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Vehicle Safety Communications – Applications (VSC-A)

Final Report: Appendix Volume 1
System Design and Objective Test

CAMP

Vehicle Safety Communications 2

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16. Abstract

The Vehicle Safety Communications – Applications (VSC-A) Project was a three-year project (December 2006 - December 2009) to develop and test communications-based vehicle-to-vehicle (V2V) safety systems to determine if Dedicated Short Range Communications (DSRC) at 5.9 GHz, in combination with vehicle positioning, can improve upon autonomous vehicle-based safety systems and/or enable new communications-based safety applications. The VSC-A Project was conducted by the Vehicle Safety Communications 2 Consortium (VSC2). Members of VSC2 are Ford Motor Company, General Motors Corporation, Honda R & D Americas, Inc., Mercedes-Benz Research and Development North America, Inc., and Toyota Motor Engineering & Manufacturing North America, Inc. This document presents the first volume set of appendices for the Final Report of the VSC-A Project which contains technical content for the DSRC+Positioning and Autonomous Safety System Analysis, Test Bed System Development, Path History Reference Design and Test Results, Minimum Performance Requirements, Objective Test Procedures and Plan, and Objective Testing Results.

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Dedicated Short Range Communications (DSRC)+Positioning and Autonomous Safety System Analysis

List of Acronyms

ACAS	Automotive Collision Avoidance Systems
BSM	Basic Safety Message
CAMP	Crash Avoidance Metrics Partnership
DSRC	Dedicated Short Range Communications
FCW	Forward Collision Warning
FLR	Forward-Looking Radar
FOT	Field Operational Test
FOV	Field of View
GPS	Global Positioning System
HV	Host Vehicle
ITS	Intelligent Transportation System
JPO	Joint Program Office
LDW	Lane Departure Warning
NHTSA	National Highway Traffic Safety Administration
OTA	Over-the-Air
RITA	Research and Innovative Technology Administration
RV	Remote Vehicle
TC	Target Classification
USDOT	United States Department of Transportation
V2V	Vehicle-to-Vehicle
VSC	Vehicle Safety Communications
VSC-A	Vehicle Safety Communications – Applications
WSU	Wireless Safety Unit

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1 Introduction

One of the objectives of the VSC-A Project was to determine if the addition of DSRC+Positioning-based vehicle safety communications can help overcome some of the limitations found in autonomous safety systems and performing a system analysis on the pre-crash and collision mitigation augmentation of autonomous systems to determine what additional elements, if any, are required for the SAE J2735 message set. To this end, a paper analysis of the root causes for the autonomous sensing safety systems limitations and possible DSRC solutions to these limitations was performed. An experimental setup was then developed and used for evaluating the performance of DSRC+Positioning based systems relative to a production-representative, autonomous, safety system with the focus being on some of the limitations identified during the paper analysis. Finally, a potential hybrid system framework, comprised of both DSRC+Positioning and autonomous sensing systems, was defined but not implemented as a means of these two systems both potentially complementing as well as overcoming the limitations of each other.

2 Limitations and Root Causes of Autonomous Safety Systems Addressed with DSRC-Based Communications

As discussed in the main body of the VSC-A Final Report, from the USDOT composite ranking list of crash scenarios (based on crash frequency, crash cost and functional years lost) the top seven (7) crash imminent scenarios that could be addressed by VSC-A were selected to be addressed under the VSC-A Project. Of the crash scenarios identified, only the following three scenarios are addressed by existing autonomous safety systems:

- Lead Vehicle Stopped
- Lead Vehicle Decelerating
- Vehicle(s) Changing Lanes – Same Direction

The various limitations autonomous safety systems have shown in addressing these crash imminent scenarios, the root causes of these limitations, and how DSRC+Positioning may address these root causes were identified and are presented in the following sections.

2.1 Lead Vehicle Stopped Scenarios

Table 1 below identifies potential solutions for DSRC-based, vehicle-to-vehicle (V2V), safety communications to improve the performance of autonomous safety system limitations and root causes with respect to lead vehicle stopped scenarios. It is assumed that the DSRC message from the stopped lead vehicle will include vehicle status information such as speed, position, time, etc., as well as path history. It is also assumed that the DSRC message can be sent at the required transmit power to reach the desired range needed by vehicle safety systems.

Table 1: VSC Enhancements for Lead Vehicle Stopped Scenarios

Limitation	Root Cause	Potential DSRC Solution
Late confirmation of stopped lead vehicle as in-path stationary target	Algorithms used for bridge rejection and road clutter rejection were reliable only at close target range	DSRC message from the stopped lead vehicle confirming stopped status are expected to eliminate this limitation.
	In-path target confirmation was possible only after host vehicle (HV) lane change was complete	DSRC message from stopped lead vehicle may be used to classify stopped vehicle relative lane location with respect to HV. This is in contrast to Automotive Collision Avoidance Systems (ACAS) system which only classifies in-path targets.
	Poor in-path target detection and tracking in straight-curve and curve-straight road transitions due to path prediction inaccuracy for longer range; Sensor field of view (FOV) limitations	DSRC message from the stopped lead vehicle containing its path history may provide better path prediction of straight-curve and curve-straight road transitions, and eliminate FOV restrictions typically faced with autonomous sensors.
	In-path target confirmation was possible only after stopped lead vehicle is within radar FOV (i.e., direct line of sight)	DSRC message from stopped lead vehicle is expected to be received by HV beyond direct line of sight thereby potentially eliminating this limitation.
Occasional incorrect out-of-path target detection and rejection	Radar misalignment, weakness in out-of-path target rejection algorithm	DSRC message from the stopped lead vehicle containing its path history is expected to provide better path prediction that may be used to eliminate this limitation.
	Weakness in road clutter rejection during vehicle lane changes	Since this is due to weakness in stationary road side target rejection of radar based system during HV lane change, it is not clear if this limitation can be eliminated with DSRC.
	Poor path prediction in certain straight-curve and curve-straight road transitions for longer range	DSRC message from the stopped lead vehicle containing its path history provides better path prediction of straight-curve and curve-straight road transition.

2.2 Lead Vehicle Decelerating Scenarios

Table 2, below, identifies potential solutions for DSRC-based vehicle safety communications to improve the performance of autonomous safety system limitations and root causes with respect to lead vehicle decelerating scenarios. It is assumed that the low latency DSRC messages from the lead vehicle will provide timely vehicle status information such as speed, position, time, deceleration, brake status, turn indicator status, yaw rate, steering angle, etc., as well as path history. It is also assumed that the DSRC messages can be sent at the required transmit power to reach the desired range needed by vehicle safety systems.

Table 2: VSC Enhancements for Lead Vehicle Decelerating Scenarios

Limitation	Root Cause	Potential DSRC Solution
Late alerts for lead vehicle decelerating	Imprecise lead vehicle deceleration value and latency, and lack of brake status value	Low Latency DSRC message from the lead vehicle containing its deceleration value and brake status may eliminate this limitation.
	Imprecise lead vehicle deceleration value and latency and lack of brake status value; Poor path prediction; Sensor FOV limitations	Low Latency DSRC message from the lead vehicle containing its deceleration value, brake status, and path history may eliminate this limitation and overcome FOV restrictions typically faced with autonomous sensors.
Late alerts for vehicle cut-ins	Unknown driver intent to cut-in	DSRC message from the lead vehicle containing driver's intent of lane change maneuver may eliminate this limitation.
False alerts for lead vehicle turning / changing lanes	Unknown driver intent to change lanes or turn	Low latency DSRC message from the lead vehicle containing lane change/turn status may eliminate this limitation.
False alerts for lead vehicle braking to turn/change lanes	Imprecise lead vehicle deceleration value and latency and lack of brake status value; Unknown driver intent to change lanes or turn	Low latency DSRC message from the lead vehicle containing its deceleration value, brake status, lane change/turn status may eliminate this limitation.
Occasional false alerts for vehicle cut-outs	Unknown driver intent to cut-out from radar	DSRC message from the lead vehicle confirming driver's intent of lane change maneuver may eliminate this limitation.

2.3 Vehicle(s) Changing Lanes – Same Direction Scenarios

Table 3, below, identifies the potential for DSRC-based vehicle safety communications to improve the performance of autonomous safety system limitations and root causes with respect to vehicle(s) changing lanes in the same direction scenarios. It is assumed that the DSRC messages from the adjacent lane vehicle will include vehicle status information such as speed, position, time, etc., as well as path history. It is also assumed that the DSRC message can be sent at the required transmit power to reach the desired range needed by vehicle safety systems, thereby, exceeding the field of view and range applicability of autonomous sensors.

Table 3: VSC Enhancements for Missed and Late Lane-Change Alerts

Limitation	Root Cause	Potential DSRC Solution
Occasional, missed detection of adjacent lane vehicles	Limited range and FOV of sensors	DSRC messages from adjacent lane vehicles are expected to significantly exceed the range needed to eliminate this limitation.
	Weather dependent sensor performance	DSRC messages from adjacent lane vehicles are not expected to be affected by adverse weather.
	Poor path prediction on curves. Limited range and FOV of sensors	DSRC message from adjacent vehicle containing its path history may provide better path prediction and range.

3 DSRC+Positioning and Autonomous Safety System Analysis (Experimental Setup)

In an effort to study the benefits of DSRC+Positioning in overcoming some of the limitations of autonomous safety systems, it was necessary to evaluate the performance of DSRC+Positioning alongside a traditional autonomous sensor in driving environments that highlight the aforementioned limitations. The experimental setup (see Figure 1) consisted of hardware and software installed on three vehicles capable of transmitting and receiving vehicle positional information via DSRC communication. Each of the three experimental vehicles was equipped with an 802.11p-based DSRC radio, an omni-directional, roof-mounted, DSRC antenna, a NovAtel® OEMV® Global Positioning System (GPS) receiver, and a DENSO Electronics Wireless Safety Unit (WSU) that allowed the exchange of information contained in the SAE J2735 Basic Safety Message (BSM) between vehicles. In addition, one of the three test vehicles (henceforth referred to as the Host Vehicle, or HV) was equipped with a production-representative, Forward-Looking Radar (FLR) sensor possessing the capability as shown in Table 4.

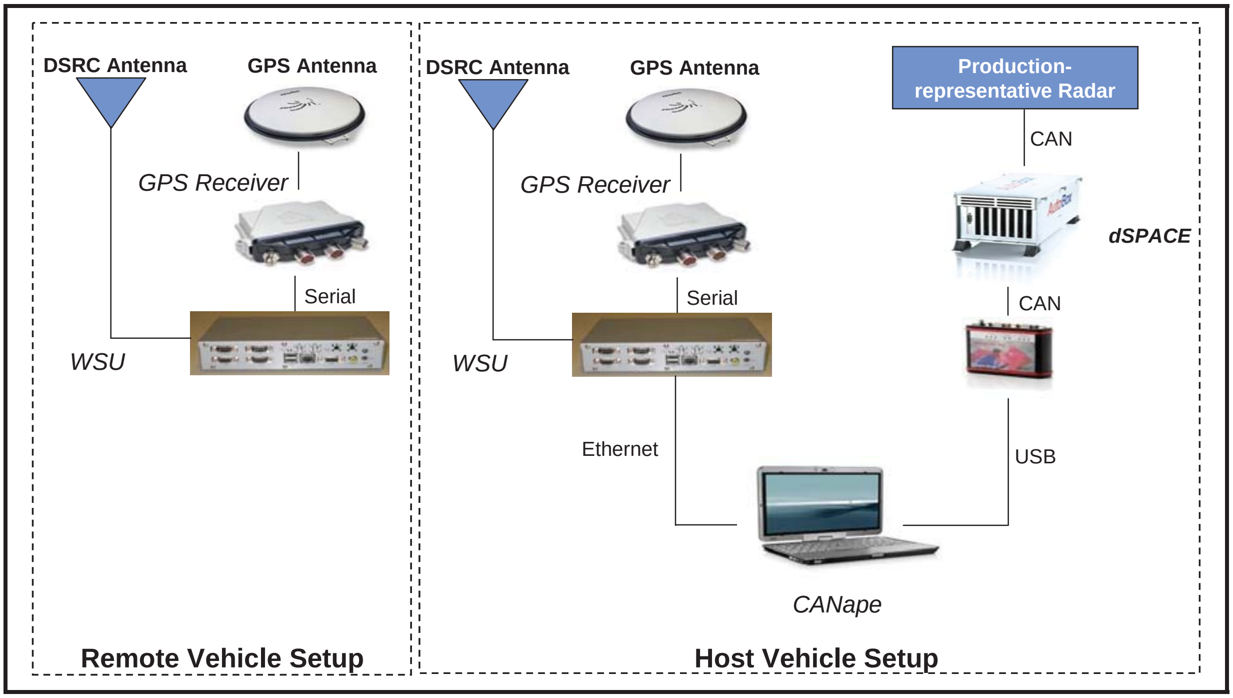

Figure 1: DSRC and Autonomous Sensing Safety System Analysis Setup

Table 4: Minimum Performance of Forward-Looking Radar Sensor

Category	Specification
Operational Frequency	76 GHz
Range	3 to 150 m (10m^2 RCS)
Range Rate	-64 to +33 m/s
Azimuth Angular FOV	+/- 7.5 deg
Update Rate	10 Hz

The DSRC+Positioning and FLR-equipped vehicle was also equipped with a high range, wide FOV (60+ degrees), forward-looking camera for capturing video of the road ahead. In order to capture data from both the FLR and the DSRC+Positioning systems (in addition to the video data), a measurement and data acquisition tool with the ability to provide synchronized data and video acquisition of both the FLR and DSRC+Positioning system was utilized (see Figure 2 below).

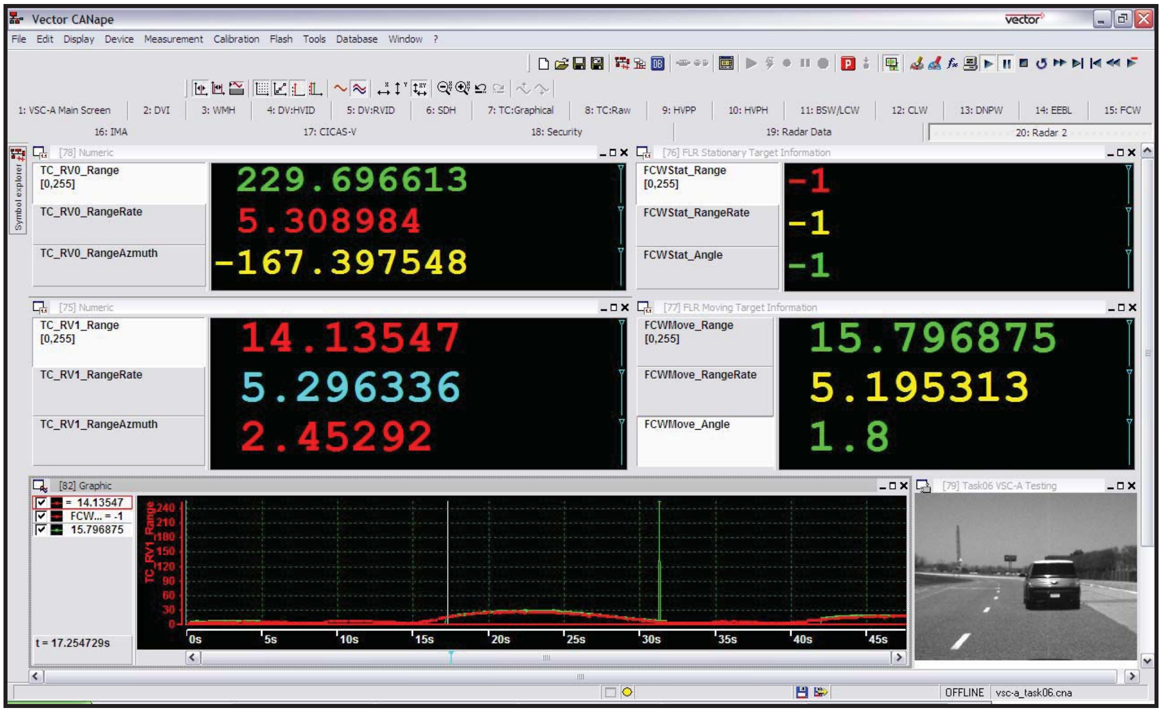

Figure 2: Measurement and Data Acquisition Tool Experimental Layout

4 Comparison of DSRC+Positioning Relative to Traditional Autonomous Safety Systems

4.1 Test 1: Detecting a Vehicle as an In-Path Stationary Target

The purpose of the first test was to assess the ability of the FLR autonomous sensor and DSRC+Positioning system to independently detect and track a stationary vehicle (henceforth referred to as a remote vehicle, or RV) several hundred meters away as in-path. As indicated in Table 1, autonomous sensing algorithms used for bridge rejection and road clutter rejection have the reverse effect of reducing the range in which a valid stationary vehicle is declared as an in-path target. It is expected that the DSRC+Positioning message from the stopped lead vehicle, confirming the stopped status of similarly equipped vehicles at ranges in excess of 300 meters (Figure 3), will eliminate this autonomous sensing limitation.

As can be seen in the left chart of Figure 4, the FLR was able to both detect and declare the RV as an in-path target when the range to the target was approximately 75 meters. Also note that in this trial run, the FLR temporarily dropped the target at a distance of approximately 38 meters and subsequently reacquired the target at a distance of 31 meters. Compare this to the right chart of Figure 4 which shows that the DSRC+Positioning system was able to detect and consistently track the RV up to 450 meters away to a distance below 3 meters.

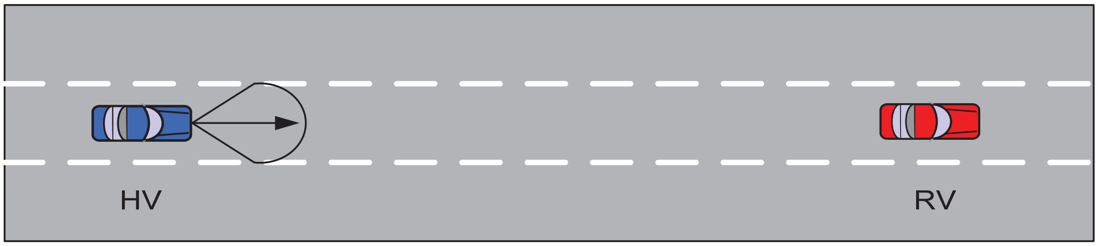

Figure 3: Confirmation of Stopped Vehicle as In-path Stationary Target

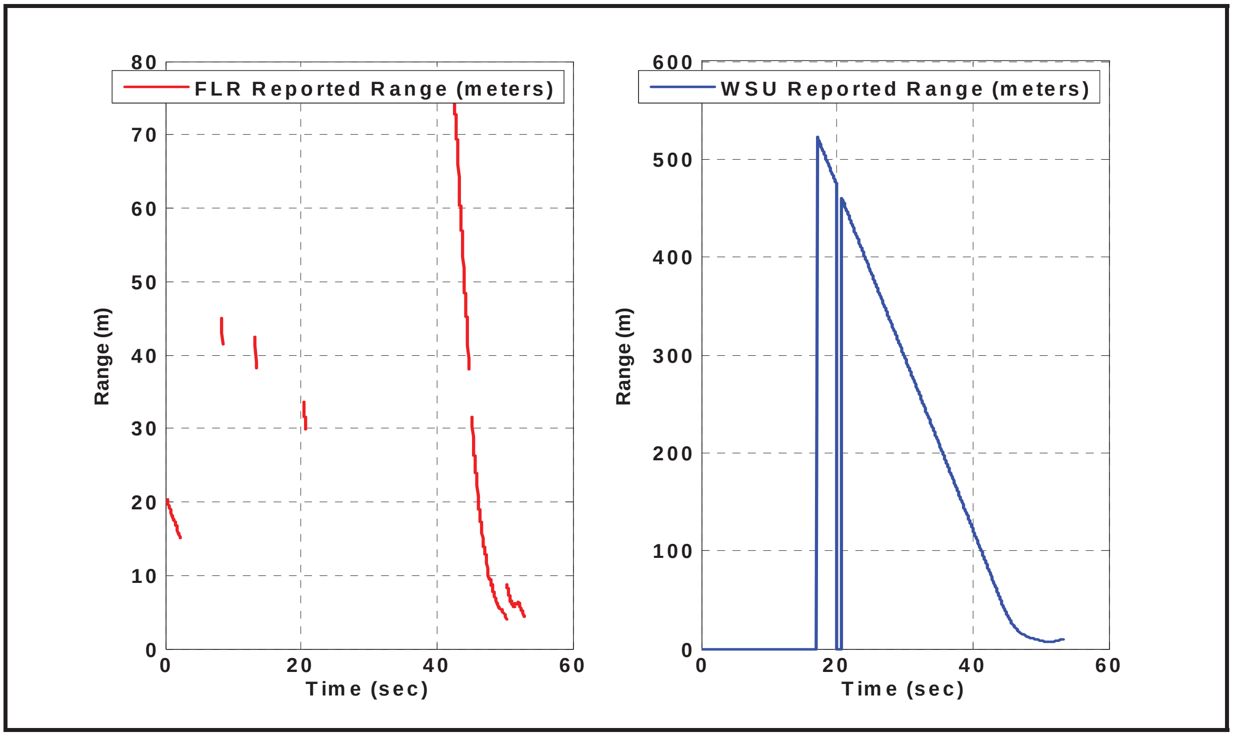

Figure 4: Sensor Performance on Detecting a Vehicle as an In-path Stationary Target

4.2 Test 2: Detecting a Stationary Vehicle in a Curve

The second test evaluated the ability to detect and track a stationary vehicle through a curve. As indicated in Table 1, traditional autonomous sensors suffer from occasional incorrect, out-of-path, target detection and rejection during these driving scenarios (due to poor path prediction in certain straight-curve and curve-straight road transitions). The expectation is that the DSRC+Positioning message from the lead vehicle, the RV, will transmit its path history and, thus, provide better path prediction during straight-curve and curve-straight road transitions for the HV (Figure 5).

As can be seen in the top chart of Figure 6, the FLR was unable to both detect and declare the RV as an in-path target until the range to the target was less than 17 meters. The second from the top chart in Figure 6 shows that the DSRC+Positioning system was able to detect the RV up to 370 meters away.

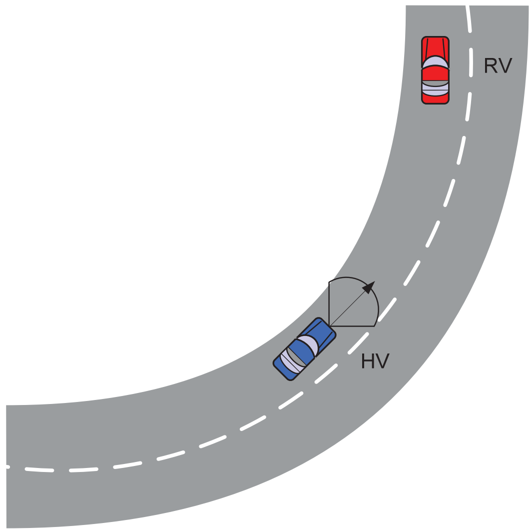

Figure 5: Detecting a Stationary Vehicle in a Curve

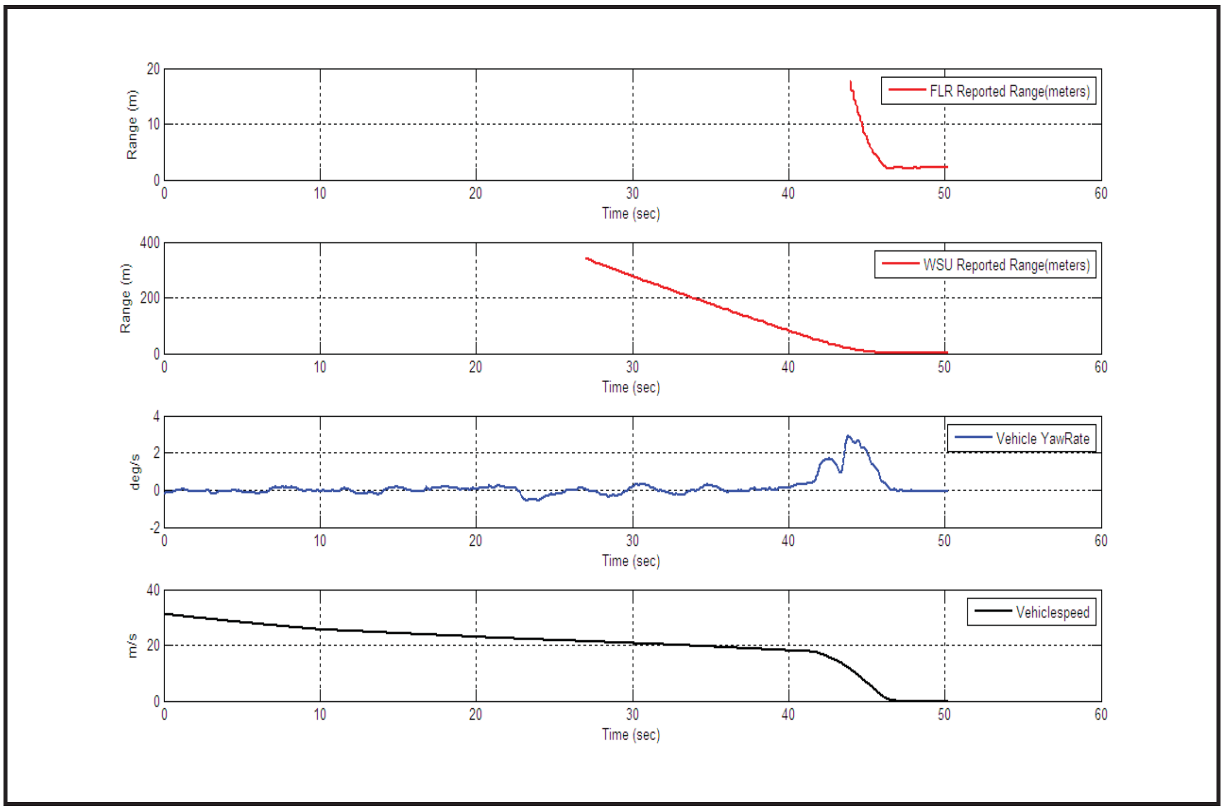

Figure 6: Sensor Performance During Detection of a Stationary Vehicle in a Curve

4.3 Test 3: Straight-Curve and Curve-Straight Road Transitions

The third test involved tracking a vehicle through a straight-curve to curve-straight road transition. The purpose of this test was to illustrate the in-path target detection and tracking in straight-curve and curve-straight road transitions of both autonomous sensors and DSRC+Positioning systems. As stated before, traditional autonomous sensors suffer from occasional, incorrect, out-of-path, target detection and rejection during these driving scenarios. The expectation is that the DSRC+Positioning message from the stationary vehicle will transmit its path history and, thus, provide better path prediction during straight-curve and curve-straight road transitions (Figure 7).

As can be seen in Figure 8, both the FLR sensor (top left chart) and DSRC+Positioning system (top right chart) provide consistent tracking of the RV through the straight-curve transition. However, the FLR sensor drops the RV at approximately Time Index 50 near the end of the curve and re-acquires the target vehicle as both vehicles enter the straight portion of the road. It is also important to note that during this test, the DSRC+Positioning vehicle experienced a GPS outage at approximately Time Index 68, which produced a large spike in the range and range rate measurements reported by the system. While DSRC messages that contain path history may provide better path prediction of straight-curve and curve-straight road transitions and eliminate FOV restrictions typically faced with autonomous sensors, long GPS outages (due to urban canyons, foliage, etc.) are a continuing limitation for DSRC+Positioning using GPS. However, short GPS outage durations, such as the one in the top right corner of Figure 8, can be addressed via dead-reckoning of the vehicle position solution through the use of on-board sensors.

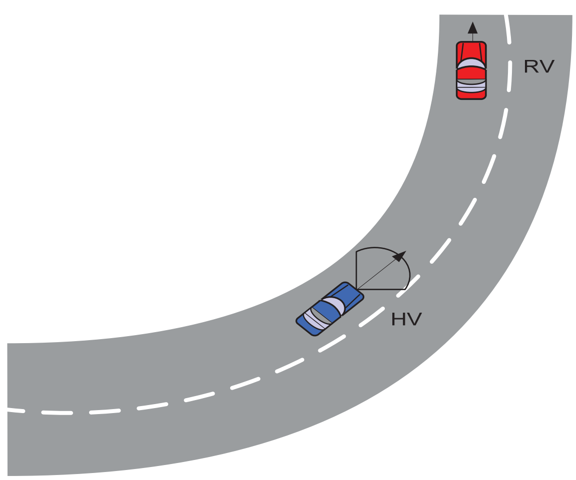

Figure 7: Curve-Straight and Straight-Curve Road Transitions

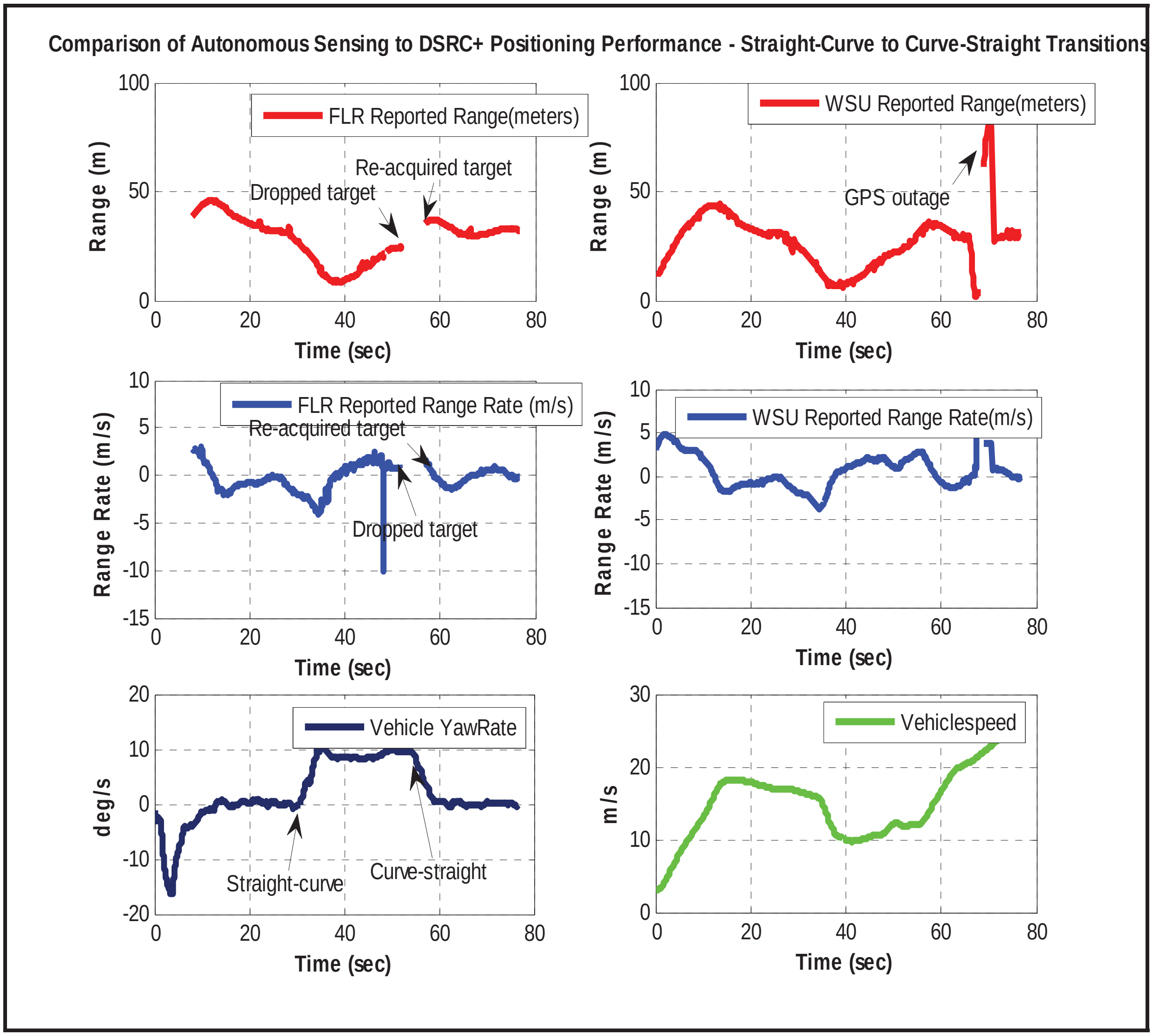

Figure 8: Sensor Performance through Curve-Straight and Straight-Curve Transitions

4.4 Test 4: Late Cut-in of Vehicle into the HV Path

The fourth test analyzes the ability of the FLR autonomous sensor in comparison to DSRC+Positioning to detect sudden vehicle cut-ins at close ranges (Figure 9).

As can be seen in top chart of Figure 10, the in-path target confirmation with the FLR was only possible after the stopped vehicle is within the radar FOV. When the primary target vehicle cuts-in the HV lane of travel, there is an approximate elapse of 1 second before this target is declared as in-path. The middle chart of Figure 10 shows that, similar to what was observed during the vehicle cut-out test scenario, the DSRC+Positioning system provides continuous ranging information to the stationary vehicle, which was further enhanced by the on-board, calculated, WSU Target Classification (TC) information (bottom chart) that provides the locations of all DSRC+Positioning-equipped vehicles, within communication range, relative to the HV.

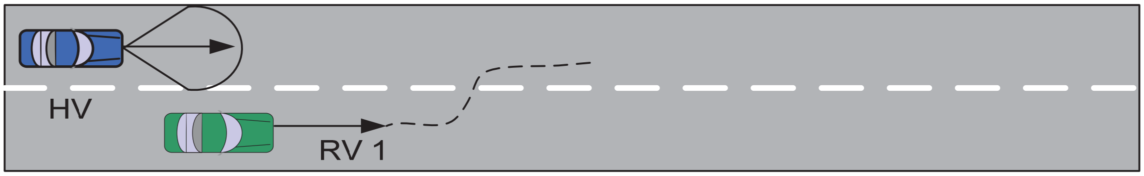

Figure 9: Cut-in of Lead Vehicle

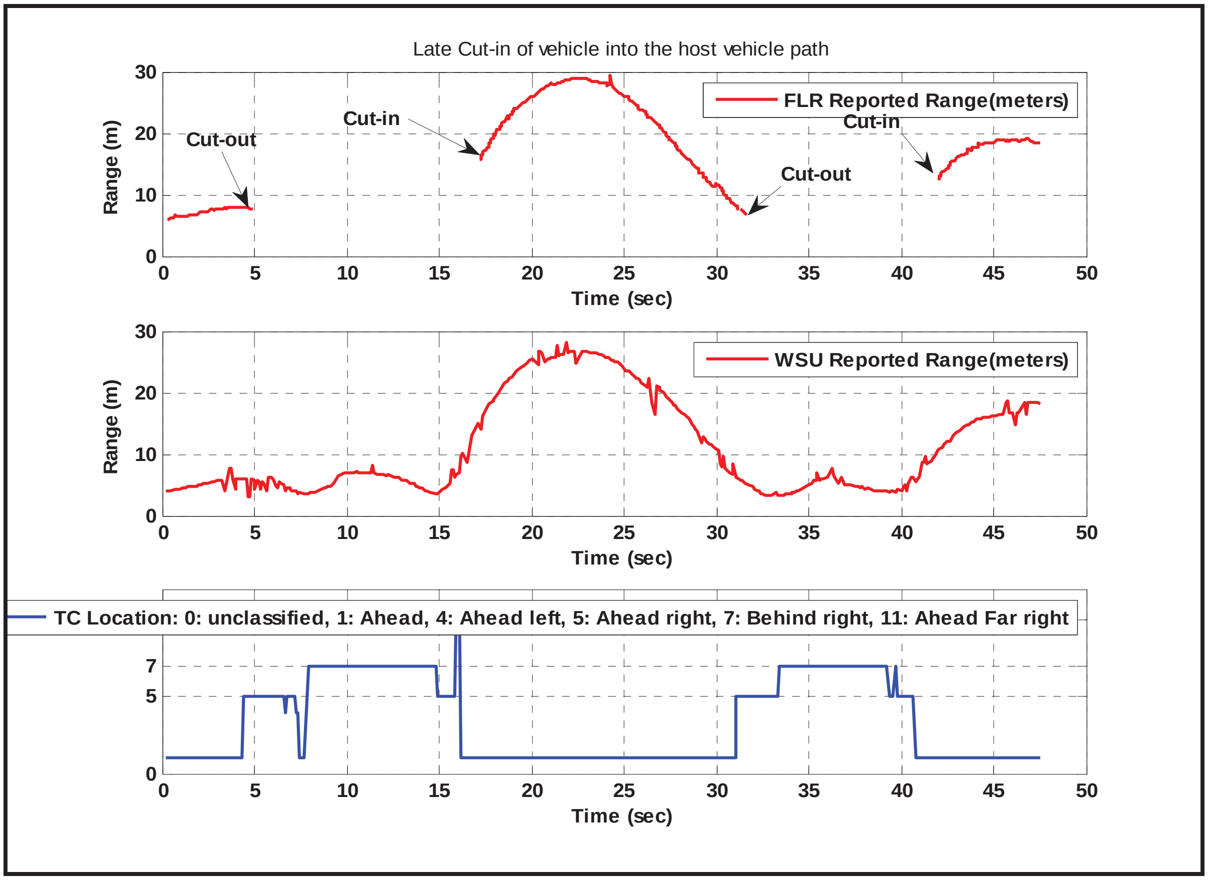

Figure 10: Sensor Performance during Vehicle Cut-in

4.5 Test 5: Cut-out of Lead Vehicle Reveals Stopped Vehicle in Lane

The fifth test analyzes the performance of the FLR autonomous sensor in comparison to DSRC+Positioning during a sudden cut-out of a previously tracked vehicle to reveal a stationary vehicle within the lane of travel (Figure 11).

As can be seen in the top chart of Figure 12, the in-path target confirmation was only possible with the FLR after the stopped vehicle is within the radar FOV. When the initial primary target vehicle (RV1) cuts-out of the HV lane of travel revealing the stationary vehicle (RV2), there is an approximate elapse of 5 seconds before RV2 is acquired by the FLR sensor. In contrast, the middle chart of Figure 12 shows that the DSRC+Positioning system on the HV received positional information from RV2 several hundred meters away. After the RV1 cut-out, it can be seen that the DSRC+Positioning system provides continuous ranging information to the stationary vehicle (bottom chart), thereby, greatly enhancing the ability for a Collision Avoidance System (i.e., Forward Collision Warning (FCW)) to provide an alert to the driver of the HV, if deemed necessary.

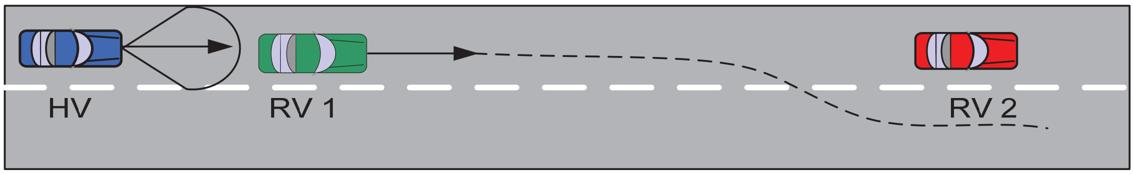

Figure 11: Cut-out of Lead Vehicle Reveals Stopped Vehicle In-lane

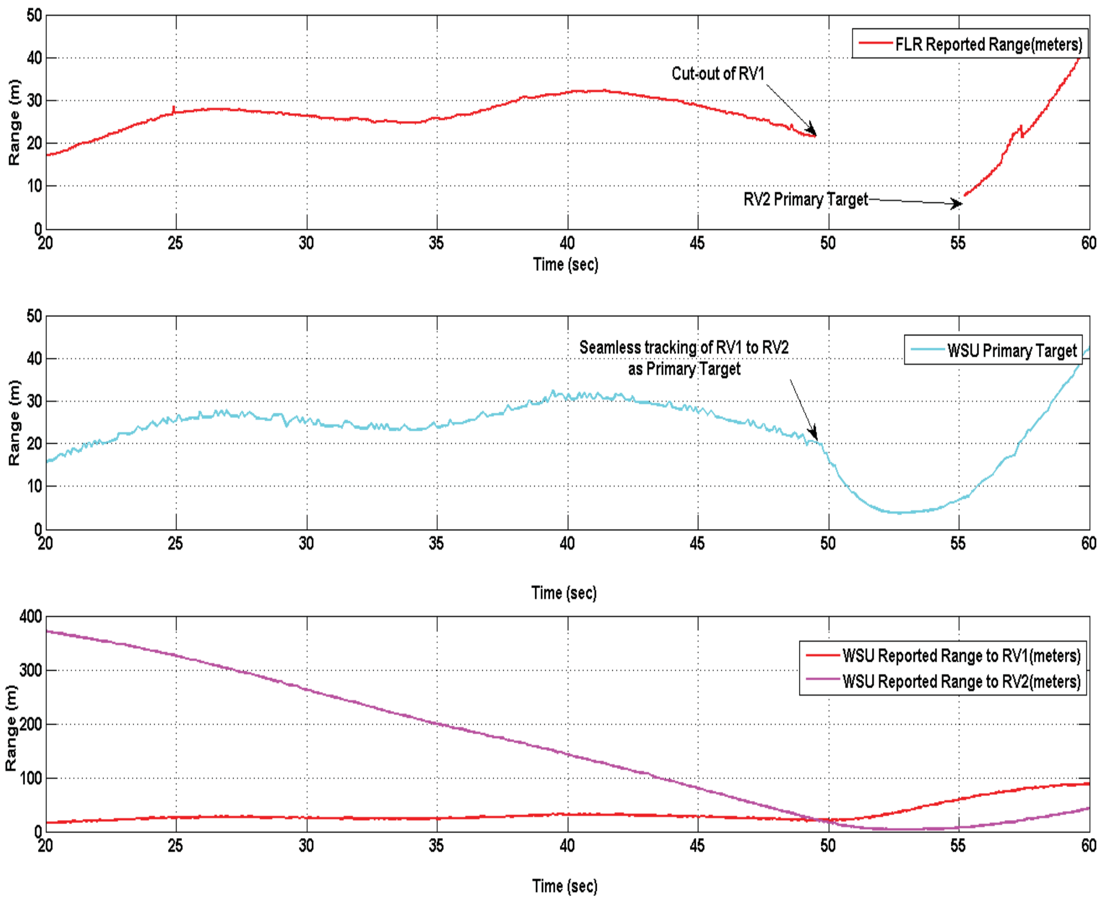

Figure 12: Sensor Performance during Vehicle Cut-Outs

4.6 Test 6: Tracking Intersecting Vehicles

The sixth and final test analyzes the ability of the FLR autonomous sensor in comparison to DSRC+Positioning to detect and track an intersecting vehicle (Figure 13). For this test, it is important to state that the FLR sensor used in this analysis was not intended to detect and track targets like those encountered during this scenario.

From the upper left charts in Figure 14, observe that the FLR sensor failed to detect the RV during the test (as was expected), while the DSRC+Positioning system was able to detect and track the RV throughout the test run (upper right charts).

