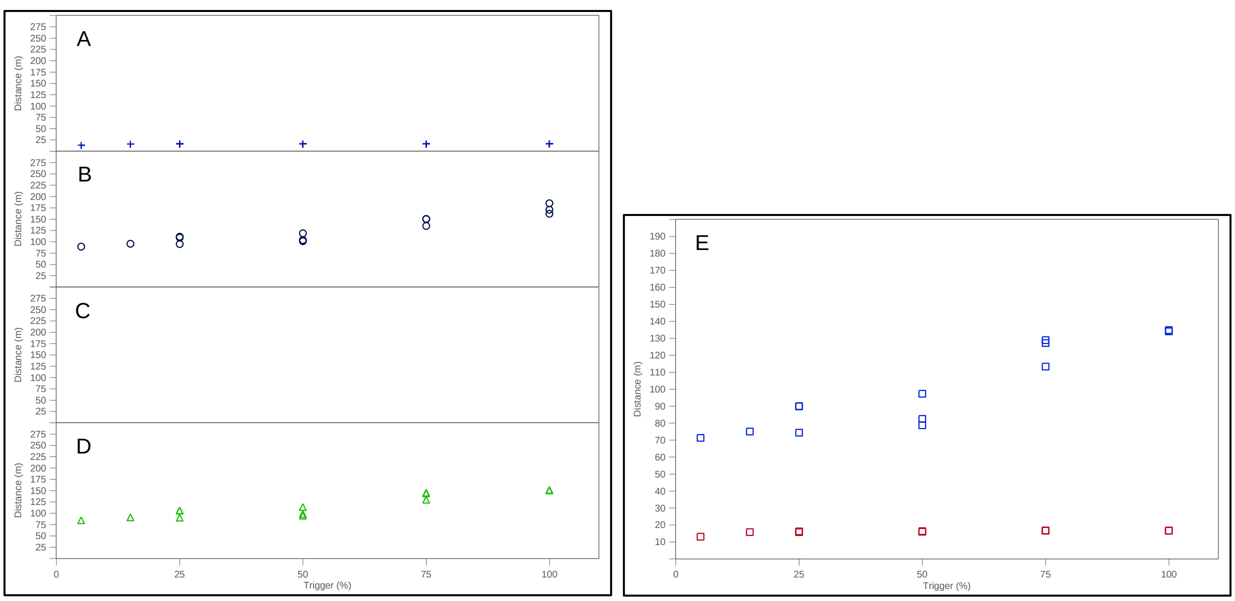
Scenario 4 - Test vehicle distance from center of rail crossing at receipt time of SPaT V2X (A), TIM V2X (B), PSM V2X (C), at instance of brake application (D) and test vehicle stop position distance from the center of the rail crossing (red) and distance travelled during braking (blue) (E)



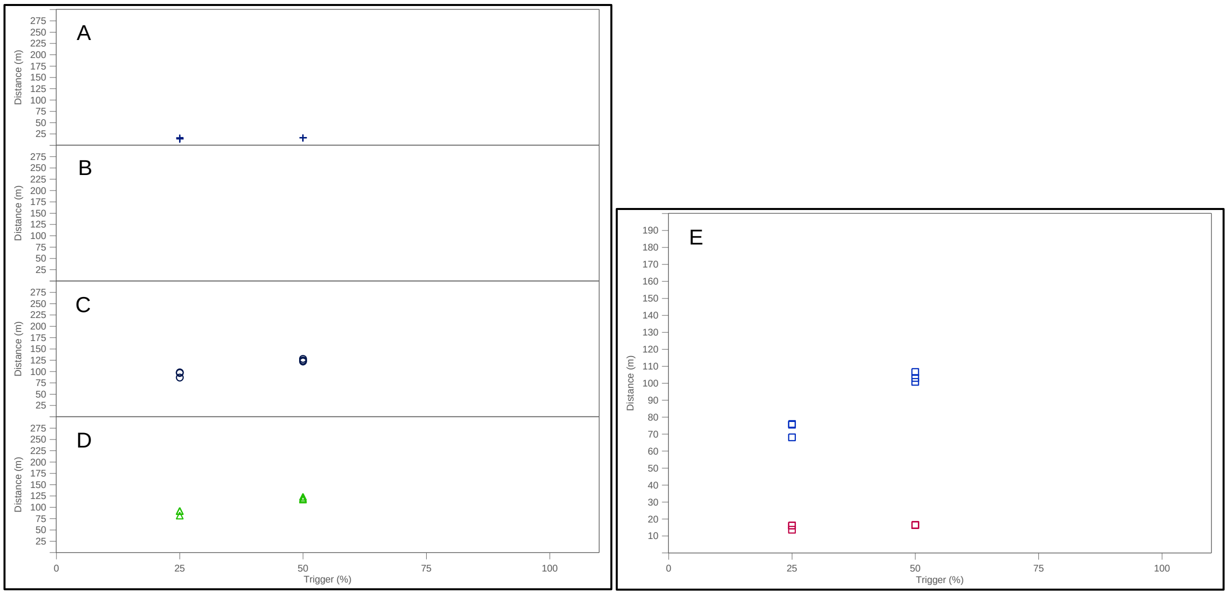
Scenario 5 - Test vehicle distance from center of rail crossing at receipt time of SPaT V2X (A), TIM V2X (B), PSM V2X (C), at instance of brake application (D) and test vehicle stop position distance from the center of the rail crossing (red) and distance travelled during braking (blue) (E)