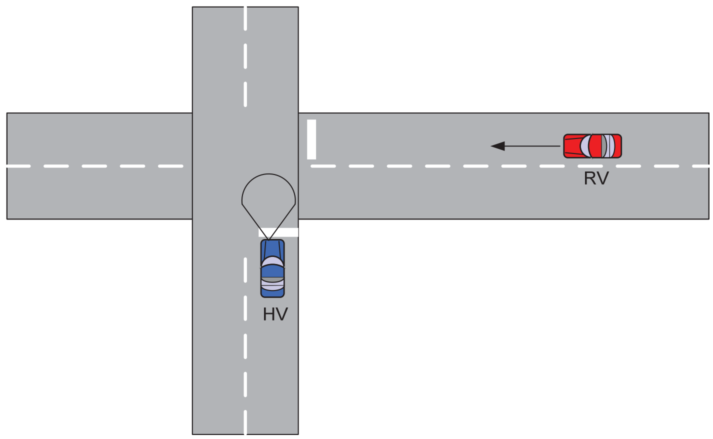

Figure 13: Detecting and Tracking Intersecting Vehicles

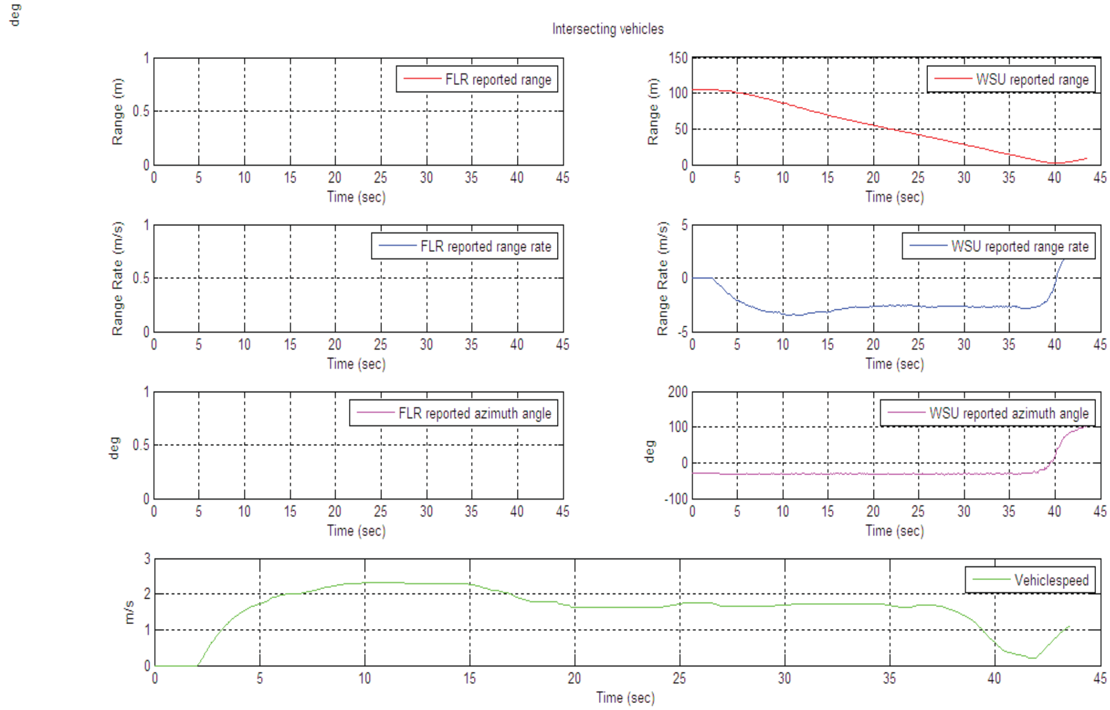

Figure 14: Sensor Performance During Detection and Tracking of Intersecting Vehicles

5 Pre-crash and Collision Mitigation Augmentation of Autonomous Systems

5.1 DSRC+Positioning and Autonomous Safety System Structure

A potential hybrid system framework, comprised of both DSRC+Positioning and autonomous sensing systems, was defined as a means of these two systems both potentially complementing as well as overcoming the limitations of each other. This framework was not developed under the VSC-A program. However, one of the key concepts of this framework was utilizing a Target Association strategy which would allow DSRC+Positioning and Autonomous safety systems to coexist and cooperate with one another. A potential Target Association strategy between radar, vision, and RV information is depicted in Figure 15 below.

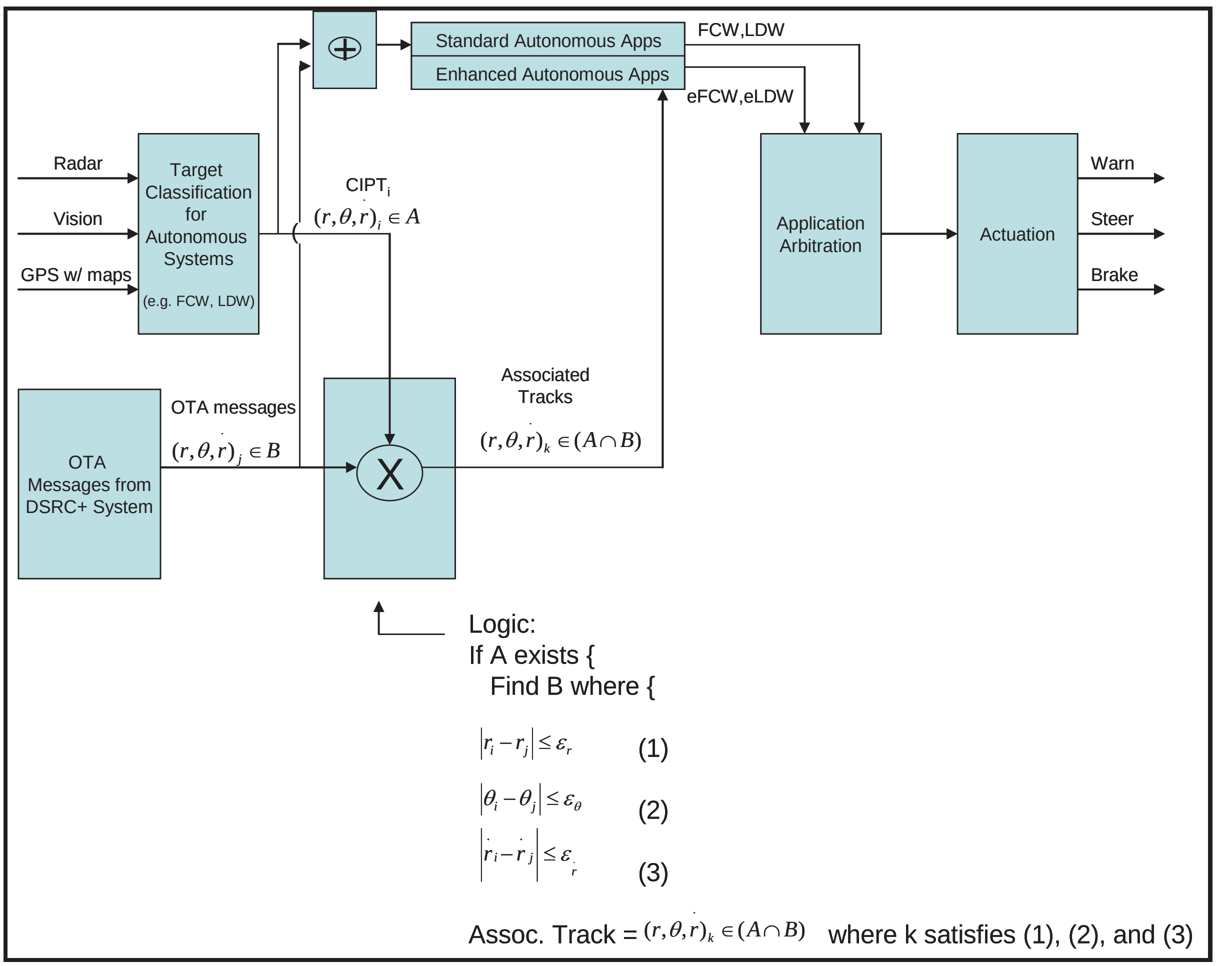

Figure 15: Potential Target Association Strategy

The Target Association strategy for the hybrid system would correlate the radar and vision tracks with the path history, path prediction, and relative positioning information for RVs within the range of the DSRC radio to extend and enhance the capabilities of the safety applications (e.g., enhanced Forward Collision Warning (eFCW), enhanced Lane Departure Warning (eLDW)). The challenge would be in performing the association between autonomous sensing targets and DSRC targets. One approach for accomplishing this task could be based on grouping autonomous sensing targets with DSRC RV targets based on similarities in range, azimuth, and range rate. After this association, the target identification of the associated autonomous sensing targets could be effectively mapped to the DSRC message ID corresponding to a RV.

Likewise, standard autonomous safety applications (e.g., FCW, LDW) could be augmented with information received from the DSRC+Positioning system to assist in overcoming some of the limitations of autonomous-only systems. For example, DSRC+Positioning could be used to fill in some of the holes for long autonomous sensing outages where the target cannot continue to be tracked via some hysteresis method.

5.2 SAE 2735 Safety Pre-crash Data Elements

The SAE DSRC J2735 Message Set Standard [1] defines the BSM which is to be used for V2V safety communications. The BSM consists of Part I data which is sent with every BSM and Part II data, some of which are required to be sent, but potentially at a different rate than the Part I data, and some of which are optional to send. Some of the Part I data elements include the vehicle position, speed, heading, acceleration, brake status, and size. For V2V safety the required Part II data frame is the Vehicle Safety Extension which includes items such as the vehicle safety event information, path history, path prediction, and raw GPS satellite information.

In addition to the BSM Part I and Part II data elements discussed above the SAE J2735 Message Set provides a comprehensive list of Message Sets, Data Frames, and Data Elements that allow for the entire transmission of driver, vehicle, and environment level information that can be reasonably perceived as having safety implications for the receiving vehicles. For example, it contains a data frame for the bumper height, data element for the vehicle mass, and a data frame that utilizes information originally defined in the SAE J1939 Standard as it relates to the tire conditions, vehicle weight, and other information.

The SAE J2735 Standard provides for the transmission of an abundance of information related to the state of DSRC+Positioning equipped vehicles, as well as information from the vehicle roadway. While it is beyond the scope of this project to perform a critical analysis on the real-world safety benefit for each message, data frame, and data element proposed in the current Standard, there does not appear to be any glaring omission from that would warrant a specific call for inclusion, especially as it relates to the augmentation of traditional autonomous safety systems.

6 References

[1] SAE International™, *"Dedicated Short Range Communications (DSRC) Message Set Dictionary,"* SAE J2735 Standard, November 2009.

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Test Bed System Development

List of Acronyms

API	Application Programming Interface
ASN1	Abstract Syntax Notation One
ABS	Anti-lock Braking System
BSM	Basic Safety Message
BSW	Blind Spot Warning
CAMP	Crash Avoidance Metrics Partnership
CAN	Controller Area Network
CCH	Control Channel
CICAS-V	Cooperative Intersection Collision Avoidance System - Violation
CLW	Control Loss Warning
CPU	Central Processing Unit
CSV	Comma Separated Values
DER	Distinguished Encoding Rules
DMU	Dynamics Measurement Unit
DNPW	Do Not Pass Warning
DSRC	Dedicated Short Range Communication
DVI	Driver-Vehicle Interface
DVIN	Driver Vehicle Interface Notifier
ECDSA	Elliptic Curve Digital Signal Algorithm
EEBL	Emergency Electronic Brake Lights
EGUI	Engineering Graphical User Interface
ERH	Error Handler
FCW	Forward Collision Warning
GPS	Global Positioning System
GPSC	GPS Correction
GUI	Graphical User Interface
HMI	Human Machine Interface
HV	Host Vehicle
HVPP	Host Vehicle Path Prediction
HW	Hardware

IMA	Intersection Movement Assistance
ITS	Intelligent Transportation System
JPO	Joint Program Office
LCW	Lane Change Warning
NHTSA	National Highway Traffic Safety Administration
NMEA	National Maritime Electronic Association
OBE	On-Board Equipment
OTA	Over-the-Air
PER	Packed Encoding Rules
PH	Path History
RITA	Research and Innovative Technology Administration
RS	Radio Services
RSE	Roadside Equipment
RSS	Received Signal Strength
RTCM	Radio Technical Commission for Maritime Services
RTK	Real Time Kinematic
RV	Remote Vehicle
SCH	Service Channel
SCTP	Stream Control Transmission Protocol
SDH	Sensor Data Handler
SDHCAN	CAN Sensor Data Handler
SDHGPS	GPS Sensor Data Handler
SM	Security Module
SMI	Security Module Interface
SR	Scenario Replicator
SW	Software
TA	Threat Arbiter
TADS	TESLA and Digital Signature
TC	Target Classification
TCP	Transport Control Protocol
TESLA	Timed Efficient Stream Loss-tolerant Authentication
TPS	Time/Position Services

USDOT	United States Department of Transportation
UTC	Coordinated Universal Time
VGA	Video Graphics Array
VII	Vehicle Infrastructure Integration
VIS	Vehicle Interface Services
VoD	Verify on Demand
VSC2	Vehicle Safety Communications 2 (Consortium)
VSC-A	Vehicle Safety Communications – Applications
VTP	Verify Then Process
V2I	Vehicle to Infrastructure
V2V	Vehicle to Vehicle
WAVE	Wireless Access in Vehicular Environments
WMH	Wireless Message Handler
WSM	WAVE Short Message
WSU	Wireless Safety Unit
XCP	Universal Measurement and Calibration Protocol

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1 Introduction

For this project, each Crash Avoidance Metrics Partnership (CAMP) Vehicle Safety Communications 2 (VSC2) Consortium Participant developed a Dedicated Short Range Communications (DSRC)+Positioning-only vehicle test bed (this will now be referred to as the test bed in the remaining text of this document) to serve as a prototype platform for the Vehicle Safety Communications–Applications (VSC-A) system. The test bed was used to validate system specifications and performance tests that were developed as part of the VSC-A Project (see Appendix C-1, C-2, and C-3). The test bed includes a common On-Board Equipment (OBE) unit with a customized positioning solution to achieve the relative vehicle position performance required by the safety applications.

Given the safety-critical nature of the applications being considered, the test bed allows for a flexible development platform necessary to answer some of the critical research questions regarding DSRC+Positioning and communications. Such issues include relative lane-level positioning, time synchronization, advanced communication protocols to mitigate loaded-channel scenarios, and practical Vehicle-to-Vehicle (V2V) security and anonymity.

The development of the vehicle test bed consists of the following activities:

1. Developing preliminary designs for the core system framework and safety application modules which support the minimum performance specifications
2. Developing a consolidated VSC-A architecture and software (SW) implementation to support the preliminary module designs
3. Identifying and developing the appropriate SW tools to assist in the development, testing, analysis, etc., of the SW implementation of the system framework and safety application modules
4. Acquiring and integrating the necessary hardware (HW) components, including vehicles, into an integrated system

Items #1 - #3 will be discussed in this appendix. For item #4, please refer to the main body of the VSC-A Final Report.

2 Test Bed System Design

The initial focus of the test bed design activities was developing the preliminary designs for the core system framework and safety application modules to be used during the implementation stage of the test bed development. These designs were to be used in developing a consolidated VSC-A architecture and SW implementation to support the preliminary module designs. In addition to the core and safety applications modules, interface, positioning and security, threat process and reporting, and data analysis system framework module groupings were identified.

As was previously mentioned in the main body of the final report, one of the objectives of the project was to develop a prototype test bed of a set of representative, communication-based safety applications. The modules developed as part of the project contain the essential elements of the test bed necessary to support this objective. For this reason, only the high-level details of the design and its corresponding implementation will be discussed in this report. The following sub-sections will describe the high-level design aspects of the core and safety applications modules. The positioning and security development are discussed in Appendix E-1 and Appendix F, respectively, of the VSC-A Final Report. The remaining modules are discussed in the test bed implementation section of this appendix.

2.1 Core Modules

The core modules are composed of the critical system framework modules that calculate data, received from the system framework modules that interface to the external environment, to support the VSC-A safety application modules. Some of the data that is calculated is additionally transmitted over-the-air (OTA) for use by nearby remote vehicles (RVs).

2.1.1 Path History (PH)

The PH module for the VSC-A system maintains a history of the past locations traversed by the Host Vehicle (HV). It provides an adaptable concise representation of recent vehicle movement over a certain distance. The PH module in the HV carries out these basic operations:

a) Maintains a buffer of its actual recent vehicle position and sensor data points over a certain distance

b) Computes concise representation(s) of the actual PH of the vehicle based on allowable position error tolerance between the actual vehicle path and its concise representation

c) Updates the PH concise representation periodically for use by the other VSC-A modules and for transmission OTA

Three methods of generating vehicle path history for the VSC-A system have been implemented and evaluated successfully. For the design details along with test results of these three methods, please refer to Appendix B-2.

2.1.2 Host Vehicle Path Prediction (HVPP)

The HVPP module for the VSC-A system utilizes positioning and dynamics information provided by the HV interface modules to calculate a radius of curvature representing the vehicle's estimated future path. This is accomplished by using basic physics equations to compute curvature based on the HV speed and the rate of change of heading (yaw rate). This curvature can be extrapolated forward to provide an estimate of the likely future path of the vehicle. The estimate is provided without dependence on future road geometry information obtained from outside sources (i.e., map databases, vision system). However, other information could be used to improve the overall prediction of the future path. The HVPP module carries out the following basic operations:

- Gathers host dynamics and positioning information from the Sensor Data Handler (SDH)

- Computes path radius using dynamics information to represent the driver's intended future path

Radius = 1/curvature (ρ)

- Computes path radius center point Global Positioning System (GPS) Latitude/Longitude coordinate
- Computes confidence of the predicted path based upon the rate of change of the HV dynamics to infer transient conditions
- Updates path prediction output periodically for use by other VSC-A modules and for transmission OTA

In the HV's local coordinate plane, the center point of the path radius is merely an offset along the Y axis (See Figure 1). The sign of the radius calculation determines if the Y offset is positive or negative.

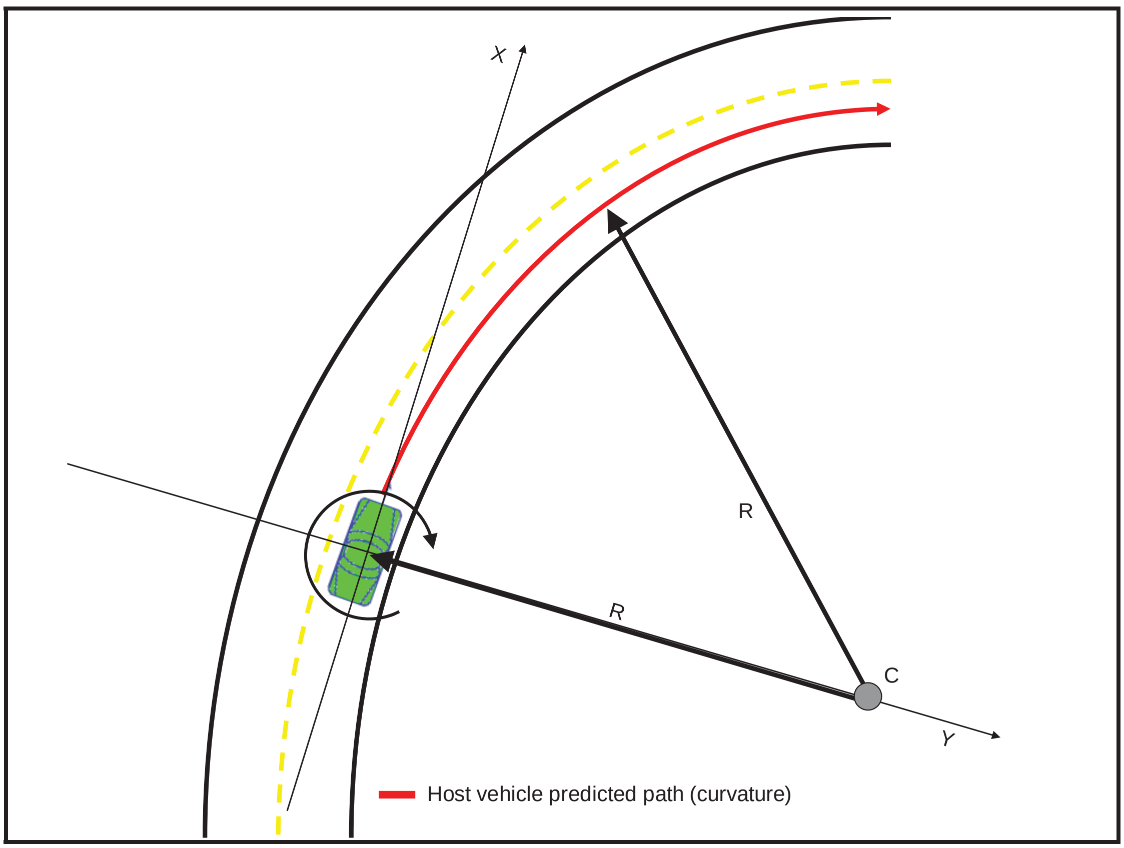


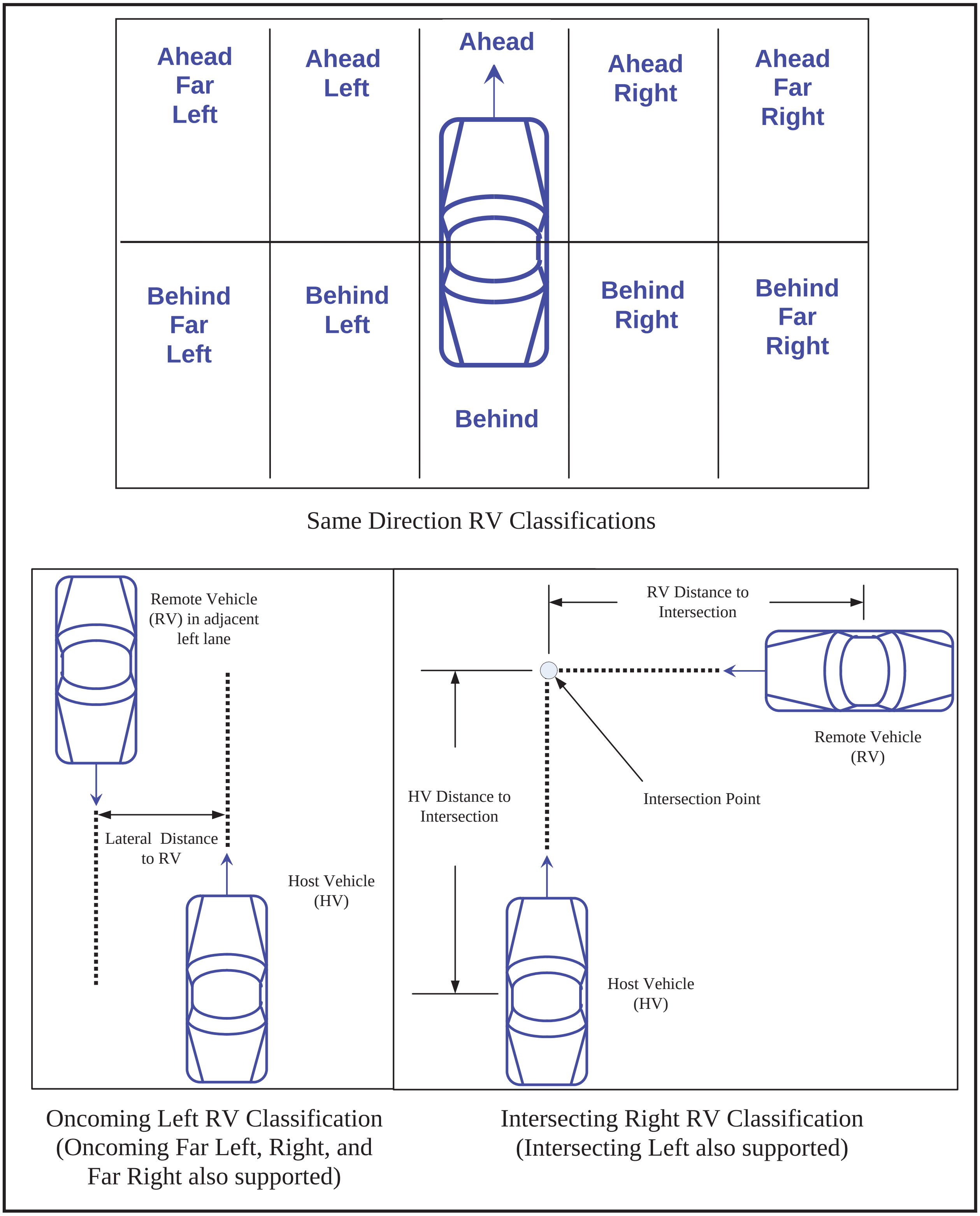
Figure 1: Host Vehicle Projected Path

2.1.3 Target Classification (TC)

The TC module for the VSC-A system provides a 360–degree, relative classification of the locations of communicating RVs relative to the HV. Based on the selection of VSC-A applications, possible classifications of RVs that would meet the classification requirements for the applications are shown below in Figure 2. For each of the remote communicating vehicles, in addition to the classification, TC also provides the Lateral

Offset, Longitudinal Offset, Relative Speed, Range, Range Rate, Azimuth, etc., of communicating RVs relative to the HV. The mapping from the TC classification to various VSC-A system safety applications is shown in Figure 3.

Note that proper classification of RVs requires data elements from the J2735 Basic Safety Message (BSM). This includes latitude, longitude and elevation from Part I and path history and path prediction objects from Part II.



Same Direction RV Classifications

Oncoming Left RV Classification (Oncoming Far Left, Right, and Far Right also supported)

Intersecting Right RV Classification (Intersecting Left also supported)

Figure 2: Remote Vehicle Target Classifications

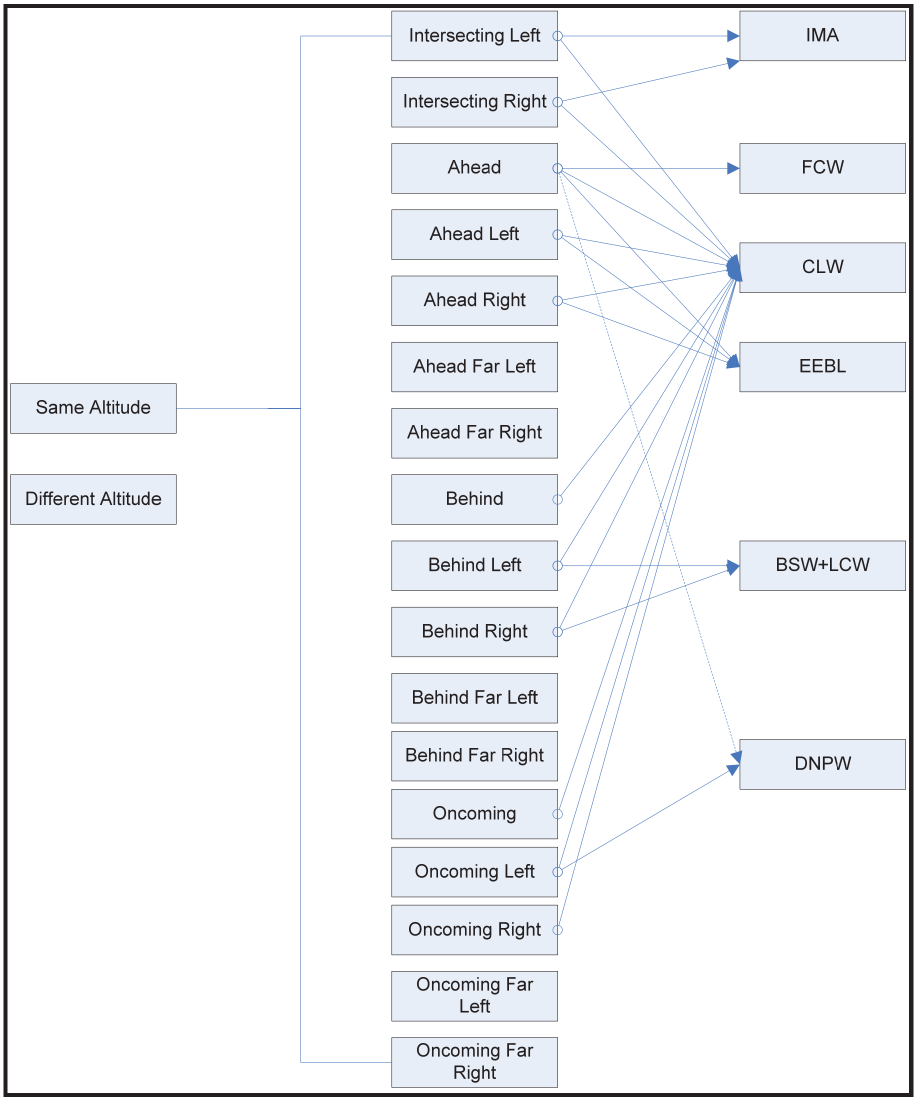


Figure 3: Target Classifications used by VSC-Applications

2.2 Safety Applications Modules

The safety application modules encapsulate the warning algorithms used to address the seven crash imminent scenarios discussed in the main body of the final report. These modules evaluate potential categorized safety threats based on the data and inputs from the core and other system framework modules.

2.2.1 Emergency Electronic Brake Lights (EEBL)

The EEBL safety application enables a HV to broadcast a self-generated emergency brake event to surrounding RVs. Upon receiving such event information, the RV determines the relevance of the event and provides a warning or an advisory to the driver, if appropriate. Figure 4 shows the TC zones for EEBL where the zone is adjusted by the application to encompass the area from the front bumper of the HV to the rear bumper of the RV.

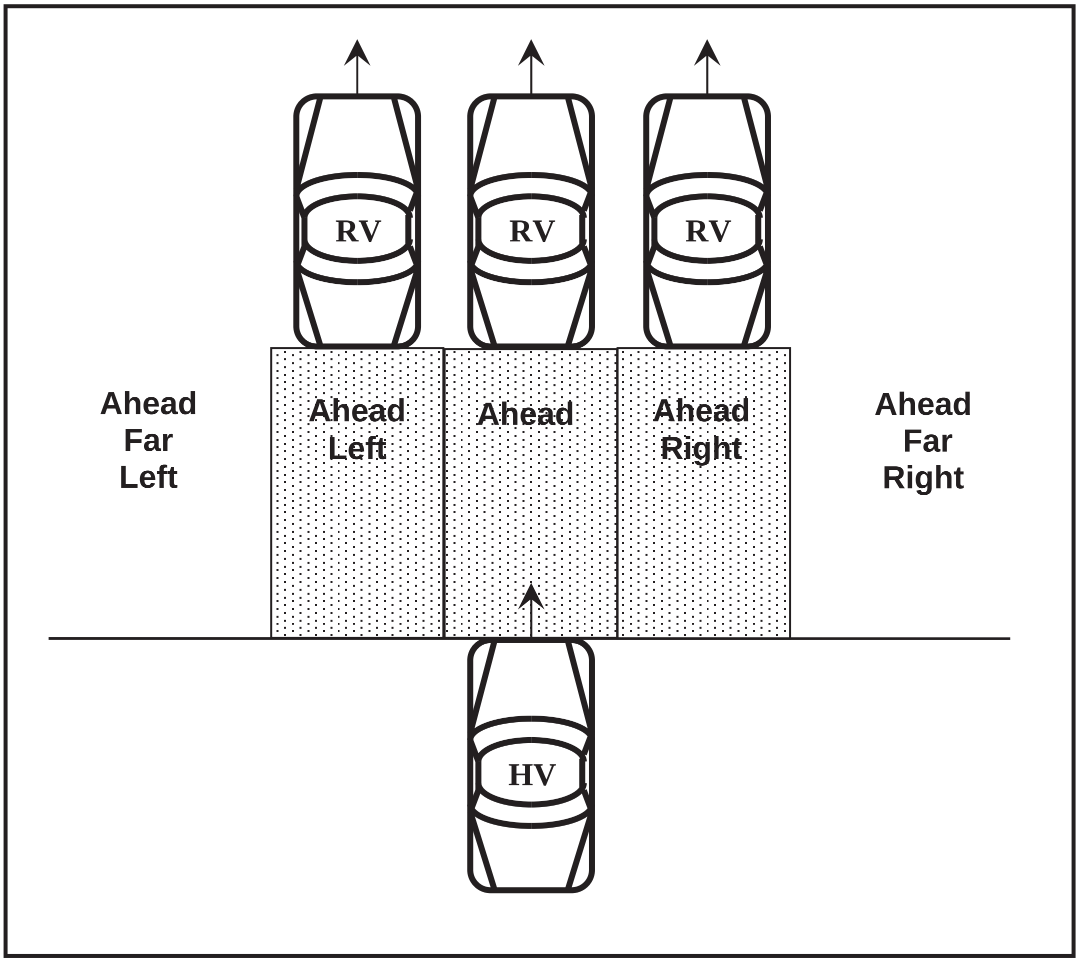


Figure 4: EEBL Target Classification Zones

2.2.2 Forward Collision Warning (FCW)

The FCW safety application issues a warning to the driver of the HV in case of an impending rear-end collision with a vehicle ahead in traffic in the same lane and direction of travel. Figure 5 shows the TC zone for FCW where the zone is adjusted to encompass the area from the front bumper of the HV to the rear bumper of the RV.

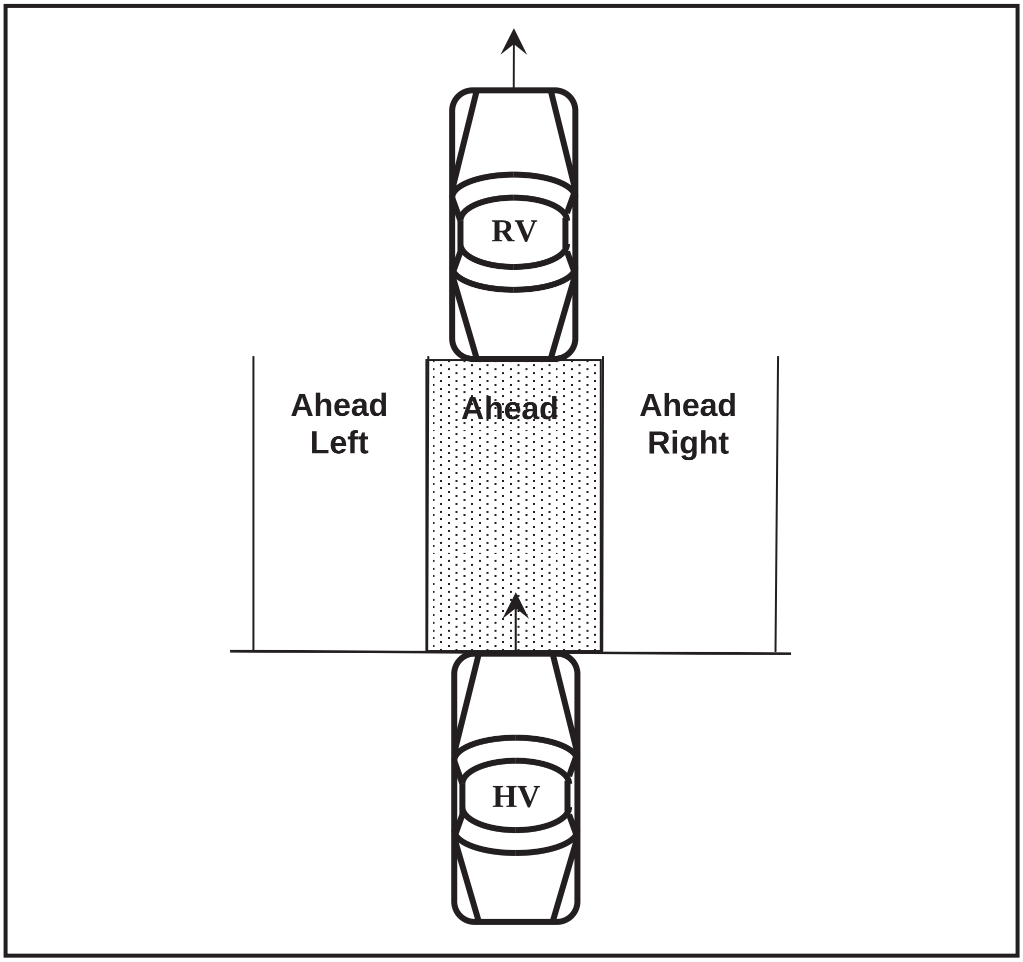


Figure 5: FCW Target Classification Zone

2.2.3 Blind Spot Warning + Lane Change Warning (BSW + LCW)

The BSW + LCW safety application is intended to warn the driver of the HV during a lane change attempt if the blind-spot zone into which the HV intends to switch is, or will soon be, occupied by another vehicle traveling in the same direction. Moreover, the application provides advisory information that is intended to inform the driver of the HV that a vehicle in an adjacent lane is positioned in a blind-spot zone of the HV when a lane change is not being attempted. Figure 6 shows the TC zones for BSW + LCW where the zone is adjusted by the application to encompass the area from the center of the HV to the front bumper of the RV.

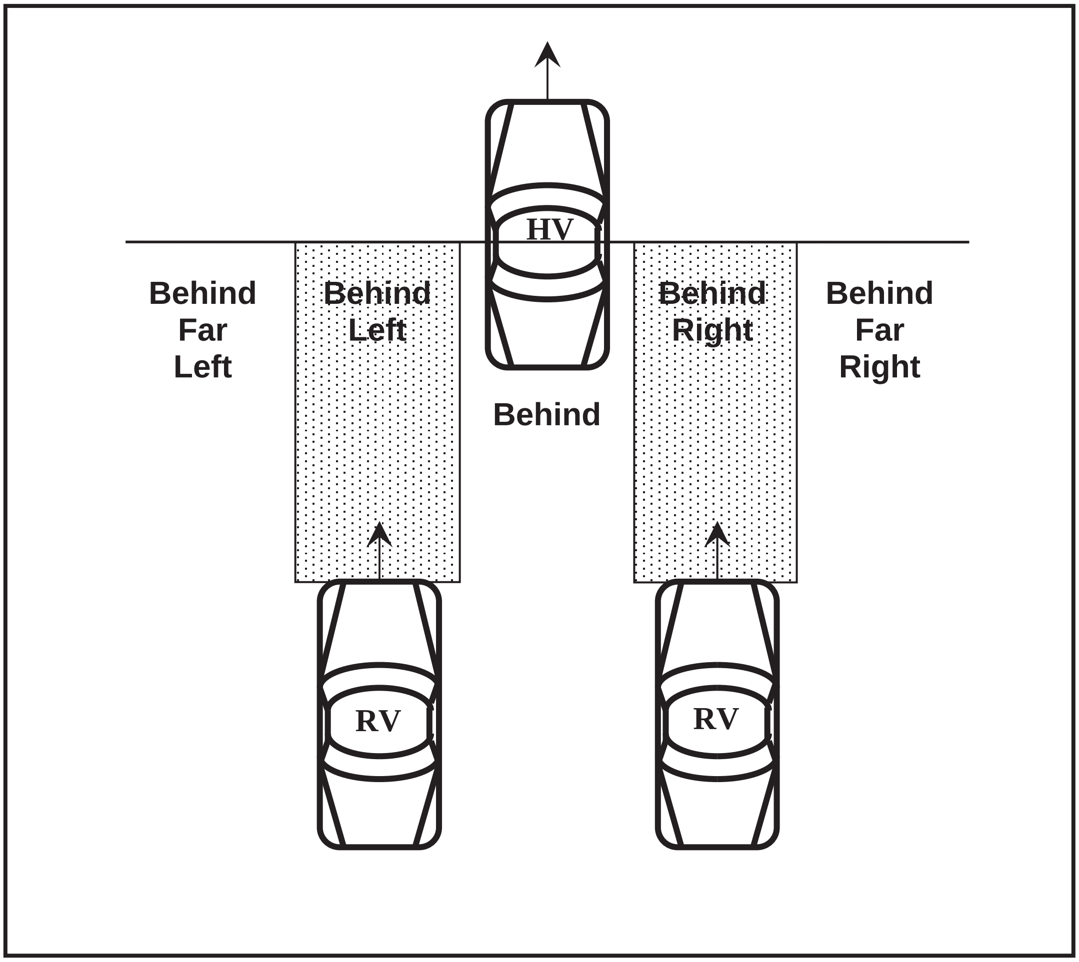


Figure 6: BSW + LCW Target Classification Zones

2.2.4 Do Not Pass Warning (DNPW)

The DNPW safety application is intended to warn the driver of the HV during a passing maneuver attempt when a slower moving vehicle, ahead and in the same lane, cannot be safely passed using a passing zone which is occupied by vehicles with the opposite direction of travel. In addition, the application provides advisory information that is intended to inform the driver of the HV that the passing zone is occupied when a vehicle is ahead and in the same lane and a passing maneuver is not being attempted. Figure 7 shows the TC zones for DNPW where the zone is adjusted by the application to encompass the area from the front bumper of the HV to the rear bumper of the Ahead RV and the front bumper of the Oncoming Left RV.

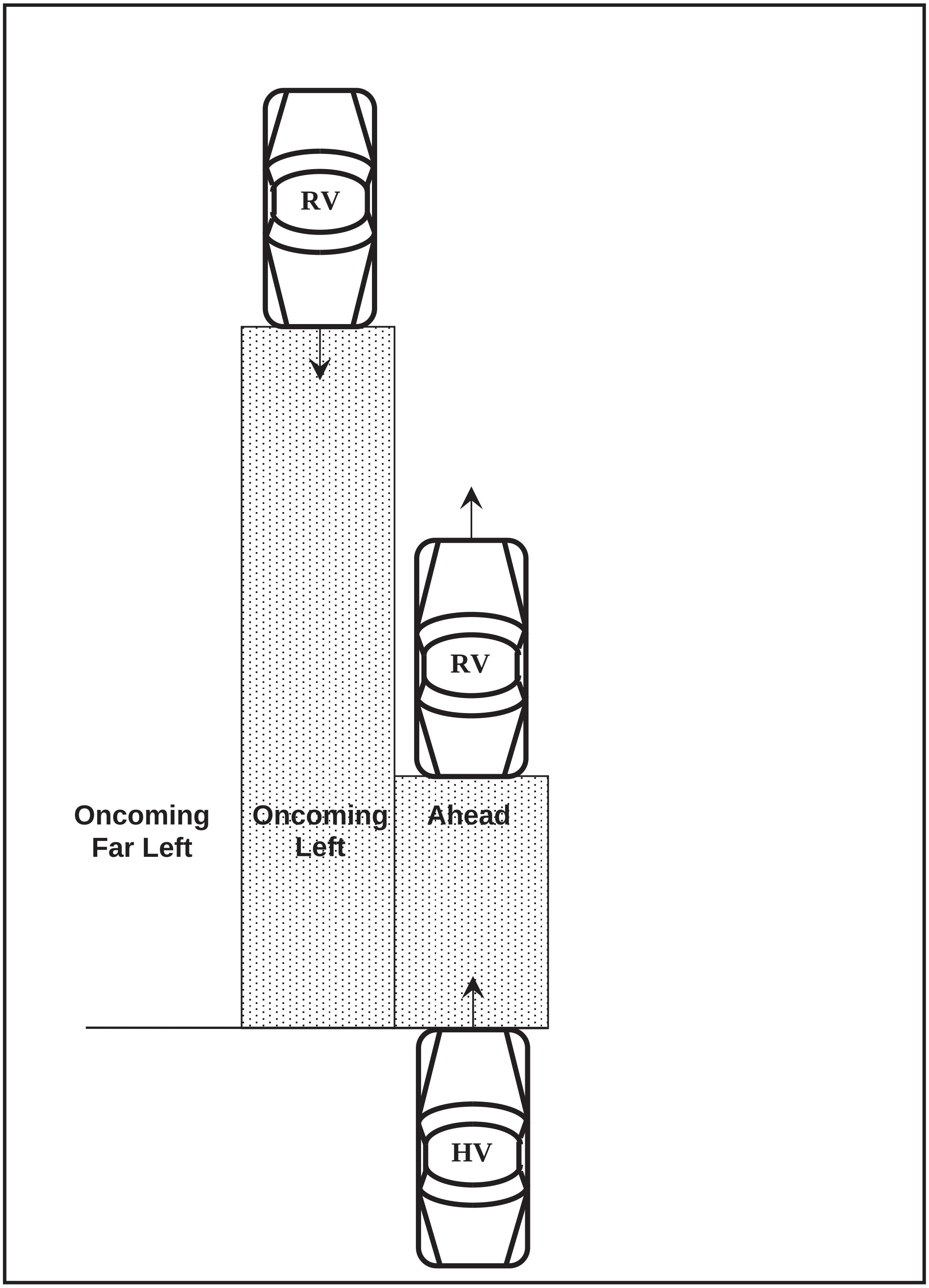


Figure 7: DNPW Target Classification Zones

2.2.5 Intersection Movement Assist (IMA)

The IMA safety application is intended to warn the driver of a HV when it is not safe to enter an intersection due to high collision probability with other RVs. Figure 8 shows the TC zones for IMA where the zone is adjusted by the application to encompass the area from the front bumper of the HV to the front bumper of the Intersecting Left or Right RV.

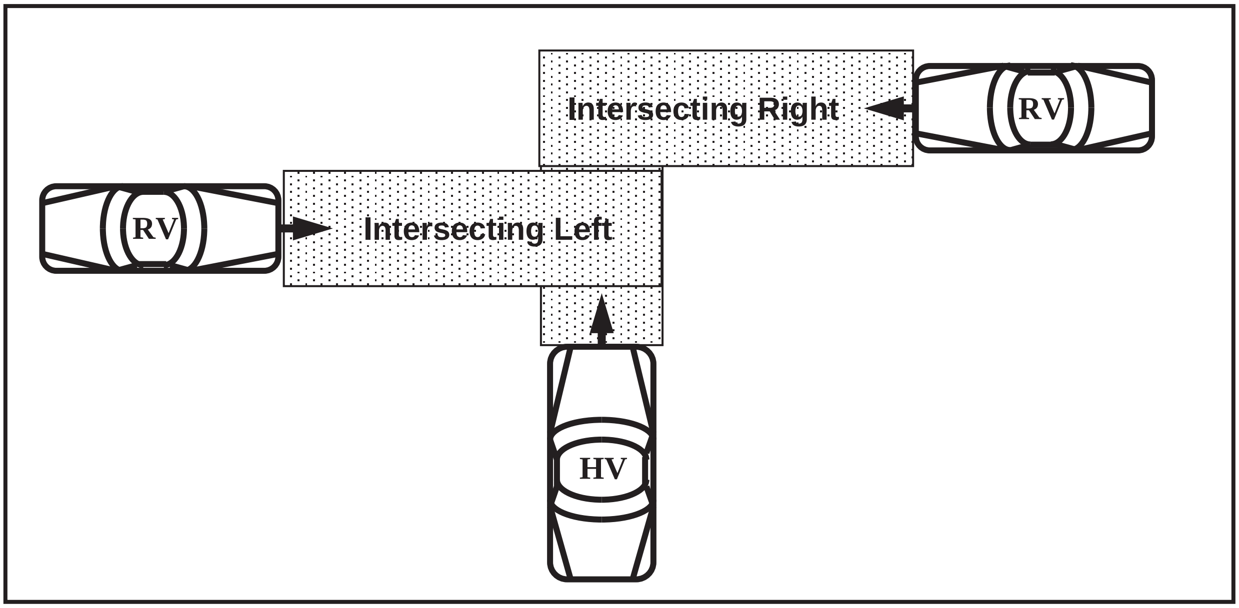


Figure 8: IMA Target Classification Zones

2.2.6 Control Loss Warning (CLW)

The CLW safety application enables a HV to broadcast a self-generated, control loss event to surrounding RVs. Upon receiving such event information, the RV determines the relevance of the event and provides a warning to the driver, if appropriate. Figure 9 shows the TC zones for CLW where the zone is adjusted by the application to encompass the area from the front bumper of the HV to the rear bumper of the Ahead/Ahead Left/Ahead Right RVs, the front bumper of the HV to the front bumper of the Oncoming/Oncoming Left/Oncoming Right RVs, the front bumper of the HV to the intersection point of the Intersecting Left/Right RVs, the front bumper of the HV to the front bumper of the Behind Left/Behind Right RVs, and rear bumper of the HV to the front bumper of the Behind RV.

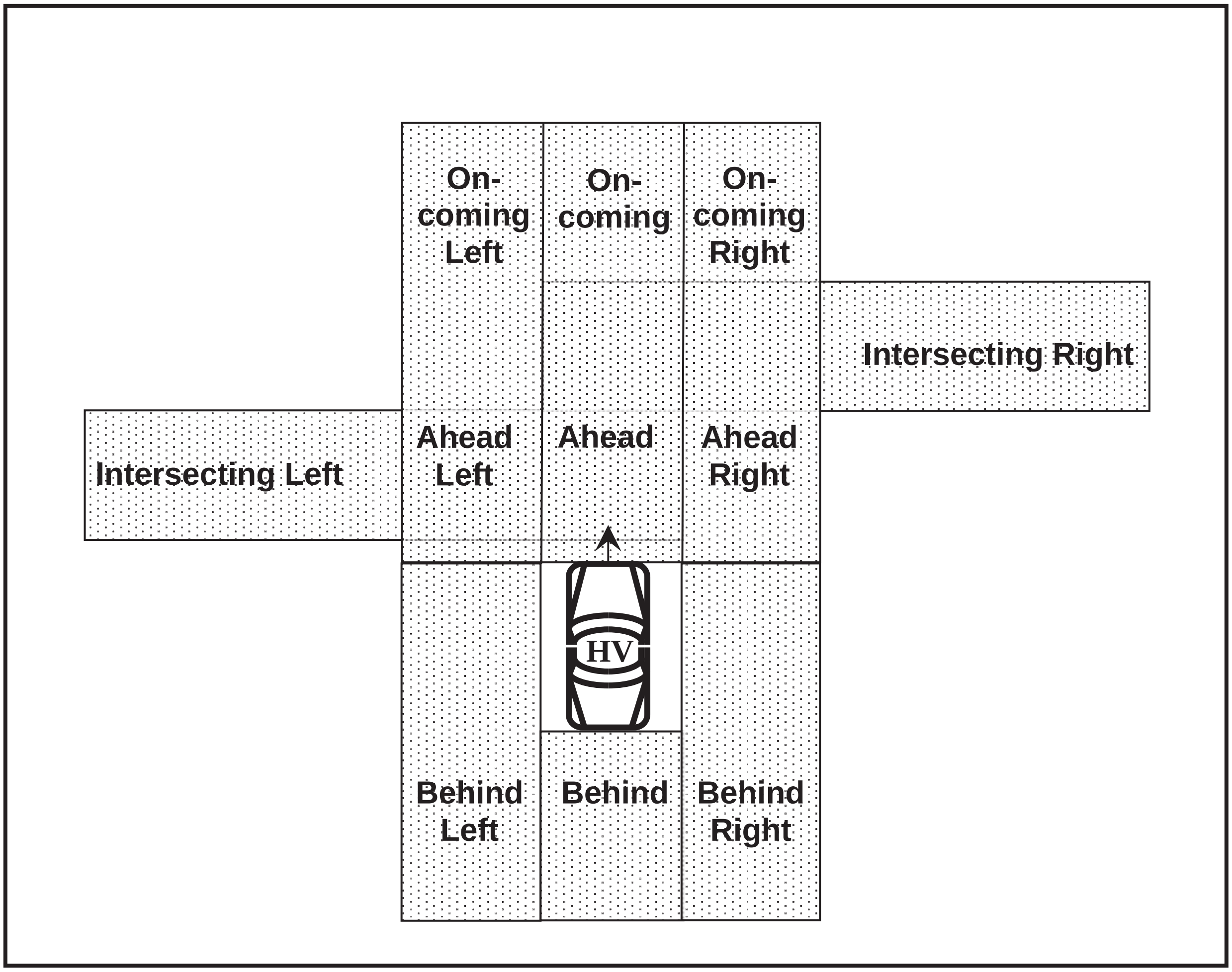


Figure 9: CLW Target Classification Zones

3 Test Bed Implementation

Figure 10 illustrates the VSC-A SW implementation. The VSC-A SW modules (above the dotted line) are specific to the VSC-A Project. The Wireless Safety Unit (WSU) software services modules (below the dotted line) are generic modules supplied with the WSU that provide services and an Application Programming Interface (API) to enable applications to interface to the Controller Area Network (CAN) buses, GPS receiver, and the DSRC Radio(s). The arrows and text between the modules show the primary data flows. The scope of this appendix includes the VSC-A modules, with the exception of the Security Module (SM) which is documented in Appendix F. Note that the Cooperative Intersection Collision Avoidance System–Violation (CICAS-V) application was developed during the CAMP VSC2 CICAS-V Project and, thus, will not be documented in this appendix.

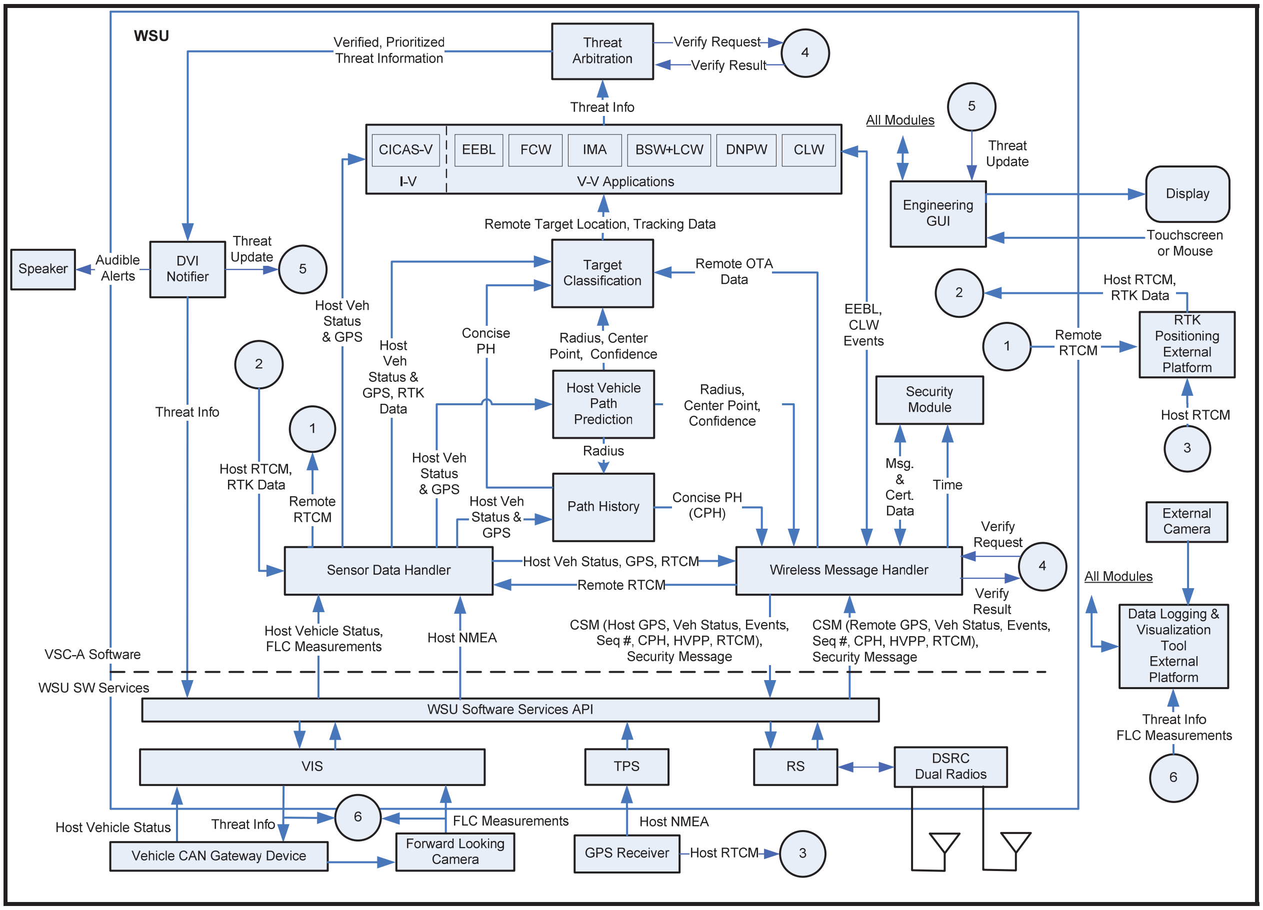


Figure 10: VSC-A Software Block Diagram

The VSC-A modules consist of system framework modules, which include the core modules discussed previously, and application modules. The system framework modules interface to external equipment, calculate data to support the VSC-A application modules, and support the User Interface. The application modules evaluate potential safety threats based on inputs from the system framework modules. The application modules consist of six V2V safety applications developed under the VSC-A program, plus the CICAS-V Vehicle-to-Infrastructure (V2I) application that was developed previously and modified to execute as an application within VSC-A.

In addition to the modules illustrated above, the VSC-A SW includes four additional system framework modules: Main, Error Handler (ERH), Data Logging and Visualization Tool Interface (XCPProc), and Scenario Replicator (SR). Table 1 provides a brief description of each module.

Table 1: VSC-A Module Descriptions

Module	Description
System Framework Modules	
VSC-A Main	Initial module launched at VSC-A startup. Parses the configuration files and starts all of the other modules. Performs shutdown functions at VSC-A termination.
CAN Sensor Data Handler (SDHCAN)	Interfaces to the Vehicle CAN Gateway Device to receive and transmit CAN messages. Interfaces to the Forward Looking Camera to receive CAN messages. Both interfaces are through the WSU Software Services.
GPS Sensor Data Handler (SDHGPS)	Interfaces to a GPS receiver (through the WSU Software Services) to receive National Maritime Electronic Association (NMEA) data, which includes Coordinated Universal Time (UTC) time, position, speed, and heading. Interfaces to Real Time Kinematic (RTK) positioning SW executing on an external platform to send RV Radio Technical Commission for Maritime Services (RTCM) data and receive HV RTCM data and relative position and velocity between the HV and the RVs.
Wireless Message Handler (WMH)	Interfaces to the DSRC Radio(s) (through WSU services) and on-board or off-board security SW. Transmits and receives Wireless Access in Vehicular Environments (WAVE) Short Messages (WSMs). When security is enabled, requests the security SW to generate and verify message signatures.
Security Module (SM)	Generates security signatures for transmitted messages and verifies signatures for received messages.
Path History (PH)	Maintains a history of locations traversed by the HV and provides a concise representation of recent movement over a specified distance.
Host Vehicle Path Prediction (HVPP)	Provides an estimated prediction of curvature to be traversed by the HV.
Target Classification (TC)	Classifies the locations of communicating RVs within a specified radius of the HV and provides relative position and velocity metrics for the classified RVs.
Threat Arbitration (TA)	Prioritizes threat warnings from application modules. When Verification on Demand (VoD) security is being used, requests verification of security signatures for messages that may result in a driver alert.
Driver Vehicle Interface Notifier (DVIN)	Determines what visual and audio indications should be provided to the user. Periodically outputs threat status data to the CAN bus.
Engineering Graphical User Interface (EGUI)	Provides a graphical user interface to enable the user to monitor system status and configure system operation.
Data Logging and Visualization Tool Interface (XCPProc)	Interfaces to a Data Logging and Visualization Tool running on an external platform. Periodically sends the contents of shared memory to the tool and receives commands to update parameters.
Error Handler (ERH)	Monitors all other VSC-A modules to verify they continue to execute and output data. Optionally reboots the system when a module is no longer outputting data.
Scenario Replicator (SR)	Provides the capability to record input data from the CAN, GPS, radio, and Ethernet interfaces and play back of the data at a later time for debug or demonstration purposes.

Application Modules	
Cooperative Intersection Collision Avoidance System–Violation (CICAS-V)	Detects when a HV may violate a traffic signal or stop sign based on map data and signal position and timing information received from Roadside Equipment (RSE). Also receives GPS correction (GPSC) information from RSE.
Emergency Electronic Brake Light (EEBL)	Detects and broadcasts HV emergency braking events. Evaluates RV emergency braking events to determine the relevance to the HV.
Forward Collision Warning (FCW)	Detects an impending rear-end collision with a RV located ahead in the same lane and direction of travel.
Intersection Movement Assistance (IMA)	Detects when it is unsafe to enter an intersection due to a high collision probability with an intersecting RV.
Blind Spot Warning (BSW) and Lane Change Warning (LCW)	Detects when the blind spot zone into which the HV intends to, or could switch to, is currently occupied, or soon will be occupied, by an RV traveling in the same direction.
Do Not Pass Warning (DNPW)	Detects when a vehicle cannot be safely passed because the passing zone is occupied by an RV traveling in the opposite direction.
Control Loss Warning (CLW)	Detects and broadcasts HV control loss events. Evaluates control loss events received from RVs to determine the relevance to the HV.

3.1 Operation

The WSU SW may be configured to start the VSC-A SW automatically at power up or the VSC-A SW may be started manually. The VSC-A SW application is started by launching the main module, which in turn starts all of the other modules.

The VSC-A application reads a set of configuration parameters from a file named vsc-a.conf. The vsc-a.conf file also specifies two other configuration files, one for security parameters and the other for vehicle identification information used during testing. The SR also reads a configuration file specific to its functionality. All of the configuration files are in text format to support user editing.

All of the modules execute as processes under the Linux operating system. The processes exchange data using shared memory. Each process reads the shared memory of other processes, and if applicable, receives data from external devices. The process executes its functionality and writes its outputs to shared memory, and if applicable, sends data to external devices. Each process may optionally be configured to generate a log file.

VSC-A supports two modes of process scheduling: timer mode and notification mode. When using timer mode, each process sets a periodic timer to schedule its execution. When using notification mode, selected processes register with other processes to be notified when to execute. Processes that have received a registration request trigger the execution of registered processes upon completion of their execution cycle. This approach minimizes data latency. Processes that do not use the notification method set a periodic timer in either mode. Processes may also execute upon receiving data from external devices, a signal from another process, or other timer expirations.

3.2 Common Processing

All processes perform some common tasks as required each time they execute. The common functionality is documented in this section and is not repeated in the sections below. The processes all use shared memory to read configuration settings and data provided by other processes. They also use shared memory to write data for use by other processes.

During initialization (first execution), each process will:

1. Register with the appropriate process to be notified when to run, if in notification mode. Or, if not in notification mode, initialize a timer that will cause the process to execute periodically.
2. Read the configuration setting for debug logging and open a debug log file if enabled.

During each execution, each process will:

1. Check an application enable/disable flag. If disabled, perform no additional processing and wait for the next timer or notification. This applies to application processes only.
2. Read configuration settings for Comma Separated Values (CSV) logging, and open or close the log if the settings have changed from the previous execution.
3. If CSV logging is enabled, write an entry to the CSV log consisting of the parameters written to shared memory. WMH and TC support binary logging in addition to CSV logging.

When each process is terminated, it will:

1. Close all log files
2. Shut down all timers and unregister for notifications

3.3 System Framework Modules

The following sections list the SW functionality for the system framework modules presented in Table 1. For each module the following is provided; a brief description of the module, the interfaces that the module supports, and the high level processing functionality that the module performs.

3.3.1 VSC-A Main Process (VSC-A)

The VSC-A main process initializes the VSC-A shared memory, parses the configuration files, and manages the startup and shutdown of all other processes.

3.3.1.1 Interfaces

Following are the interfaces and interface functionality supported by the VSC-A main process:

- VSC-A main reads configuration data from the vsc-a.conf file and other subordinate configuration files it references. If the CICAS-V process is enabled, it reads CICAS-V configuration data from the cicas-v.dflt and cicas-v.conf files.

- VSC-A main initializes shared memory and writes configuration data to it
- VSC-A main executes upon launch of the VSC-A application

3.3.1.2 Processing

During initialization, VSC-A main will:

1. Allocate and initialize shared memory
2. Parse the VSC-A and CICAS-V configuration files, and write the parameters to shared memory
3. Start all of the processes that are enabled in the VSC-A configuration file

VSC-A main waits in a sleep state until it receives a signal indicating the VSC-A application should be shut down (resulting from a user command, WSU power down, or abnormal termination of a process). It then terminates all of the VSC-A processes and releases shared memory.

3.3.2 CAN Sensor Data Handler Process (SDHCAN)

SDHCAN processes incoming CAN messages from the vehicle CAN gateway device, which include vehicle CAN messages and Dynamics Measurement Unit (DMU) messages. SDHCAN also processes CAN messages from the Forward Looking Camera. SDHCAN sends heartbeat messages to the vehicle CAN gateway device. If a configuration parameter indicates the vehicle CAN messages are unavailable, SDHCAN derives selected vehicle parameters from GPS data.

3.3.2.1 Interfaces

Following are the interfaces and interface functionality supported by SDHCAN:

- SDHCAN interfaces with WSU Vehicle Interface Services (VIS) to:
    1. Exchange data with the vehicle CAN gateway device
    2. Receive data from the Forward Looking Camera
- SDHCAN accesses shared memory to read configuration data plus inputs from SDHGPS and EGUI and write its results
- SDHCAN executes upon receiving data from VIS or expiration of timers
- If operating in notification mode, SDHCAN notifies the HVPP process when updated vehicle CAN data has been written to shared memory

3.3.2.2 Processing

During each execution caused by receipt of data from VIS:

1. If the data is vehicle CAN data, SDHCAN will check the validity of the data and, if valid, unpack and scale the data. SDHCAN reads EGUI shared memory to determine if a forced turn signal flag has been set. If so, it sets the corresponding turn signal status to on. SDHCAN also sends a heartbeat message to the vehicle CAN gateway.

2. If the data is DMU data, SDHCAN will:
    a. Unpack and scale the data to obtain roll, pitch, and yaw; X, Y, and Z acceleration; and apply a second-order low-pass filter to each parameter
    b. Calculate the bias for each of the values whenever the HV is stationary by averaging the values over a configurable period of time
    c. Calculate the final value for each parameter by adjusting the input value by the calculated bias
3. If the data is Forward Looking Camera data, SDHCAN will unpack and scale the data

SDHCAN sets a vehicle CAN data expiration timer to a configurable interval. The timer is reset each time valid vehicle CAN data is received. If the timer expires, the CAN data is zeroed in shared memory and the data is marked as invalid.

SDHCAN supports an alternate mode if a configuration parameter indicates vehicle CAN data is unavailable. In this mode, it sets a periodic timer to execute at a configurable interval. Upon timer expiration, it reads SDHGPS data and sets the selected SDHCAN outputs to values derived from the GPS data or to values determined from configuration parameters.

3.3.3 GPS Sensor Data Handler Process (SDHGPS)

SDHGPS obtains time, vehicle location, speed, and heading information from a GPS receiver. If no GPS updates are received, SDHGPS coasts the previous data for a configurable period of time. SDHGPS also interfaces to RTK positioning SW executing on an external platform which calculates relative position and velocity between the HV and the RVs.

3.3.3.1 Interfaces

Following are the interfaces and interface functionality supported by SDHGPS:

- SDHGPS uses an Ethernet connection to communicate with RTK SW running on an external platform
- SDHGPS interfaces with WSU Time/Position Services (TPS) to:
    1. Receive parsed GPS NMEA data
    2. Send GPS corrections to the GPS receiver (to support CICAS-V)
- SDHGPS accesses shared memory to read configuration data plus inputs from CICAS-V and write its results
- SDHGPS executes upon:
    1. Receiving data from TPS
    2. Receiving a signal from WMH that new RV RTCM data is available
    3. Receiving data from the RTK SW

4. Receiving a posted semaphore from CICAS-V that GPS corrections are available
5. Expiration of timers

- If operating in notification mode, SDHGPS notifies the PH process when updated GPS data has been written to shared memory

3.3.3.2 Processing

SDHGPS will perform the following processing based on the type of input:

1. Upon receiving parsed GPS NMEA data from TPS, SDHGPS will check the validity of the data, calculate the filtered heading, adjust the latitude and longitude to compensate for configurable antenna offsets, and update the HV GPS data
2. Upon receiving new RV RTCM data from WMH, SDHGPS will output the RTCM data to the RTK SW (if enabled)
3. Upon receiving HV RTCM data from the RTK SW, SDHGPS will update the HV RTCM data
4. Upon receiving RTK delta positioning and velocity data from the RTK SW, SDHGPS will verify the received message checksum, check the data quality, and update the RV’s delta data
5. Upon receiving GPSC data from CICAS-V, SDHGPS will verify the checksum, message ID, and length and then send the data to the GPS receiver via TPS

SDHGPS uses timers to determine when data has expired and when NMEA data should be coasted.

1. SDHGPS sets a NMEA expiration timer to a configurable interval. The timer is reset each time valid NMEA data is received. If this timer expires, SDHGPS will mark the NMEA data as invalid if coasting is disabled. If coasting is enabled, SDHGPS will calculate the elapsed time since the previous NMEA data, and estimate the current latitude, longitude, and altitude based on the most recent heading and speed. SDHGPS coasts the data every configurable interval until the configured coasting duration has elapsed and then marks the data as invalid.
2. SDHGPS sets an HV RTCM time to a configurable interval. If this timer expires, SDHGPS marks the RTCM data as invalid.

3.3.4 Wireless Message Handler Process (WMH)

WMH constructs and sends HV OTA messages and processes received RV OTA messages. It supports both the VSC-A internal common safety message and the SAE J2735 Basic Safety Message formats. If security is enabled, WMH interfaces to the Security Module Interface (SMI) library to generate signatures for transmitted messages and verify signatures for received messages.

3.3.4.1 Interfaces

Following are the interfaces and interface functionality supported by WMH:

- WMH interfaces with WSU Radio Services (RS) to:
    1. Configure the DSRC radios
    2. Receive notifications at the beginning of the Control Channel (CCH) and Service Channel (SCH) intervals
    3. Send OTA messages for transmission when security is disabled.
- WMH accesses shared memory to read configuration data plus inputs from SDHGPS, SDHCAN, HVPP, PH, EEBL, and CLW and write its results
- WMH executes upon:
    1. Receiving data from RS
    2. Receiving a signal from EEBL or CLW that a new event has occurred
    3. Receiving a signal or notification from TA that messages must be verified
    4. Expiration of timers
- If operating in notification mode, WMH notifies TC at the end of the CCH interval and notifies EEBL and CLW upon receiving a new event in an OTA message. If operating in timer mode, WMH signals EEBL and CLW upon receiving a new event.
- WMH signals to SDHGPS when RTCM 1002 data is received in an OTA message
- WMH interfaces to the SMI library to provide configuration parameters, send OTA messages when security is enabled, receive all OTA messages (both secured and unsecured), request certificate changes, and obtain statistics
- When the SAE J2735 message format is being used, WMH interfaces to Abstract Syntax Notation One (ASN1) encoding/decoding libraries

3.3.4.2 Processing

During initialization, WMH will:

1. Call the SMI initialization API and pass relevant configuration parameters. WMH then waits for SMI to establish socket connections to the SM
2. Configure the radio and register callbacks with RS

WMH supports five different transmit timing methods and operation using the CCH in WAVE mode or on the safety channel. It supports operation on one or two radios. When operating in dual radio mode, it generates independently timed messages on each radio. In all cases, WMH sets timers to expire when a message should be constructed. WMH also constructs a message whenever EEBL or CLW signals it that a new event has occurred.

When a message should be constructed, WMH will:

- Read shared memory information from SDHGPS, SDHCAN, HVPP, PH, EEBL, and CLW to obtain the data for the message

- If the data is valid, construct the message in VSC-A internal or SAE J2735 format
- If the message is in SAE J2735 format, encode the message using the encoding library. WMH supports three encoding methods: Distinguished Encoding Rules (DER), Packed Encoding Rules (PER) aligned, and PER unaligned
- Call the SMI API to get the HV statistics
- If security is enabled, provide the message to SMI for signature generation
- If the transmit method is timer based, WMH or SMI then sends the message immediately to RS for transmission
- If the transmit method is CCH notification based, WMH sets another timer to expire when the message should be transmitted. Upon expiration, WMH or SMI sends the message to RS.
- Determine if a security certificate change is needed (required at a random time within a window since the last change). If a certificate change is needed, call SMI to initiate a change request.
- If the transmit method is timer based and the re-randomization time has occurred, re-randomize the transmit timer.

Upon receiving an OTA message, WMH will:

- Decode the message using the decoding library, if the SAE J2735 message format is being used
- Parse the message (VSC-A internal or SAE J2735 format), perform validity checks, unpack, and scale the data
- Determine if the OTA message corresponds to an RV with previous data stored in shared memory by searching for a vehicle ID match. If no match is found and vehicle ID randomization is on, determine if the OTA message corresponds to an existing RV using a tracking algorithm.
- Calculate packet error rate (PER), plus pre-encoding and post-encoding latency statistics
- Obtain the security statistics, plus post-security and inter-packet gap latency statistics from SMI
- Update an existing RV record or create a new record with the received data along with calculated PER, latency, and security statistics
- Notify or signal the corresponding process to trigger its execution, if the message contains a new EEBL or CLW event
- Provide SMI with the WMH assigned sequence number for the message for use in VoD security processing
- Signals SDHGPS when RTCM 1002 data is received

When VoD security is being used, WMH will receive a signal or notification from the TA when messages must be verified. Upon receiving either input, WMH will:

- Read TA's shared memory to determine the WMH sequence numbers of the messages to be verified and call SMI to verify each message
- After all the messages have been verified, write the verification results to shared memory and signal or notify TA

WMH also periodically updates the RV records in shared memory.

- If the elapsed time since the last OTA message is greater than a configurable expiration time, WMH checks if coasting is enabled. If coasting is enabled, it coasts the GPS data for a configurable period.
- If coasting is disabled or the coasting period has expired, WMH marks the RV as expired

3.3.5 Security Module Interface Library (SMI)

SMI is a library that interfaces with the SM SW. SMI provides an API to processes that want to utilize the SM functionality. For VSC-A, WMH uses SMI to request the SM to generate signatures for messages to be transmitted and to verify signatures on received messages. SMI interfaces to the SM to provide Elliptic Curve Digital Signal Algorithm (ECDSA), Timed Efficient Stream Loss-tolerant Authentication (TESLA), and TESLA and Digital Signature (TADS) security methods. SMI supports Verify Then Process (VTP) and VoD security approaches.

3.3.5.1 Interfaces

Following are the interfaces and interface functionality supported by SMI:

- SMI interfaces to the SM using a socket connection. The SM may execute on-board the WSU or off-board on an external platform. If the SM is executing off-board, the interface is through an Ethernet connection.
- SMI interfaces with RS to:
    1. Output signed OTA messages to be transmitted
    2. Input received OTA messages
- SMI executes as a dynamic library linked to WMH and not as a separate process. SMI provides an API which WMH uses to access its functionality. The API includes callable functions and also enables WMH to register callbacks to be notified of specified events.

3.3.5.2 Processing

During initialization, SMI will:

1. Receive configuration parameters from WMH for security, socket connection, OTA message transmit and receive, and logging
2. Create a server socket and wait for the SM to connect to it. After the connection is established, SMI waits on the socket to receive messages. This socket is used for protocol exchanges initiated by the SM. SMI supports Transport Control Protocol (TCP), Stream Control Transmission Protocol (SCTP), and AF_UNIX sockets.

However, AF_UNIX sockets are only supported when SM is executing on-board the WSU.

3. Attempt to connect to the SM's server socket. After the connection is successful, SMI waits on the socket to receive messages. This socket is used for protocol exchanges initiated by the SMI.
4. Wait for an initialization complete indication from the SM
5. WMH uses an API function to check whether the socket connections are established and the SM initialization is complete
6. If the sockets disconnect, SMI automatically attempts to re-establish communication with the SM

Upon receiving a message from WMH for OTA transmission, SMI will:

- Buffer the message and send a signature request to the SM. Upon receiving a response, SMI adds the signature and other security information provided in the sign response to the message, and sends it to RS for transmission.

Upon receiving a message from RS, SMI will:

- Determine the type of data: TESLA key or OTA message (i.e., BSM)
- If a TESLA key is received, send it to the SM
- If an unsigned OTA message is received, send it to WMH if security is disabled or discarded if security is enabled. If a signed message is received and security is disabled, it is sent to WMH with no security verification.
- If a signed OTA message is received and security is enabled, buffer the message and check the security approach
    - If the security approach is VTP, SMI sends a verification request to SM. Upon receiving a response, SMI extracts the OTA message data and sends the data to WMH along with the verification result.
    - If the security approach is VoD, SMI sends a certificate verify request to SM if the security contents of the message contain a certificate and sends the unverified OTA message data to WMH. WMH provides a sequence number to be used for subsequent verify requests, and SMI stores the number with the message. VoD is supported for ECDSA only.
    - Upon receiving a subsequent VoD verify request, SMI finds the message in its buffer based on the sequence number input and sends a verify request to SM. Upon receiving a response, it provides the results to WMH.

Upon receiving a certificate change request from WMH, SMI will:

- Send a certificate change request to the SM
- Upon receiving the response, provide WMH with the result

Upon receiving an unsolicited message from SM, SMI will:

- Determine the type of request
- If a TESLA key broadcast request is received, it sends it to RS for transmission
- If a get time request is received, it sends the WSU's time to SM

SMI maintains signing, verification, latency, and interpacket gap statistics. SMI supports requests from WMH to read the statistics and to stop and restart the statistics.

3.3.6 Path History Process (PH)

PH generates a concise representation of the HV movement over a specified distance. The PH consists of a subset of the recent GPS data points selected such that the error between the actual path traveled and the path represented by the history is below a threshold. PH supports three methods, which are selectable by a configuration parameter.

3.3.6.1 Interfaces

Following are the interfaces and interface functionality supported by PH:

- PH accesses shared memory to read configuration data plus inputs from SDHGPS, SDHCAN, and HVPP and write its results
- PH executes periodically upon notification from SDHGPS when in notification mode, or when its configurable timer expires when in timer mode

3.3.6.2 Processing

During each periodic execution, PH will:

1. Calculate the chord length (PH_ActualChordLength in Figure 11) between the latest GPS point (from SDHGPS) and the most recent GPS point stored in the PH concise buffer
2. Calculate the angle subtended by the latest GPS point and the most recent stored concise GPS point and the estimated radius of curvature. These calculations use speed and yaw rate from SDHCAN and the HVPP radius as needed based on the configured method.
3. Calculate the maximum path error (PH_ActualError in Figure 11) between the actual path traveled by the HV and the path that would be represented if the latest GPS point is stored in the PH concise buffer
4. If the path error exceeds a configurable threshold, then store the previous GPS point from the PH actual buffer in the PH concise buffer
5. If the chord length exceeds a configurable threshold, add the point regardless of the path error
6. Calculate the distance along the path represented by the stored concise points, beginning at the most recent point. After the distance exceeds a configured threshold, delete the remaining (oldest) points.

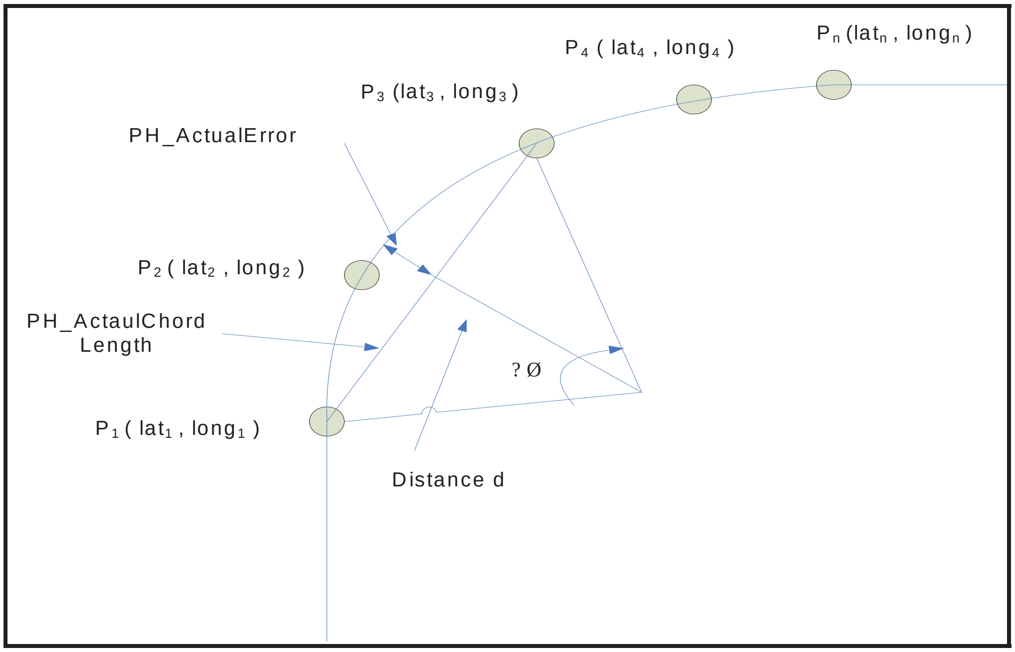


Figure 11: Representation of PH Error

3.3.7 Host Vehicle Path Prediction Process (HVPP)

The HVPP calculates the HV's estimated radius of curvature, based on the HV speed and yaw rate, along with an associated confidence factor. As a secondary method, it also supports calculating the radius using data from a Forward Looking Camera or using a combination of the vehicle and camera data.

3.3.7.1 Interfaces

Following are the interfaces and interface functionality supported by HVPP:

- HVPP accesses shared memory to read configuration data plus inputs from SDHGPS, SDHCAN, and HVPP and write its results
- HVPP executes periodically upon notification from SDHCAN when in notification mode or when its configurable timer expires when in timer mode

3.3.7.2 Processing

During initialization, HVPP will initialize the second order filters used in path prediction. During each periodic execution, HVPP will:

1. Calculate curvature from HV yaw rate and speed (from SDHCAN) and filter the curvature using a second-order-low-pass filter
2. Calculate the radius as 1/filtered curvature. If the radius exceeds a configurable threshold, set the radius to a straight path.
3. Calculate the latitude and longitude of the predicted path center position using HV position (from SDHGPS) and the calculated radius
4. Calculate the confidence by putting the yaw rate through a second order filter with differentiator and use the output to index into a lookup table for confidence

5. If Forward Looking Camera data is available, calculate a second radius value from filtered camera curvature data using the same algorithm described above. Calculate a second confidence value from camera left and right lane confidence data.
6. Select final radius and confidence values from the values derived from CAN input data and/or optionally camera input data. The final selection is determined from mix factors in the configuration file and the validity of the input data.

3.3.8 Target Classification (TC) Process

TC uses data from WMH to classify the position and heading of each RV relative to the HV. Other VSC-A processes use this position and heading classification information to determine the threat potential of each RV.

3.3.8.1 Interfaces

Following are the interfaces and interface functionality supported by TC:

- TC accesses shared memory to read configuration data plus inputs from SDHCAN, SDHGPS, WMH, PH, and HVPP and write its results
- TC executes periodically upon notification from WMH when in notification mode or when its configurable timer expires when in timer mode
- If operating in notification mode, TC notifies the EEBL, FCW, IMA, BSW + LCW, DNPW, and CLW processes when updated target classification data has been written to shared memory

3.3.8.2 Processing

During each periodic execution, TC will:

1. Read shared memory for SDHGPS, SDHCAN, PH, and PP to retrieve HV data for GPS, CAN, PH, and PP, respectively
2. If extrapolation is enabled, estimate the current HV position based on the elapsed time since the time of the GPS data and the most recent position, heading, and speed
3. For each RV:
    a. Read GPS, CAN, PH, and PP data from WMH
    b. Estimate the current RV position, if extrapolation is enabled
    c. Calculate the relative position between the HV and RV using the GPS data. This relative position is used if RTK data is disabled or unavailable.
    d. Read the RTK data from SDHGPS to obtain relative position and velocity between the HV and RV and apply the antenna offsets, if the use of RTK positioning data is enabled and data is available. If the RTK data is older than a configurable threshold, coast the data to estimate the current relative position.

e. Determine the primary classification (same direction, oncoming, intersecting, or unclassified) based primarily on delta heading

f. Refine each primary classification:

    i. For same direction, refine the classification relative to the HV lane of travel (e.g., same, left, far left) and position (e.g., ahead, behind)

    ii. For oncoming, refine the classification based on relative lane (e.g., oncoming left, oncoming far left)

    iii. For intersecting, refine the classification based on path (intersecting left, intersecting right)

g. If the RV is oncoming, refine calculations based on consideration of lateral offsets with respect to the closest ahead vehicle in a second pass through the logic

3.3.9 Threat Arbiter (TA) Process

TA prioritizes the threat information identified by the Application Modules, and requests verification of threat message security signatures when necessary.

3.3.9.1 Interfaces

Following are the interfaces and interface functionality supported by TA:

- TA accesses shared memory to read configuration data plus inputs from BSW + LCW, CLW, DNPW, EEBL, FCW, and IMA and write its results
- TA executes periodically upon notification from BSW + LCW, CLW, DNPW, EEBL, FCW, or IMA when in notification mode (the last application completing its execution cycle notifies TA) or when its configurable timer expires when in timer mode
- TA signals WMH whenever threat message signature verification is being requested and receives a notification or signal from WMH when the signature verification has been completed
- TA notifies or signals DVIN after the prioritized threat data has been written to shared memory

3.3.9.2 Processing

During each execution, TA will:

1. Collect threat information generated by each application module via shared memory
2. Determine the priority of each threat identified by the application modules using a priority equation identified via a configurable setting
3. Sort the threats based on:
    a. The application threat level (detect, inform, warn)
    b. The calculated application threat priority

   c. The proximity of the threat to the HV

4. If the configurable security approach is VoD, TA will notify or signal WMH to request verification of message(s) that resulted in threats being generated
5. If no threats need verification, TA will update the threat data in its section of shared memory

If message verifications were requested, TA will receive a notification or signal from WMH indicating threat message verification is complete and ready for TA to process. When TA receives this notification or signal, it will:

1. Read the application threat verification data from WMH's section of shared memory
2. Determine which, if any, threat messages were not successfully verified and change the threat state for these threats to "none"
3. If any threat messages were not successfully verified, re-sort the threats as in (3) above
4. For threats that were successfully verified TA will update the threat data in its section of shared memory

3.3.10 Driver Vehicle Interface Notifier (DVIN) Process

DVIN controls what application threat information is conveyed to the driver through Video Graphics Array (VGA), audio, and CAN interfaces.

3.3.10.1 Interfaces

Following are the interfaces and interface functionality supported by DVIN:

- DVIN writes threat status information to the CAN bus using WSU VIS and outputs audio alerts
- DVIN accesses shared memory to read configuration data plus inputs from TA, WMH, and SDHCAN and write its results
- DVIN executes periodically upon notification from TA when in notification mode or when its configurable timer expires when in timer mode
- DVIN signals EGUI whenever new threat information is to be displayed

3.3.10.2 Processing

During initialization, DVIN will:

1. In notification mode, register with TA to be notified. In timer mode, initialize the periodic timer.
2. Initialize VIS API interface

During each execution DVIN reads the application threat status from TA shared memory and performs separate processing for VGA, audio, and CAN outputs. For VGA and audio outputs, each threat type (e.g., EEBL, FCW) and level (detect, inform, warn) has a configurable duration time and suppression time. The duration time is the minimum time an alert must remain active. The suppression time is the minimum time after a previous alert before a new alert may be given. DVIN maintains the state of each threat type and level as none, duration, or suppress for the VGA, audio, and CAN alerts.

DVIN VGA processing will:

1. Determine if the current threat state is none, duration, or suppress for the highest priority threat from TA shared memory. DVIN also determines if the current threat is the same as the previous threat or is of higher priority. Based on this information, DVIN determines if it is necessary to update the VGA threat information.

2. Read the VGA icon configuration data, write the threat icon and threat string to be displayed on the VGA to shared memory and signal EGUI, if the threat information must be updated

DVIN audio processing will:

1. Determine if the threat state is none, duration, or suppress for the highest priority threat from TA shared memory. DVIN also determines if the current threat is the same as the previous threat or is of higher priority. Based on this information, DVIN determines if it is necessary to update the audio threat information.