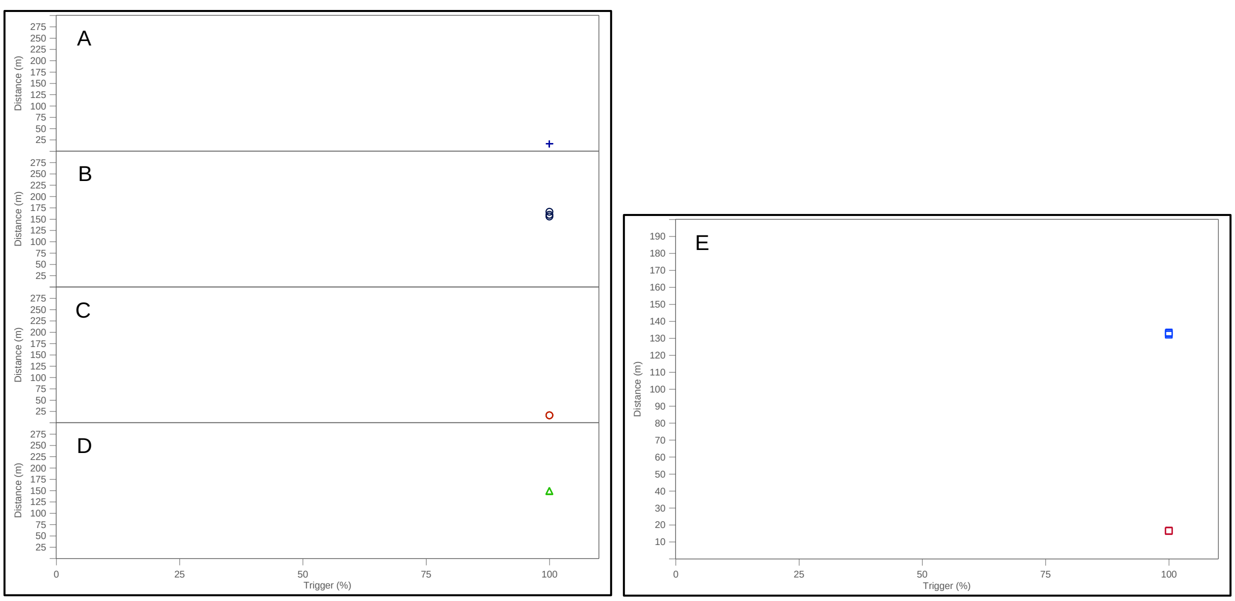
Scenario 6 - Test vehicle distance from center of rail crossing at receipt time of SPaT V2X (A), TIM V2X (B), PSM V2X (C), at instance of brake application (D) and test vehicle stop position distance from the center of the rail crossing (red) and distance travelled during braking (blue) (E)



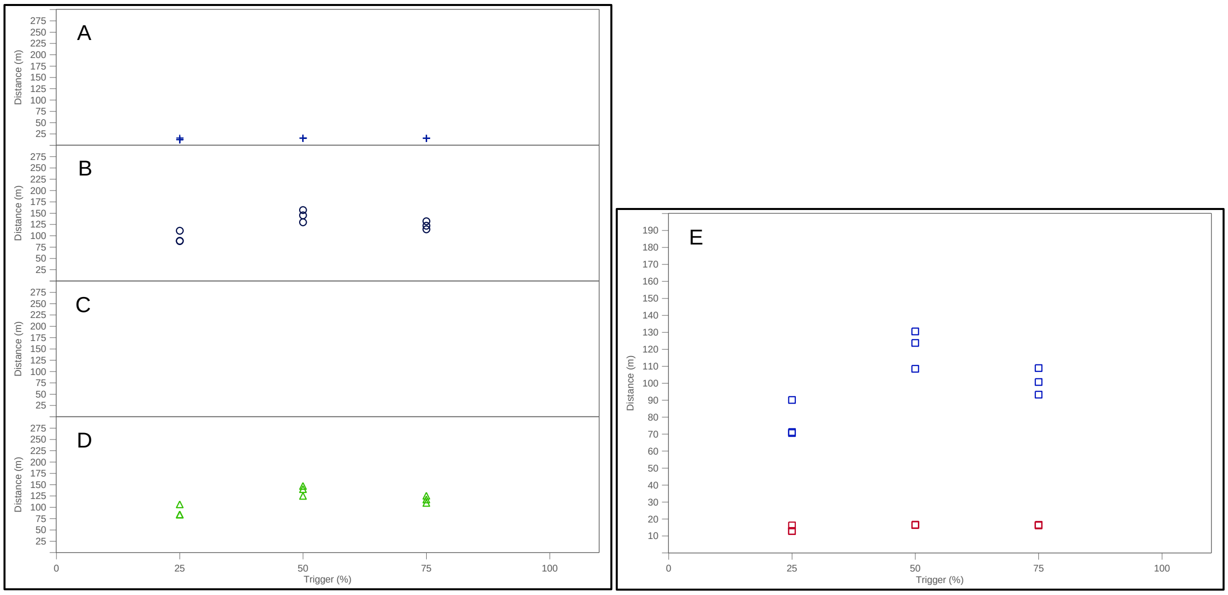
Scenario 7 - Test vehicle distance from center of rail crossing at receipt time of SPaT V2X (A), TIM V2X (B), PSM V2X (C), at instance of brake application (D) and test vehicle stop position distance from the center of the rail crossing (red) and distance travelled during braking (blue) (E)



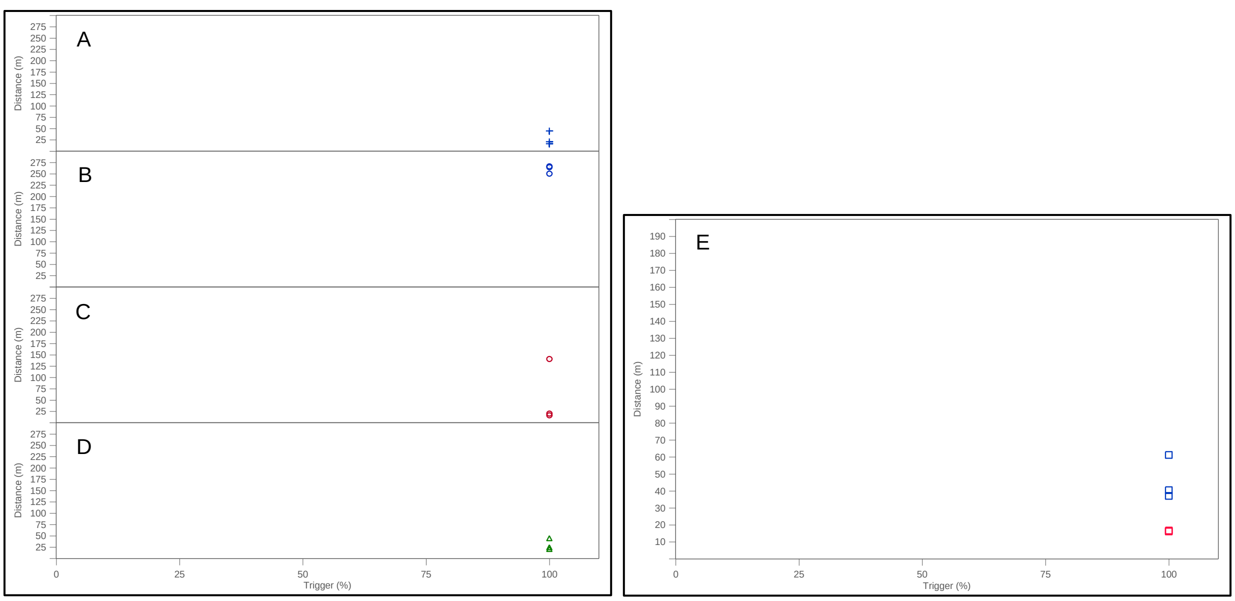
Scenario 8 - Test vehicle distance from center of rail crossing at receipt time of SPaT V2X (A), TIM V2X (B), PSM V2X (C), at instance of brake application (D) and test vehicle stop position distance from the center of the rail crossing (red) and distance travelled during braking (blue) (E)