2. DVIN reads the audio configuration data and calls the audio API with the corresponding sample filename and the sample volume, if the threat information must be updated

During each execution, DVIN CAN processing will:

1. Determine if the threat state is none, duration, or suppress for each application entry in TA shared memory. DVIN also determines if the current threat is the same as the previous threat or is of higher priority. Based on this information, DVIN determines if it is necessary to update the threat information for CAN bus output.

2. Sets the CAN 705 values for the new threat in accordance with the configuration parameters if a new threat has to be processed

3. Constructs and sends the CAN bus message 705 using the updated CAN output threat information for all the applications

3.3.10.3 Engineering Graphical User Interface (EGUI) Process

The EGUI enables the user to configure selected parameters, monitor VSC-A status, and be alerted to safety threats.

3.3.10.4 Interfaces

Following are the interfaces and interface functionality supported by EGUI:

- EGUI outputs display data to a VGA device and processes user inputs from a mouse or touch screen

- EGUI interfaces to a graphics library to format data for the screen and create handlers for user inputs (e.g., button pushes)

- EGUI accesses shared memory to read configuration data plus data for display and write user configured parameters
- EGUI executes whenever a user action occurs, whenever it receives a signal from DVIN, and every 100 ms based on a timer

3.3.10.5 Processing

During initialization, EGUI will:

1. Initialize graphical forms and associated variables (e.g., tables, labels, buttons, and other widgets) plus handlers that will execute upon a user input
2. Initialize a timer that will cause EGUI to execute periodically and a signal to allow DVIN to indicate when it has updated threat information
3. Read configuration parameters. Set the display to the default screen selected by a configuration parameter.

After initialization, EGUI executes whenever a user action occurs (e.g., button pushed to select a screen, box checked to enable/disable logging), whenever it receives a signal from DVIN, and every 100 ms based on a timer.

When a user action occurs, an EGUI handler specific to the item (e.g., button, checkbox) executes and performs the appropriate action.

1. If a screen selection button is pushed, EGUI changes the display to the selected screen
2. For user inputs that affect the VSC-A functionality (e.g., enable/disable logging, stop/start statistics), EGUI updates the display and writes parameters to shared memory that are read by the affected processes
3. For user inputs that affect SR recording, EGUI establishes a socket connection to SR and sends messages to start or stop the recording. When an SR recording is started, EGUI creates a tar file containing the configuration files and stores it in the same directory as the SR recording. EGUI may also be configured to automatically start an SR recording at initialization time.

When EGUI receives a signal from DVIN, it updates the threat information on the DVI screen. If the DVI screen is not currently selected, EGUI begins flashing the DVI screen select button in red for a warning or yellow for an inform alert.

When EGUI executes due to the 100 ms timer expiration, it reads shared memory and updates the current screen parameters as appropriate based on the update rate for the current screen. EGUI controls the update rate to avoid excessive Central Processing Unit (CPU) loading. The graphics on the screens for the VSC-A applications (EEBL, FCW, IMA, BSW + LCW, DNPW, CLW) plus HVPP and TC are updated every 200 ms. All other graphics and data are updated every 500 ms. EGUI also checks the compact flash status and, if it is getting full, stops SR recording if active.

3.3.11 XCPProc Module

XCPProc provides a visualization tool running on an external platform with read and write access to the VSC-A shared memory.

3.3.11.1 Interfaces

Following are the interfaces and interface functionality supported by XCPProc:

- XCPProc communicates with a visualization tool running on an external platform using the Universal Measurement and Calibration (XCP) protocol, which transfers data via sockets over an Ethernet connection
- XCPProc accesses shared memory to read configuration data plus all data stored in shared memory and to write data values received from the visualization tool
- XCPProc executes periodically upon notification from DVIN, TC, or WMH when in notification mode or when its configurable timer expires when in timer mode

3.3.11.2 Processing

During initialization, XCPProc will:

1. Create a TCP socket for communicating with the visualization tool and begin listening for a connection request from the visualization tool
2. Initialize the XCP protocol layer
3. Initialize a timer that will cause XCPProc to execute periodically

During each periodic execution, XCPProc will:

1. Synchronize write requests from the visualization tool with the shared memory information for each process then read the shared memory information for each process, if connected to the visualization tool
2. Send the shared memory information for each process to the XCP protocol layer for transmission to the visualization tool

3.3.12 Error Handler (ERH) Process

ERH implements the watchdog mechanism for all VSC-A processes except the SM and VSC-A Main.

3.3.12.1 Interfaces

Following are the interfaces and interface functionality supported by ERH:

- ERH interfaces to the WSU HW watchdog timer
- ERH accesses shared memory to read configuration data plus inputs from all processes except the SM and VSC-A Main
- ERH executes when its configurable timer expires

3.3.12.2 Processing

During initialization, ERH will:

1. Rename the previous debug log file (if it exists) and create a new debug log file if logging is enabled
2. If the HW watchdog timer is enabled through configuration settings, ERH starts it by opening a device file in "dev/watchdog"

During each periodic execution, ERH will:

1. Determine whether each process should be executing by checking if it was started by VSC-A main and is currently enabled
2. Check the heartbeat for each process that should be executing by comparing the current keep-alive sequence number in shared memory with the sequence number saved during the last ERH execution. Each process increments its' keep-alive sequence number in shared memory upon each execution.
3. Write the name of the processes which should be executing but fail the heartbeat check (i.e., the keep-alive sequence number did not increment) to a debug log file
4. If the HW watchdog is enabled, ERH resets the HW watchdog timer, if it detects a heartbeat from all of the processes which should be executing. If the HW watchdog is not reset, the WSU will reboot.

3.3.13 Scenario Replicator (SR) Process

The SR process provides the ability to record inputs to selected VSC-A processes from the WSU system. These recorded inputs can then be played back at a later time to aid in debugging, application enhancement, and regression testing.

3.3.13.1 Interfaces

Following are the interfaces and interface functionality supported by SR:

- SR uses sockets to interface with processes that receive CAN data from VIS, GPS data from TPS, OTA data messages from RS, security messages from the SM, or data from the RTK SW
- SR writes to shared memory to indicate if recording is turned on
- SR writes to a recording file or reads from a recording file for playback

3.3.13.2 Processing

The SR process works in two modes–record and playback.

During record mode, SR will:

1. Create a record file in the compact flash file system and write a file header which includes system timestamp and version numbers
2. Wait for input data received over sockets and record all input data received into the record file. This process continues until the user stops the record process or until the file system is full.

During playback mode, SR will:

1. Open the user-specified record file and validate it

2. Set the current system time to be the time stored in the record file header
3. Connect to processes that are waiting for the recorded data over a socket
4. Start playing back the previously recorded input data contained in the record file
5. For each recorded input in the record file, SR determines the corresponding process waiting for the input and sends the data over the connected socket at the timestamp set in the recorded data. Playback continues until there is no more input data.

3.4 Application Modules

3.4.1 Emergency Electronic Brake Light (EEBL) Process

EEBL analyzes RVs classified by TC as ahead, ahead left, or ahead right that have reported an emergency braking event to determine the threat level of the RV closest to the HV. It also signals or notifies WMH if the HV detects an emergency braking event.

3.4.1.1 Interfaces

Following are the interfaces and interface functionality supported by EEBL:

- EEBL accesses shared memory to read configuration data plus inputs from TC, WMH, EGUI, and SDHCAN and write its results
- EEBL executes periodically upon notification from TC when in notification mode or when its configurable timer expires when in timer mode
- If operating in notification mode, EEBL notifies the TA process when updated threat data has been written to shared memory
- EEBL signals WMH when a new emergency braking event has been detected on the HV
- If operating in notification mode, WMH notifies EEBL when a new emergency braking event has been detected on an RV or WMH signals EEBL when an emergency braking event has been detected on an RV in timer mode

3.4.1.2 Processing

During each periodic execution, or when a notification or signal is received from WMH, EEBL will:

1. Determine which, if any, RVs in WMH shared memory have reported an emergency braking event
2. For each RV that has reported an emergency braking event and is classified by TC as ahead, ahead left, or ahead right, determine if the longitudinal offset from the RV's rear bumper to the HV's front bumper is less than a configurable distance
3. If SDHCAN shared memory indicates the HV is moving forward at a speed above a configurable threshold, calculate the EEBL threat levels among all RVs identified above as having a longitudinal offset less than a configurable distance,

then determine the closest threat and set the appropriate threat status for that vehicle

During each periodic execution, EEBL will:

1. Signal WMH to send the EEBL event OTA, if EGUI shared memory indicates a forced EEBL event or if SDHCAN shared memory indicates the HV is moving forward at a speed above a configurable threshold and the HV is determined to be decelerating above a configurable threshold

3.4.2 Forward Collision Warning (FCW) Process

FCW analyzes RVs classified by TC as ahead to determine if the HV is at risk of being involved in a rear-end collision with an RV located in the same lane of travel.

3.4.2.1 Interfaces

Following are the interfaces and interface functionality supported by FCW:

- FCW accesses shared memory to read configuration data plus inputs from TC, WMH, and SDHCAN and write its results
- FCW executes periodically upon notification from TC when in notification mode or when its configurable timer expires when in timer mode
- If operating in notification mode, FCW notifies the TA process when updated threat data has been written to shared memory

3.4.2.2 Processing

During each periodic execution, FCW will:

1. Determine which, if any, RVs classified by TC as ahead and in the same lane are within a configurable longitudinal range
2. Calculate HV deceleration and collision avoidance range for each “ahead” RV to determine potential forward collision threats, if SDHCAN shared memory indicates the HV is moving forward at a speed above a configurable threshold and is not braking
3. Identify the principal threat, if at least one RV is determined to be a threat

3.4.3 Intersection Movement Assistance (IMA) Process

IMA analyzes all RVs classified by TC as intersecting left or intersecting right to determine if there is a possibility of collision between the HV and intersecting RVs.

3.4.3.1 Interfaces

Following are the interfaces and interface functionality supported by IMA:

- IMA accesses shared memory to read configuration data plus inputs from TC, WMH, and SDHCAN and write its results
- IMA executes periodically upon notification from TC when in notification mode or when its configurable timer expires when in timer mode

- If operating in notification mode, IMA notifies the TA process when updated threat data has been written to shared memory

3.4.3.2 Processing

During each periodic execution, IMA will:

1. Identify all RVs in TC shared memory classified as intersecting left or intersecting right
2. Determine if SDHCAN shared memory indicates the HV is moving forward at a speed equal to or above a configurable threshold and if TC shared memory data indicates an RV identified as intersecting left or right is moving at a speed above a configurable threshold. If so:
    a. Determine if the HV and RV will arrive at the intersection at roughly the same time based on configurable minimum and maximum cross-path values. If true:
        i. Indicate a warning threat level for this RV if the HV's distance to stop is within a configurable minimum stopping distance
        ii. Or indicate an inform threat level for this RV if the HV's distance to stop is within a configurable multiplier times a configurable minimum stopping distance
3. Determine if the HV is moving forward at a speed below a configurable threshold and if an RV identified as intersecting left or right is moving at a speed above a configurable threshold. If so:
    a. Determine if the distance to the intersection of the HV and RV paths is between configurable minimum and maximum cross-path values. If true:
        i. Indicate a warning threat level for this RV if the RV's distance to stop is less than a configurable minimum stopping distance and SDHCAN shared memory indicates the HV is not braking
        ii. Or indicate an inform threat level for this RV if the RV's distance to stop is within a configurable multiplier times a configurable minimum distance and SDHCAN shared memory indicates the HV is braking
4. Determine if the HV is moving forward at a speed equal to or above a configurable threshold and if an RV identified as intersecting left or right is moving at a speed below a configurable threshold and does not have its brakes applied. If so:
    a. Determine if the distance to the intersection of the HV and RV paths is between configurable minimum and maximum cross-path values. If true:
        i. Indicate an inform threat level for this RV if the HV's distance to stop is within a configurable multiplier times a configurable minimum distance

5. Determine if any RVs are determined to be at risk of having a collision with the HV, and identify which, if any, RV classified as intersecting left has the highest threat level for that classification, and identify which, if any, RV classified as intersecting right has the highest threat level for that classification.

3.4.4 Blind Spot Warning + Lane Change Warning (BSW + LCW) Process

BSW + LCW analyzes each RV classified by TC as behind left or behind right to determine if it is or will be in the HV blind spot zone and set the threat level.

3.4.4.1 Interfaces

Following are the interfaces and interface functionality supported by BSW + LCW:

- BSW + LCW accesses shared memory to read configuration data plus inputs from TC and SDHCAN and write its results
- BSW + LCW executes periodically upon notification from TC when in notification mode or when its configurable timer expires when in timer mode
- If operating in notification mode, BSW + LCW notifies the TA process when updated threat data has been written to shared memory

3.4.4.2 Processing

During each periodic execution, BSW + LCW will:

1. Determine which RVs have been classified by TC as behind left or behind right
2. Evaluate the position of each RV relative to the HV to determine if that RV is currently positioned within the HV's blind-spot zone or if that RV will be positioned within the HV's blind-spot zone for each RV that has been classified as behind left or behind right
3. Set the threat status corresponding to each side (left and right) to Inform if an RV is determined to be located in the corresponding left or right blind-spot zone if the SDHCAN shared memory indicates the HV is moving forward at a speed above a configurable threshold
4. Set the threat status to Warn for the side corresponding to the active turn signal, as a proxy, if the SDHCAN shared memory indicates the HV speed is above a configurable threshold and the HV's left or right turn signal is active and an RV is or will be located in the corresponding left or right blind-spot zone

3.4.5 Do Not Pass Warning (DNPW) Process

DNPW uses HV and RV data to determine if it is unsafe to pass one RV due to another oncoming RV. If the HV is following an RV classified by TC as ahead, DNPW analyzes all RVs classified by TC as oncoming left to determine whether any RV will be in the passing zone or is already in the passing zone. DNPW uses the left turn indicator status, as a proxy, to differentiate between an Inform or Warn threat state.

3.4.5.1 Interfaces

Following are the interfaces and interface functionality supported by DNPW:

- DNPW accesses shared memory to read configuration data plus inputs from TC, WMH, and SDHCAN and write its results
- DNPW executes periodically upon notification from TC when in notification mode or when its configurable timer expires when in timer mode
- If operating in notification mode, DNPW notifies the TA process when updated threat data has been written to shared memory

3.4.5.2 Processing

During each periodic execution, DNPW will:

1. Determine if the HV is following an RV classified by TC as ahead
2. Determine if SDHCAN shared memory indicates the HV is moving forward at a speed above a configurable threshold and if the time gap between the HV and the ahead RV is within a configurable time. If so:
    a. Use HV speed, acceleration, and vehicle length information from SDHCAN shared memory plus speed, acceleration, longitudinal distance, and vehicle length information for the ahead RV from TC shared memory and factor in configurable driver reaction time to determine the adjacent-lane passing zone necessary for the HV to safely pass the ahead RV
    b. Use longitudinal distance, vehicle length, speed, and acceleration information from TC shared memory for the closest oncoming left RV and factor in configurable passing parameters to determine if the oncoming left RV is currently occupying or will be occupying the previously determined adjacent lane passing zone
    c. Set the threat state to Warn if SDHCAN shared memory indicates the HV's left turn signal is on and the brake status is off. Otherwise, set the threat state to Inform
    d. Suppress a DNPW warning if the HV is not closing on the ahead RV, if configured accordingly

3.4.6 Control Loss Warning (CLW) Process

CLW analyzes data for all RVs classified by TC to determine if each RV has reported a control-loss event. It also signals or notifies WMH if the HV has detected a control-loss event due to Anti-lock Braking System (ABS) activation, Traction Control Loss, and/or Stability Control activation.

3.4.6.1 Interfaces

Following are the interfaces and interface functionality supported by CLW:

- CLW accesses shared memory to read configuration data plus inputs from TC, WMH, EGUI, and SDHCAN and write its results

- CLW executes periodically upon notification from TC when in notification mode or when its configurable timer expires when in timer mode
- If operating in notification mode, CLW notifies the TA process when updated threat data has been written to shared memory
- CLW signals WMH when a new HV control-loss event has been detected
- If operating in notification mode, WMH notifies CLW when a new RV control-loss event has been detected. Or if in timer mode, WMH signals CLW when a new RV control-loss event has been detected.

3.4.6.2 Processing

During each periodic execution or when notified or signaled by WMH, CLW will:

1. Determine which, if any, RVs in WMH's shared memory have reported a control-loss event
2. Determine if TC has classified that vehicle as ahead, ahead left, ahead right, behind, behind left, behind right, intersecting left, intersecting right, oncoming, oncoming left, or oncoming right for each RV that has reported a control-loss event
3. Calculate the CLW threat levels among all RVs reporting a control-loss event; and then determine the closest threat and set the appropriate threat status for that vehicle if the SDHCAN shared memory indicates the HV speed is above a configurable threshold and the HV is not braking
4. Determine if EGUI shared memory indicates a forced CLW event or if the SDHCAN shared memory indicates a control-loss event for the HV due to ABS activation, Traction Control Loss, and/or Stability Control activation and the HV speed is above a configurable threshold, and then signal WMH to transmit the control-loss event, if necessary

4 Engineering Development Tools

A number of SW tools were developed to assist in the development, testing, analysis, etc., of the SW implementation of the system framework and safety application modules. Each of these tools was essential in their own right to the final test bed implementation. The primary SW tools developed are the:

- Scenario Replicator (SR): This tool provides the ability to record inputs from the WSU SW services to applications into a log file. These inputs can then be played back at a later time, in a bench set-up, to aid in application debugging, enhancement, and regression testing. Refer to the main body of the VSC-A Final Report for further discussion on this tool.
- Data Logging and Visualization Tool: This tool was the primary tool used to log and analyze data collected as part of the OTP testing efforts and is discussed in Appendix C-3.

- Engineering Graphical User Interface (EGUI): This tool enables the user to monitor system status and configure system operation and is discussed below.

The purpose of the EGUI is to provide a universal Human Machine Interface (HMI) to the development community that can be used to understand, evaluate, and configure the VSC-A platform. It is also used to represent visual and auditory vehicle driver warnings as a result of the application module algorithmic processes. Finally, the touch screen interface allows the user to control parameters associated with the operation of the VSC-A applications. Shown below are examples of the various graphical interfaces as depicted on a VGA touch screen.

The first image (Figure 12) shows four examples of the DVIN screen. This screen allows the EGUI to display the warning states of a particular threat and, in this case, the DNPW is displayed. To conserve computing power, only one of the warning screens is visible at any particular time. In order to ensure the most important warning is shown on the DVI screen (and, if appropriate, auditory response), the TA uses threat level, relative speed, and location of the threat from each of the application modules to assess the severity and determine the highest priority request to be used by DVIN.

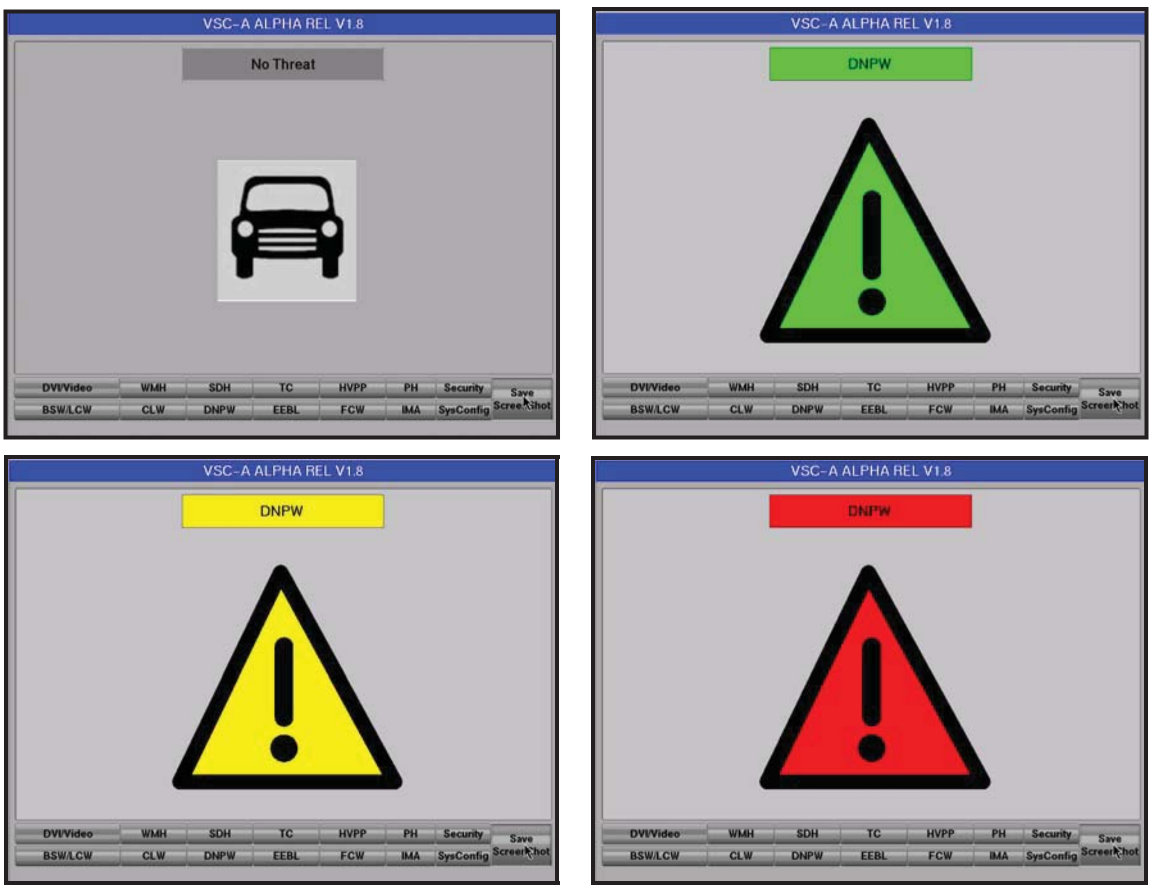


Figure 12: DVIN Stages: (left → right, top → bottom) No Threat, Threat Detected, Inform Driver, Warn Driver

The EGUI can also show the particular operating scenario for an individual warning application. For the DNPW example used above, Figure 13 shows the screen shot information available in the EGUI. Data such as lateral and longitudinal offsets and relative speed are important to monitor as the effectiveness of the warning algorithm is evaluated. The green/yellow colored graphics provide a quick view of the position and status of potential threat vehicles relative to the HV.

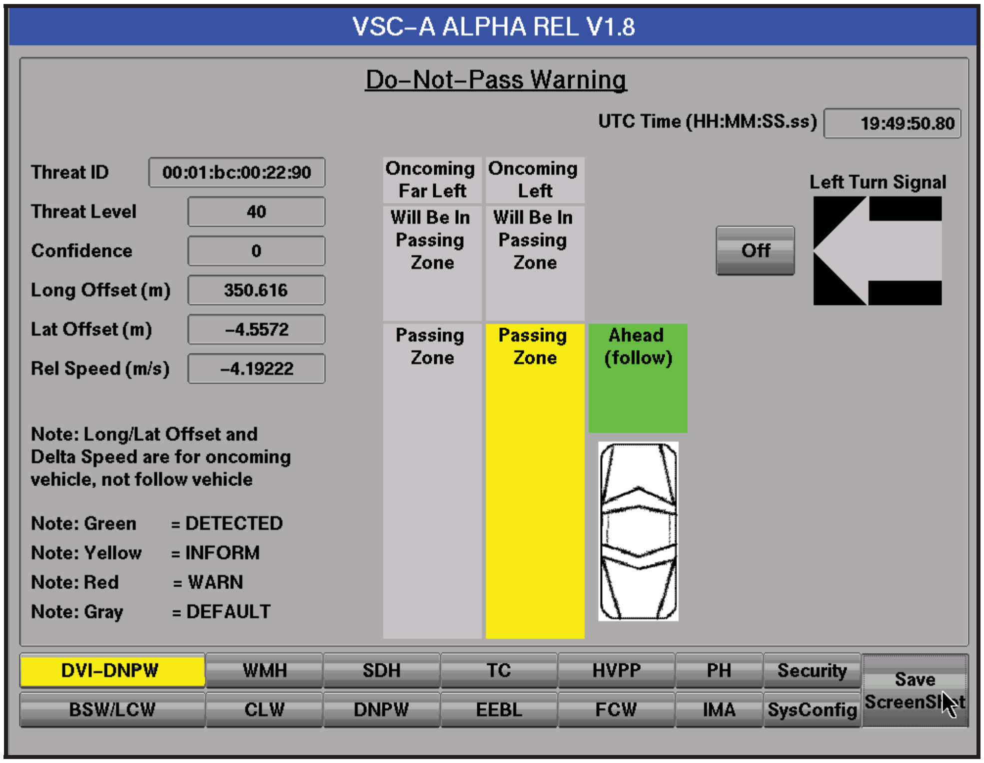


Figure 13: DNPW EGUI Screen

The other five VSC-A applications have similar type data screens available for debugging and evaluation and, like the DNPW screen, were used by the VSC-A Team to monitor the safety applications during system testing. Figure 14 through Figure 18 below illustrate EGUIs screens for EEBL, FCW, IMA, BSW + LCW, and CLW.

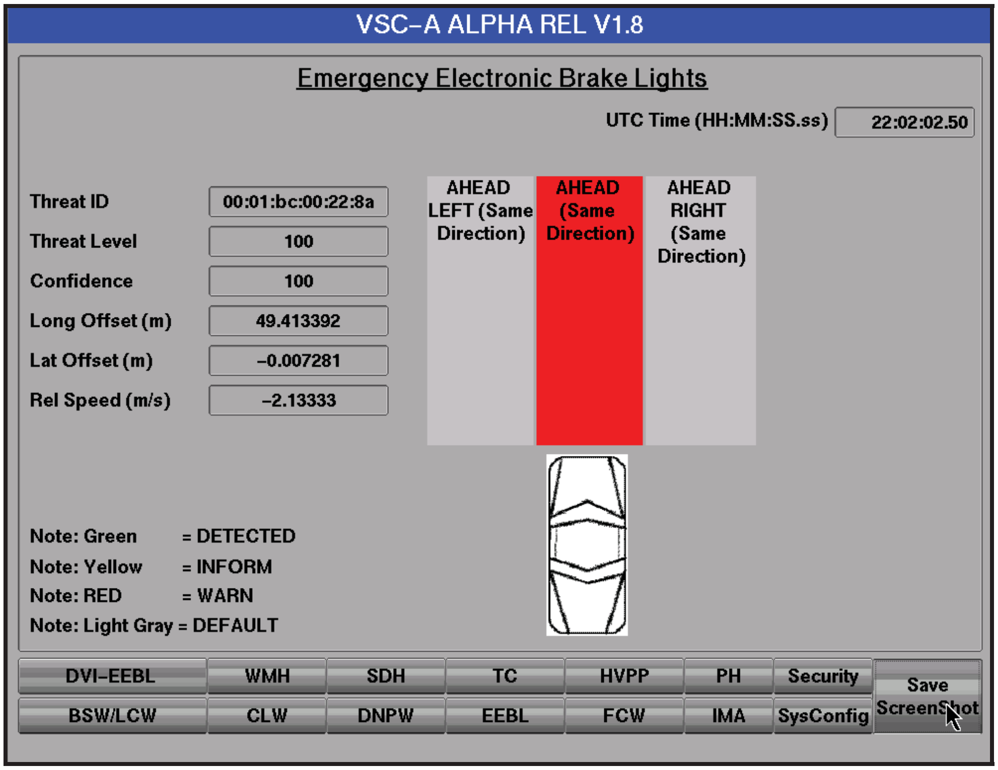


Figure 14: EEBL EGUI Screen

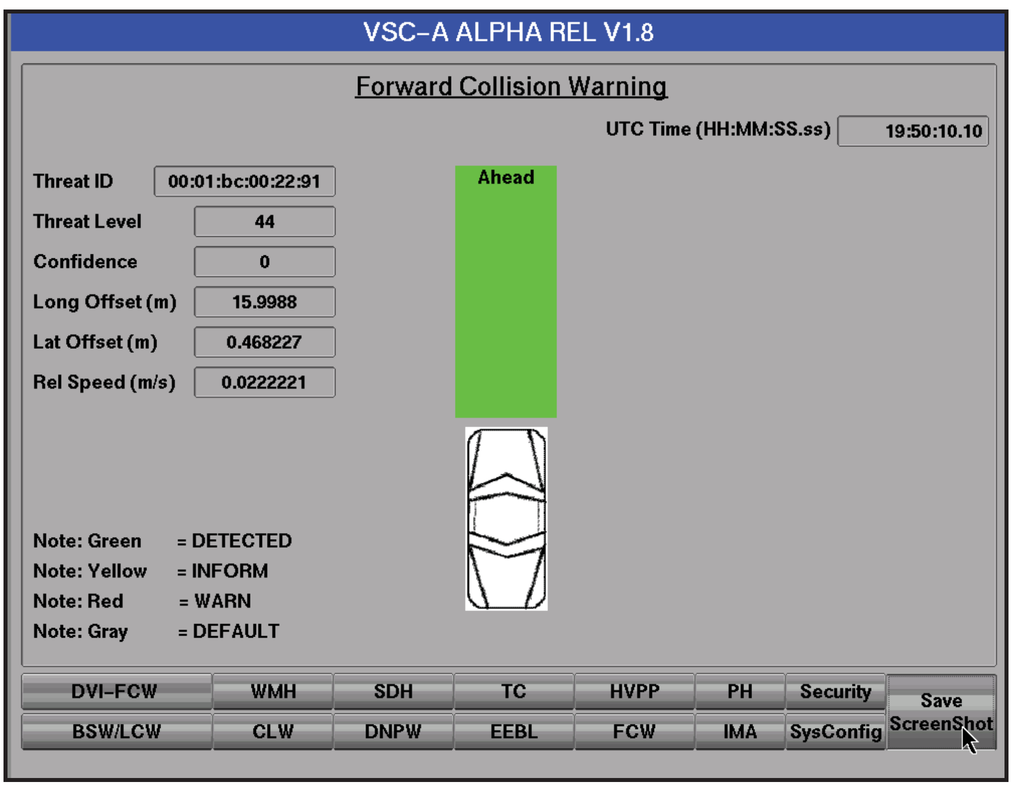


Figure 15: FCW EGUI Screen

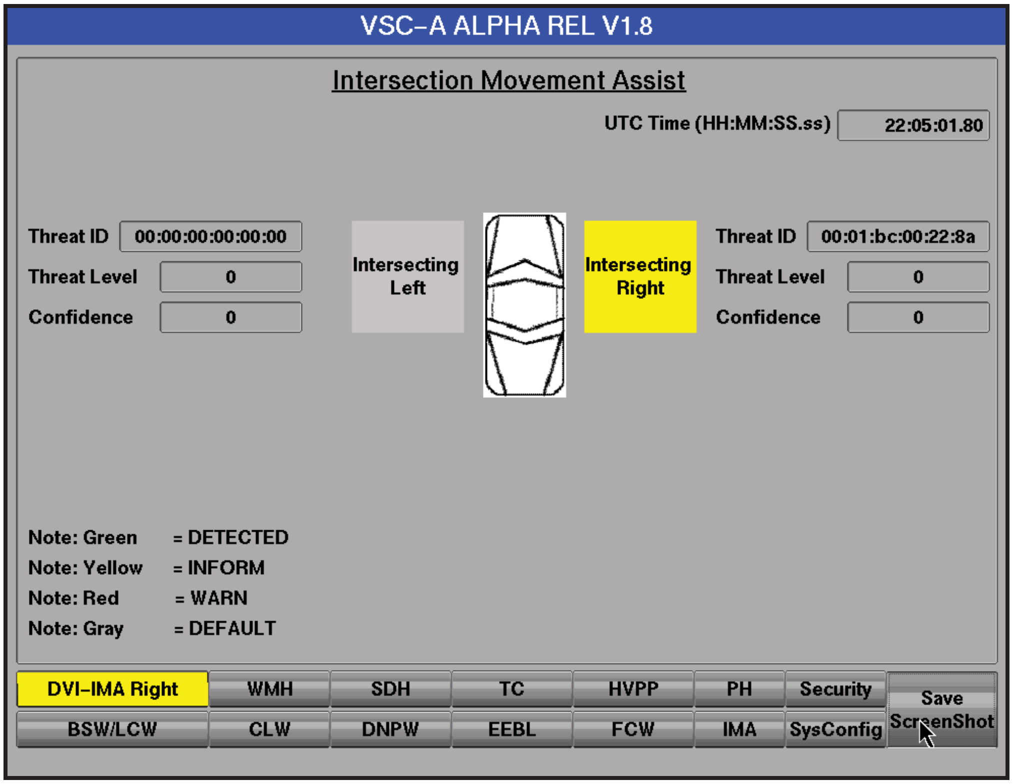


Figure 16: IMA EGUI Screen

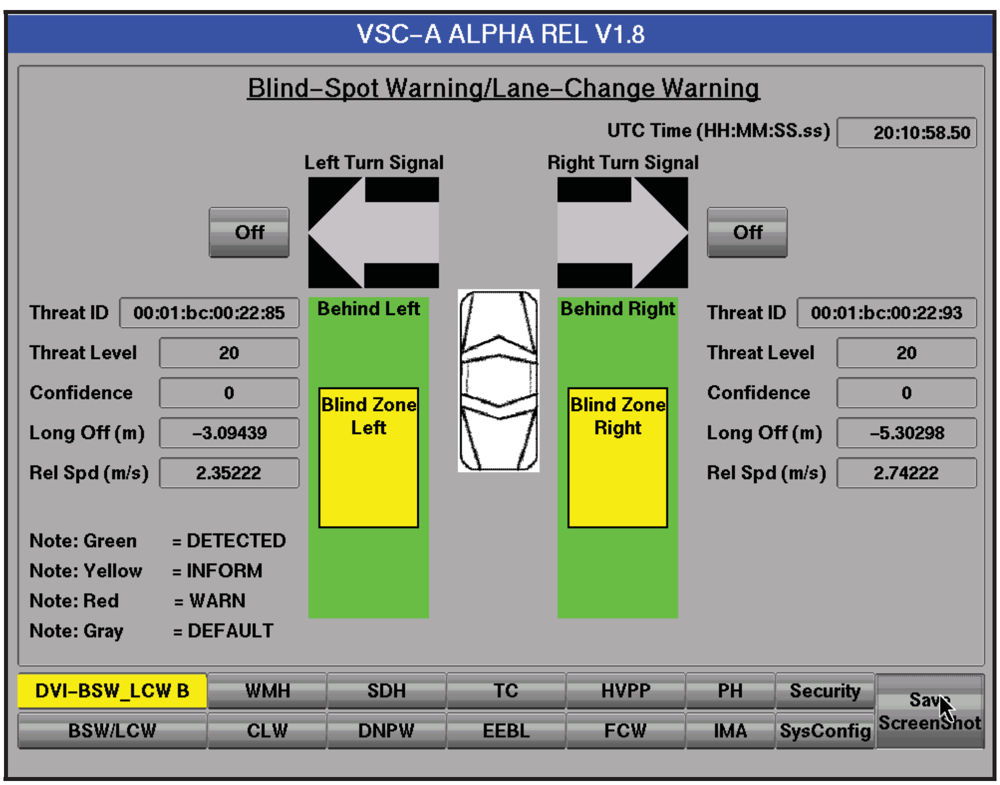


Figure 17: BSW + LCW EGUI Screen

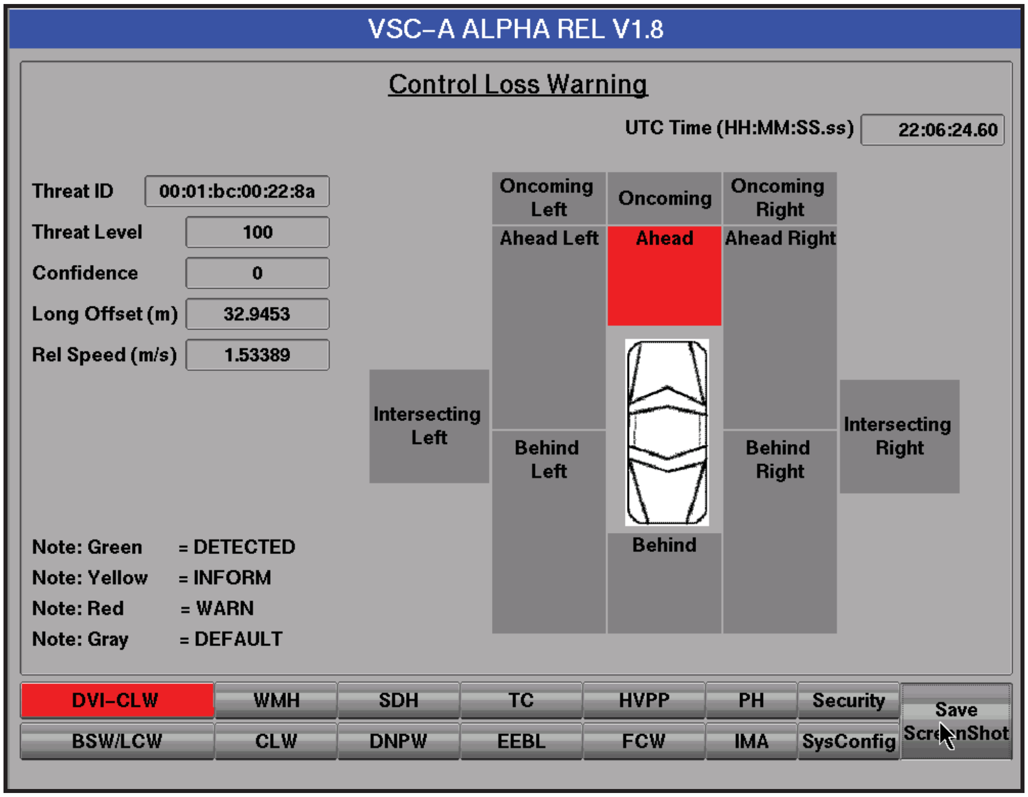


Figure 18: CLW EGUI Screen

In addition to the DVIN and safety application screens, a number of EGUI screens were developed to provide information collected and tracked by the system framework support modules (e.g., WMH, SDH, etc.). Such information is extremely valuable in assessing the capability of the support module and determining, along with other data, whether or not the threat detecting applications are correctly processing the sensor information.

Figure 19 and Figure 20 provide examples of the WMH screens. Figure 19 provides an example of the received data and other information for all of the RVs on a single screen, where as Figure 20 provides an example of the detailed WMH data for a single RV (vehicle ID #1 is provided). Scroll bars are provided when more information is available than can be displayed on the screen. The data presented is gathered from the OTA safety message. Therefore, information such as RV heading, brake status, latitude/longitude location, yaw rate, etc., is shown on the screen.

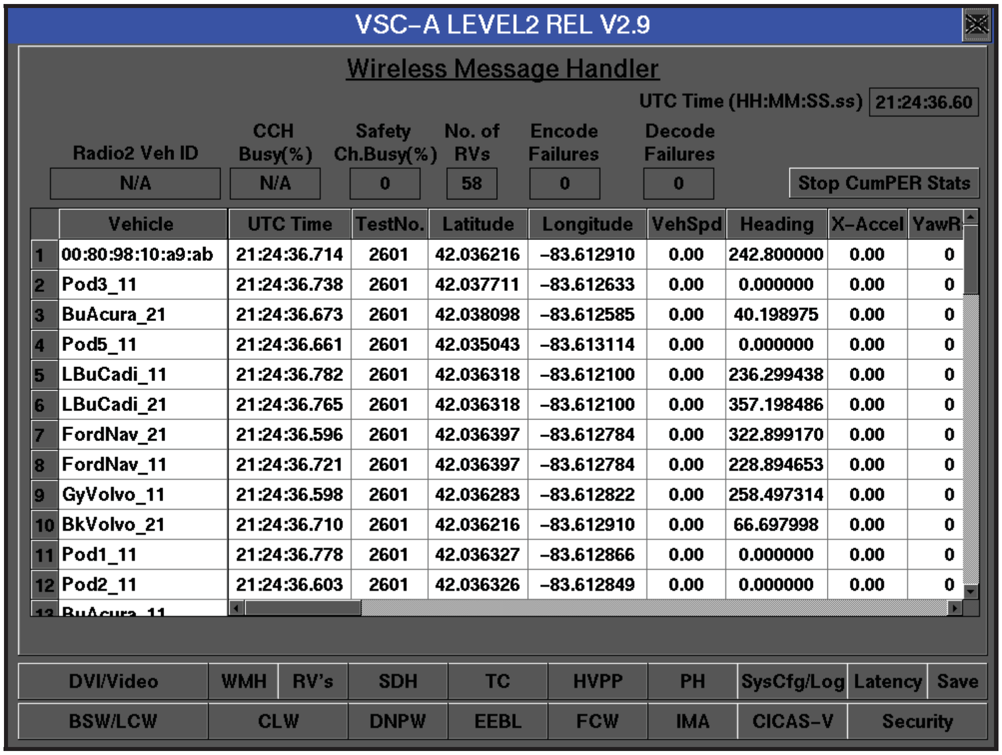


Figure 19: WMH EGUI Screen

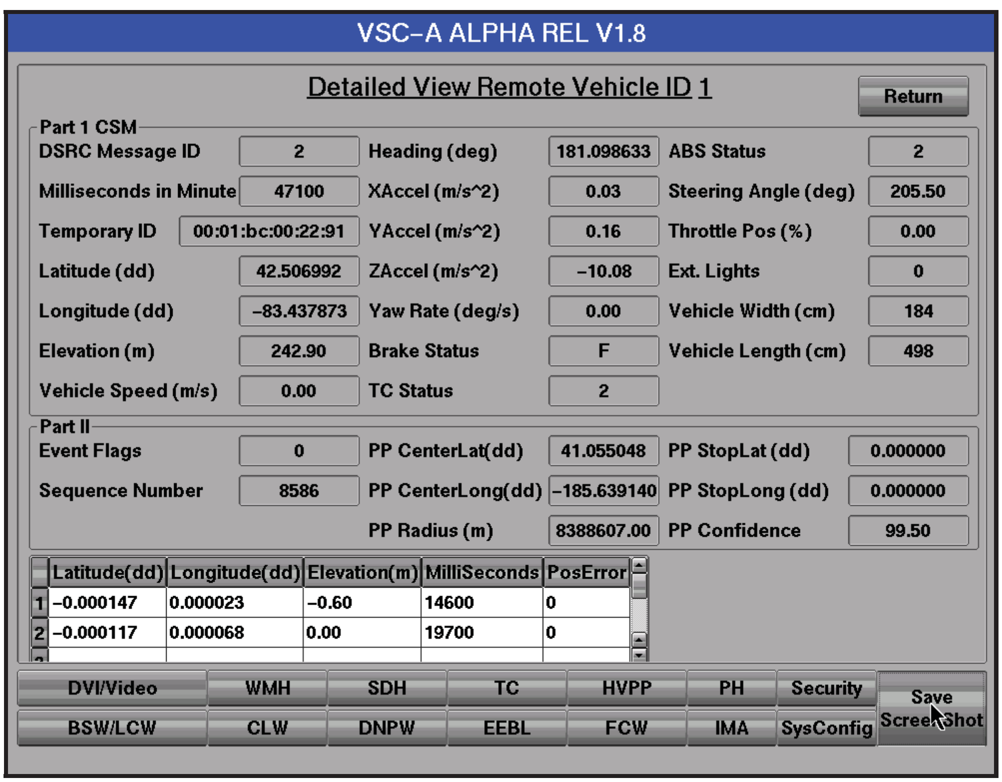


Figure 20: WMH – Remote Vehicle Detailed View EGUI Screen

Figure 21 is an example of the security EGUI screen which provides information on the message signature and verification success and error rates as well as certificate change counts and other information. This screen was particularly useful for comparing the security performance results of the different security protocols which were implemented.