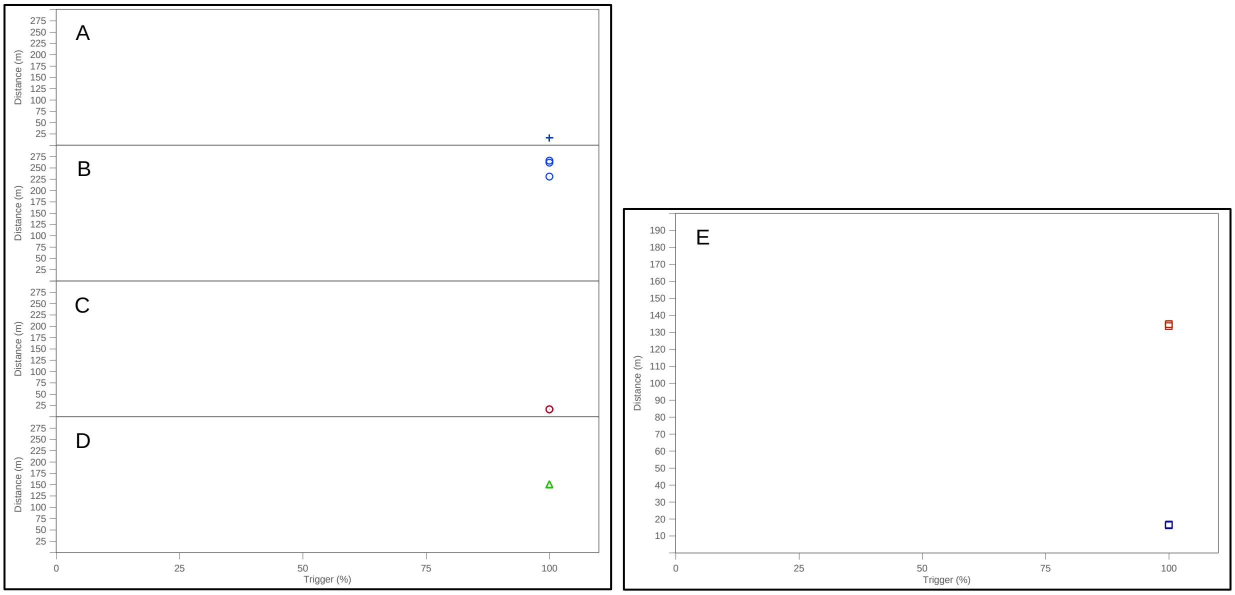
Scenario 9 - Test vehicle distance from center of rail crossing at receipt time of SPaT V2X (A), TIM V2X (B), PSM V2X (C), at instance of brake application (D) and test vehicle stop position distance from the center of the rail crossing (red) and distance travelled during braking (blue) (E)



Scenario 10 - Test vehicle distance from center of rail crossing at receipt time of SPaT V2X (A), TIM V2X (B), PSM V2X (C), at instance of brake application (D) and test vehicle stop position distance from the center of the rail crossing (red) and distance travelled during braking (blue) (E)



Scenario 11 - Test vehicle distance from center of rail crossing at receipt time of SPaT V2X (A), TIM V2X (B), PSM V2X (C), at instance of brake application (D) and test vehicle stop position distance from the center of the rail crossing (red) and distance travelled during braking (blue) (E)



Scenario 12 - Test vehicle distance from center of rail crossing at receipt time of SPaT V2X (A), TIM V2X (B), PSM V2X (C), at instance of brake application (D) and test vehicle stop position distance from the center of the rail crossing (red) and distance travelled during braking (blue) (E)

Appendix D - Weather and roadway conditions during testing

Environment and Climate Change Canada Ottawa MacDonald-Cartier Int'l Airport weather station

	TIME	Temp °C	Dew Point °C	Rel Hum %	Precip. Amount mm	Wind Dir 10's deg	Wind Spd km/h	Visibility km	Stn Press kPa	Wind Chill	Weather
January 24, 2024	6:00	-10.4	-12.8	83		6	18	8.1	101.69	-18	Snow
	7:00	-10.1	-12.4	83		6	16	9.7	101.7	-17	Snow
	8:00	-9.8	-12.1	83		6	21	12.9	101.64	-18	Snow
	9:00	-9.4	-11.9	82		7	14	16.1	101.65	-16	Snow
	10:00	-9.1	-11.6	82		5	14	24.1	101.6	-15	Snow
	11:00	-8.8	-11.2	83		6	10	24.1	101.55	-14	Snow
	12:00	-8.6	-10.7	85		7	11	16.1	101.43	-14	Snow
	13:00	-8.7	-9.8	92		4	13	2.4	101.33	-15	Snow
	14:00	-8.7	-9.4	95		4	13	1.6	101.29	-15	Freezing Drizzle, Fog
	15:00	-8.2	-8.9	95		6	10	1.6	101.24	-13	Freezing Drizzle, Fog
	16:00	-8.1	-8.8	95		7	10	1.2	101.18	-13	Freezing Drizzle, Fog
	17:00	-8.0	-8.7	95		7	12	1.6	101.12	-13	Freezing Drizzle, Fog
	18:00	-7.8	-8.5	95		6	10	2.4	101.07	-13	Freezing Drizzle, Fog

	TIME	Temp °C	Dew Point °C	Rel Hum %	Precip. Amount mm	Wind Dir 10's deg	Wind Spd km/h	Visibility km	Stn Press kPa	Wind Chill	Weather
February 2, 2024	6:00	0.4	-1.8	85		33	22	24.1	100.08		
	7:00	0.1	-2.0	86		33	22	24.1	100.17		Snow
	8:00	-0.1	-2.4	84		35	19	24.1	100.26	-5	
	9:00	-0.1	-2.6	83		33	17	24.1	100.32	-5	
	10:00	0.0	-3.3	79		35	28	24.1	100.39	-6	Mostly Cloudy
	11:00	-0.2	-3.6	77		34	22	24.1	100.48	-6	
	12:00	0.1	-4.3	72		34	23	24.1	100.49		
	13:00	-0.1	-4.9	70		34	28	24.1	100.51	-6	Mostly Cloudy
	14:00	-0.8	-5.0	73		36	25	24.1	100.52	-7	
	15:00	-1.1	-5.6	72		36	21	24.1	100.56	-7	
	16:00	-1.7	-5.8	74		35	19	24.1	100.63	-7	Mostly Cloudy
	17:00	-2.3	-6.5	73		35	20	24.1	100.7	-8	
	18:00	-2.5	-6.7	73		35	21	24.1	100.78	-9	

	TIME	Temp °C	Dew Point °C	Rel Hum %	Precip. Amount mm	Wind Dir 10's deg	Wind Spd km/h	Visibility km	Stn Press kPa	Wind Chill	Weather
February 15, 2024	6:00	-12.8	-15.6	80		24	8	24.1	100.84	-18	
	7:00	-13.0	-15.9	79		22	8	24.1	100.83	-18	Clear
	8:00	-11.6	-14.9	77		21	5	24.1	100.76	-15	
	9:00	-9.3	-13.5	72		21	4	24.1	100.7	-12	
	10:00	-7.4	-14.6	57		17	12	24.1	100.6	-13	Mostly Cloudy
	11:00	-6.8	-15.1	52		20	10	24.1	100.52	-11	
	12:00	-5.8	-14.6	50		23	8	24.1	100.41	-10	
	13:00	-5.4	-14.1	51		16	6	24.1	100.18	-8	Mostly Cloudy
	14:00	-4.6	-14.4	47		14	10	24.1	100	-9	
	15:00	-4.4	-12.7	53		11	16	24.1	99.81	-10	
	16:00	-4.8	-12.8	54		8	15	24.1	99.63	-10	Mostly Cloudy
	17:00	-5.1	-12.2	57		8	19	24.1	99.45	-12	
	18:00	-5.0	-12.7	55		5	14	24.1	99.45	-10	

	TIME	Temp °C	Dew Point °C	Rel Hum %	Precip. Amount mm	Wind Dir 10's deg	Wind Spd km/h	Visibility km	Stn Press kPa	Wind Chill	Weather
February 16, 2024	6:00	-7.0	-8.7	88		28	16	16.1	99.45	-13	Snow
	7:00	-7.6	-9.0	89		28	16	24.1	99.51	-14	Snow
	8:00	-8.1	-9.4	90		25	10	16.1	99.59	-13	
	9:00	-6.5	-8.3	87		27	15	16.1	99.66	-12	Snow
	10:00	-5.8	-8.3	83		28	21	16.1	99.69	-13	Snow
	11:00	-4.4	-8.6	73		30	26	24.1	99.77	-12	
	12:00	-3.5	-8.3	70		29	22	24.1	99.8	-10	
	13:00	-2.5	-7.4	69		30	24	24.1	99.77	-9	Snow
	14:00	-2.8	-8.6	65		28	27	24.1	99.75	-10	Snow
	15:00	-3.4	-9.9	61		28	24	24.1	99.77	-10	Snow
	16:00	-4.1	-11.4	57		29	25	24.1	99.78	-11	Mainly Clear
	17:00	-4.3	-11.2	59		29	18	24.1	99.79	-10	
	18:00	-5.3	-11.3	63		28	15	24.1	99.84	-11	

	TIME	Temp °C	Dew Point °C	Rel Hum %	Precip. Amount mm	Wind Dir 10's deg	Wind Spd km/h	Visibility km	Stn Press kPa	Wind Chill	Weather
March 11, 2024	6:00	-2.6	-7.0	72		30	34	24.1	98.82	-10	
	7:00	-2.9	-7.5	71		30	36	24.1	98.95	-11	Cloudy
	8:00	-3.0	-8.0	69		30	37	24.1	99	-11	
	9:00	-2.0	-7.8	64		31	44	24.1	99.1	-10	
	10:00	-1.4	-8.1	60		29	34	24.1	99.16	-9	Mainly Clear
	11:00	0.0	-7.3	58		29	39	24.1	99.2	-7	
	12:00	2.0	-7.7	49		28	34	24.1	99.25		
	13:00	3.4	-10.1	37		28	39	24.1	99.24		Mainly Clear
	14:00	4.0	-9.4	37		29	34	24.1	99.25		
	15:00	4.4	-10.4	33		28	39	24.1	99.26		
	16:00	4.9	-11.5	30		27	36	24.1	99.32		Mainly Clear
	17:00	4.5	-12.1	29		28	31	24.1	99.33		
	18:00	3.4	-13.2	28		28	27	24.1	99.35		