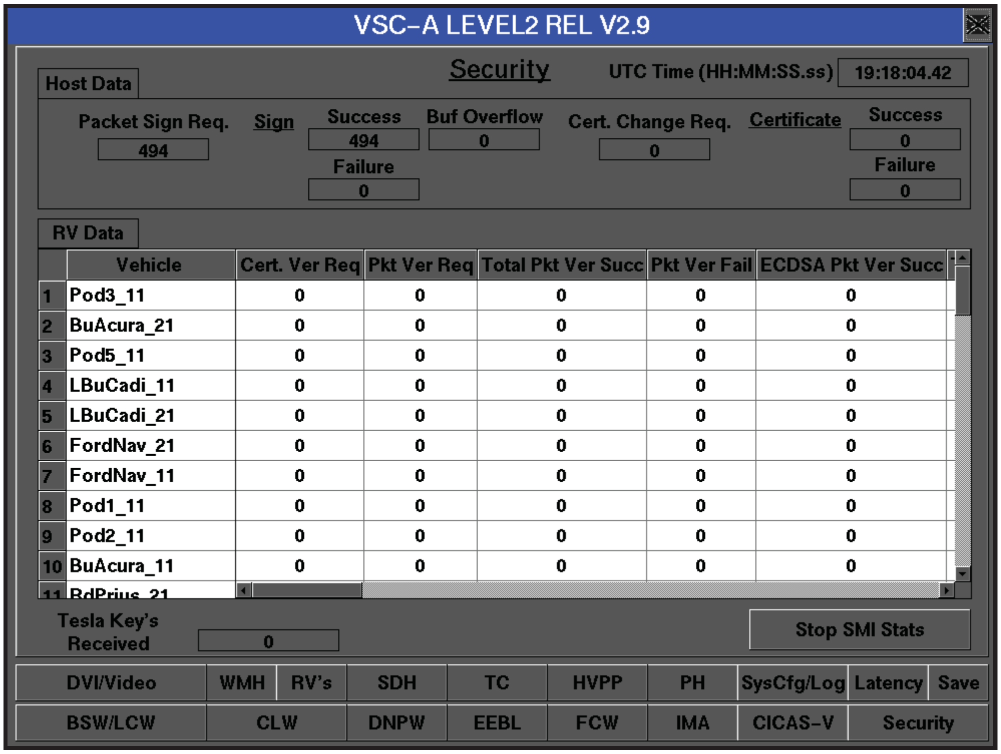


Figure 21: Security EGUI Screen

Finally, Figure 22 and Figure 23 provide examples of the EGUI screens that were primarily used during the multiple-OBE scalability testing to assess, live, the performance of the channel as the number of radios increases. The RVs screen (Figure 22) shows the PER and Receive Signal Strength (RSS) information for each of the RVs taking place in the test. It also displays the test number of the current test being performed. If any of the RVs are not reporting the same test number as the HV is configured for, their information will be highlighted in red to indicate this. The Latency screen (Figure 23) shows the packet latency information for each of the RVs.

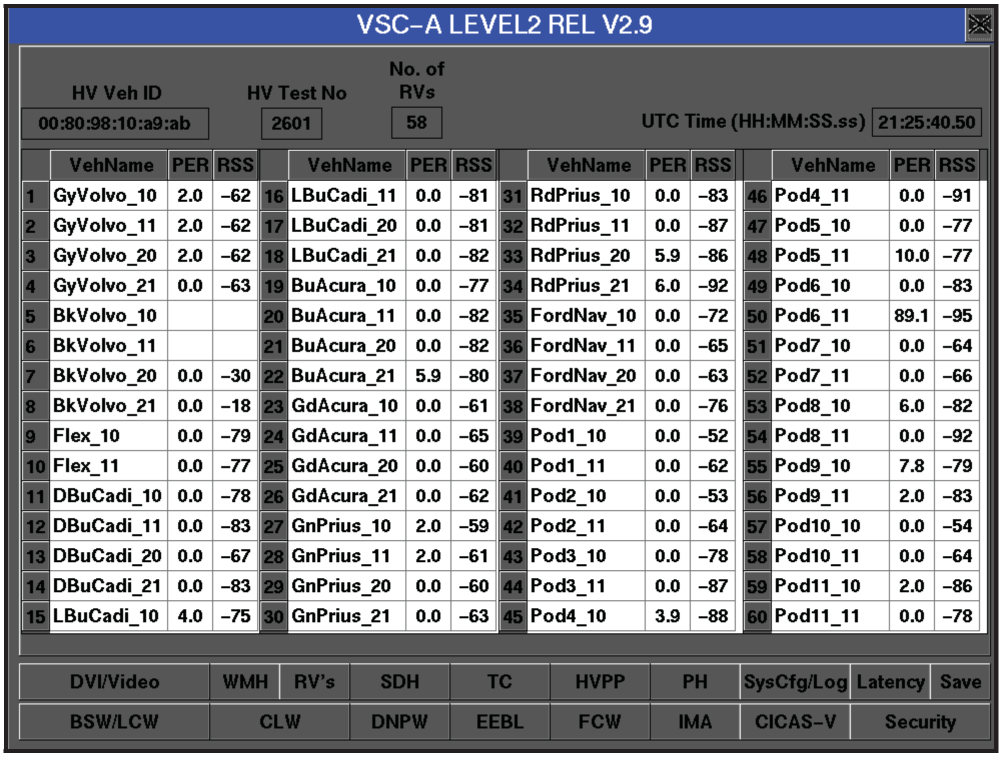


Figure 22: Number of RVs EGUI Screen

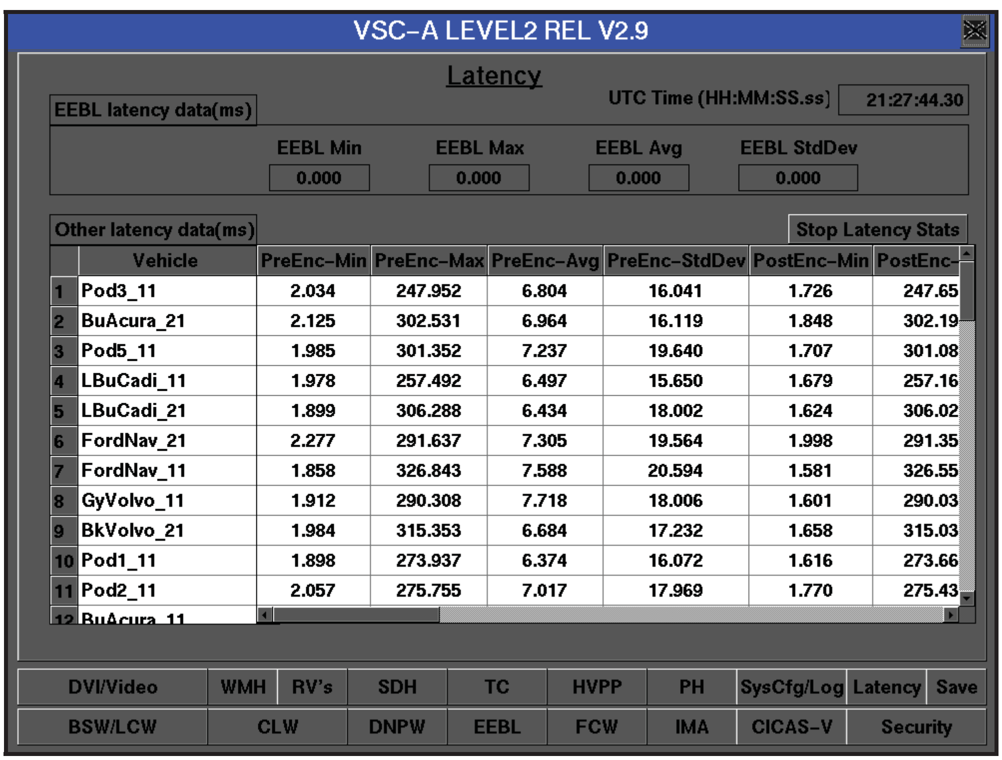


Figure 23: Message Latency EGUI Screen

VSC-A Final Report: Appendix B-2

Path History Reference Design and Test Results

List of Acronyms

CAMP	Crash Avoidance Metrics Partnership
GPS	Global Positioning System
ITS	Intelligent Transportation Systems
JPO	Joint Program Office
NHTSA	National Highway Traffic Safety Administration
PH	Path History
RITA	Research and Innovative Technology Administration
USDOT	United States Department of Transportation
UTC	Coordinated Universal Time
VSC2	Vehicle Safety Communications 2 (Consortium)
VSC-A	Vehicle Safety Communications - Applications

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1 Introduction

The Path History (PH) module for the Vehicle Safety Communications – Applications (VSC-A) system uses a history of the past Global Positioning System (GPS) locations traversed by the host vehicle (HV) and computes an adaptable, concise PH representation of recent vehicle movement over a certain distance. PH communicated by a vehicle provides other vehicles with information needed for predicting the roadway geometry. It plays an important role in target vehicle classification, relative to the HV, with reference to the roadway. There are different methods for design and implementation of the PH module. Three different design methods are described here, each with a slightly different approach.

The PH module in the HV carries out these basic operations:

- Maintains a buffer of its recent GPS positions and sensor data (e.g., updated at 100 ms) over a certain travel distance
- Computes concise representation(s) of the actual PH of the vehicle based on allowable position error tolerance between the actual vehicle path and its concise path history representation
- Updates the PH concise representation as an output periodically for use by other VSC-A subsystems

Besides having the capability to represent its PH adequately and use it internally, the HV transmits the concise representation of the path history data wirelessly over-the-air (OTA) to other vehicles in the vicinity. Other vehicles use this information for predicting the roadway geometry and for target vehicle classification.

2 Path History Requirements

The PH module requirements are as follows:

- PH shall represent the HV actual path with a set of concise data elements. The concise data elements shall be a sampled subset of the actual data elements. As shown in Figure 1, the orange circle represents the sampled data concise points and the chord connecting two consecutive concise data elements represents an approximation of the actual vehicle path segment.
- The concise data elements shall be selected such that the perpendicular distance between any point on the actual vehicle path and the chord connecting two concise points (the concise representation of the actual vehicle path) is less than PH_ActualError meters, as shown in Figure 1.
- The size of the buffer containing the concise data elements shall be adaptable so that the represented PH distance computed using the elements of the buffer is at least a certain minimum length defined by the calibration parameter, K_PHDISTANCE_M meters. Referring to Figure 1, the total distance of all the

chords connecting the orange concise data elements is a minimum distance of, K_PHDISTANCE_M meters.

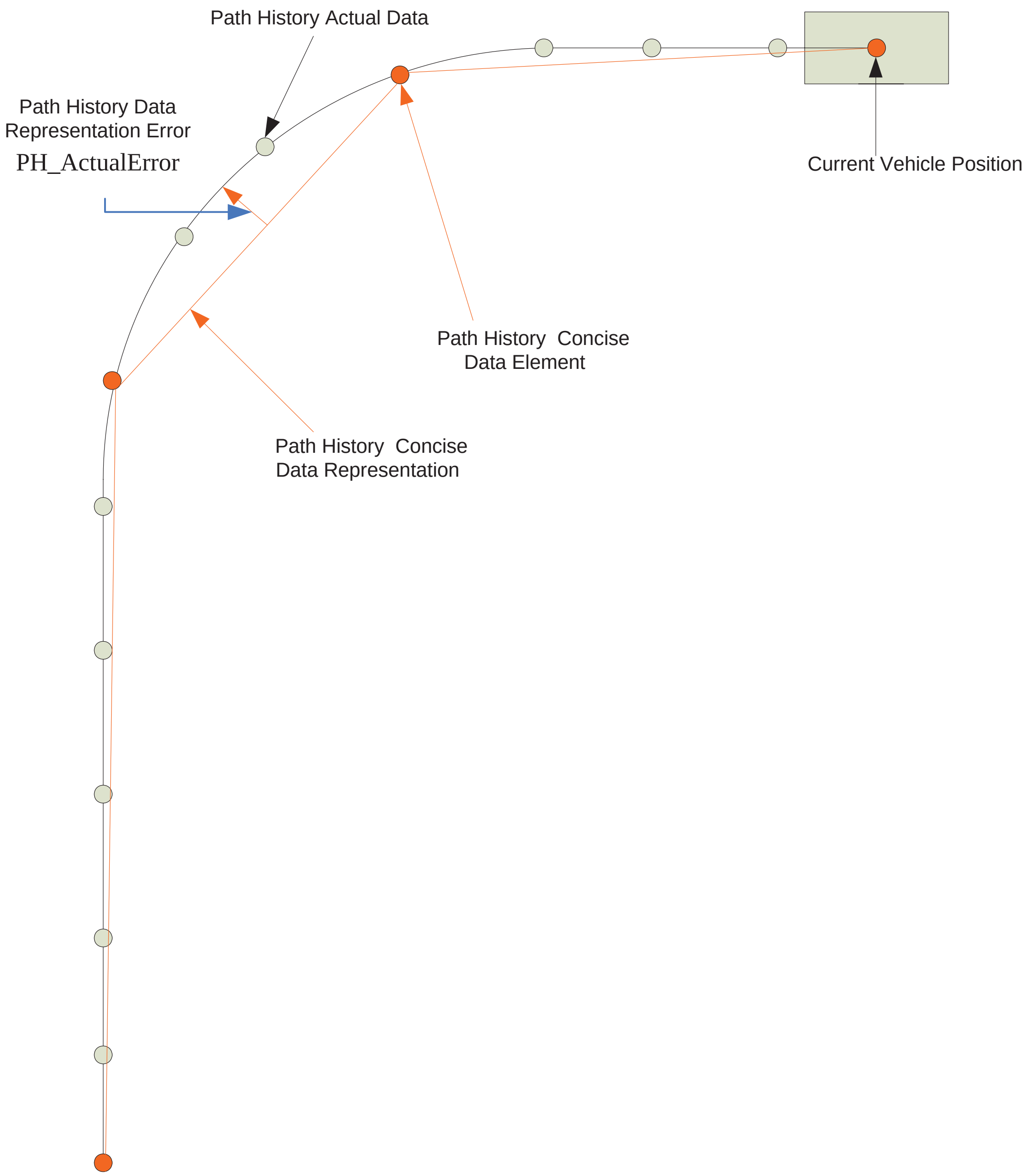

Figure 1: Concise and Actual Path History Representation

3 Path History Design

3.1 Design Preliminaries

Three design methods for PH are presented below. This section defines some basic design preliminaries used by path history design.

a) It is assumed that the vehicle path is composed of straight and circular segments

b) The PH_ActualError is defined as the perpendicular distance between any point on the actual vehicle path and the chord connecting two concise points on the concise representation of the vehicle path. Some of the sampled points on the actual vehicle path may become part of the concise PH representation data element according to the algorithm used. Please refer to Figure 1 for an illustration of PH_ActualError and actual and concise PH data elements.

c) Figure 2 illustrates points P_1, P_2, P_3, etc. that lie on a circular vehicle path. As illustrated, PH_ActualError varies based on the location of the points selected on the circular path.

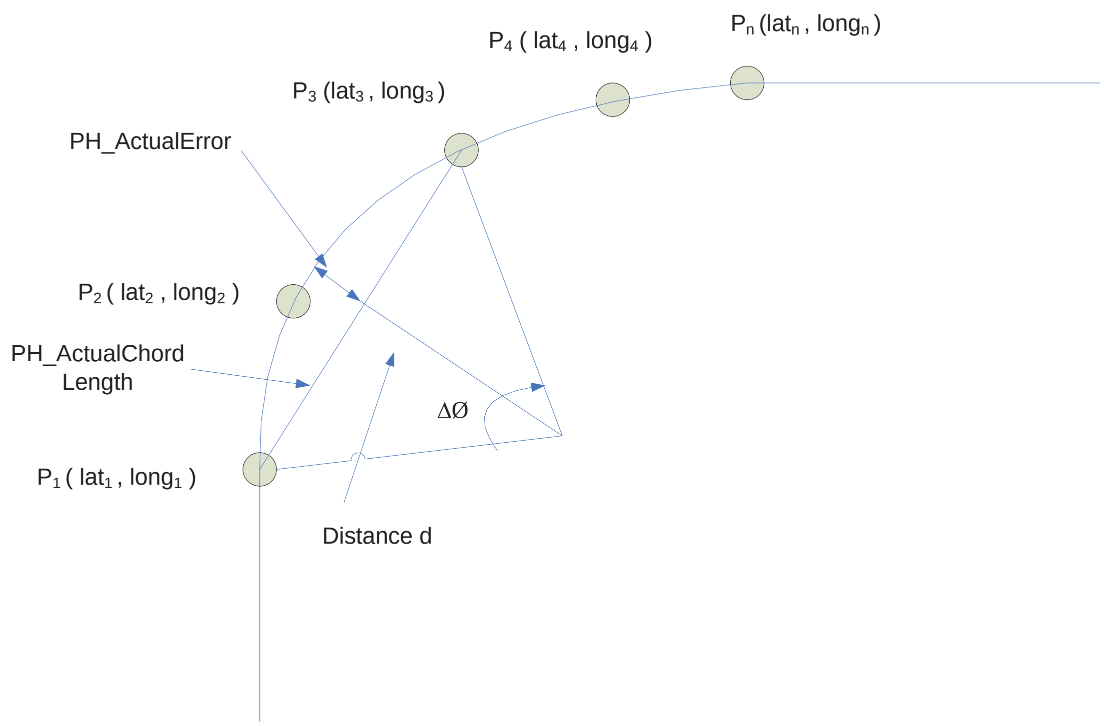

Figure 2: Representation of Error

d) Consider Figure 3. The angle ΔØ subtended by points P_1 and P_2 at the center of the circle can be approximated as $\Delta Ø = H_2 - H_1$, where H_1 and H_2 represent the GPS headings of the vehicle at locations P_1 and P_2 respectively on the circular path.

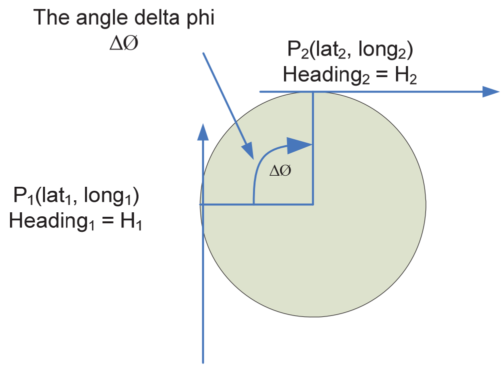

Figure 3: Representation of ΔØ

e) Referring to Figure 2, we define the actual chord length between two PH GPS points on the circular vehicle path as PH_ActualChordLength. PH_ActualChordLength is the distance between two GPS data points each defined by its latitude and longitude

f) Let P_1 be defined by latitude, lat_1, and longitude, $long_1$. Similarly, let P_2 be defined by latitude, lat_2, and its longitude, $long_2$, and these values are in radians. Define the radius of the earth (in meters) at the meridian as REarthMeridian. Then the actual distance of the chord is given by:

$$PH\_ActualChordLength = REarthMeridian * \cos^{-1}[\cos(lat_1)\cos(lat_2)\cos(long_1 - long_2) + \sin(lat_1)\sin(lat_2)] \quad (1)$$

g) Another critical parameter that is calculated during the design is PH_EstimatedR, which is the radius of curvature of a circular vehicle path connecting two PH GPS data points.

3.2 Design Method One

The steps involved in the design of the concise PH representation of a vehicle path using Method One are described as pseudo code next.

Step One: Assume that a number of actual vehicle path GPS data points that follow the circular vehicle path are sampled. The minimum number of points required is three. Initial conditions of these points are (see Figure 2):

i = 3

Starting Point, $P_{starting} = P_{i-2}$

Previous Point, $P_{previous} = P_{i-1}$

Next Point, $P_{next} = P_i$

elementPos = 0

totalDist = 0

incrementDist = 0

Include the GPS point, $P_{starting,}$ as part of the concise PH representation data buffer and increment the elementPos by one as follows:

PH_ConciseDataBuffer[elementPos] = $P_{starting}$

elementPos++

Step Two: Calculate PH_ActualChordLength (i.e., chord length in meters) between two points, the starting point, $P_{starting}$, and the next point P_{next}, as shown in Figure 2 and equation (1). Now check if this value is greater than a certain threshold as follows:

If PH_ActualChordLength > K_PH_CHORDLENGTHTHRESHOLD,

Set PH_ActualError to K_PHALLOWABLEERROR_M + 1,

Go to Step Seven,

Otherwise Continue.

Step Three: Calculate the angle ΔØ (in radians) subtended by points $P_{starting}$ and P_{next} at the center of the circle as ΔØ = $H_2 - H_{1,}$ where H_1 and H_2 represent the GPS headings (in radians) of the vehicle at locations $P_{starting}$ and P_{next} respectively (see Figure 2).

Step Four: Using PH_ActualChordLength (Step Two), and ΔØ (Step Three), calculate the estimated radius of the curvature, PH_EstimatedR (in meters), between two points $P_{starting}$ and P_{next} as follows:

PH_EstimatedR = PH_ActualChordLength/(2*sin(ΔØ/2)). (2)

This is the estimated radius of curvature for a circular arc joining $P_{starting}$ and P_{next}.

During this step a specific precaution needs to be taken. If ΔØ is very small or equal to zero (i.e. straight road path) then PH_EstimatedR will be a very large number. To detect such a case, ΔØ is compared to a calibration parameter K_PHSMALLDELTAPHI_R. If ΔØ is less than this calibration parameter, then the radius is very large. In this case the radius is to be limited to a value of K_PH_MAXESTIMATEDRADIUS, and

If ΔØ < K_PHSMALLDELTAPHI_R,

Set PH_ActualError to Zero,

Set PH_EstimatedR to K_PH_MAXESTIMATEDRADIUS,

Go to Step Eight,

Otherwise Continue.

Step Five: Calculate the distance d value (equation (3)) which is the perpendicular distance from the center of curvature to the actual chord connecting the sampled GPS points $P_{starting}$ and P_{next} on the vehicle PH. From Figure 2,

d = PH_EstimatedR*cos(ΔØ/2). (3)

Step Six: Calculate the actual maximum error PH_ActualError as

PH_ActualError = PH_EstimatedR – d. (4)

Step Seven: If PH_ActualError is greater than an allowable PH error, K_PHALLOWABLEERROR_M, then add the previous point $P_{previous}$ to the concise data buffer as follows:

If PH_ActualError > K_PHALLOWABLEERROR_M

PH_ConciseDataBuffer[elementPos] = $P_{previous}$

elementPos++

Redefine three GPS data points for further processing. The new points are set to the Starting Point, Previous Point, and Next Point as follows:

$P_{starting} = P_{i-1}$

$P_{next} = P_{i+1}$

$P_{previous} = P_i$

i = i + 1

Go to Step Nine.

Step Eight: If PH_ActualError < K_PHALLOWABLEERROR_M, redefine the Previous Point and Next Point as:

$P_{next} = P_{i+1}$

$P_{previous} = P_i$

i = i + 1

Go to Step Two.

The algorithm repeats itself with the assigned values of Starting Point, Previous Point, and Next Point. This procedure repeats until the error violation occurs.

Step Nine: Calculate the sum of the actual distances between the consecutive PH GPS data points in the concise buffer PH_ConciseDataBuffer as follows:

totalDist = totalDist + incrementDist.

totalDist is the sum of distances between PH GPS points in the concise data buffer PH_ConciseDataBuffer.

incrementDist is the distance between the last two PH GPS data points added to the concise data buffer. Hence, if the total distance is greater or equal to K_PHDISTANCE_M, then keep deleting elements from the bottom of the concise buffer (i.e. the oldest points) until the total distance becomes just enough to maintain a minimum value of K_PHDISTANCE_M. Output the radius of curvature between the recent two selected concise data points as PH_EstimatedSumR.

Go to Step Two.

3.3 Design Method Two

Method Two follows the same steps as Method One except for the calculation of the radius of curvature (PH_EstimatedR defined in equation (2) of Method One). For Method Two the radius of curvature is an average calculation of the radius calculated in method one and the radius calculated using vehicle speed and yaw-rate. The steps involved in the design of the concise PH representation of a vehicle path using Method Two are described in pseudo code next:

Step One: Perform Method One Step One.

Step Two: Perform Method One Step Two.

Step Three: Perform Method One Step Three.

Consider Figure 4 such that there exist n GPS points, P_1, ….. P_n. Consider P_1 as the Starting Point, and P_n as the Next Point. Define P_2,…..P_{n-1} as the Intermediate Points. Method Two calculates a running average (step four) of radii calculated by equation (5) as follows:

$$\text{Radius} = v/w, \tag{5}$$

where, ν is vehicle speed (meter/s) and w is the vehicle yaw rate (radian/s).

Given n points as in Figure 4, define R_{2i} to be the radii calculated by Method Two at points i such that i = 1, ….n-1. Hence, define the following radii as:

$$R_{21} = v_1/w_1$$

$$R_{22} = v_2/w_2$$

$$R_{23} = v_3/w_3$$

$$R_{2(n-1)} = v_{n-1}/w_{n-1}.$$

If the radius calculation is higher than a threshold value, set it to the maximum value K_PH_MAXESTIMATEDRADIUS and then ignore that radius and remove it from the radii buffer and do not include it in the running average calculation in step four.

Step Four: Perform Method One Step Four. We define the radius calculation from equation (2) as PH_EstimatedR_1. The running average of radii, PH_EstimatedR_2, saved in the radii buffer computed in step three is given below as:

$$\text{PH\_EstimatedR}_2 = \sum_{i=1}^{i=n-1} R_{2i} \big/ n-1 \tag{6}$$

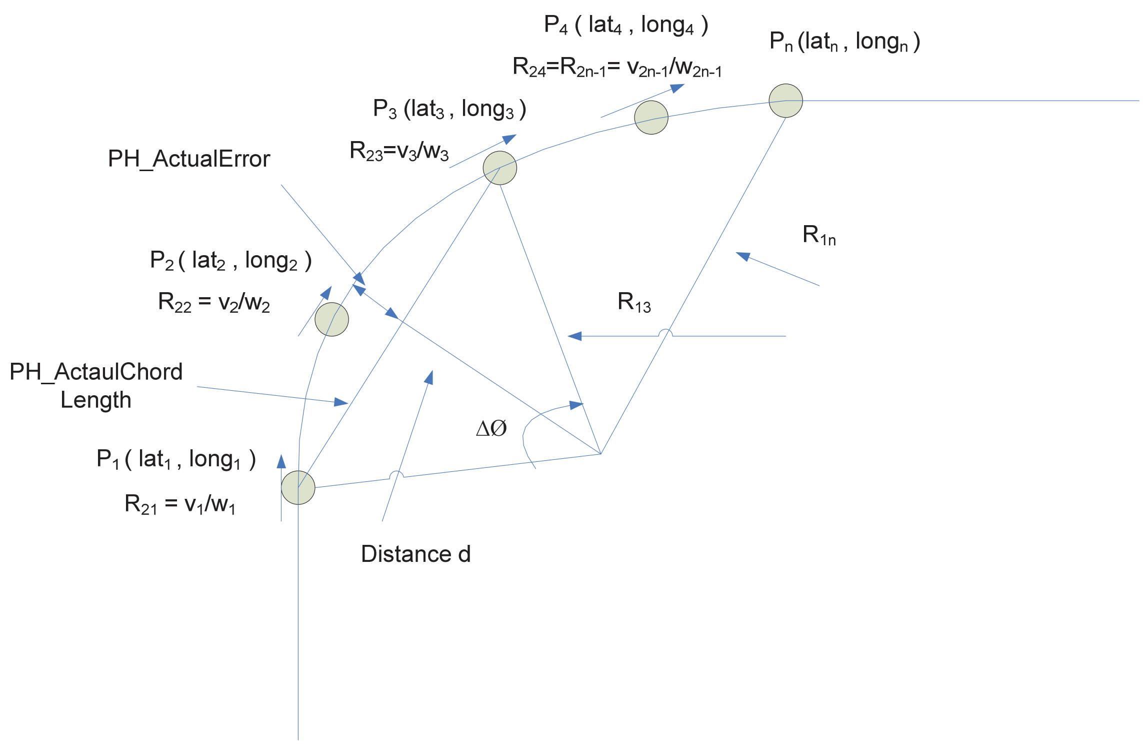

Figure 4: Representation of Estimated Radius Calculation

The estimated radius of curvature, PH_EstimatedR, is then calculated as a weighted sum between $PH\_EstimatedR_1$ and $PH\_EstimatedR_2$ as shown below:

$$PH\_EstimatedR = K\_PH\_RADIUSWEIGHTONE*PH\_EstimatedR_1 + K\_PH\_RADIUSWEIGHTTWO*PH\_EstimatedR_2, \quad (7)$$

where, K_PH_RADIUSWEIGHTONE and K_PH_RADIUSWEIGHTTWO are weights that sum up to 1. If the running average radius $PH\_EstimatedR_2$ is zero as a result of all the radii in the buffer being set to the maximum value K_PH_MAXESTIMATEDRADIUS, then set K_PH_RADIUSWEIGHTONE = 1, and K_PH_RADIUSWEIGHTTWO = 0.

Step Five: Perform Method One Step Five.

Step Six: Perform Method One step Six.

Step Seven: Perform Method One Step Seven.

In addition, one has to adjust the running average $PH\_EstimatedR_2$ to the following. If radii at the new points, $P_{starting}$ and $P_{next,}$ are both equal to K_PH_MAXESTIMATEDRADIUS, then $PH\_EstimatedR_2$ would be the resulting running average of these points as calculated using equation (6). Otherwise if the radius at the new point, $P_{next,}$ is not equal to K_PH_MAXESTIMATEDRADIUS, then $PH\_EstimatedR_2$ would be set to this radius value. Otherwise if the radius at the new point, $P_{starting,}$ is not equal to K_PH_MAXESTIMATEDRADIUS, then $PH\_EstimatedR_2$ would be set to this radius value. If none of the above is true, then $PH\_EstimatedR_2$ would be set to zero.

Step Eight: Perform Method One Step Eight.

Step Nine: Perform Method One Step Nine.

3.4 Design Method Three

Method Three follows the same steps as Method One except for the calculation of the PH error. In this method the definition of the PH_ActualError and the selection process of the concise PH data element are modified. As seen in Figure 5, PH_ActualError is the maximum perpendicular distance between the actual vehicle PH data elements and the chord connecting the concise PH representation data elements.

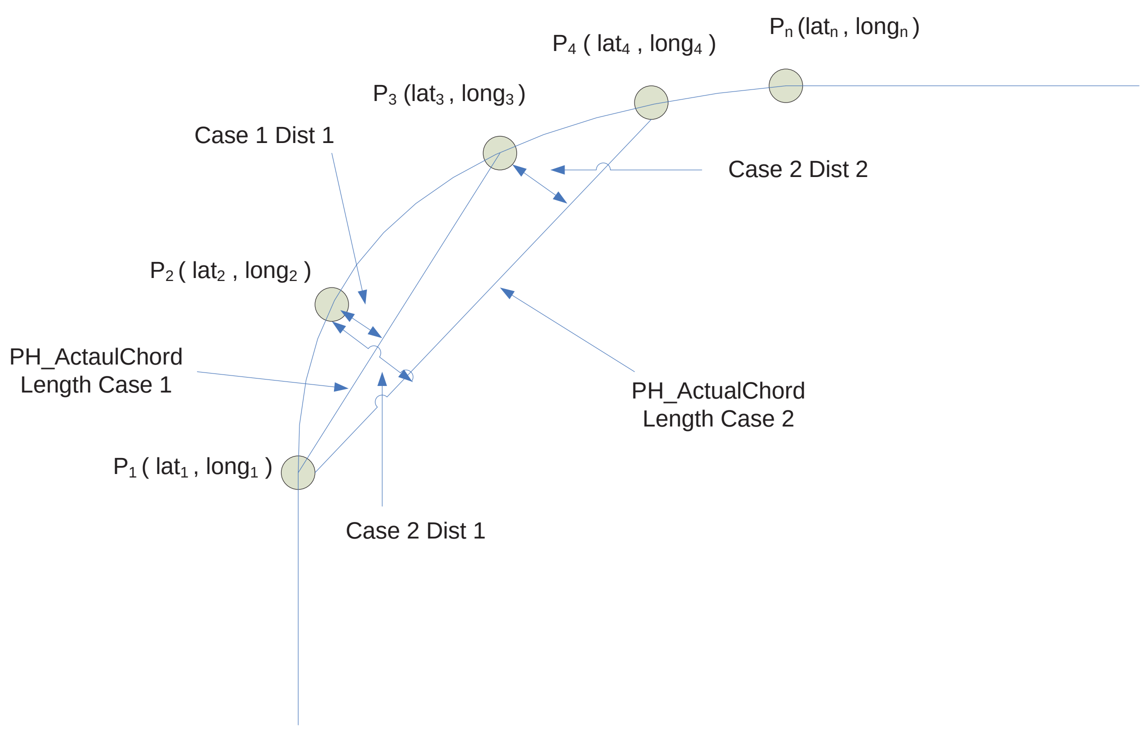

Figure 5: Representation of PH Error for Method Three

The steps involved in the design of the concise PH representation of a vehicle path using Method Three are described in pseudo code next.

Step One: Perform Method One Step One.

Step Two: Calculate PH_ActualChordLength (i.e., chord length in meters) between two points, the Starting Point, $P_{starting}$, and the Next Point P_{next}, as shown in Figure 2 and equation (1).

If PH_ActualChordLength > K_PH_CHORDLENGTHTHRESHOLD,

Set PH_ActualError to K_PHALLOWABLEERROR_M + 1

Go to Step Six.

Step Three: Perform Method One Step Three.

Step Four: Perform Method One Step Four.

Step Five: Calculate PH_ActualError as follows:

Define PH data elements, such that P_1 is the Starting Point, P_n is the Next Point, and the Intermediate Points are P_2 through P_{n-1} as shown in Figure 5. Define the perpendicular distance between the Intermediate Points and the chord connecting $P_{starting}$ and P_{next} as D_i, where i = 2, ….n-1. Define PH_ActualError as

$$PH\_ActualError = MAX(D_i); \quad i = 2, \ldots n-1. \qquad (8)$$

The procedure of calculating the distances D_i is described next. Before performing the following calculations the GPS coordinates of the points must be represented into the North-East coordinate frame. The following provides a solution to finding the shortest distance from a point to a line or line segment.

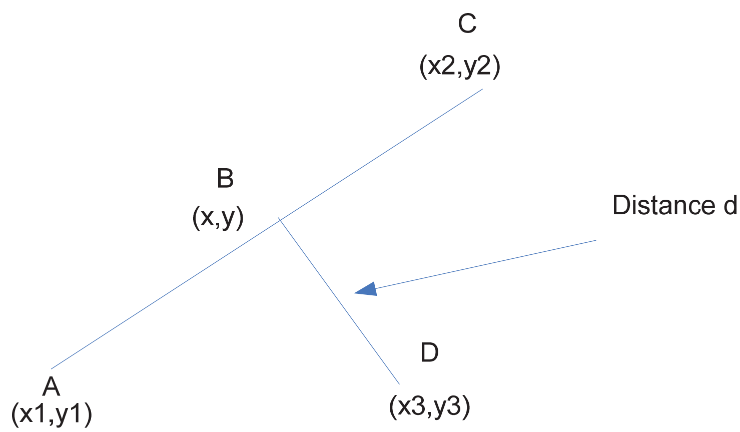

Figure 6: Shortest Distance from a Point to a Line Segment

Consider Figure 6. A solution is provided to the shortest distance from point **D** to the line segment AC. The equation of a line segment defined through two points **A** (x1,y1) and **C** (x2,y2) is given by

$$\mathbf{B} = \mathbf{A} + u\,(\mathbf{C} - \mathbf{A}),$$

where u is a value between 0 and 1. The point **B** (x,y) on the line segment AC that is closest to **D**, satisfies

$$(\mathbf{D} - \mathbf{B}) \text{ dot } (\mathbf{C} - \mathbf{A}) = 0,$$

where “dot” indicates the dot product of the vectors. Substituting for **B** in the above equation gives

$$[\mathbf{D} - \mathbf{A} - u(\mathbf{C} - \mathbf{A})] \text{ dot } (\mathbf{C} - \mathbf{A}) = 0.$$

Solving this gives the value of u as

$$u = ((x3-x1)(x2-x1) + (y3-y1)(y2-y1)) / \| C - A \|^2 .$$

Substituting this into the equation of the line gives the point of intersection **B** (x,y) as

$$x = x1 + u(x2 - x1),$$

$$y = y1 + u(y2 - y1) .$$

The distance therefore between the point **D** and the line is the Euclidean distance between (x,y) and **D**:

$$d = \text{sqrt}((x3-x)^2 + (y3-y)^2).$$

Note: Before computing the distance of the point to a line segment, it is necessary to first test that u lies between 0 and 1.

Step Six: Perform Method One Step Seven.

Step Seven: Perform Method One Step Eight.

Step Eight: Perform Method One Step Nine.

3.5 PH Module Signal Interface Description

In this subsection, the inputs, outputs, and calibration parameters used in the PH module are provided.

- Inputs to the PH module are:

  Coordinated Universal Time (UTC) Time; Latitude; Longitude; Altitude; Speed; Heading; Yaw rate

- Calibration parameters for the PH Module are:

K_PHDISTANCE_M	300 (meters)
K_PHDATAPOINTSSAMPLETIME_S	100 (ms)
K_PHALLOWABLEERROR_M	1 (meters)
K_PHSMALLDELTAPHI_R	0.02 (radians)
K_PH_RADIUSWEIGHTONE	0.5 (unitless)
K_PH_RADIUSWEIGHTTWO	0.5 (unitless)
K_PH_CHORDLENGTHTHRESHOLD	310 (meters)
K_PH_MAXESTIMATEDRADIUS	7FFFFF (meters)

- The outputs are available in the concise PH data structure buffer and shall be the PH data elements. Outputs of the PH module are:

  N; // number of PH concise representation data elements

  PH_CONCISE_DATA_ELEMENT_1,

  ….

  ….

  PH_CONCISE_DATA_ELEMENT_N,

  where, PH_CONCISE_DATA_ELEMENT consists of,

  PH_UTCTime; PH_Latitude; PH_Longitude; PH_Altitude; PH_Speed; PH_Heading; PH_YawRate; PH_EstimatedSumR.

Note: If PH_EstimatedSumR is greater than K_PH_MAXESTIMATEDRADIUS, then set PH_EstimatedSumR to K_PH_MAXESTIMATEDRADIUS.

4 Test Results

4.1 Concise PH Representation of Vehicle Path

Data was collected over a certain vehicle path as shown in Figure 7 below. GPS data was collected using NovAtel® OEMV® receiver with the data sampling interval of the actual vehicle position data being 100 ms. The actual vehicle path shown in Figure 7 is represented by 10,500 GPS data points.

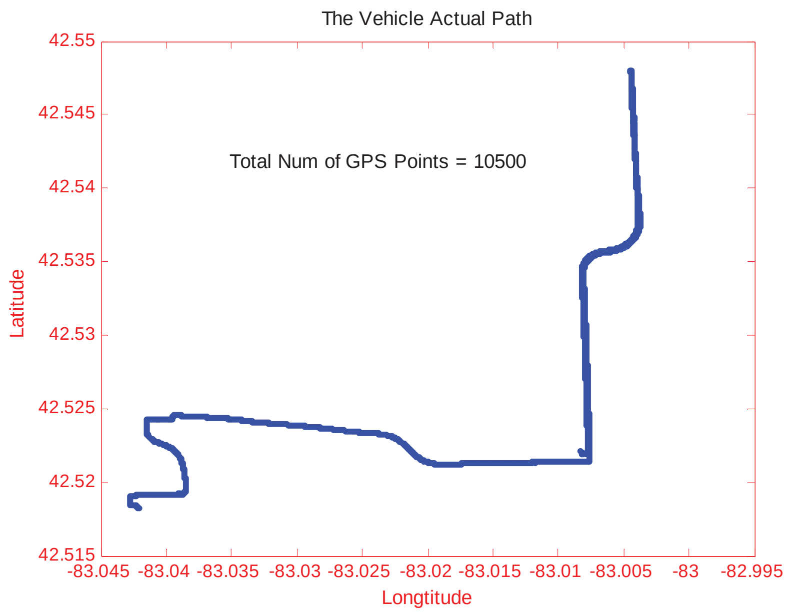

Figure 7: Vehicle Actual Path

The test results evaluated the three PH methods and calculated the concise PH that approximates the actual vehicle path within an error tolerance of one meter. Figure 8, Figure 9, and Figure 10 show in red circles the concise PH data elements representing the actual vehicle path. The actual vehicle path is shown in blue. Figure 8 (Method One) shows that the number of concise PH data elements needed to represent the vehicle path is 111. Figure 9 (Method Two) shows that the number of concise PH data elements needed to represent the vehicle path is 129. Figure 10 (Method Three) shows that the number of concise PH data elements needed to represent the vehicle path is 124.

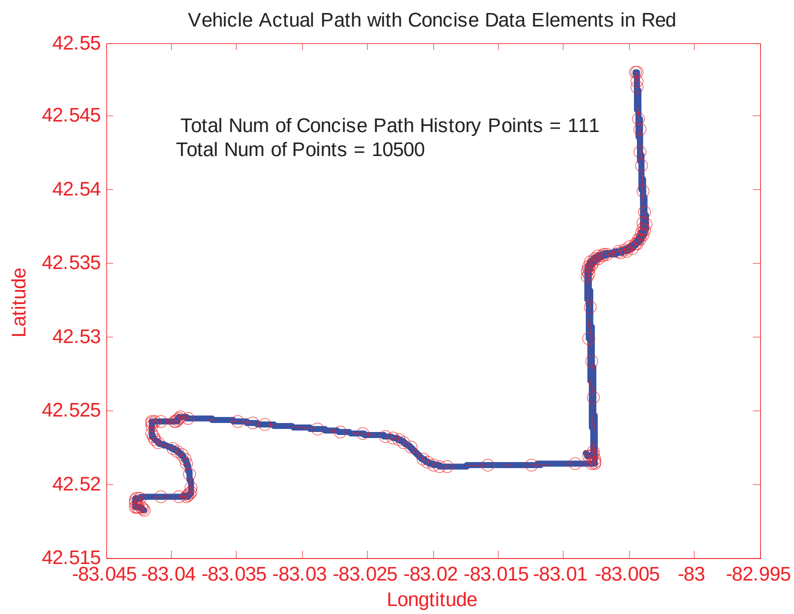

Figure 8: Method One – Representation of Vehicle Path

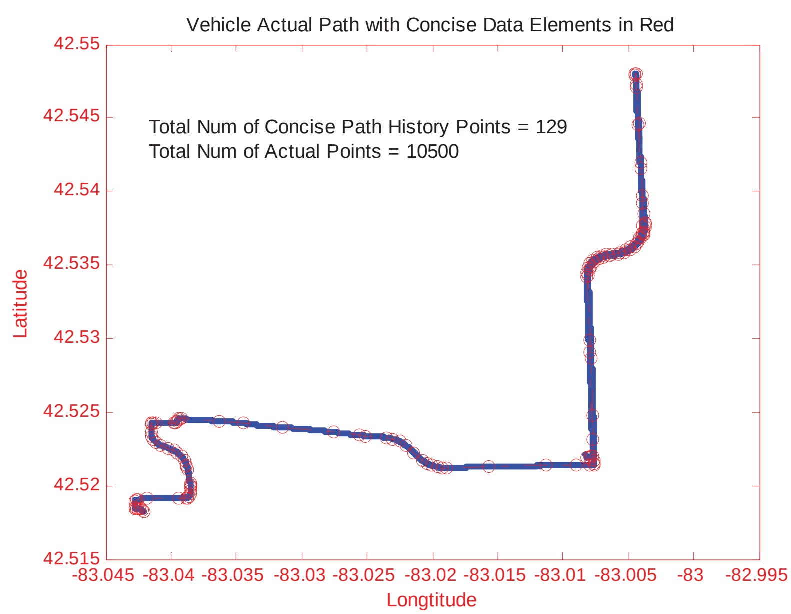

Figure 9: Method Two – Representation of Vehicle Path

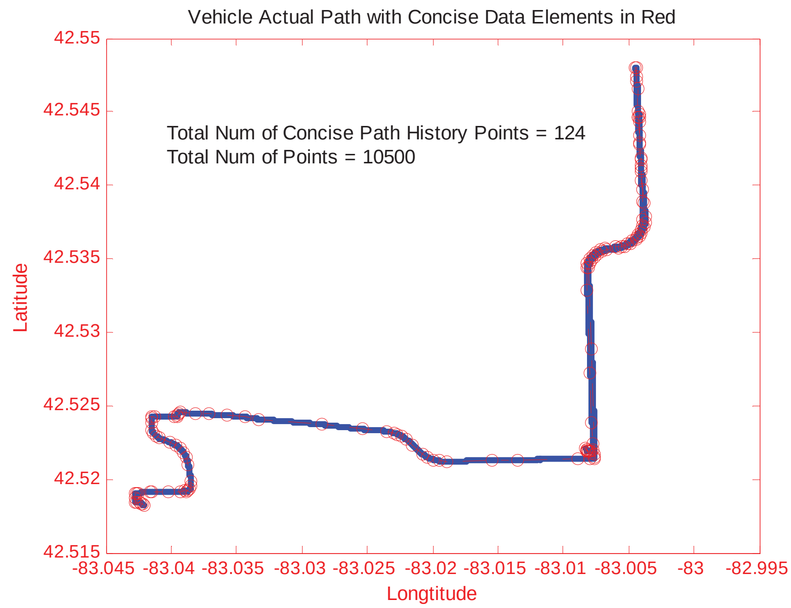

Figure 10: Method Three – Representation of Vehicle Path

4.2 Radii of Curvature for a Curved Road

Figure 11 (Method One and Method Three) and Figure 12 (Method Two) shows the radii of curvature (in meters) between successive, concise PH data points for a sharp, curved road segment of the vehicle path. The radii of curvature clearly indicate the curved nature of the road segment. Notice that the road segment also includes a reasonably straight section represented in Figure 11 and Figure 12 with a larger radius of curvature. Curved road segment radii are expected to be within the indicated range. In Figure 11 and Figure 12, the solid line indicates the actual vehicle path and the dotted lines indicate the concise PH representation.

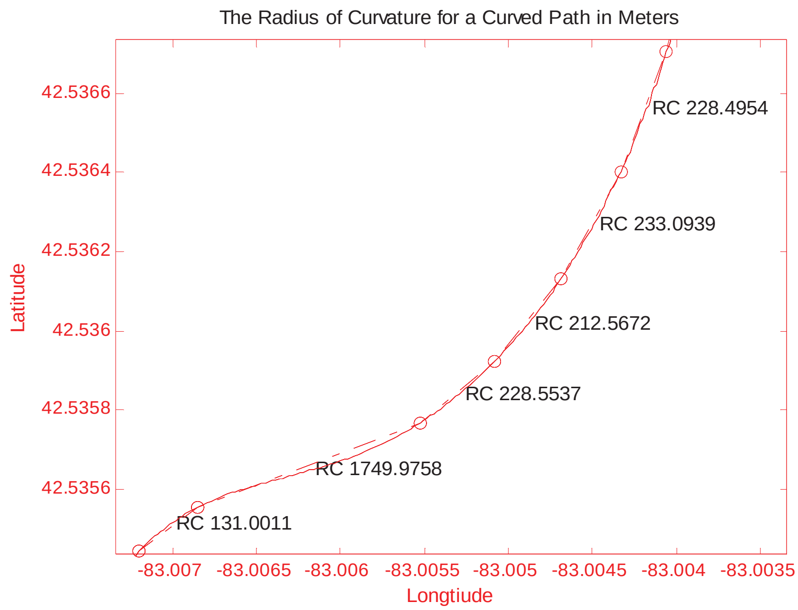

Figure 11: Method One and Three – Radii of Curvature for Curved Road

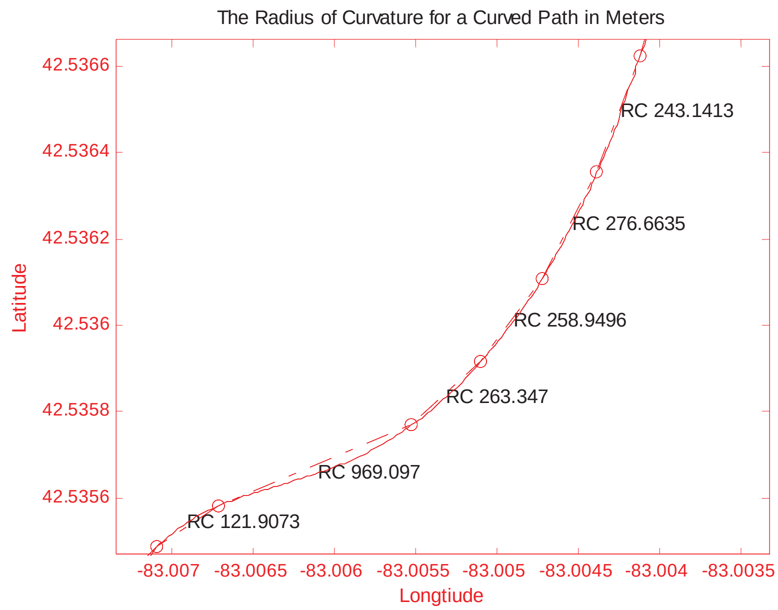

Figure 12: Method Two – Radii of Curvature for Curved Road

4.3 Radii of Curvature for a Straight Road

Figure 13 (Method One and Method Three) and Figure 14 (Method Two) shows the radii of curvature (in meters) between successive concise data points for a straight road segment. The numbers indicate that the radius of curvature for a straight road segment is large. By examining these numbers, it is clear that the straight road segments are easily identified by using a certain threshold for radius of curvature. In Figure 13 and Figure 14, the solid line indicates the actual vehicle path and the dotted lines indicate the concise PH representation.

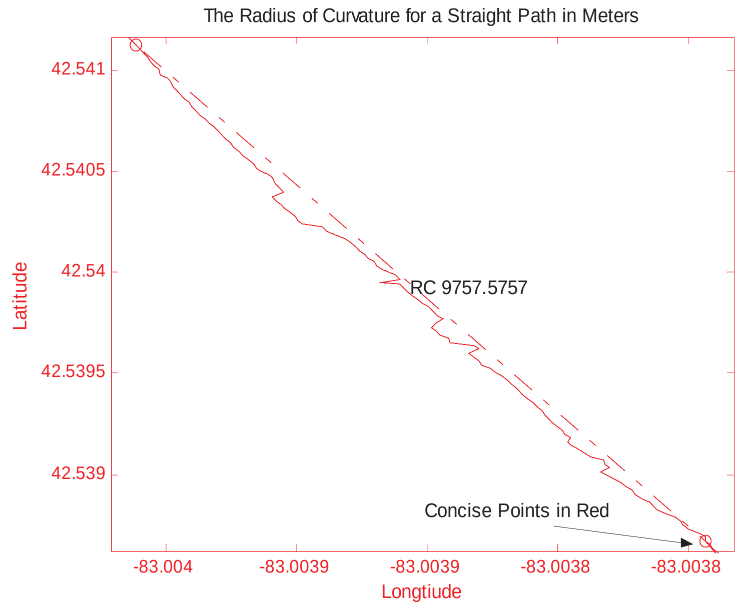

Figure 13: Method One and Three – Radii of Curvature for Straight Road

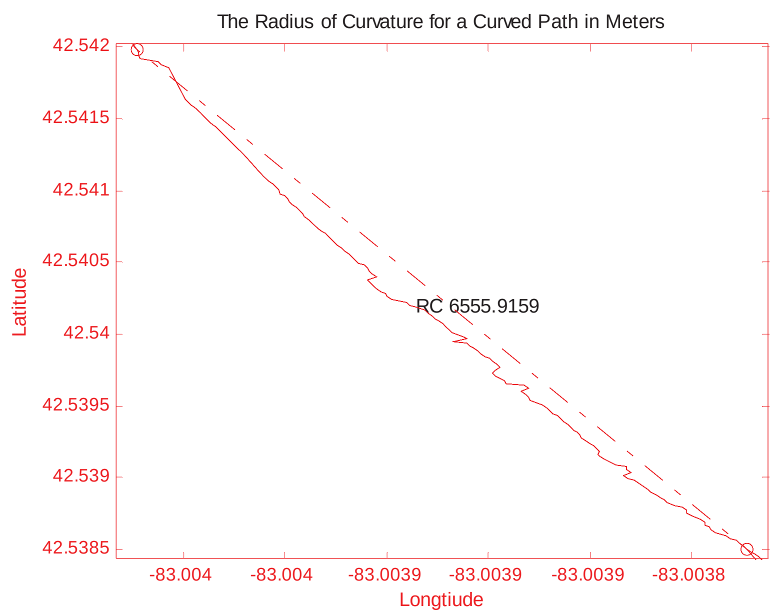

Figure 14: Method Two – Radii of Curvature for Straight Road

4.4 PH Concise Points and Distances between Them for a Curved Road

Figure 15 (Method One), Figure 16 (Method Two), and Figure 17 (Method Three) show the result for a curved road segment after concise data points have been computed to maintain the PH distance of at least 300m from the current vehicle position (shown in green). No additional PH points can be dropped without violating the requirement of a minimum 300 meter PH distance. It is clear all methods require only a few PH points to represent a vehicle PH over a curved roadway segment as shown.

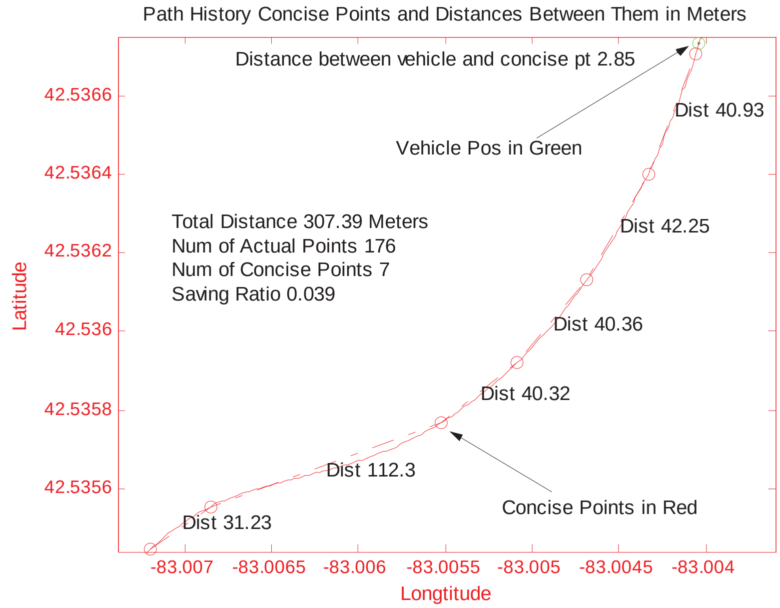

Figure 15: Method One – PH Representation of Curved Road

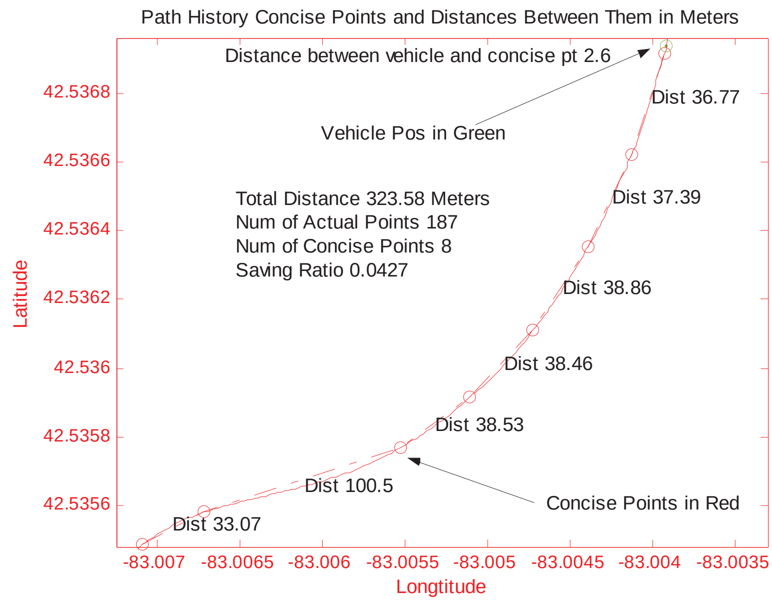

Figure 16: Method Two – PH Representation of Curved Road

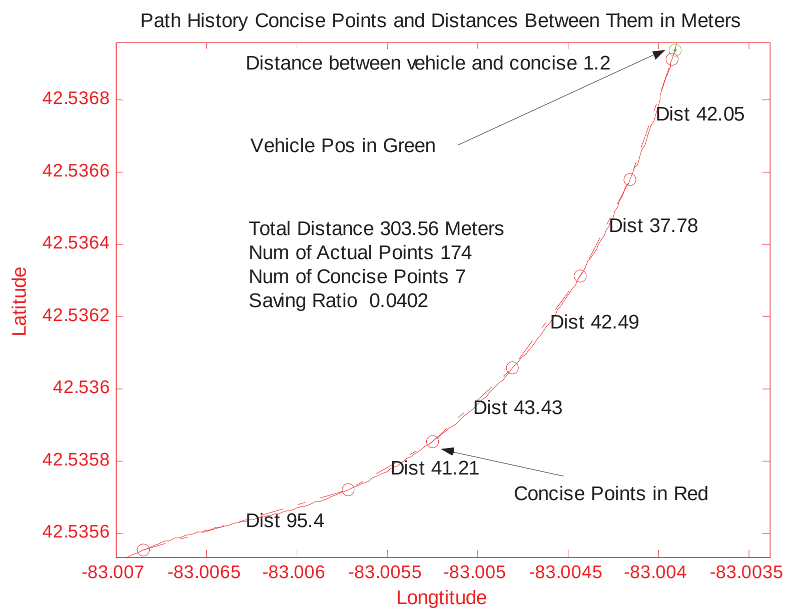

Figure 17: Method Three – PH Representation of Curved Road

The saving ratio shown in Figure 15 through Figure 17 indicates the ratio of concise data elements to the actual data elements. The ratio indicates the saving in the representation of the actual path when using a concise PH representation for each of the proposed methods. In Figure 15 through Figure 17, the solid line indicates the actual vehicle path and the dotted lines indicate the concise PH representation.

4.5 PH Concise Points and Distances Between Them for a Straight Road

Figure 18 (Method One), Figure 19 (Method Two), and Figure 20 (Method Three) show the result for a straight road segment after concise data points have been computed to maintain the PH distance of at least 300 meters from the current vehicle position (shown in green). No additional PH points can be dropped without violating the requirement of a minimum 300-meter PH distance. From Figure 18, the algorithm of Method One selects two successive PH concise points for this road segment with a distance between them equal to 375.3 meters. Similarly, from Figure 19, the algorithm of Method Two selects two successive PH concise points for this road segment with a distance between them equal to 391.4 meters. Subsequent to collection of these test results, Step 2 of all the algorithms were modified so that the maximum distance between two successive PH concise points never exceeds the stated threshold distance of K_PH_CHORDLENGTHTHRESHOLD, the default value of which is 310 meters. Also notice from Figure 18 and Figure 19 that the total distance of the path history representation is 381.83 meters and 396.4 meters, respectively. The increase in path history representation distance is obtained without the need for any additional PH points over the minimum number of PH points needed to represent the path history for a minimum distance defined by the calibration parameter K_PHDISTANCE_M, with a default value of 300 (meters).

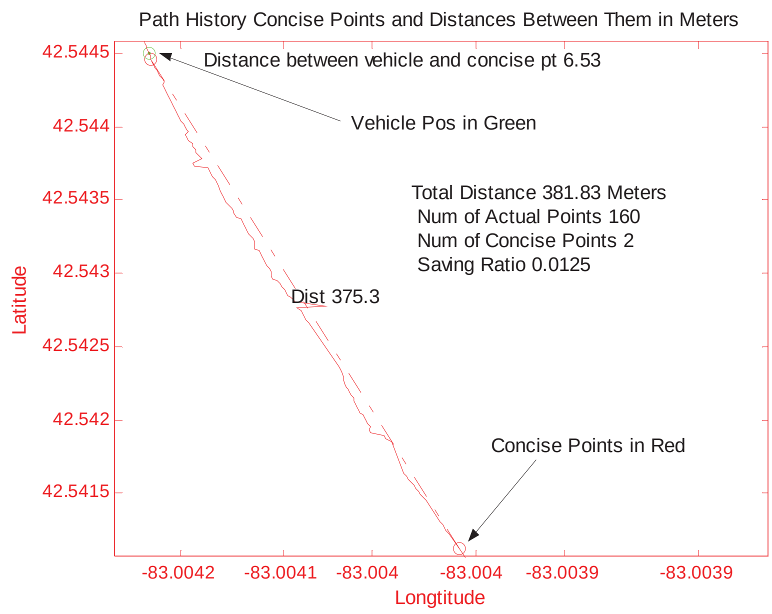

Figure 18: Method One – PH Representation of Straight Road

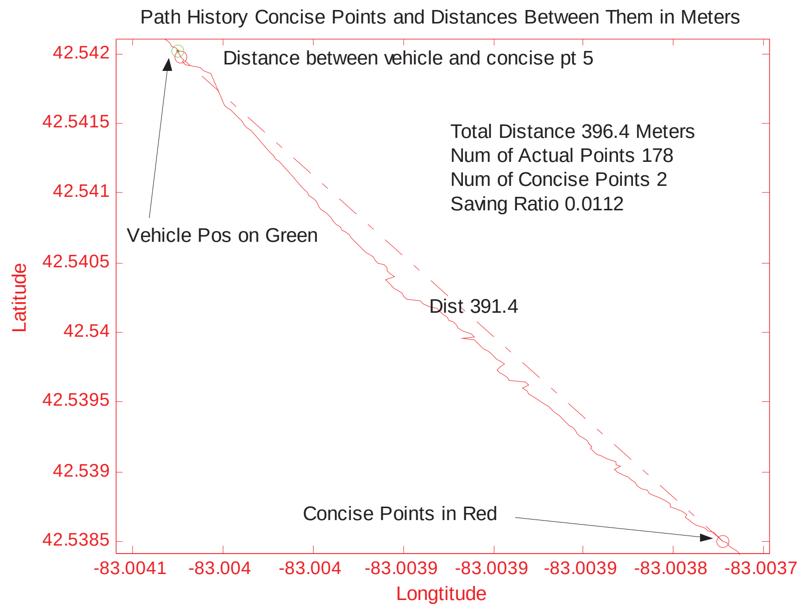

Figure 19: Method Two – PH Representation of Straight Road

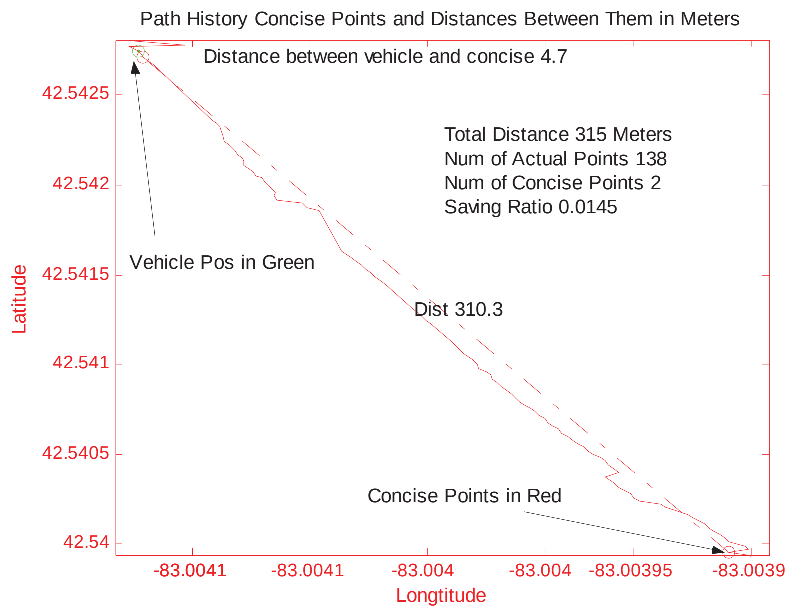

Figure 20: Method Three – PH Representation of Straight Road

The saving ratio shown in Figure 18 through Figure 20 indicates the ratio of concise data elements to the actual data elements. The ratio indicates the saving in the representation of the actual path when using a concise PH representation for each of the proposed methods. In Figure 18 through Figure 20, the solid line indicates the actual vehicle path and the dotted lines indicate the concise PH representation.

4.6 PH Requirement Analysis

Figure 21 (Method One), Figure 22 (Method Two), and Figure 23 (Method Three) show the actual error between concise PH data elements. Since the concise data points are chosen based on the fact that they do not violate the actual error criteria of one meter, it is clearly shown and verified in these diagrams that the actual error is always less than one meter. Similar results are generated for straight path. The significance of these results is that the concise PH data points can be used reliably to represent the actual vehicle PH. In Figure 21 through Figure 23, the solid line indicates the actual vehicle path and the dotted lines indicate the concise PH representation.

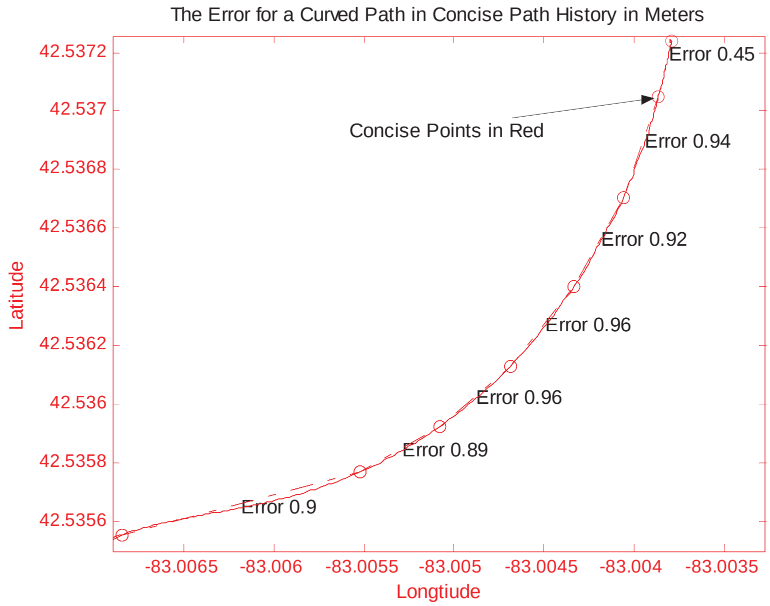

Figure 21: Method One – PH Error Analysis

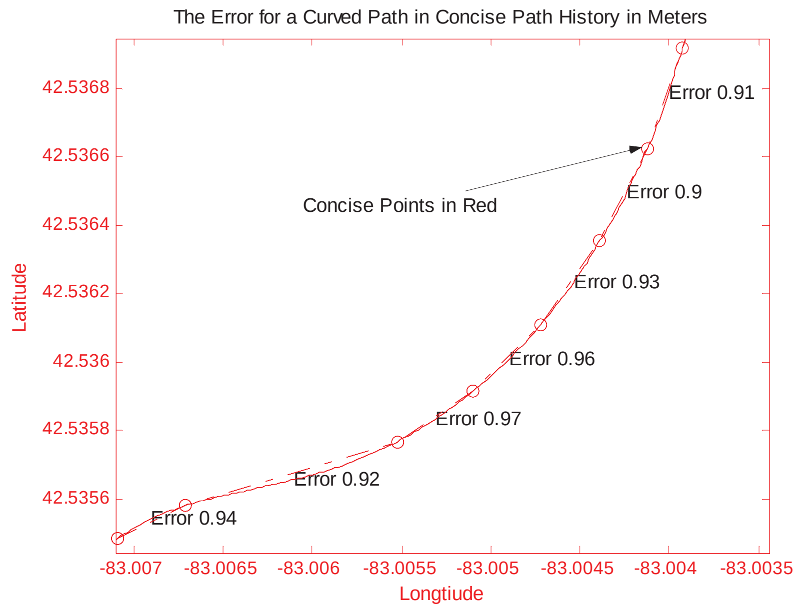

Figure 22: Method Two – PH Error Analysis

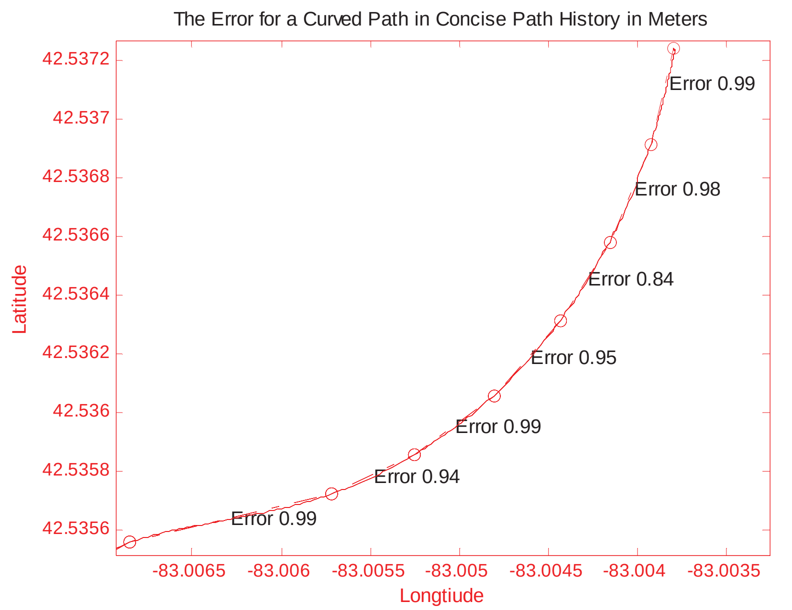

Figure 23: Method Three – PH Error Analysis

5 Summary

This document has presented the PH module for the VSC-A vehicle safety communications system. The module uses a history of the past GPS locations traversed by the HV and computes an adaptable concise PH representation of recent vehicle movement over a certain distance. The PH communicated by a vehicle provides other vehicles with important information needed for predicting the roadway geometry. It plays an important role in target vehicle classification in vehicle safety communications. Three different methods for design and implementation of the PH module have been presented. These methods have also been implemented in the VSC-A test bed and their performance has been evaluated. Extensive testing of the VSC-A test bed has shown that the concise representations of the vehicle PH computed by the various methods are very optimal and offer significant savings in OTA wireless bandwidth when transmitting the PH information to other vehicles wirelessly, while guaranteeing that the PH error remains within the allowable tolerance of one meter. Method One was chosen as the primary method used subsequently for VSC-A objective testing. The objective testing of VSC-A applications have also shown that the PH error tolerance of one meter that was chosen as default, satisfies the needed accuracy and meets the performance requirements of target classification and the safety applications that were developed and demonstrated in the VSC-A Project.

VSC-A Final Report: Appendix C-1

Minimum Performance Requirements

List of Acronyms

ABS	
BSW	
CAMP	Crash Avoidance Metrics Partnership
CLW	Control Loss Warning
DNPW	Do Not Pass Warning
DSRC	Dedicated Short Range Communications
EEBL	Emergency Electronic Brake Lights
ESC	Electronic Stability Control
FCW	Forward Collision Warning
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
HV	Host Vehicle
IMA	Intersection Movement Assist
ITS	Intelligent Transportation Systems
JPO	Joint Program Office
LCW	Lane Change Warning
NHTSA	National Highway Traffic Safety Administration
NLOS	Non-Line-of-Sight
OTA	Over-the-Air
OTP	Objective Test Procedures
PDOP	Percent Dilution of Precision
RITA	Research and Innovative Technology Administration
RV	Remote Vehicle
TC	Traction Control
USDOT	United States Department of Transportation
VSC2	Vehicle Safety Communications 2
VSC-A	Vehicle Safety Communications – Applications

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1 Introduction

The minimum performance requirements serve as the basis for the Vehicle Safety Communications – Applications (VSC-A) Objective Test Procedure (OTP) development.

This document provides quantitative and measurable performance metrics that are considered achievable and appropriate for the VSC-A applications. The minimum performance requirements in this document are based on the system functional requirements and design documents. These performance requirements take into account the potential impact on overall system requirements, including communications and positioning requirements.

2 Domain in Which Minimum Performance Requirements Apply

2.1 Subject and Target Vehicle Types

Both subject vehicles and target vehicles shall be equipped with Dedicated Short Range Communications (DSRC) radios and safety applications and shall be capable of exchanging and processing standard over-the-air (OTA) vehicle safety messages.

2.2 Roadway Characteristics

2.2.1 Horizontal Roadway Characteristics

The system shall function on all roads that meet the following horizontal roadway characteristics:

Table 1: Horizontal Roadway Characteristics

Category	Minimum	Maximum
Superelevation rate (%)	0	8
Maximum Side Friction Factor	0.18	0.1
Curvature Radius (m)	500	infinite

2.2.2 Vertical Roadway Characteristics

The system shall function on all roads that meet the following vertical roadway characteristics:

Table 2: Vertical Roadway Characteristics

Category	Minimum	Maximum
Terrain	Level	Rolling
Grades (%)	0	5

2.3 Global Navigation Satellite System (GNSS) Coverage Constraints

The GNSS coverage and availability shall satisfy all of the following conditions:

- The standard deviation of its Global Positioning System (GPS) position estimate is less than 1.5 meters in the horizontal plane
- The Percent Dilution of Precision (PDOP) is less than 5.0
- At least five satellites are used in the computations

2.4 Weather Conditions

The ambient temperature is between 1^{o}C and 38^{o}C with no precipitation.

3 Warning Repeatability

The minimum performance requirements for warnings focuses on specifying a variance in the warning range and/or timing, taking into consideration an assumed amount of variation in the warning due to the variables in the measurement system and test setup. The repeatability requirements are detailed in each application section.

The warning repeatability criteria will be defined separately for each application based on the nature of the application warning.

4 Maximum Warning Latency

For applications that use the warning latency for analyzing the warning repeatability, the Maximum Warning Latency will be a combination of the maximum Host Vehicle (HV) application processing latency and the maximum application warning status output to DVI modality input latency. The maximum application processing latency will be defined separately for each application. The maximum application warning status output to DVI modality input latency shall be 300ms.

5 Requirement of Overall Correctness of Warnings

5.1 True Positive Warning Rate

True Positive Warning Rate is the percentage of the total predicted non-suppressible crash warning events that were tallied as "True Positive Warnings."

True Positive Warning Rate = (True Positive Tally) / (Total Warning Event Tally)

The true positive warning rate shall be greater than or equal to 80 percent.

5.2 False Positive Warning Rate

False Positive Warning Rate is the percentage of the total predicted *non-crash warning* events that were tallied as "False Positive Warnings." In other words, the percentage of the total events in which the VSC-A system issued a warning that was not needed.

False Positive Warning Rate = (False Positive Tally) / (Total Warning Event Tally)

The false positive warning rate shall be less than 20 percent.

6 Emergency Electronic Brake Lights (EEBL) Minimum Performance Requirements

6.1 Operating Speeds

The minimum operational speed range for EEBL shall be 11.4 – 30 meters per second (25-67 mph).

6.2 Remote Vehicle (RV) Hard-Braking Status Broadcasting

The RV shall send out a hard brake status as part of the OTA messages as soon as hard braking is detected. Hard braking is defined as deceleration greater than 0.4 g.

6.3 Host Vehicle Driver-Vehicle Interface Performance Requirements

6.3.1 Warning Levels

EEBL shall provide at least one level of warning to the driver.

6.3.2 Warning Dismissal

EEBL shall dismiss the warning once the threat vehicle's hard braking status is alleviated. The warning shall be suppressed if the driver of the HV is pressing the brakes at the time of the alert.

6.4 EEBL Maximum Processing Latency

The warning shall be issued as soon as the HV detects that the RV's deceleration exceeds the HV's pre-defined threshold. The maximum application processing latency shall be 200 ms from the time the HV receives a message which indicates the EEBL event for an RV in addition to the RV's deceleration exceeding the HV's pre-defined EEBL warning threshold, to the time EEBL-HV application outputs the warning status. The maximum warning latency will be the maximum application processing latency plus the maximum application warning status to DVI modality input latency defined in section 4.

6.5 Warning Repeatability

The warning shall be issued within the total of Maximum Warning Latency defined in section 6.4.

6.6 EEBL Zone Definition

The EEBL zone is defined as: same direction traffic, ahead (same lane), ahead-left, and ahead-right (left and right immediate adjacent lanes). The longitudinal detection distance is no greater than 300 meters from the front bumper of the HV to the rear bumper of the RV. The EEBL zone shall follow the curvature of the HV's forward road geometry in both lateral and longitudinal directions.

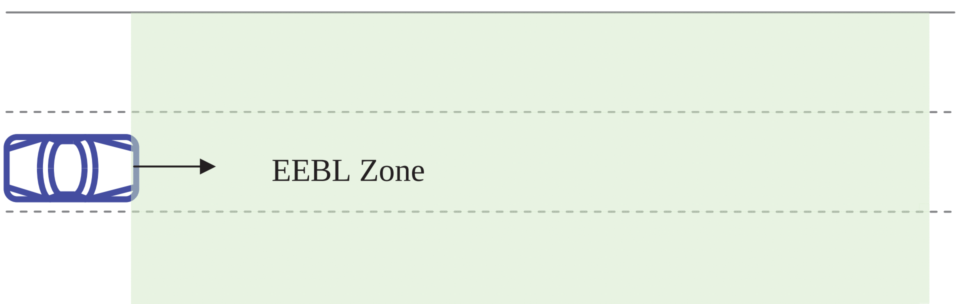

Figure 1: EEBL Zone

6.7 Non-Line-of-Sight (NLOS) Threat Detection

EEBL is intended to function even when the view to the threat vehicles is blocked by other vehicles, inclement weather, or terrain conditions.

6.7.1 Performance under NLOS Vehicle Obstruction

EEBL shall function with at least one obstructing vehicle between the HV and the RV. The dimensions of an obstructing vehicle that satisfies this minimum performance requirement shall be no greater than 7.3 meters long, 2.2 meters high, and 2.4 meters wide.

6.8 False Positive Warnings

6.8.1 Remote Braking Vehicle Below Minimum Speed Threshold

EEBL shall not set the braking vehicle's hard-brake status to TRUE if the braking vehicle is traveling below the minimum operational speed threshold.

6.8.2 Host Vehicle Below Minimum Speed Threshold

EEBL shall not issue a warning if the HV is traveling below the minimum operational speed threshold.

6.8.3 Remote Vehicle not Performing EEBL Defined Hard Brake

EEBL shall not issue a warning for a RV that did not issue a hard brake status, or the braking did not satisfy the hard brake threshold defined by the application.

6.8.4 Remote Vehicle not in EEBL Zone

EEBL shall not issue a warning for a RV that is outside of the EEBL zone.

6.8.5 Remote Vehicle not in the Same Travel Direction

EEBL shall not issue a warning for a RV that is inside the EEBL zone but not traveling in the same direction.

7 Forward Collision Warning (FCW) Minimum Performance Requirements

7.1 Operating Speeds

The minimum operational speed range for FCW shall be 11.4 – 30 meters per second.

7.2 Roadway Characteristics

FCW will detect equipped vehicles that pose a forward collision threat, including stopped vehicles on a roadway with a radius of curvature of 500 meters or greater.

7.3 Remote Vehicle Status Broadcasting

The RV(s) shall periodically send out status as part of the OTA messages. The system shall support periodic broadcast updates with a minimum update rate of 100 ms.

7.4 Host Vehicle Driver-Vehicle Interface Performance Requirements

7.4.1 Warning Levels

FCW shall provide at least one level of alert warning to the driver. Graded advisory levels in between are optional. FCW may provide an indication to the driver that it is tracking a forward vehicle.

7.4.2 Warning Dismissal

FCW shall dismiss the warning alert once the threat vehicle's alert status is alleviated. The warning shall be suppressed if the HV driver is pressing the brakes at the time of the alert.

7.5 Warning Repeatability

Given that the FCW testing parameters of each test is adequately controlled and specified in the test scenarios, FCW warning repeatability is considered satisfied under the condition that the actual warning range as provided by each test run is within ± 10 percent of the nominal warning range for that specific run. The nominal warning range differs among each of the test runs and is computed based on the actual reported test scenario parameters.

7.6 FCW Zone Definition

The FCW zone is defined as: same direction traffic, ahead (same lane). The longitudinal detection distance is no greater than 300 meters from the front bumper of the HV. The lateral detection distance is one-half of a lane width about each side of the HV's center. The FCW zone shall follow the curvature of the HV's forward road geometry in both lateral and longitudinal directions.

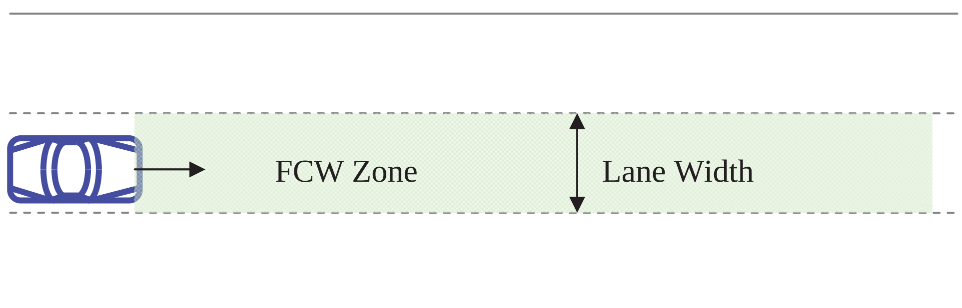

Figure 2: FCW Zone

7.7 Non-Line-of-Sight (NLOS) Threat Detection

FCW is intended to function even when the view to the threat vehicle(s) is blocked by other vehicles, inclement weather, or terrain conditions.

7.7.1 Performance under LOS Vehicle Obstruction

FCW shall function with at least one obstructing (equipped or unequipped) vehicle between the host and the remote threat vehicle. The dimensions of an obstructing vehicle that satisfies this minimum performance requirement shall be no greater than 7.3 meters long, 2.2 meters high, and 2.4 meters wide.

7.8 Unnecessary/False Warnings

7.8.1 Host Vehicle Below Minimum Speed Threshold

FCW shall not issue a warning if the HV is traveling below the minimum operational speed threshold.

7.8.2 Remote Vehicle not a forward collision threat

FCW shall not issue a warning alert for a RV that is not a forward collision threat as defined by the application design.

7.8.3 Remote Vehicle not in FCW Zone

FCW shall not issue a warning alert for a RV that is outside of the FCW zone.

7.8.4 Remote Vehicle not in the Same Travel Direction

FCW shall not issue a warning alert for a RV that is inside the FCW zone but not oriented in the same travel direction as the HV.

8 Blind Spot Warning+Lane Change Warning (BSW+LCW) Minimum Performance Requirements

8.1 Operational Speeds

The minimum operational speed range for BSW+LCW shall be 10 - 30 meters per second. Warnings will not be given for stationary vehicles.

8.2 Driver-Vehicle Interface Performance Requirements

8.2.1 Warning Levels

BSW+LCW shall provide at least one level of warning to the driver.

8.2.2 Maximum Warning Latency

A warning shall be issued to the driver when the driver initiates the lane-change intent via the driver activating the turn signal. This warning initiation event is chosen, only as an aid, to assist in correlating the event of activating the turn signal with the warning. The maximum application processing latency shall be 200 ms from the time the HV receives a vehicle CAN message, which indicates the turn signal indication, to the time BSW+LCW application outputs the warning status. The maximum warning latency will be the maximum application processing latency plus the maximum application warning status to DVI modality input latency defined in section 4.

8.2.3 Warning Dismissal

BSW+LCW shall dismiss the warning no sooner than three (3) seconds after it is first classified as a threat. BSW+LCW shall dismiss the warning either after the warning times out (defined by DVI module), or after the RV is no longer a threat, whichever lasts longer.

8.3 Warning Repeatability

The warning time shall be within the timing requirements defined in section 8.2.2, from the initiation of the lane-change intent (turn signal) until the HV BSW+LCW warning modality receives the warning input.

8.4 Blind Spot Zone Definition

The blind spot zone is defined as an area which is, or will soon be, occupied by another vehicle traveling in the same direction in the immediate adjacent left or right lane up to 20 meters behind the center of the HV, as indicated in the figure below.

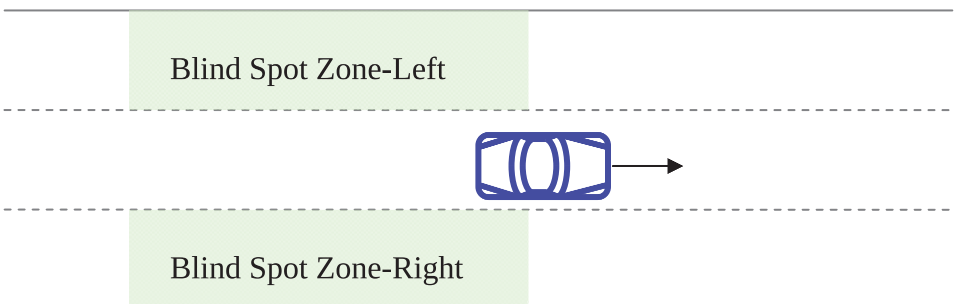

Figure 3: Vehicle Blind Spot Zone Definition

The blind spot zone is parameterized as indicated by the figure below:

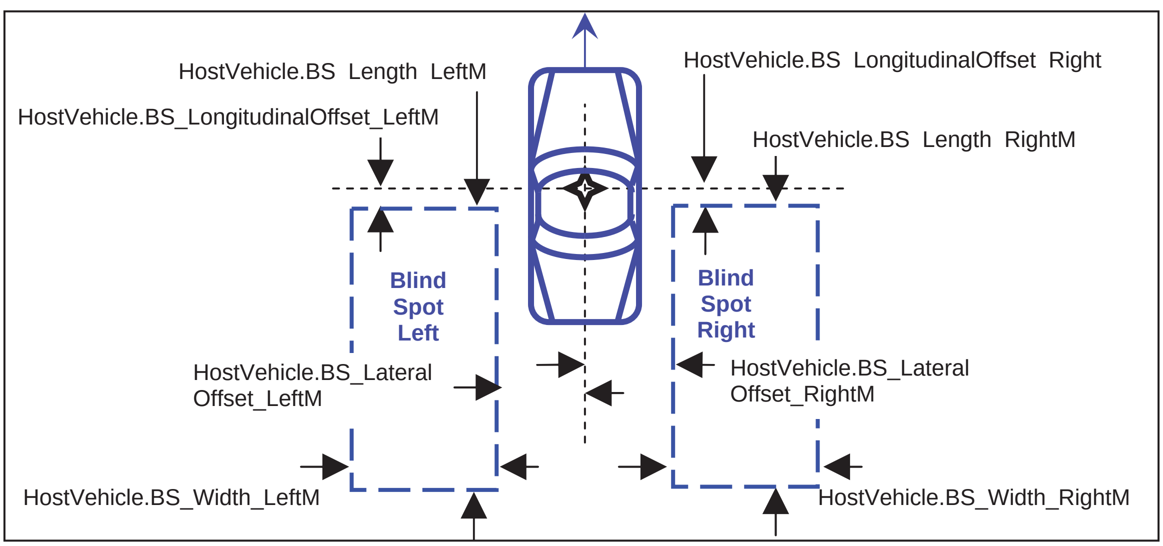

Figure 4: Vehicle Blind Spot Zone Parameters

Blind spot length will not exceed 20 meters, and blind spot width will not exceed 4 meters.