	TIME	Temp °C	Dew Point °C	Rel Hum %	Precip. Amount mm	Wind Dir 10's deg	Wind Spd km/h	Visibility km	Stn Press kPa	Wind Chill	Weather
March 12, 2024	6:00	-1.8	-8.1	62		21	4	24.1	99.57	-3	
	7:00	-2.4	-6.7	72		23	9	24.1	99.62	-6	Clear
	8:00	0.9	-5.7	61		26	11	24.1	99.7		
	9:00	2.8	-6.5	50		28	10	24.1	99.73		
	10:00	4.7	-6.3	45		29	4	24.1	99.73		Clear
	11:00	5.6	-5.8	44		27	8	24.1	99.73		
	12:00	7.2	-6.0	38		26	7	24.1	99.7		
	13:00	9.0	-4.9	37		29	14	24.1	99.66		Clear
	14:00	9.7	-5.2	35		29	21	24.1	99.59		
	15:00	10.4	-5.5	32		31	19	24.1	99.57		
	16:00	11.3	-6.0	29		29	18	24.1	99.56		Mainly Clear
	17:00	10.4	-5.6	32		30	17	24.1	99.58		
	18:00	7.8	-5.6	38		31	5	24.1	99.6		

	TIME	Temp °C	Dew Point °C	Rel Hum %	Precip. Amount mm	Wind Dir 10's deg	Wind Spd km/h	Visibility km	Stn Press kPa	Wind Chill	Weather
March 13, 2024	6:00	0.3	-5.1	67		8	19	24.1	99.75		
	7:00	0.6	-4.5	69		6	20	24.1	99.76		Mostly Cloudy
	8:00	1.2	-4.4	66		5	21	24.1	99.76		
	9:00	1.6	-4.1	66		6	17	24.1	99.79		
	10:00	3.0	-3.9	61		6	21	24.1	99.78		Mostly Cloudy
	11:00	5.1	-4.3	51		9	22	24.1	99.74		
	12:00	6.0	-3.8	50		10	24	24.1	99.71		
	13:00	7.6	-2.7	48		9	22	24.1	99.64		Mainly Clear
	14:00	8.2	-1.6	50		7	18	24.1	99.61		
	15:00	9.3	-0.9	49		6	16	24.1	99.61		
	16:00	10.2	-0.6	47		5	16	24.1	99.62		Mainly Clear
	17:00	8.2	-0.6	54		7	19	24.1	99.63		
	18:00	6.0	-1.0	61		6	18	24.1	99.71		

	TIME	Temp °C	Dew Point °C	Rel Hum %	Precip. Amount mm	Wind Dir 10's deg	Wind Spd km/h	Visibility km	Stn Press kPa	Wind Chill	Weather
March 15, 2024	6:00	4.0	4.0	100		4	9	24.1	99.8		
	7:00	4.4	4.4	100		2	16	24.1	99.84		Mostly Cloudy
	8:00	5.2	4.7	96		3	13	24.1	99.82		
	9:00	7.1	3.6	79		3	14	24.1	99.87		
	10:00	8.4	3.4	70		4	14	24.1	99.83		Mostly Cloudy
	11:00	9.2	2.6	63		6	9	24.1	99.8		
	12:00	9.1	2.3	63		36	2	24.1	99.83		
	13:00	10.7	2.0	55		33	7	24.1	99.74		Mostly Cloudy
	14:00	10.8	0.5	49		36	3	24.1	99.64		
	15:00	10.5	0.7	50		34	19	24.1	99.6		
	16:00	10.5	0.5	50		6	3	24.1	99.58		Mostly Cloudy
	17:00	9.4	0.0	52		11	8	24.1	99.54		
	18:00	7.9	2.9	71		22	11	24.1	99.55		

	TIME	Temp °C	Dew Point °C	Rel Hum %	Precip. Amount mm	Wind Dir 10's deg	Wind Spd km/h	Visibility km	Stn Press kPa	Wind Chill	Weather
March 27, 2024	6:00	4.5	4.5	100		7	11	16.1	99.91		
	7:00	4.9	4.9	100		7	11	16.1	99.93		Cloudy
	8:00	7.0	7.0	100		12	15	24.1	99.96		
	9:00	9.4	7.3	86		17	15	24.1	99.94		
	10:00	11.3	6.4	72		20	14	24.1	99.96		Mostly Cloudy
	11:00	13.4	6.4	62		19	17	24.1	99.95		
	12:00	13.9	5.8	58		19	19	24.1	99.92		
	13:00	14.8	5.9	55		23	22	24.1	99.93		Mostly Cloudy
	14:00	15.0	6.1	55		21	21	24.1	99.91		
	15:00	12.8	7.1	68		21	23	24.1	99.92		
	16:00	13.1	4.8	57		23	23	24.1	99.94		Mostly Cloudy
	17:00	11.8	4.0	59		23	22	24.1	100.06		
	18:00	11.1	3.5	59		21	14	24.1	100.09		