8.4.1 Threat Vehicle which will soon be in Blind Spot Zone

BSW+LCW shall consider a RV to be a threat if it will soon be in the blind spot zone. If a RV is predicted to be in the blind zone within 5 seconds, that vehicle can be considered for a LCW.

8.5 Unnecessary/False Warnings

8.5.1 Remote Vehicle below Minimum Operational Speed

BSW+LCW shall not issue a warning for a RV that has a current speed lower than 10 meters per second.

8.5.2 Remote Vehicle not in Blind Spot Zone

BSW+LCW shall not issue a warning in regard to a vehicle that is outside of the blind spot zones, except for vehicles that are predicted to enter the blind zone within 5 seconds.

8.5.3 Remote Vehicle not in the Same Travel Direction

BSW+LCW shall not issue a warning for a RV that is inside the blind spot zone but not traveling in the same direction.

8.5.4 Incorrect Lane Classification of a BSW+LCW Threat

BSW+LCW shall not issue a warning when the threat vehicle is traveling in the same lane. BSW+LCW shall not issue a left-lane warning when the threat vehicle is traveling in the right blind spot, and vice versa.

9 Do Not Pass Warning (DNPW) Minimum Performance Requirements

9.1 Operating Speeds

The operational speed range for DNPW shall be 11.4 to 30 meters per second. The minimum operational delta speed range between the DNPW-equipped vehicle and an oncoming vehicle will be 11.4 to 60 meters per second.

The threat vehicle speed is within +/- 5 mph of the HV speed, and the threat vehicle's acceleration is negligible (+/- 0.1 m/s^2).

9.2 Roadway Characteristics

DNPW will detect DSRC+ Positioning equipped vehicles that pose a head-on collision threat, including stopped vehicles on a roadway with level terrain, possessing a radius of curvature of 500 meters or greater.

9.3 Remote Vehicle Status Broadcasting

The RV(s) will periodically send out status as part of the OTA messages. The system will support periodic broadcast updates up to a minimum of at least 100 ms.

9.4 Host Vehicle Driver-Vehicle Interface Performance Requirements

9.4.1 Warning Levels

DNPW shall provide at least one level of alert warning to the driver. Graded advisory levels in between are optional. DNPW may provide an indication to the driver that it is tracking a forward vehicle.

9.4.2 Warning Alert Modalities

DNPW warning alerts will have visual and audio cues. Haptic and other modalities are optional. Advisories, if used, may only include either visual or audio cues, or a combination of both.

9.4.3 Warning Dismissal

DNPW will suspend warnings when <u>any</u> of the following conditions exist:

1. The DNPW feature is disabled
2. A vehicle is no longer present in the adjacent lane passing zone
3. The driver activates the brakes or disengages the left-turn signal
4. The DNPW algorithm has determined that it lacks the necessary information to warn the driver without inducing DNPW failures
5. The distance to the oncoming vehicle is below the minimum range defined within section 9.6.1

9.5 Warning Alert Repeatability

The DNPW minimum performance requirements for warning alert range/timing shall consider the variability in the DNPW warning range/timing, based on an assumed amount of variation in the warning due to the repeatability of the test setup. As such, the DNPW warning range/timing will be based on a nominal value for the warning based on an assumed variation in the test setup (e.g., variation in the vehicle speed of the DNPW vehicle and/or oncoming vehicle). DNPW warning repeatability is considered satisfied under the condition that the actual warning range as provided by each test run is within ± 10 percent of the nominal warning range for that specific run. The nominal warning range differs among each of the test runs and is computed based on the actual reported test scenario parameters.

9.6 DNPW Zone

9.6.1 DNPW Zone Definition

The DNPW zones (see Figure 5) are defined as:

1. Same direction traffic, ahead (same lane) with a speed delta dependent longitudinal time gap that is measured from the front bumper of the HV to the rear bumper of the ahead RV

2. Opposite direction traffic, adjacent left lane with a longitudinal detection distance at the extent of DSRC communication range

The DNPW zone will follow the curvature of the HV's forward road geometry in both lateral and longitudinal directions.

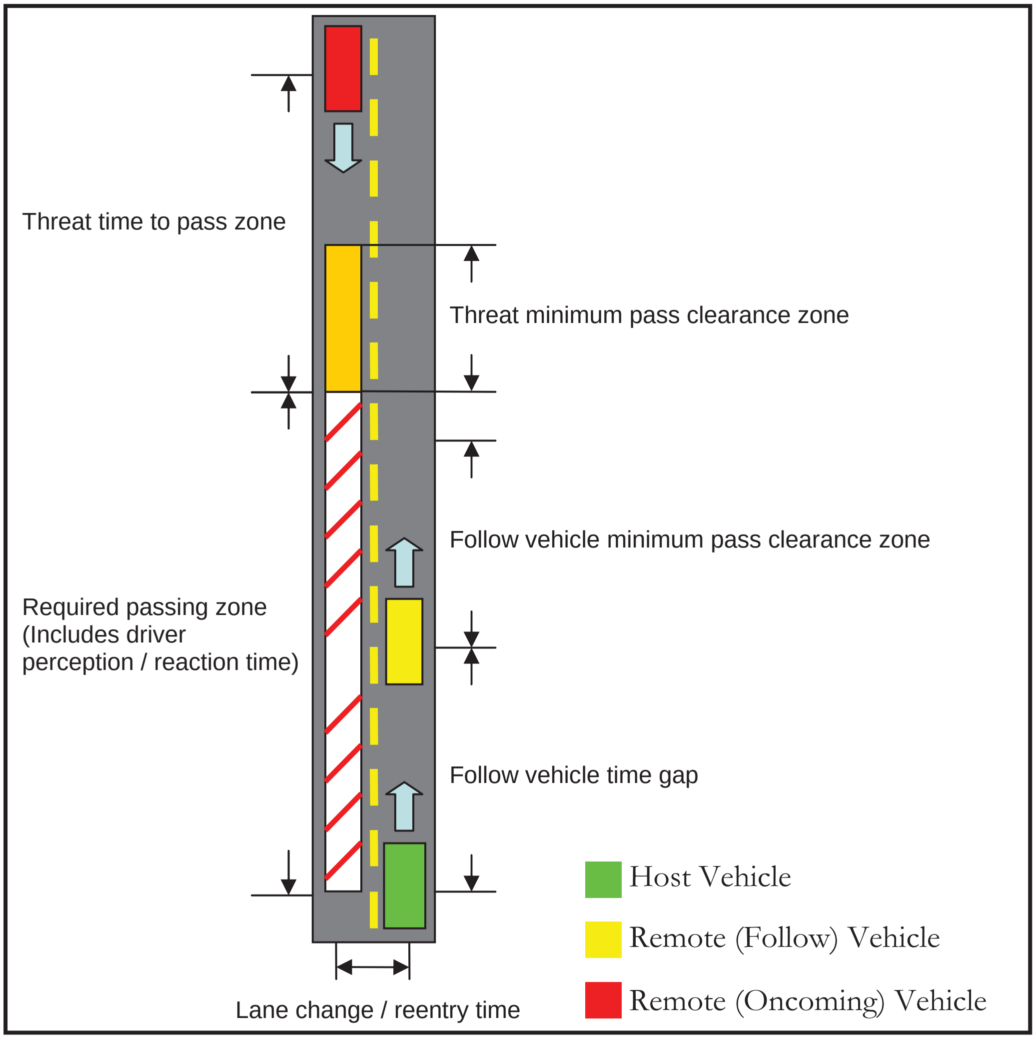

Figure 5: DNPW Zone

9.6.2 Threat Vehicle Partially in DNPW Zone

The DNPW feature will issue a warning if any portion of the vehicle within a lane adjacent to the DNPW-equipped vehicle is in the passing zone.

9.7 Unnecessary/False Warnings

9.7.1 Incorrect Lane Classification of a DNPW Threat

DNPW will not warn the driver of the DNPW-equipped vehicle when an oncoming RV is traveling in a lane not immediately adjacent to the traveling lane of the DNPW-equipped vehicle.

10 Intersection Movement Assist (IMA) Minimum Performance Requirements

10.1 Operating Speeds

The minimum operational speed range for IMA shall be 7 to 30 meters per second for the RV. The minimum operational speed range for the HV is 0 to 30 meters per second.

10.2 Remote Vehicle Status Broadcasting

The RV(s) shall periodically send out a status as part of the OTA messages. The system shall support periodic broadcast updates with a minimum of at least 100 ms.

10.3 Host Vehicle Driver-Vehicle Interface Performance Requirements

10.3.1 Warning Levels

IMA shall provide at least one level of alert warning to the driver to reduce the likelihood of a crash. IMA may provide an indication to the driver that it is tracking a vehicle that might provide a potential threat.

10.3.2 Warning Dismissal

IMA shall dismiss the warning alert once the threat vehicle's alert status is alleviated. If the HV presses the brake, the alert shall be suppressed. The HV may issue an inform if the brake is pressed and the speed of the RV exceeds a threshold of 15 meters per second.

10.4 Warning Repeatability

Given that the IMA testing parameters of each test are adequately controlled and specified in the test scenarios, IMA warning repeatability is considered satisfied under the condition that the actual warning range as provided by each test run is within ± 10 percent of the nominal warning range for that specific run.

10.5 IMA Zone

10.5.1 IMA Zone Definition

The IMA zone is defined as intersecting left or intersecting right cross direction traffic out to a length of 300 meters from the projected Intersection Point (Figure 6). The detection distance is no greater than 300 meters for clear line-of-sight between the front bumpers of the HV and the RV. The width of the IMA zone is one half vehicle length to the left and right of the longitudinal axis through the center of the vehicle.

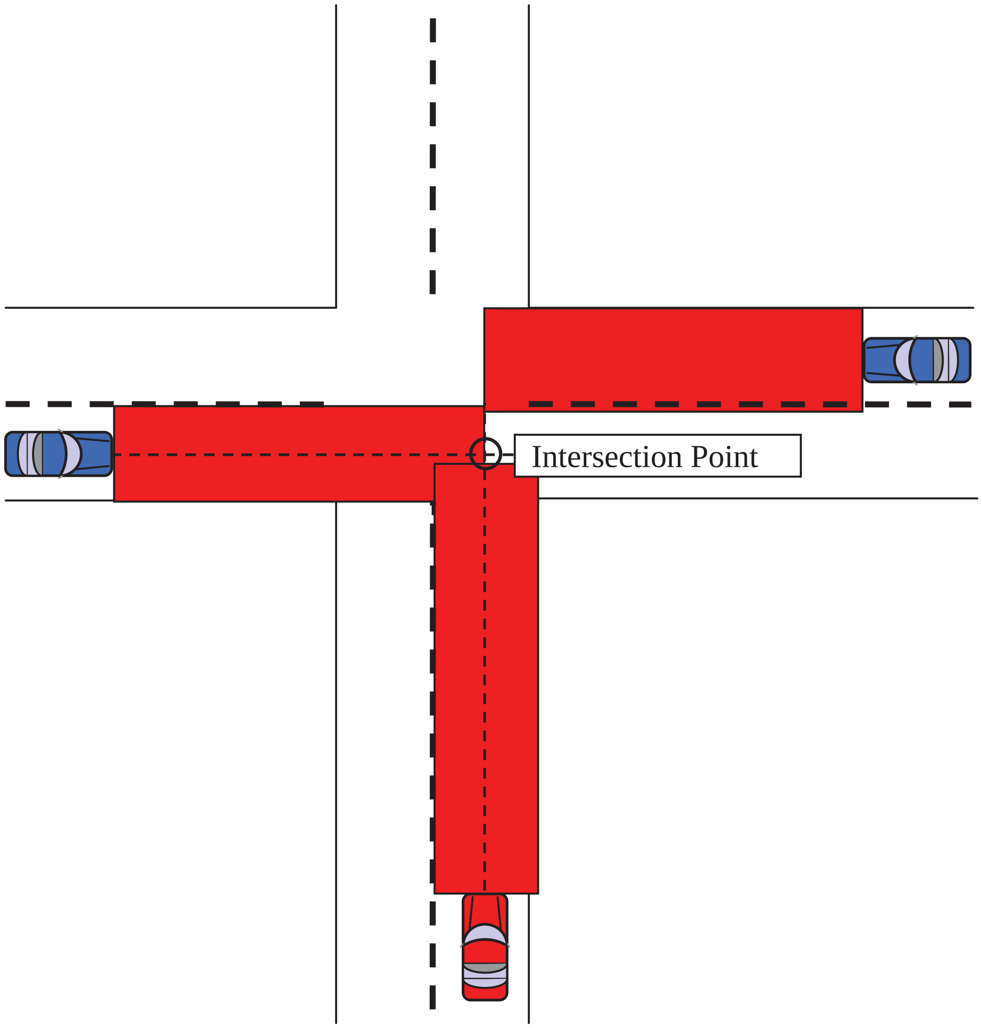

Figure 6: IMA Zone

10.6 Non-Line-of-Sight (NLOS) Threat Detection

IMA is intended to function even when the view to the threat vehicles is blocked by other vehicles, inclement weather, or terrain conditions.

10.6.1 Performance under LOS Vehicle Obstruction

IMA shall function with at least one obstructing (equipped or unequipped) vehicle between the HV and the remote-threat vehicle. The dimensions of an obstructing vehicle that satisfies this minimum performance requirement shall be no greater than 7.3 meters long, 2.2 meters high, and 2.4 meters wide.

10.7 False Positive Warnings

10.7.1 Host Vehicle Below Minimum Speed Threshold

IMA shall not issue a warning if the RV is traveling below the minimum operational speed threshold.

10.7.2 Remote Vehicle Not a Collision Threat

IMA shall not issue a warning alert for a RV that is not a lateral collision threat as defined by the application design.

10.7.3 Remote Vehicle Not in IMA Zone

IMA shall not issue a warning alert for a RV that is outside of the IMA zone.

10.7.4 Remote Vehicle Not in the Same Travel Direction

IMA shall not issue a warning alert for a RV that is inside the IMA zone but not oriented such that the paths of the subject vehicle and the RV intersect.

11 Control Loss Warning (CLW) Minimum Performance Requirements

11.1 Operating Speeds

The minimum operational speed range for CLW shall be 11.4 – 30 meters per second (25-67 mph).

11.2 Remote Vehicle Control Loss Status Broadcasting

The RV shall send out control loss status as part of the OTA messages as soon as the control loss situation is detected. The control loss event is defined as any of the following when the vehicle system is activated and engaged for longer than 400 ms:

- Antilock Brake System (ABS)
- Electronic Stability Control (ESC)
- Traction Control (TC)

11.3 Host Vehicle Driver-Vehicle Interface Performance Requirements

11.3.1 Warning Levels

CLW shall provide at least one level of warning to the driver.

11.3.2 Warning Dismissal

CLW shall dismiss the warning once the threat vehicle's control loss status is alleviated. The warning shall be suppressed if the HV driver is currently pressing the brakes.

11.4 CLW Maximum Processing Latency

The maximum application processing latency shall be 200 ms from the time the HV receives a message which indicates the CLW event for an RV to the time the CLW-HV application outputs the warning status. The maximum warning latency will be the maximum application processing latency plus the maximum application warning status to DVI modality input latency defined in section 4.

11.5 Warning Repeatability

The warning shall be issued within the total of Maximum Warning Latency as defined in section 11.4.

11.6 CLW Zone Definition

The CLW zone is defined as:

- Same direction traffic:
  - Ahead (same lane), ahead-left, and ahead-right (left and right immediate adjacent lanes) within 150 meters of the longitudinal distance from the front bumper of HV to the rear bumper of RV
  - Behind with less than 150 meters of the longitudinal distance from the rear bumper of the HV to the front bumper of the RV
  - Behind-left, behind-right less than 150 meters and greater than or equal to 1.5 meters of the longitudinal distance from the front bumper of the HV to the front bumper of the RV
  - Side-left and side-right with less than 1.5 meters of the longitudinal distance from the front bumper of the HV to the front bumper of the RV
  - Intersecting-left, intersecting-right within 150 meters of the longitudinal distance from the front bumper of the HV to the intersection point with the RV
- Opposite direction traffic:
  - Oncoming, oncoming-left, oncoming-right within 300 meters of the longitudinal distance from the front bumper of the HV to the front bumper of the RV

The CLW zone shall follow the curvature of the HV's forward road geometry in both lateral and longitudinal directions.

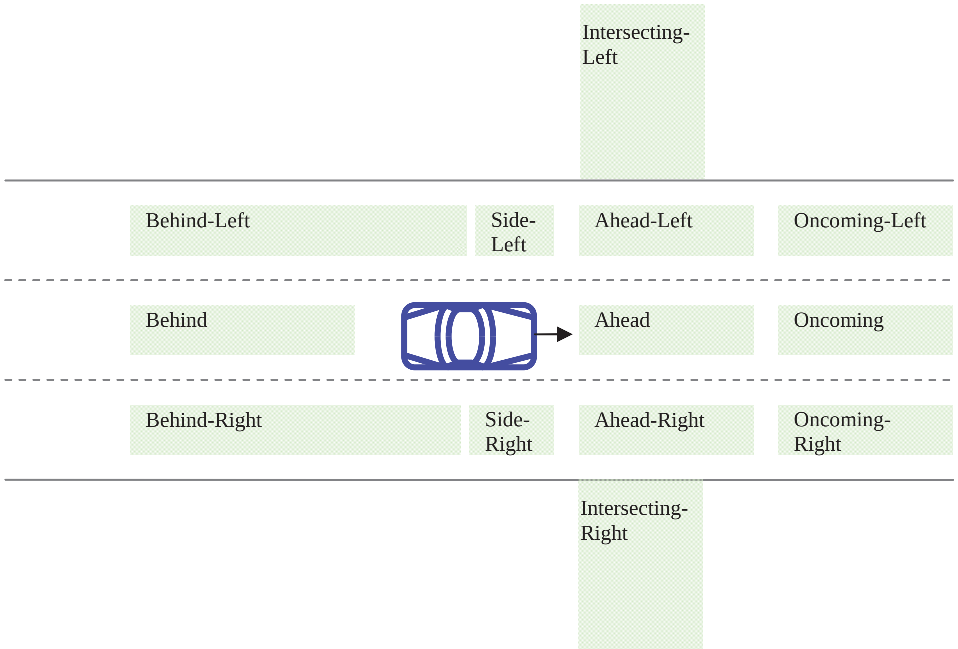

Figure 7: CLW Zone

(Note: The green blocks are shrunk in order to distinguish among various zones. The actual zones cover the entire lane width.)

11.7 Non-Line-of-Sight (NLOS) Threat Detection

CLW is intended to function even when the view to the threat vehicles is blocked by other vehicles, inclement weather, or terrain conditions.

11.7.1 Performance under NLOS Vehicle Obstruction

CLW shall function with at least one obstructing vehicle between the HV and the RV. The dimensions of an obstructing vehicle that satisfies this minimum performance requirement shall be no greater than 7.3 meters long, 2.2 meters high, and 2.4 meters wide.

11.8 False Positive Warnings

11.8.1 Remote CLW Vehicle Below Minimum Speed Threshold

CLW shall not set the vehicle's control loss status to TRUE if the control loss vehicle is traveling below the minimum operational speed threshold.

11.8.2 Host Vehicle Below Minimum Speed Threshold

CLW shall not issue a warning if the HV is traveling below the minimum operational speed threshold.

11.8.3 Remote Vehicle not Encountering CLW Event

CLW shall not issue a warning for a RV that did not have control loss, or one or more of the following systems were not engaged/activated longer than the threshold: ABS, ESC, and/or TC.

11.8.4 Remote Vehicle not in CLW Zone

CLW shall not issue a warning for a RV that is outside of the CLW zone.

11.8.5 Remote Vehicle not in the Same Travel Direction

CLW shall not issue a warning for a RV that is inside the CLW zone but not traveling in the specified direction in that sub-zone.

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Objective Test Procedures and Plan

List of Acronyms

BSW	Blind Spot Warning
BSW+LCW	Blind Spot Warning+Lane Change Warning
CAMP	Crash Avoidance Metrics Partnership
CAN	Controller Area Network
CLW	Control Loss Warning
CPU	Central Processing Unit
DMU	Dynamics Measurement Unit
DNPW	Do Not Pass Warning
DSRC	Dedicated Short Range Communications
DVI	Driver Vehicle Interface
DVIN	Driver Vehicle Interface Notifier
ECDSA	Elliptic Curve Digital Signature Algorithm
ECU	Electronic Control Unit
EEBL	Emergency Electronic Brake Lights
EGUI	Engineering Graphical User Interface
FCW	Forward Collision Warning
GPS	Global Positioning System
GUI	Graphical User Interface
HV	Host Vehicle
ID	Identifier
IMA	Intersection Movement Assist
ITS	Intelligent Transportation Systems
JPO	Joint Program Office
LCW	Lane Change Warning
MPR	Minimum Performance Requirements
NHTSA	National Highway Traffic Safety Administration
OEM	Original Equipment Manufacturer
OLRV	Oncoming Left Remote Vehicle
OTA	Over-the-Air
OTP	Objective Test Procedure(s)

RITA	Research and Innovative Technology Administration
RV	Remote Vehicle
TC	Target Classification
TRC	Transportation Research Center
USDOT	United States Department of Transportation
VDA	Vehicle Dynamics Area
VOD	Verify on Demand
VRTC	Vehicle Research & Testing Center
VSC	Vehicle Safety Communications
VSC2	Vehicle Safety Communications 2
VSC-A	Vehicle Safety Communications – Applications
V-V or V2V	Vehicle-to-Vehicle
WSU	Wireless Safety Unit

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1 Introduction

1.1 Purpose

This appendix describes the Objective Test Procedures (OTPs) developed for the VSC-A Project. The OTPs were designed to verify that the VSC-A test bed and its safety applications performed according to the VSC-A Minimum Performance Requirements [2]. In addition, the OTPs provided data that the Volpe National Transportation Systems Center uses to estimate the safety benefits of the VSC-A Project. The results of the OTPs can be found in the Objective Testing Results Appendix [3].

1.2 Scope

The tests described in this document are designed to validate the functionality of the VSC-A test bed and its applications at a system level. The warning timings that were chosen for the individual applications were selected for engineering purposes and do not represent actual warning timings that would be used in systems used by naïve drivers.

Sub-system performance is not evaluated as part of these procedures. If sub-systems were to fail during a test procedure but the system successfully warns or does not warn the driver as required by the procedures, the test is considered successful. Likewise, a failure of a sub-system that prevents a warning or warns inappropriately is considered an unsuccessful test. A failure of the system to warn when all subsystems are operating correctly is considered an unsuccessful test.

1.3 Procedure

Since the OTPs in this document test the application performance at the system level, only system-level-performance details need to be recorded during the test. Additional sub-system-level-performance details may be recorded to assist in diagnosing certain system or sub-system issues as long as this does not impact the results of the test.

For the OTPs, a successful test is a test in which: the procedure is correctly completed, all validation criteria are fulfilled, and during which the driver is warned or not warned as required by the test procedure. A warning is defined as the VSC-A Driver Vehicle Interface Notification (DVIN) module submitting a warning request to one or more warning modalities installed on the given test vehicle. The maximum delay from the application submitting a warning request to the DVI device presenting the alert is defined in the Minimum Performance Requirements document. Since the applications that are tested in this test plan do not have the final Driver Vehicle Interface (DVI), the tests will not include the latency of the DVI itself as evaluation criteria.

For the OTPs, an unsuccessful test is a test in which the driver was warned when a warning was not required by the test procedure or a test in which the driver was not warned when a warning was required by the test procedure.

Test procedures shall be conducted at a closed test facility. Open road testing is not part of the OTPs defined in this document.

Each test will involve at least two people, a test driver and a test observer, in the Host Vehicle (HV) in which the warning is tested. The test driver operates the vehicle as specified by the test procedure while concurrently the test observer observes and records test conditions, apparent test validity, and results. In the Remote Vehicle (RV) necessary for the tests, only a driver will be present. An RV is any other vehicle participating in the test so that the conditions for the HV to issue a warning are present. In this context a HV is defined as the test vehicle in which the correct issuing of the warning (or suppression of the warning in case of false positive tests) is tested.

1.4 Assumptions

It is assumed that the test observers are not naïve. It is assumed that the test drivers are familiar with the test procedures. It is also assumed that the test observers are familiar with the basic operation of the vehicle and the safety applications that are tested in the procedures. However, it is not assumed that the test observers and test drivers are knowledgeable of the sub-systems or the design and construction of the VSC-A system. This does not preclude VSC-A team members to drive the vehicles as test drivers in the objective tests.

1.5 Test Scenarios Overview

The tests specified in this document are grouped into test scenarios. A test scenario defines the test conditions, the test procedure, the expected results, and the number of test runs. A test run is one execution of the test scenario's test procedure.

The tests are divided into true positive tests and false positive tests. A true positive test is a test where the objective is to test whether the system issues a correct warning, defined as a necessary warning at the correct distance and/or time within the allowed error range, specified in each test scenario.

A false positive test is a test where the objective is to test whether the system can successfully avoid issuing a warning in a situation where no warning should be given. In contrast to the true positive tests, false positive tests have no successful/unsuccessful criteria associated with them.

Table 1-1 is an overview of test scenarios included in this document. Each scenario is presented with its name and a reference to the section that details its procedure.

Table 1-1: Test Scenario Table

Scenario Code	Name	Section	Test Type	Scenario Number
EEBL-T1	HV at constant speed with decelerating RV in same lane	4.1	True positive	1
EEBL-T2	HV at constant speed with decelerating RV in left lane on curve	4.2	True positive	2
EEBL-T3	HV at constant speed with decelerating RV in same lane and obstructing vehicle in between	4.3	True positive	3

Scenario Code	Name	Section	Test Type	Scenario Number
EEBL-T4	HV at constant speed with mild-decelerating RV in same lane	4.4	False positive	4
EEBL-T5	HV at constant speed with decelerating RV in 2nd right lane	4.5	False positive	5
FCW-T1	HV travel at a constant speed\RV stopped	5.1	True positive	6
FCW-T2	HV travel behind RV1/RV1 travel behind RV2/RV2 stopped	5.2	True positive	7
FCW-T3	HV drive on a curve/RV stopped at the curve	5.3	True positive	8
FCW-T4	HV tailgate RV	5.4	False positive	9
FCW-T5	HV follows RV/RV brakes hard	5.5	True positive	10
FCW-T6	HV driving into a curved right lane/RV stopped in the left curved lane	5.6	False positive	11
FCW-T7	HV travels behind a slower RV	5.7	True positive	12
FCW-T8	HV changes lanes behind a stopped RV	5.8	True positive	13
FCW-T9	HV approaches two RVs in left and right adjacent lanes and passes between them	5.9	False positive	15
BSW+LCW-T1	LCW Warning, Left	6.1	True positive	16
BSW+LCW-T2	LCW Warning, Right	6.2	True positive	17
BSW+LCW-T3	LCW Warning, Right with Left BSW Advisory	6.3	True positive	18
BSW+LCW-T4	BSW Advisory Alert, Left	6.4	True positive	19
BSW+LCW-T5	BSW Advisory Alert, Right	6.5	True positive	20
BSW+LCW-T6	No Warning or Advisory for RV behind HV	6.6	False positive	21
BSW+LCW-T7	No Warning or Advisory for RV in far right lane	6.7	False positive	22
BSW+LCW T8	LCW Warning in Curve, Right	6.8	True positive	23
DNPW-T1	Attempt to pass with oncoming RV in adjacent lane	7.1	True positive	24
DNPW-T2	Attempt to pass with stopped RV	7.2	True	25

Scenario Code	Name	Section	Test Type	Scenario Number
	in adjacent lane		positive	
DNPW-T3	Attempt to pass with oncoming RV not in adjacent lane	7.3	False positive	26
IMA-T1	Variable speed approaches with stopped HV/moving RV/open intersection	8.3	True positive	27
IMA-T2	Stopped HV/moving RV/open intersection	8.4	False positive	28
IMA-T3	Variable speed approaches with moving HV/moving RV/open intersection	8.5	True positive	29
IMA-T4	Moving HV/moving RV/open intersection	8.6	False positive	30
IMA-T5	Stopped HV/moving RV/open intersection/parked vehicle	8.7	True positive	31
CLW-T1	HV at constant speed with CLW RV in same lane ahead in same travel direction	9.1	True positive	32
CLW-T2	HV at constant speed with CLW RV in 2nd right lane	9.2	False positive	33
CLW-T3	HV at constant speed with CLW RV in adjacent lane ahead in opposite travel direction	9.3	True positive	34

1.6 Individual Test Successful and Unsuccessful Definitions

A test can be valid or invalid. Only a valid test can be defined as successful or unsuccessful. The results of an invalid test are not considered for successful/unsuccessful evaluation. As such, there are three test outcomes:

1. Invalid
2. Valid and Successful
3. Valid and Unsuccessful

These outcomes are defined in the sections below.

1.6.1 Test Validity

The test is valid only if all the following conditions are met:

- The recorded vehicle speed shall not deviate from the stated test speed by greater than +/-2.5 mph unless specified otherwise in the test scenarios
- The packet error rate (PER) of the Dedicated Short Range Communications (DSRC) message exchange between the HV and the RV shall not exceed 20 percent within a 300 meter separation distance between vehicles at any given

time, unless the test is designed to increase PER (for example, Emergency Electronic Brake Lights (EEBL) with obstructing vehicles). The PER is calculated both continuously as well as over a sliding 1-second window using the message sequence number as an indication of missing packets. The corruption of received packets is not required to be included in the PER calculation.

- The GPS coverage shall satisfy the following conditions:
  - For relative positioning solutions that uses Real-time Kinematic (RTK) Positioning:
    - The solution status shall indicate a RTK solution
    - The solution quality shall be four or less
  - For relative positioning solutions that do not use RTK:
    - The number of visible satellites in each vehicle shall be at least four
    - The number of common satellites visible from both vehicles shall be at least four
    - Both receivers shall operate in the same mode (i.e., with Wide Area Augmentation System (WAAS) or without WAAS)
    - Percent Dilution of Precision (PDOP) shall be less than 5.0
- The test vehicles shall be driven within 1.5 meters of the centerline of the lane of travel, unless required otherwise by the scenarios

Additional criteria are specified within the test procedures for each scenario.

1.6.2 Definition of Successful Test and Unsuccessful Test

The minimum requirements to determine successful or unsuccessful tests are:

- The test must be valid according to the test validity section and possible additional validation criteria within the test procedures
- A warning must be issued or not be issued as required by the individual test description
- For a true positive test, the warning repeatability measurement must meet the specified criteria indicated in each test description
- For false positive tests, no criteria for successful or unsuccessful will be specified

Additional requirements for a successful and unsuccessful test are defined in the appropriate subsection that describes each test. Overall test success of a scenario is defined as successful passes of eight (8) of ten (10) runs. Overall test success of an application is defined as successful passes of all the scenarios for that application. Overall test success of the project is defined as successful passes of all the applications. See Table 1-2 and Table 1-3 for example.

Table 1-2: Example of Test Result Table - EEBL-Successful

Test Nam	Speed	Comment	Tests Conducted	Tests Successful	Successful/ Unsuccessful
HV at constant speed with decelerating RV in same lane	50		10	10	Successful
HV at constant speed with decelerating RV in left lane on curve	50		10	8	Successful
HV at constant speed with decelerating RV in same lane and obstructing vehicle in between	50		10	10	Successful
HV at constant speed with mild-decelerating RV in same lane	50		10	10	Successful
HV at constant speed with decelerating RV in 2nd right lane	50		10	10	Successful
EEBL-Overall					**Successful**

Table 1-3: Example of Test Result Table – EEBL-Unsuccessful

Test Name	Speed	Comment	Tests Conducted	Tests Successful	Successf Unsucces
HV at constant speed with decelerating RV in same lane	50		10	10	Successful
HV at constant speed with decelerating RV in left lane on curve	50		10	8	Successful
HV at constant speed with decelerating RV in same lane and obstructing vehicle in between	50		10	7	Unsuccessful
HV at constant speed with mild-decelerating RV in same lane	50		10	10	Successful
HV at constant speed with decelerating RV in 2nd right lane	50		10	10	Successful
Overall					**Unsuccessful**

2 Objective Test Procedures Requirements

The following sections provide a description of the general requirements for conducting the tests described in this document. This description is intended to describe the test requirements sufficiently in order to allow objective testing to be conducted at any sufficiently equipped vehicle test facility.

2.1 General Requirements

This document section defines the requirements for data collection and the test facility for all applications. In addition, the specific test scenarios may define additional requirements based on the test.

2.1.1 Vehicle-Vehicle Data Exchange

The Over-the-Air (OTA) data elements exchanged among the vehicles are described in the latest published standards document SAE J2735 Basic Safety Message (BSM).

2.1.2 Data Collection/Logging Requirements

The following data elements must be collected for the HV and RVs for all tests described in this document:

- Number of Global Position System (GPS) satellites visible and each satellite ID recorded using the GPS receiver's output
- PDOP and Horizontal Dilution of Positioning (HDOP) recorded using the GPS receiver's output
- Target Classification (TC) related data logged on the HV system for each RV: Vehicle ID, Range, Range rate, Velocity, Azimuth, Location relative to HV, Longitudinal Offset, Longitudinal Path Distance between HV and RV, Lateral Offset, and Relative Speed. For the Intersection Movement Assist (IMA) application, additional data logged includes the HV's distance to intersecting point, the RV's distance to intersecting point. In addition to the data listed, each application may define additional data that should be logged to evaluate the test validity and success
- Warning status of the applications including RV vehicle identification (ID), and warning level
- Vehicle latitude and longitude
- System configuration settings if different from the system configuration in the test plan
- Message sequence number defined in SAE J2735 BSM Part I
- Vehicle speed with at least 0.5 mph resolution using the output from the test vehicle's Controller Area Network (CAN) bus
- Vehicle left and right turn signal status
- Vehicle brake status recorded using the vehicle brake status output
- Vehicle Traction Control/Stability Control/Anti-lock Braking System (ABS) status recorded using the vehicle sensor output

- Numeric data rate shall be 10 Hz or greater. Video shall be recorded at 15 Hz or greater
- Vision sensor data including forward target range, lane offsets and lane change state
- Cone position, distance, and time-to-pass-cone setup for each test scenario if the setup deviates from the specification described in each scenario
- HV lane assignment and RV lane assignment
- Video recording of views necessary to view the test. For example, Forward view for EEBL/Forward Collision Warning (FCW), side views for Blind Spot and Lane Change Warning

2.1.3 Environmental and Roadway Conditions

All the track test scenarios shall be conducted in the following conditions unless specified otherwise:

- Daytime
- Good atmospheric visibility
- Dry pavement
- Smooth pavement
- Well-marked lanes with the lane width of at least 3.6 meters

The definition of the above environmental variables can be found in the CAMP-NHTSA FCW report [1].

Unless otherwise stipulated in the test itself, the road geometry for each test should be straight and flat, where straight means the road having a horizontal curvature of less than 0.1 km (curvature radius greater than 10000m) and flat means a grade of less than 0.1 percent. (Refer to [1])

2.2 Assumptions

Unless required by the test, the driver of the HV shall not press the brakes when the vehicle is expecting a warning because most of the applications are designed to suppress the warnings once the vehicle brake status is on.

2.3 Test Facility Requirements

All tests will be conducted in a closed facility (no public access or open roadways). To support the objective tests, the minimum requirements are:

- A straight road with at least three lanes and a length of 1200 meters
- A curved road with at least two lanes with an inside curve radius that allows the conduction of the curve tests at the test speed. This curve should reflect curves normally found on freeways. A curve radius of larger than 250 meters is preferred.

- An intersection of two, 2-lane roads that represent a normal stop-controlled intersection
- The approaches should be at least 150 meters in length. If such an intersection is not available at the test facility, it can be substituted by an intersection that is laid out by using cones on a flat area such as a parking lot or a Vehicle Dynamics Area (VDA) found on vehicle proving grounds.
- The width of the intersection box should be at least 7.2 meters, representing a lane width of 3.6 meters

The objective tests for the VSC-A Project were conducted at the Transportation Research Center (TRC) in East Liberty, Ohio. For the tests, the following facilities were used:

- The airplane landing strip/skid pad as the 1200 meter straight road for the straight road tests in Emergency Electronic Brake Lights (EEBL), Forward Collision Warning (FCW), Blind Spot Warning+Lane Change Warning (BSW+LCW), and Do Not Pass Warning (DNPW) tests
- The VDA with the 233 meter radius loop for the curve tests in EEBL, BSW+LCW, and FCW
- The VDA for the Intersection Movement Assist (IMA) and Control Loss Warning (CLW) tests

3 Evaluation of Results

Collision alert test procedures are driving maneuvers involving two or more vehicles. These maneuvers are designed in such a way that the countermeasure-equipped HV encounters situations that should trigger a collision alert for a countermeasure system that meets the minimum functional requirements. The significant data from each test run is a comparison of the position, velocity, and/or timing at which the collision alert onset actually occurred (if they occurred) and the position, velocity, and/or timing at which the alerts were required to occur.

Data analysis must evaluate and document the performance of the countermeasure for the required alerts. Due to the variations in range, velocity, and acceleration of the vehicles when performing maneuvers, the alert onset for each individual test run may vary. The nominal alert criteria should not be used as the pass/fail criteria for a test run. Rather, the alert criteria should be recomputed for each test run using the actual (achieved) range, velocity, and acceleration variables. For example, a test procedure may specify a 60 mph speed for the HV. The actual test run may report the HV traveling at 58 mph rather than the nominal 60 mph. The 2 mph difference in speed may result in different alert criteria minimum and maximum for the test run. Instead of using the 60 mph nominal alert criteria values, the alert criteria values should be recomputed for the 58 mph speed to determine the pass/fail of the test run.

The computation of the test run alert criteria should be performed by the same mechanism that generated the original nominal alert criteria given in the test procedure. With the new alert criteria, pass/fail of the test run may be determined.

The maximum and minimum alert criteria are ± X percent of the nominal alert criteria. For example, if the alert criterion is the range at which the alert occurred and if X percent of the nominal alert range is 0.5 meters, the maximum and minimum alert ranges are the nominal alert range ± 0.5 meters.

[Note: Each test will have a different computed ± X percent based on possible alert criteria calculations that factors in test conditions, system delays, and possible test run failures.]

Alert onset for an individual run should not occur outside of the allowable alert range. If alert onset occurs between the minimum and maximum ranges specified by the computed values for the test run, the countermeasure passes the test run. Unless otherwise noted, the countermeasure must pass eight out of ten test runs for the test to be successful.

4 EEBL Objective Test Procedures

The operational goal of EEBL as defined in the Concept of Operations is to warn the driver of a hard braking event by a vehicle ahead in the traffic, even when the driver's view is obstructed by other vehicles or bad weather conditions.

To pass this objective test, the system must warn the driver when one or more leading vehicles apply the brakes and decelerate at a level exceeding that as called for in the minimum performance specifications. The following scenarios are selected to cover the typical EEBL cases with RVs in the same lane/left lane/right lane while traveling in the same direction ahead of the HV. A single speed setting of 50 mph is selected as a moderate and appropriate representative speed for EEBL objective testing.

4.1 EEBL-T1: HV at Constant Speed with Decelerating RV in Same Lane

4.1.1 Background

This test is to verify that the EEBL system will issue a warning when the brakes of a vehicle in its forward path and direction of travel have been applied abruptly and the instantaneous braking of the RV exceeds the braking threshold as defined by the application. While the primary objective of the EEBL system is to enhance driver visibility of potential hazards via wireless communication amongst similarly equipped vehicles, this test can be used to verify EEBL performance in the presence of obstructing vehicles and/or adverse weather conditions that obstructs the view of the RV from the HV.

An illustration of this test procedure is shown in Figure 4-1.

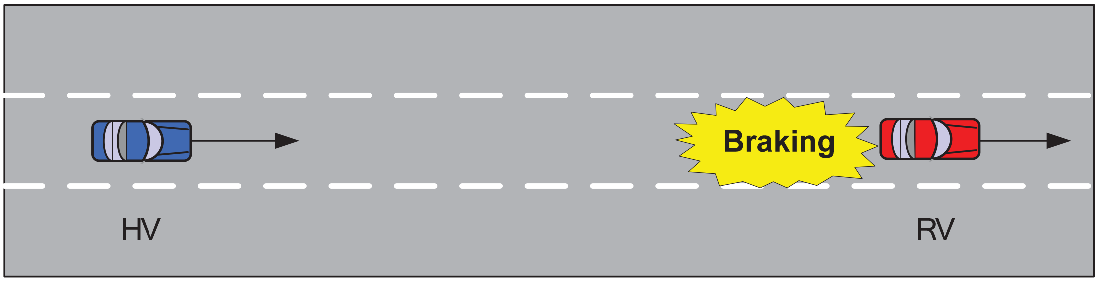

Figure 4-1: RV in Same Lane

4.1.2 Scenario Specific Test Assumptions

None.

4.1.3 Test Setup

Cones with flags will be placed so the driver of the HV is aware of the vehicle's location in reference to the required maneuvers. These flags will be located by their distance from the starting point for the HV. It is assumed that flags will be placed using a L1 GPS handheld receiver. Alternate methods of flag location can be used.

Flag locations are: Red flags placed at the starting point where the HV and RV begin their maneuver (flags not shown in the figure).

4.1.4 Scenario Specific Initial Conditions

- The RV's deceleration shall occur at 0.4 g or greater and continue decelerating to reach at least 0.5 g or greater
- The headway between the HV and RV should be greater than 3 seconds

4.1.5 Driving Instructions

- The RV starts at the red flag, accelerates to 50 mph, and maintains this speed in the center lane.
- The HV starts at the red flag, accelerates to 50 mph, and maintains this speed in the center lane, leaving at least a 3 second headway to the RV
- Once the RV test observer and the HV test observer communicate to each other that 50 mph is maintained, the RV decelerates hard and then stops
- The HV observes the warning and comes to a stop

4.1.6 Successful Criteria

The HV issues a warning to the driver within the maximum latency specified in the Minimum Performance Requirements EEBL application section for at least six out of eight test runs.

4.1.7 Unsuccessful Criteria

The test is Unsuccessful if the warning is not issued or is issued outside the time range specified in the successful criteria for three or more out of eight test runs.

4.1.8 Evaluation Criteria

Number of Valid Test Runs	HV Speed (mph)	RV Speed (mph)	Number of Successful Test Runs
8	50	50	>= 6

4.2 EEBL-T2: HV at Constant Speed with Decelerating RV in Left Lane on Left Curve

4.2.1 Background

This test is to verify that the EEBL system will issue a warning on a curved road when a vehicle traveling in the same direction and in the forward path and adjacent left lane applies its brakes in an abrupt manner. The EEBL system will issue a warning for vehicles in the same lane and adjacent lanes.

An illustration of this test procedure is shown in Figure 4-2.