	TIME	Temp °C	Dew Point °C	Rel Hum %	Precip. Amount mm	Wind Dir 10's deg	Wind Spd km/h	Visibility km	Stn Press kPa	Wind Chill	Weather
April 3, 2024	6:00	4.0	-4.3	55		8	34	24.1	99.41		
	7:00	4.3	-4.4	53		7	35	24.1	99.41		Mostly Cloudy
	8:00	4.8	-4.2	52		8	40	24.1	99.21		
	9:00										
	10:00	5.8	-3.9	49		9	27	16.1	99.37		Cloudy
	11:00	5.2	-0.7	66		8	32	16.1	99.38		Rain
	12:00	4.2	0.0	74		10	30	12.9	99.29		Rain
	13:00	4.2	0.1	74		8	36	12.9	99.15		Rain
	14:00	3.9	0.5	78		9	32	12.9	99.08		Rain
	15:00	3.0	1.6	90		9	42	12.9	99.05		Rain
	16:00	2.6	1.7	93		8	31	9.7	99.14		Rain, Fog
	17:00	1.6	1.5	100		8	41	2.4	99.19		Moderate Rain, Snow
	18:00	0.4	0.4	100		7	25	1.2	99.2		Snow, Fog

Source for weather data: [Historical Data - Climate - Environment and Climate Change Canada (weather.gc.ca)]

Roadway surface conditions experienced during testing included partly snow covered, bare and dry and bare and wet.


January 24, 2024 (SPAT scenario)


February 2, 2024 (PSM and PSM/SPAT scenarios)


April 3, 2024 (TIM/PSM/SPAT and TIM/SPAT/PSM scenarios)

Appendix E – Test vehicle ROStopics analyzed

/v2x/personal_safety_message	
	Time
	header.seq
	header.stamp.secs
	header.stamp.nsecs
	header.frame_id
	dsrc_msg_id.id
	basic_type.type
	sec_mark
	msg_cnt
	id
	position.lat
	position.lon
	position.elev
	accuracy.semi_major
	accuracy.semi_minor
	accuracy.orientation
	speed
	heading
	accel_set.lon
	accel_set.lat
	accel_set.vert
	accel_set.yaw
	path_history.initial_position.utc_time.year
	path_history.initial_position.utc_time.month
	path_history.initial_position.utc_time.day
	path_history.initial_position.utc_time.hour
	path_history.initial_position.utc_time.minute
	path_history.initial_position.utc_time.second
	path_history.initial_position.utc_time.offset
	path_history.initial_position.lat
	path_history.initial_position.lon
	path_history.initial_position.elev
	path_history.initial_position.heading
	path_history.initial_position.speed.transmission.state
	path_history.initial_position.speed.speed

/light_color	
	Time
	header.seq
	header.stamp.secs
	header.stamp.nsecs
	header.frame_id
	traffic_light

/pacmod/as_rx/brake_cmd	
	Time
	header.seq
	header.stamp.secs
	header.stamp.nsecs
	header.frame_id
	enable
	ignore_overrides
	clear_override
	clear_faults
	command

/pacmod/parsed_tx/brake_rpt	
	Time
	header.seq
	header.stamp.secs
	header.stamp.nsecs
	header.frame_id
	enabled
	override_active
	command_output_fault
	input_output_fault
	output_reported_fault
	pacmod_fault
	vehicle_fault
	manual_input
	command
	output

	path_history.initial_position.pos_accuracy.semi_major
	path_history.initial_position.pos_accuracy.semi_minor
	path_history.initial_position.pos_accuracy.orientation
	path_history.initial_position.time_confidence.confidence
	path_history.initial_position.pos_confidence.pos.confidence
	path_history.initial_position.pos_confidence.elevation.confidence
	path_history.initial_position.speed_confidence.heading.confidence
	path_history.initial_position.speed_confidence.speed.confidence
	path_history.initial_position.speed_confidence.throttle.confidence
	path_history.curr_gnss_status.unavailable
	path_history.curr_gnss_status.is_healthy
	path_history.curr_gnss_status.is_monitored
	path_history.curr_gnss_status.base_station_type
	path_history.curr_gnss_status.a_pdop_of_under_5
	path_history.curr_gnss_status.in_view_of_under_5
	path_history.curr_gnss_status.local_corrections_present
	path_history.curr_gnss_status.network_corrections_present
	path_history.crumb_data
	path_prediction.radius_of_curve
	path_prediction.confidence
	propulsion.human.type
	propulsion.animal.type
	propulsion.motor.type
	use_state.unavailable
	use_state.other
	use_state.idle
	use_state.listending_to_audio
	use_state.typing
	use_state.calling
	use_state.playing_games
	use_state.reading
	use_state.viewing
	cross_request
	cross_state
	cluster_size.value
	cluster_radius
	event_responder_type.type
	activity_type.unavailable
	activity_type.working_on_road
	activity_type.setting_up_closures
	activity_type.responding_to_events
	activity_type.directing_traffic
	activity_type.other_activities

/ssc/brake_command_echo	
	Time
	header.seq
	header.stamp.secs
	header.stamp.nsecs
	header.frame_id
	brake_pedal

/ssc/brake_feedback	
	Time
	header.seq
	header.stamp.secs
	header.stamp.nsecs
	header.frame_id
	brake_pedal

/pacmod/as_tx/vehicle_speed	
	Time
	data

/trigger_script	
	Time
	data

/vaisala_md30_driver/data	
	Time
	header.seq
	header.stamp.secs
	header.stamp.nsecs
	header.frame_id
	air_temperature
	air_temperature_data_warning
	air_temperature_data_error
	relative_humidity
	relative_humidity_data_warning
	relative_humidity_data_error
	dew_point_temperature
	dew_point_temperature_data_warning
	dew_point_temperature_data_error
	frost_point_temperature
	frost_point_temperature_data_warning
	frost_point_temperature_data_error

	activity_sub_type.unavailable
	activity_sub_type.police_and_traffic_officers
	activity_sub_type.traffic_control_persons
	activity_sub_type.railroad_crossing_guards
	activity_sub_type.civil_defense_national_guard_military_police
	activity_sub_type.emergency_organization_personnel
	activity_sub_type.highway_service_vehicle_personnel
	assist_type.unavailable
	assist_type.other_type
	assist_type.vision
	assist_type.hearing
	assist_type.movement
	assist_type.cognition
	sizing.unavailable
	sizing.small_stature
	sizing.large_stature
	sizing.erratic_moving
	sizing.slow_moving
	attachment.value
	attachment_radius
	name
	DateTime

/v2x/signal_phase_and_timing	
	Time
	header.seq
	header.stamp.secs
	header.stamp.nsecs
	header.frame_id
	dsrc_msg_id.id
	time_stamp
	name
	intersections
	id
	road_regulator_id
	intersection_id
	revision
	status
	manual_control_is_enabled
	stop_time_is_activated
	failure_flash
	preempt_is_active
	signal_priority_is_active

	surface_temperature
	surface_temperature_data_warning
	surface_temperature_data_error
	md30_surface.state
	md30_surface_data_warning
	md30_surface_data_error
	en15518_surface.state
	en15518_surface_data_warning
	en15518_surface_data_error
	grip
	grip_data_warning
	grip_data_error
	water_layer_thickness
	water_layer_thickness_data_warning
	water_layer_thickness_data_error
	ice_layer_thickness
	ice_layer_thickness_data_warning
	ice_layer_thickness_data_error
	snow_layer_thickness
	snow_layer_thickness_data_warning
	snow_layer_thickness_data_error
	unit_status
	unit_error

/gps/fix	
	Time
	header.seq
	header.stamp.secs
	header.stamp.nsecs
	header.frame_id
	status.status
	status.service
	latitude
	longitude
	altitude
	position_covariance_0
	position_covariance_1
	position_covariance_2
	position_covariance_3
	position_covariance_4
	position_covariance_5
	position_covariance_6
	position_covariance_7

	fixed_time_operation
	traffic_dependent_operation
	standby_operation
	failure_mode
	off
	recent_map_message_update
	recent_change_in_map_assigned_lanes_ids_used
	no_valid_map_is_available_at_this_time
	no_valid_spat_is_available_at_this_time
	moy
	time_stamp
	enabled_lanes
	states
	movement_name
	signal_group
	state_time_speed
	event_state
	state
	timing
	start_time
	min_end_time
	max_end_time
	likely_time
	confidence
	next_time
	speeds
	maneuver_assist_list

/v2x/traveler_information_message	
	Time
	header.seq
	header.stamp.secs
	header.stamp.nsecs
	header.frame_id
	dsrc_msg_id.id
	msg_cnt
	time_stamp
	data_frames
	Advisory_its

/v2x/basic_safety_message	
	Time
	header.seq

	position_covariance_8
	position_covariance_type

/novatel/oem7/time	
	Time
	header.seq
	header.stamp.secs
	header.stamp.nsecs
	header.frame_id
	nov_header.message_name
	nov_header.message_id
	nov_header.message_type
	nov_header.sequence_number
	nov_header.time_status
	nov_header.gps_week_number
	nov_header.gps_week_milliseconds
	clock_status
	offset
	offset_std
	utc_offset
	utc_year
	utc_month
	utc_day
	utc_hour
	utc_min
	utc_msec
	utc_status

	header.stamp.secs
	header.stamp.nsecs
	header.frame_id
	dsrc_msg_id.id
	msg_cnt
	id
	sec_mark
	lat
	lon
	elev
	accuracy.semi_major
	accuracy.semi_minor
	accuracy.orientation
	transmission.state
	speed
	heading
	angle
	accel_set.lon
	accel_set.lat
	accel_set.vert
	accel_set.yaw
	brakes.wheel_brakes.unavailable
	brakes.wheel_brakes.left_front
	brakes.wheel_brakes.left_rear
	brakes.wheel_brakes.right_front
	brakes.wheel_brakes.right_rear
	brakes.traction.status
	brakes.abs.status
	brakes.scs.status
	brakes.brake_boost.status
	brakes.aux_brakes.status
	size.width
	size.length

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