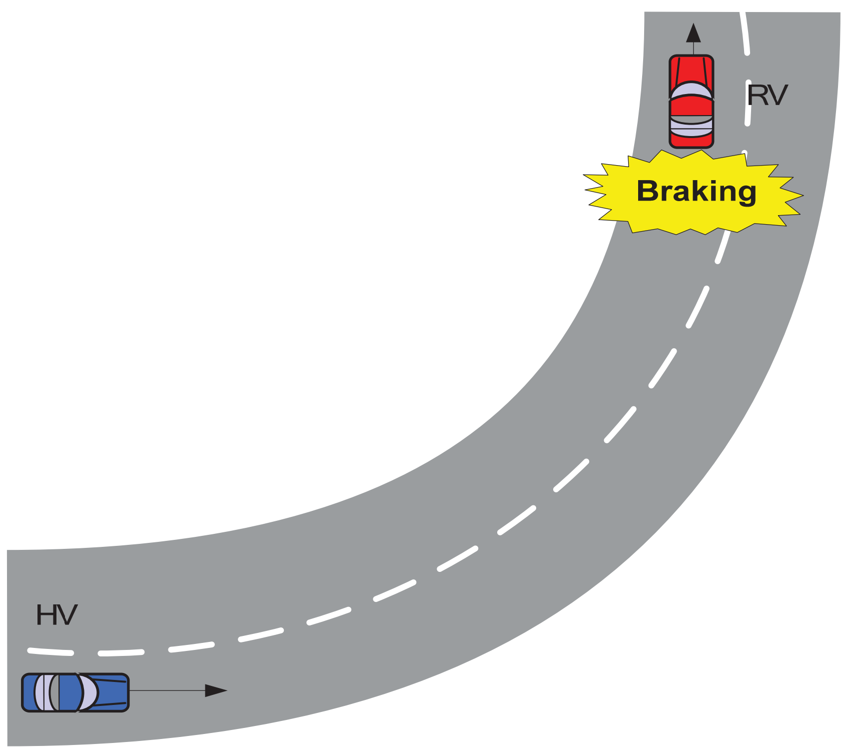

Figure 4-2: RV in Left Lane

4.2.2 Scenario Specific Test Assumptions

None.

4.2.3 Test Setup

Cones with flags will be placed so the drivers of the HV and RV are aware of the vehicle's location in reference to the required maneuvers. These flags will be located by their distance from the starting point for the HV and RV. It is assumed that flags will be placed using a L1, GPS handheld receiver. Alternate methods of flag location can be used.

Flag locations are: Red flags placed at the starting point where the HV and RV begin their maneuver (flags not shown in the figure).

4.2.4 Scenario Specific Initial Conditions

- The RV's hard deceleration shall occur at 0.4 g or greater and continue decelerating to reach at least 0.5 g or greater
- Headway between the HV and RV should be greater than 3 seconds until the RV begins deceleration
- The HV and RV shall both be on the constant radius portion of the curve with a 233 meter curve radius (based on test facility used)

4.2.5 Driving Instructions

- The RV starts at the red flag, accelerates to 50 mph, and maintains this speed in the left lane
- The HV starts at the red flag, accelerates to 50 mph and maintains this speed in the right lane, leaving at least 3 seconds of headway to the RV
- Once the RV test observer and the HV test observer communicate to each other that 50 mph is maintained, the RV decelerates hard then stops
- The HV responds to the warning and stops

4.2.6 Successful Criteria

The HV issues a warning to the driver within the maximum latency as specified in the Minimum Performance Requirements EEBL application section for at least six out of eight test runs.

4.2.7 Unsuccessful Criteria

The test is unsuccessful if the warning is missed or issued outside the time range specified in the successful criteria for three or more out of eight test runs.

4.2.8 Evaluation Criteria

Number of Valid Test Runs	HV Speed (mph)	RV Speed (mph)	Number of Successful Test Runs
8	50	50	≥ 6

4.3 EEBL-T3: HV at Constant Speed with Decelerating RV in Same Lane and Obstructing Vehicle in Between

4.3.1 Background

This test is to verify that the EEBL system will issue a warning when the brakes of a vehicle within its forward path and direction of travel have been applied in an abrupt manner, and the line of sight of the view to the braking vehicle is blocked (e.g., by a truck). This test can be used to verify EEBL performance in the presence of obstructing vehicles and/or adverse weather conditions. An illustration of this test procedure is shown in Figure 4-3.

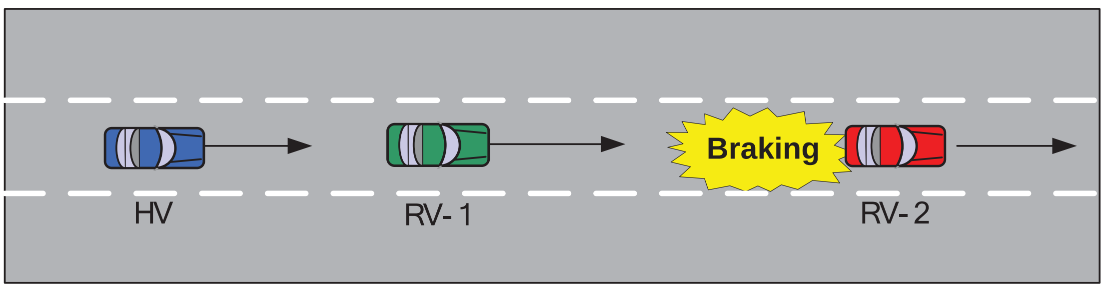

Figure 4-3: RV in Same Lane with Blocking Vehicle

4.3.2 Scenario Specific Test Assumptions

None.

4.3.3 Test Setup

Cones with flags will be placed so the driver of the HV is aware of the vehicle's location in reference to the required maneuvers. These flags will be located by their distance from the starting point for the HV. It is assumed that flags will be placed using a L1 GPS handheld receiver. Alternate methods of flag location can be used.

Flag locations are: Red flags placed at the starting point where the HV, RV-1, and RV-2 begin their maneuver (flags not shown in the figure).

4.3.4 Scenario Specific Initial Conditions

- The RV's deceleration shall occur at 0.4 g or greater and continue decelerating to reach at least 0.5 g or greater
- Headway between the HV and RV-1 should be greater than 3 seconds until RV-2 begins deceleration

4.3.5 Driving Instructions

- RV-2 starts at the red flag, accelerates to 50 mph, and maintains this speed in the center lane
- RV-1 starts at the red flag, accelerates to 50 mph, and maintains this speed in the center lane, leaving at least a 3-second headway to RV-2
- The HV starts at the red flag, accelerates to 50 mph, and maintains this speed in the center lane, leaving at least a 3-second headway to RV-1
- Once the RV test observer and the HV test observer communicate to each other that 50 mph is maintained, the RV-2 decelerates hard and then stops
- RV-1 observes the warning and comes to a stop
- HV observes the warning and comes to a stop

4.3.6 Successful Criteria

The HV issues a warning to the driver within the maximum latency as specified in the Minimum Performance Requirements EEBL application section for at least six out of eight test runs.

4.3.7 Unsuccessful Criteria

The test is unsuccessful if the warning is missed or issued outside the time range specified in the successful criteria for three or more out of eight test runs.

4.3.8 Evaluation Criteria

Number of Valid Test Runs	HV Speed (mph)	RV Speed (mph)	Number of Successful Test Runs
8	50	50	≥ 6

4.4 EEBL-T4: HV at Constant Speed with Mild-Decelerating RV (False Positive)

4.4.1 Background

This test is to verify that the EEBL system will NOT issue a warning when the brakes of a vehicle inside of the HV's forward-path (including immediate adjacent lanes) traveling in the same direction have been applied below the threshold set for the activation of the EEBL event. An illustration of this test procedure is shown in Figure 4-4.

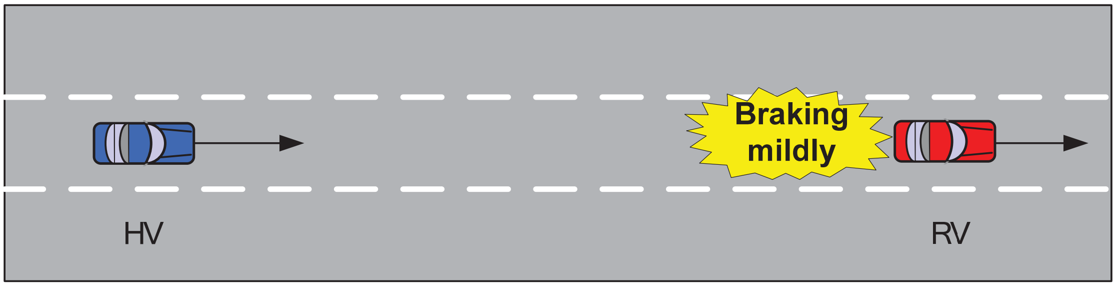

Figure 4-4: RV in Same Lane, Mildly Braking

4.4.2 Scenario Specific Assumptions

None.

4.4.3 Test Setup

Cones with flags will be placed so the drivers of the HV and RV are aware of the vehicle's location in reference to the required maneuvers. These flags will be located by their distance from the starting point for the HV. It is assumed that flags will be placed using a L1, GPS handheld receiver. Alternate methods of flag location can be used.

Flag locations are: Red flag placed at the starting point where the HV and RV begin their maneuver (flags not shown in the figure).

4.4.4 Scenario Specific Initial Conditions

- The RV will decelerate mildly with deceleration less than 0.4 g
- Headway between the HV and RV should be at least 3 seconds until the RV begins deceleration

4.4.5 Driving Instructions

- The RV starts at the red flag, accelerates to 50 mph, and maintains this speed in the center lane
- The HV starts at the red flag, accelerates to 50 mph, and maintains this speed in the center lane, leaving at least a 3-second headway to the RV
- Once the RV test observer and the HV test observer communicate to each other that 50 mph is maintained, the RV decelerates below the EEBL deceleration threshold and then stops
- The HV observes the RV's braking and comes to a stop

4.4.6 Successful Criteria

None.

4.4.7 Unsuccessful Criteria

None.

4.4.8 Evaluation Criteria

Number of Valid Test Runs	HV Speed (mph)	RV Speed (mph)	Number of Successful Test Runs
2	50	50	N/A

4.5 EEBL-T5: HV at Constant Speed on Straight Road with Decelerating RV in Second Right Lane (False Positive)

4.5.1 Background

This test is to verify that the EEBL system will NOT issue a warning when the brakes of a vehicle outside of the HV's forward path (including immediate adjacent lanes) and in the same direction of travel have been applied in an abrupt manner. An illustration of this test procedure is shown in Figure 4-5.

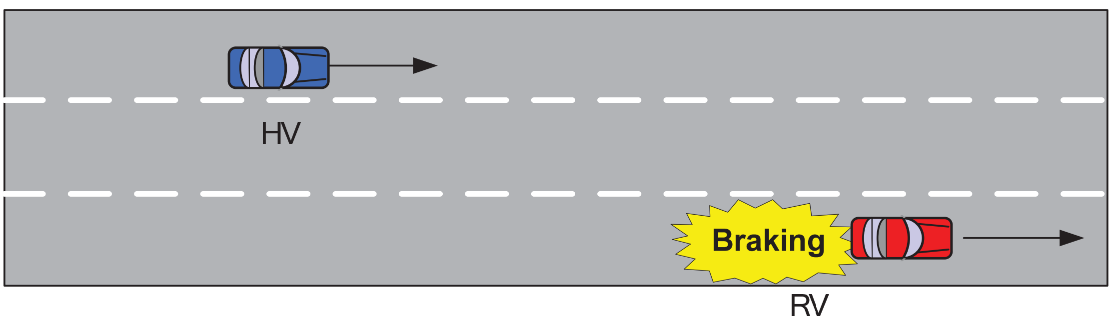

Figure 4-5: RV in 2nd Right Lane

4.5.2 Scenario Specific Test Assumptions

None.

4.5.3 Test Setup

Cones with flags will be placed so the drivers of the HV and RV are aware of the vehicle's location in reference to the required maneuvers. These flags will be located by their distance from the starting point for the HV. It is assumed that flags will be placed using a L1, GPS handheld receiver. Alternate methods of flag location can be used.

Flag locations are: Red flag placed at the starting point where the HV and RV begin their maneuver (flags not shown in the figure).

4.5.4 EEBL Specific Initial Conditions

- The RV's deceleration shall occur at 0.4 g or greater
- Headway between the HV and RV should be at least 3 seconds until the RV begins deceleration

4.5.5 Driving Instructions

- The RV starts at the red flag, accelerates to 50 mph, and maintains this speed in the right lane (right of the center lane)
- The HV starts at the red flag, accelerates to 50 mph, and maintains this speed in the left lane (left of the center lane), leaving at least a 3-second headway to the RV
- Once the RV test observer and the HV test observer communicate to each other that 50 mph is maintained, the RV decelerates hard and then stop
- The HV observes whether a warning is issued and comes to a safe stop

4.5.6 Successful Criteria

None.

4.5.7 Unsuccessful Criteria

None.

4.5.8 Evaluation Criteria

Number of Valid Test Runs	HV Speed (mph)	RV Speed (mph)	Number of Successful Test Runs
2	50	50	N/A

5 FCW Objective Test Procedures

Forward Collision Warning (FCW) is a vehicle-to-vehicle (V2V) communication based safety feature that issues a warning to the driver of the HV in case of an impending rear-end collision with a vehicle ahead in traffic in the same lane and direction of travel. FCW will help drivers in avoiding or mitigating rear-end vehicle collisions in the forward path of travel.

5.1 FCW-T1: HV Travel at a Constant Speed to a Stopped RV

5.1.1 Background

This test begins with the HV traveling on a straight, flat road at 50 mph. Ahead of the HV, in the same lane, is a single RV stopped in the lane of travel. The test determines whether the countermeasure’s required collision alert occurs at the expected range. This test especially explores the ability of the countermeasure to accurately identify stationary in-path targets on a flat, straight road.

5.1.2 Scenario Specific Assumptions

None.

5.1.3 Test Setup

Figure 5-1, below, shows the vehicle positions and test setup for Test 1.

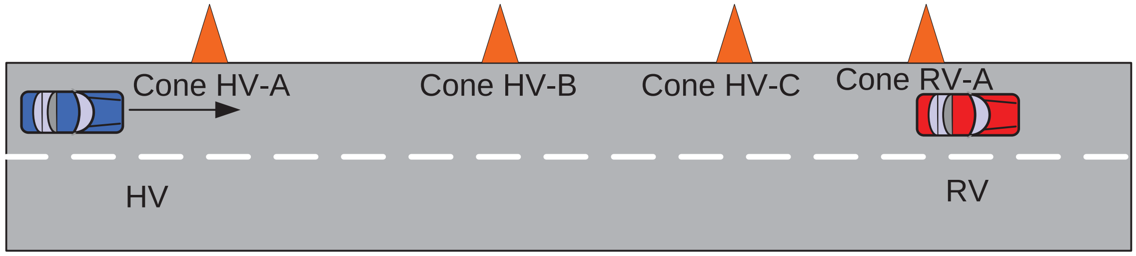

Figure 5-1: RV in Same Lane

Cones with flags will be placed so the driver of the HV is aware of the vehicle's location in reference to the required maneuvers. These flags will be located by their distance from the starting point for the HV. It is assumed that flags will be placed using a L1 GPS handheld receiver. Alternate methods of flag location can be used. Flag locations are:

- A red flag is placed at the starting point where the HV begins its maneuver (cone not shown)
- A yellow flag is placed at the point where the HV reaches the target speed (cone HV-A), at least 650 meters from the red flag
- A white flag is placed at the earliest valid (from the driver's perspective) WARN point (cone HV-B)
- A checkered flag is placed where the HV will make an evasive maneuver by changing lanes if the WARN has failed to occur (cone HV-C) which is positioned at 90 percent of the allowable alert range. At the test speed of 50 mph, this is 9 meters from HV-B cone
- A green flag is placed at the stopping position for the RV (cone RV-A), at least 800 meters from the red flag

5.1.4 Driving Instructions

- The RV begins at the starting point and stops with its front bumper at the green flag.
- The HV starts accelerating at least 800 meters behind the RV in the same lane to reach a speed of 50 mph.
- The HV Cruise Control is set at the required speed of 50 mph.
- The HV Cruise Control shall be engaged at least 150 meters behind the RV.
- The warning will be given at around the nominal warn range (cone HV-B) after which the HV will change lane.

[Note: If the warning is not given when the HV reaches the checkered flag (cone HV-C), the HV shall make an evasive maneuver by changing lanes and come to a safe stop in the adjacent lane.]

5.1.5 Successful Criteria

- The collision alert shall occur within the ranges specified in Table 5-1 in order to pass the run
- If at least six runs out of eight runs pass, then the test is successful

5.1.6 Unsuccessful Criteria

A run is unsuccessful if any of the conditions below occur:

- Collision alert occurrence outside the range calculated in Table 5-1 using run-specific variables
- The warning is missed such that the HV passes cone HV-C and no alert is triggered
- If at least three runs out of eight runs fail, the test is unsuccessful

Table 5-1: Alert Range for Test 5.1

	Collision Alert Test
Maximum Range	93.7
Nominal Range	85.2
Minimum Range	76.7

5.1.7 Evaluation Criteria

Number of Valid Test Runs	**HV Speed (mph)**	**RV Speed (mph)**	**Number of Successful Test Runs**
8	50	0	≥ 6

5.2 FCW-T2: HV Following RV1, and RV1 Changes Lanes to Reveal Stopped RV2

5.2.1 Background

This test begins with the HV traveling on a straight, flat road at a speed of 50 mph. Ahead of the HV, in the same lane, is a single RV-2 traveling at the same speed as the HV. The HV is following RV-2 at a small distance. Far ahead of the RV-2 is another vehicle, RV-1, stopped in the lane. RV-2 changes lanes to avoid the stopped RV-1. During this test, the HV maintains a constant speed until the required warning alert is triggered. The brakes are applied and the HV comes to a complete stop before a collision with RV-1. The test determines whether the countermeasure's required alert occurs at a range that is consistent with the collision alert onset timing requirements. This test especially explores the ability of the countermeasure to switch primary targets and issue timely alerts.

5.2.2 Scenario Specific Assumptions

None.

5.2.3 Test Setup

Figure 5-2, below, shows the vehicle positions and test setup for Test 2.

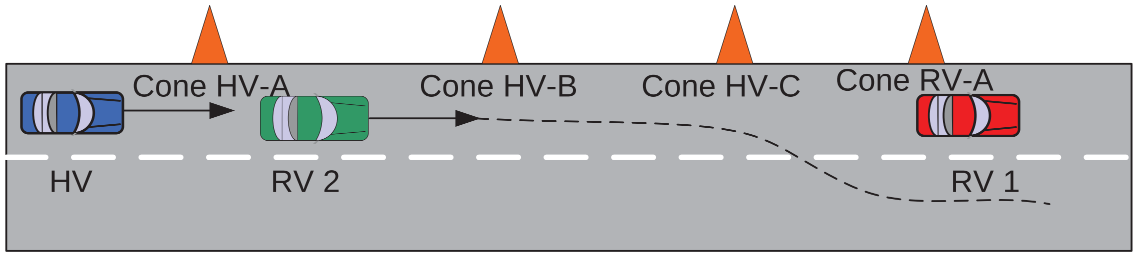

Figure 5-2: Lane Change Reveals Stopped RV

Cones with flags will be placed so the driver of the HV is aware of the vehicle's location in reference to the conflict point. These flags will be located by their distance from the starting point for the HV. It is assumed that flags will be placed using a L1 GPS handheld receiver. Alternate methods of flag location can be used. Flag locations are:

- A red flag is placed at the starting point where the HV and RV-1 begin their maneuver (cone not shown)
- A green flag is placed at the point where RV-2 starts its maneuver (cone not shown) 20 meters from red flag
- A yellow flag is placed at the point where the HV and RV-2 reach the target speed (cone HV-A), at least 650 meters from the red flag
- A white flag is placed at the earliest valid (from the driver's perspective) WARN point (cone HV-B). RV-2 starts the late lane change maneuver after passing cone HV-B
- A checkered flag is placed where the HV will make an evasive maneuver by changing lanes if the WARN has failed to occur (cone HV-C) which is positioned at 90 percent of the allowable alert range. At the test speed of 50 mph, this is 9 meters from the HV-B cone.
- A rainbow flag is placed at the stopping position for the RV-1, at least 800 meters from the starting point

5.2.4 Driving Instructions

- The RV-1 drives for at least 800 meters in the left lane and stops at the green flag
- The RV-2 drives and stops at the green flag in the left lane
- The RV-2 accelerates to reach a constant speed of 50 mph at which time the Cruise Control is set
- The HV accelerates to reach a constant speed of 50 mph at which time the Cruise Control is set
- The HV and RV-2 Cruise Control shall be engaged by the time it reaches cone HV-A

- The RV-2 will make a late transition to the right lane after passing HV-B and keeps on driving
- The warning will be given around the nominal warn range at the white flag (cone HV-B) after which the HV shall change lanes and come to a safe stop

[Note: IF the warning is not given when the HV reaches the checkered flag (cone HV-C), the HV shall make an evasive maneuver by changing lanes and come to a safe stop.]

[Note: The range between the HV and RV-2 may not deviate from the nominal range by more than one vehicle length after cone HV-A is passed.]

5.2.5 Successful Criteria

- The warning shall occur within the ranges specified in Table 5-2 in order to pass the run
- If at least six runs out of eight runs pass, then the test is successful

5.2.6 Unsuccessful Criteria

A run fails if any of the conditions below occur:

- A warning occurs outside the range calculated in Table 5-2 using run-specific variable results
- The warning is missed such that the HV passes cone HV-C and no warning is triggered
- The test fails if at least three runs out of eight runs fail

Table 5-2: Alert Range for Test 5.2

	Collision Alert Test
Maximum Range	93.7
Nominal Range	85.2
Minimum Range	76.7

5.2.7 Evaluation Criteria

Number of Valid Test Runs	**HV Speed (mph)**	**RV1 Speed (mph)**	**RV2 Speed (mph)**	**Number of Successful Test Runs**
8	50	50	0	≥ 6

5.3 FCW-T3: HV Encounters Stopped RV, Both in Curve

5.3.1 Background

This test begins with the HV traveling on a curved road at a speed of 50 mph. Ahead of the HV, in the same lane, is a single stationary RV. The test determines whether the countermeasure's required collision alert occurs at the expected ranges. This test especially explores the ability of the countermeasure to accurately identify stationary in-path targets around a curve and generate a warning at the expected range.

5.3.2 Scenario Specific Assumptions

None.

5.3.3 Test Setup

Figure 5-3, below, shows the vehicle positions and test setup for Test 3.

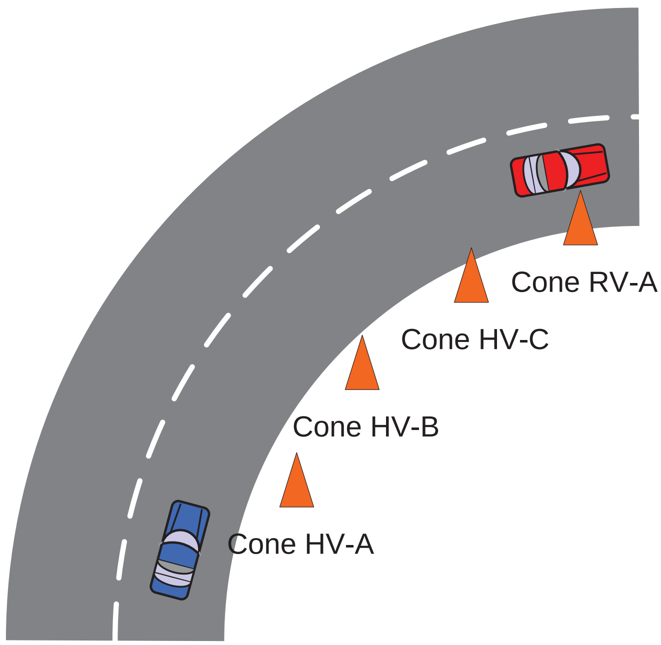

Figure 5-3: HV Drives on Curve/RV Stopped

Cones with flags will be placed so the driver of the HV is aware of the vehicle's location in reference to the conflict point. These flags will be located by their distance from the starting point for the HV. It is assumed that flags will be placed using a L1 GPS handheld receiver. Alternate methods of flag location can be used. Flag locations are:

- A red flag is placed at the starting point where the HV begins its maneuver (cone not shown)
- A yellow flag is placed at the point where the HV reaches the target speed (cone HV-A), at least 650 meters from the red flag

- A white flag is placed at the earliest valid (from the driver's perspective) WARN point (cone HV-B)
- A checkered flag is placed where the HV will make an evasive maneuver by changing lanes if the WARN has failed to occur (cone HV-C) which is positioned at 90 percent of the allowable alert range. At the test speed of 50 mph, this is 9 meters from the white flag (cone HV-B).
- A green flag is placed at the stopping position for the RV, at least 800 meters from the red flag

Both vehicles are well into the curve of 800 meter radius (based on availability).

5.3.4 Driving Instructions

- The RV starts at the starting point and stops with its front bumper at the green flag
- The HV starts accelerating at least 800 meters behind the RV in the same lane to reach a speed of 50 mph
- The HV Cruise Control is set at the required speed of 50 mph
- The HV Cruise Control shall be engaged at least 150 meters behind the RV
- The warning will be given at around the nominal warn range at the white flag (cone HV-B) after which the HV shall change lanes

[Note: If the warning is not given when the HV reaches the checkered flag (cone HV-C), the HV shall make an evasive maneuver by changing lanes.]

5.3.5 Successful Criteria

- The collision alert shall occur within the ranges specified in Table 5-3 in order to pass the run
- If at least six runs out of eight runs pass, then the test is successful

5.3.6 Unsuccessful Criteria

A run fails if any of the conditions below occur:

- Collision alert occurs outside the range calculated in Table 5-3 using run-specific variables
- The warning is missed such that the HV passes cone HV-C and no alert is triggered
- The test fails if at least three out of eight runs fail

Table 5-3: Alert Range for Test 5.3

	Collision Alert Test
Maximum Range	93.7
Nominal Range	85.2
Minimum Range	76.7

Table 1-2: Example of Test Result Table - EEBL-Successful

Test Nam	Speed	Comment	Tests Conducted	Tests Successful	Successful/ Unsuccessful
HV at constant speed with decelerating RV in same lane	50		10	10	Successful
HV at constant speed with decelerating RV in left lane on curve	50		10	8	Successful
HV at constant speed with decelerating RV in same lane and obstructing vehicle in between	50		10	10	Successful
HV at constant speed with mild-decelerating RV in same lane	50		10	10	Successful
HV at constant speed with decelerating RV in 2nd right lane	50		10	10	Successful
EEBL-Overall					**Successful**

Table 1-3: Example of Test Result Table – EEBL-Unsuccessful

Test Name	Speed	Comment	Tests Conducted	Tests Successful	Successf Unsucces
HV at constant speed with decelerating RV in same lane	50		10	10	Successful
HV at constant speed with decelerating RV in left lane on curve	50		10	8	Successful
HV at constant speed with decelerating RV in same lane and obstructing vehicle in between	50		10	7	Unsuccessful
HV at constant speed with mild-decelerating RV in same lane	50		10	10	Successful
HV at constant speed with decelerating RV in 2nd right lane	50		10	10	Successful
Overall					**Unsuccessful**

2 Objective Test Procedures Requirements

The following sections provide a description of the general requirements for conducting the tests described in this document. This description is intended to describe the test

Scenario Code	Name	Section	Test Type	Scenario Number
	in adjacent lane		positive	
DNPW-T3	Attempt to pass with oncoming RV not in adjacent lane	7.3	False positive	26
IMA-T1	Variable speed approaches with stopped HV/moving RV/open intersection	8.3	True positive	27
IMA-T2	Stopped HV/moving RV/open intersection	8.4	False positive	28
IMA-T3	Variable speed approaches with moving HV/moving RV/open intersection	8.5	True positive	29
IMA-T4	Moving HV/moving RV/open intersection	8.6	False positive	30
IMA-T5	Stopped HV/moving RV/open intersection/parked vehicle	8.7	True positive	31
CLW-T1	HV at constant speed with CLW RV in same lane ahead in same travel direction	9.1	True positive	32
CLW-T2	HV at constant speed with CLW RV in 2nd right lane	9.2	False positive	33
CLW-T3	HV at constant speed with CLW RV in adjacent lane ahead in opposite travel direction	9.3	True positive	34

1.6 Individual Test Successful and Unsuccessful Definitions

A test can be valid or invalid. Only a valid test can be defined as successful or unsuccessful. The results of an invalid test are not considered for successful/unsuccessful evaluation. As such, there are three test outcomes:

1. Invalid
2. Valid and Successful
3. Valid and Unsuccessful

These outcomes are defined in the sections below.

1.6.1 Test Validity

The test is valid only if all the following conditions are met:

- The recorded vehicle speed shall not deviate from the stated test speed by greater than +/-2.5 mph unless specified otherwise in the test scenarios
- The packet error rate (PER) of the Dedicated Short Range Communications (DSRC) message exchange between the HV and the RV shall not exceed 20 percent within a 300 meter separation distance between vehicles at any given

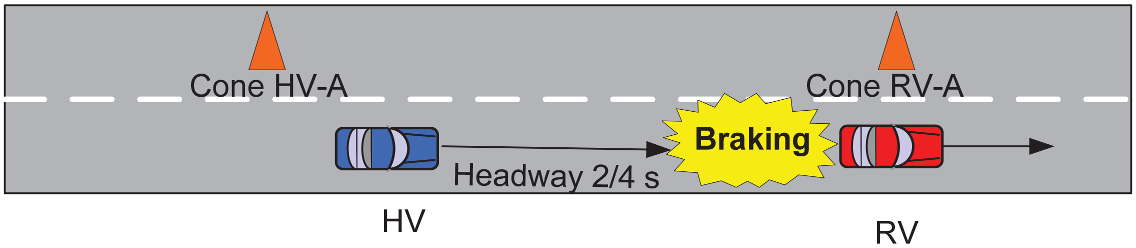

Figure 5-5: HV Follows RV/ RV Brakes Hard

Cones with flags will be placed so the driver of the HV is aware of the vehicle's location in reference to the conflict point. These flags will be located by their distance from the starting point for the HV. It is assumed that flags will be placed using a L1 GPS handheld receiver. Alternate methods of flag location can be used. Flag locations are:

- A checkered flag is placed where the HV starts its maneuver, 45 meters (for a 2-second headway) or 90 meters (for a 4-second headway) before the red flag (cone not shown)
- A red flag is placed at the starting point where RV begins its maneuver (cone not shown)
- A yellow flag is placed at the point where the HV and RV reach the target speed (cone HV-A), at least 650 meters from the red flag
- A green flag is placed where the RV starts braking hard at least 800 meters from the red flag (cone RV-A)

5.5.4 Driving Instructions

- The RV starts at the red flag, 45 meters (for a 2-second headway) or 90 meters (for a 4-second headway) ahead of the HV and accelerates to 40 mph, after which the cruise control is set to 40 mph
- The HV starts at the checkered flag, 45 meters (for 2 second headway) or 90 meters (for 4 second headway) behind the RV, and accelerates to 40 mph
- After the HV passes the yellow flag, the vehicles adjust their headway to be between 2 or 4 seconds which translates to 45 or 90 meters
- The HV's Cruise Control is set at 40 mph
- When the RV passes the green flag, the RV will brake hard (0.5 g+/-0.05 g). The RV will signal braking by sending a verbal message such as "one, two, three, brake."
- The observer in the HV will observe RV's brake lights and whether the HV issues a warning
- If the warning is given at the alert nominal range, the HV will make a lane change and come to a safe stop

- If the warning is not given and the range between the HV and the RV is less than the nominal range, the RV will make a lane change and come to a safe stop
- The RV comes to a stop

5.5.5 Successful Criteria

- The collision alert shall occur within the ranges specified in Table 5-4 in order to pass the run
- Four out of five runs should pass to result in a successful test

5.5.6 Unsuccessful Criteria

A run fails if any of the conditions below occur:

- Collision alert occurs outside the range calculated in Table 5-4 using run-specific variables
- The warning is missed such that no alert is triggered
- If at least two out of five runs fail, then the test is unsuccessful

Table 5-4: Alert Range for Test 5.5

	Collision Alert Test
Maximum Range	57.5
Nominal Range	52.3
Minimum Range	47.1

5.5.7 Evaluation Criteria

Number of Valid Test Runs	**HV Speed (mph)**	**RV Speed (mph)**	**Headway**	**Number of Successful Test Runs**
5	40	40	2 sec	≥ 4
5	40	40	4 sec	≥ 4

5.6 FCW-T6: HV Approaches Stopped RV in Adjacent Lane, Both in Curve (False Positive)

5.6.1 Background

This test begins with the HV traveling on a curved road at a speed of 50 mph in the right lane. Ahead of the HV, in the left lane, is a single stationary RV. The test determines whether the countermeasure’s required collision alerts are not generated when there are no FCW threats along the HV path.

5.6.2 Scenario Specific Assumptions

None.

5.6.3 Test Setup

Figure 5-6, below, shows the vehicle positions and test setup for Test 6.

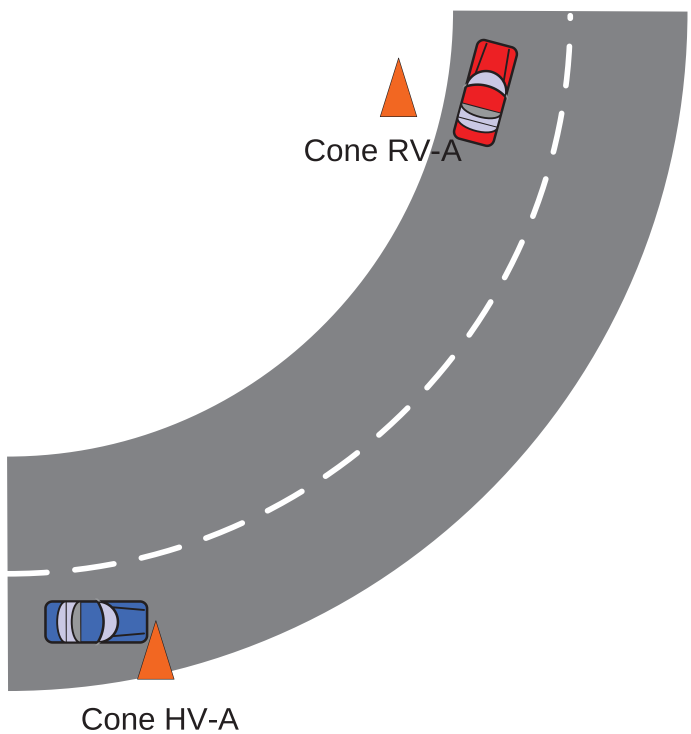

Figure 5-6: RV in Left Lane on Curve (False Positive)

The HV and RV are well into the curve which satisfies the minimum requirements for the curvature as document in the MPR.

Cones with flags will be placed so the driver of the HV is aware of the vehicle's location in reference to the conflict point. These flags will be located by their distance from the starting point for the HV. It is assumed that flags will be placed using a L1 GPS handheld receiver. Alternate methods of flag location can be used. Flag locations are:

- A red flag is placed at the starting point where the HV and RV begin their maneuvers (cone not shown)
- A yellow flag is placed at the point where the HV reaches the target speed (cone HV-A), at least 650 meters from the red flag
- A green flag is placed where RV is stopped, 150 meters from the yellow flag (cone RV-A)

5.6.4 Driving Instructions

- The RV drives in the left lane of the curve and stops at the green flag. This is necessary for each run of this scenario.
- The RV stopped at least 70 meters into a curved left lane. [Note: This depends on the layout of the test track. If possible, the RV should be stopped 150 meters into the curved left lane.]
- The driver of the HV is driving at 50 mph in the curved right lane
- The HV passes the RV without stopping

5.6.5 Successful Criteria

None.

5.6.6 Unsuccessful Criteria

None.

5.6.7 Evaluation Criteria

Number of Valid Test Runs	HV Speed (mph)	RV Speed (mph)	Number of Successful Test Runs
2	50	0	N/A

5.7 FCW-T7: HV Approaches a Slower RV

5.7.1 Background

This test begins with the HV traveling on a straight road at 50 mph speed. Ahead of the HV, in the same lane, is a single RV traveling at a much slower speed of 25 mph.

The test determines whether the countermeasure's required warning occurs at a range that is consistent with the warning onset timing requirements. This test especially explores the ability of the countermeasure to issue a timely warning in response to a slowly moving vehicle.

5.7.2 Scenario Specific Assumptions

None.

5.7.3 Test Setup

Figure 5-7, below, shows the vehicle positions and test setup for Test 7.

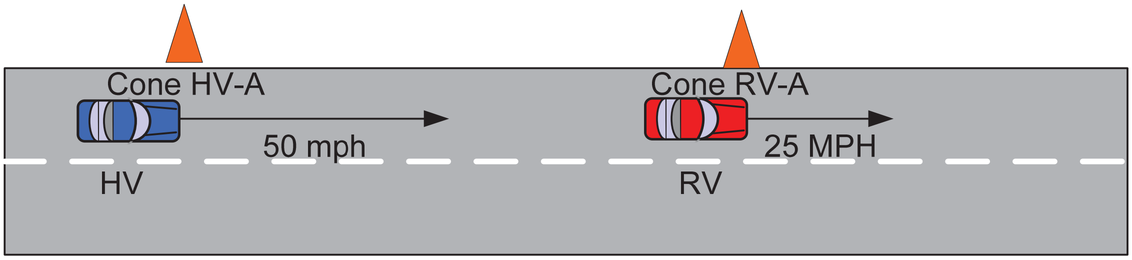

Figure 5-7: HV Behind Slow RV

Cones with flags will be placed so the driver of the HV is aware of the vehicle's location in reference to the conflict point. These flags will be located by their distance from the starting point for the HV. It is assumed that flags will be placed using a L1 GPS handheld receiver. Alternate methods of flag location can be used. Flag locations are:

- A red flag is placed at the starting point where the HV begins its maneuver (cone not shown)
- A green flag is placed where the RV begins its maneuver (cone RV-A), 200 meters from the red flag
- A yellow flag is placed at the point where the HV reaches the target speed (cone HV-A), at least 650 meters from the red flag
- A white flag is placed at the end of the track at least 800 meters from the red flag where the RV reaches the end of the test and stop. The HV makes a maneuver to the next lane.

5.7.4 Driving Instructions

- The RV starts at the green flag and accelerates to 25 mph after which the cruise control is set to 25 mph
- The HV starts at the red flag and accelerates to 50 mph after which the cruise control is set to 50 mph
- The observer in the HV shall note whether the warning is given as the HV closes in on the RV. The observer shall note the warning range.
- If the warning occurs at the nominal range, the HV shall make a lane change and come to a safe stop
- If the HV range to the RV is outside the nominal expected ranges (max and min), then the warning failed to occur. The HV shall make a lane change and come to a safe stop.

5.7.5 Successful Criteria

- The collision alert shall occur within the ranges specified in Table 5-5 in order to pass the run
- If six out of eight runs pass, then the test is successful

5.7.6 Unsuccessful Criteria

A run fails if any of the conditions below occur:

- Collision alert occurs outside the range calculated in Table 5-5 using run-specific variables
- The warning is missed such that no alert is triggered
- If at least three out of eight runs fail, then the test is unsuccessful

Table 5-5: Alert Range for Test 5.7

	Collision Alert Test
Maximum Range	31.0
Nominal Range	28.2
Minimum Range	25.4

5.7.7 Evaluation Criteria

Number of Valid Test Runs	HV Speed (mph)	RV Speed (mph)	Number of Successful Test Runs
8	50	25	≥ 6

5.8 FCW-T8: HV Change Lanes and Encounters Stopped RV

5.8.1 Background

This test begins with the HV traveling on a straight, flat road. Ahead of the HV is a single RV stopped in the adjacent lane of travel. The HV maneuvers into the adjacent lane of the stopped RV.

The test determines whether the countermeasure's required collision alert occurs at a range that is consistent with the collision alert onset timing requirements. This test verifies the ability of the countermeasure to issue timely warning during a lane change on a straight roadway.

5.8.2 Test Setup

Figure 5-8, below, shows the vehicle positions and test setup for Test 8.

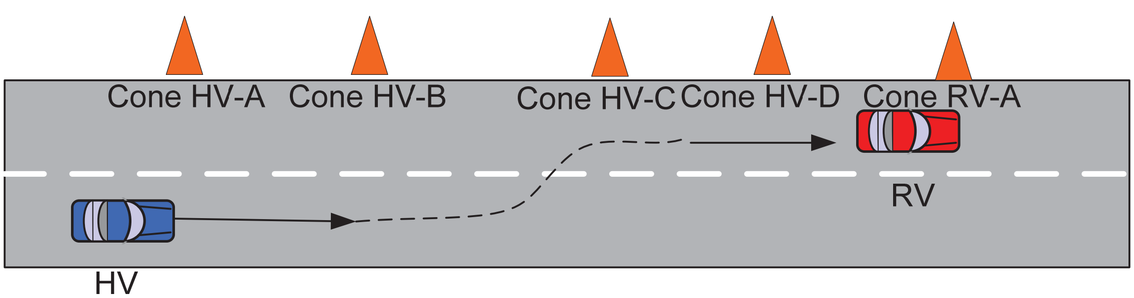

Figure 5-8: HV Change Lanes behind Stopped RV

Cones with flags will be placed so the driver of the HV is aware of the vehicle's location in reference to the conflict point. These flags will be located by their distance from the starting point for the HV. It is assumed that flags will be placed using a L1 GPS handheld receiver. Alternate methods of flag location can be used. Flag locations are:

- A red flag is placed at the starting point where the HV and RV begin their maneuvers (cone not shown)
- A yellow flag is placed at the point where the HV reaches the target speed (cone HV-A), at least 650 meters from the red flag
- A green flag placed where the HV starts the lane change maneuver (cone HV-B)
- A white flag placed where the HV ends the lane change maneuver (cone HV-C)
- A checkered flag is placed where the HV will change lanes if a warning is not given (cone HV-D)
- A rainbow flag is placed where the RV is stopped, at least 800 meters from the red flag (cone RV-A)

5.8.3 Test Requirements and Assumptions

None.

5.8.4 Driving Instructions

- The RV drives at least for 300 meters in the left lane and stops ahead of the HV at the rainbow flag (cone RV-A). [Note: This is only necessary for the first test run.]
- The HV starts at the red flag in the right lane, and accelerates to 50 mph, after which the Cruise Control is set to 50 mph
- The HV's Cruise Control shall be engaged before the vehicle reaches the yellow flag
- When the HV reaches the checkered flag (cone HV-B), it will start the lane change maneuver into the left lane. The lane change maneuver shall be completed in 4 seconds, before the HV reaches the green flag (cone HV-C).
- The warning will be given at around the nominal warn range after the white flag, after which the HV shall make a lane change into the right lane and come to a safe stop

[Note: If the warning is not given by the time the vehicle reaches the checkered flag (cone HV-D), the HV will make a lane change into the right lane and come to a safe stop.]

5.8.5 Successful Criteria

- The collision alert shall occur within the ranges specified in Table 5-6 in order to pass the run
- If six out of eight runs pass, then the test is successful

5.8.6 Unsuccessful Criteria

A run fails if any of the conditions below occur:

- A collision alert occurs outside the range calculated in Table 5-6 using run-specific variables
- The warning is missed such that the HV passes cone HV-D and no alert is triggered
- If at least three out of eight runs fail, then the test is unsuccessful

Table 5-6: Alert Range for Test 5.8

	Collision Alert Test
Maximum Range	93.7
Nominal Range	85.2
Minimum Range	76.7

5.8.7 Evaluation Criteria

Number of Valid Test Runs	HV Speed (mph)	RV Speed (mph)	Number of Successful Test Runs
8	50	0	≥ 6

5.9 FCW-T9: HV Passes Between Two RV (False Positive)

5.9.1 Background

This test begins with the HV traveling on a straight, flat road in the middle lane. Ahead of the HV, in the left adjacent lane and in the right adjacent lane, are two RVs traveling at a constant speed of 30 mph and driving side-by-side. The HV is approaching the RVs and passing between them at a constant speed of 50 mph.

The test determines whether the countermeasure's warning is not generated when the HV passes the RVs since they are in different lanes.

5.9.2 Scenario Specific Assumptions

None.

5.9.3 Test Setup

Figure 5-9, below, shows the vehicle positions and test setup for Test 9.

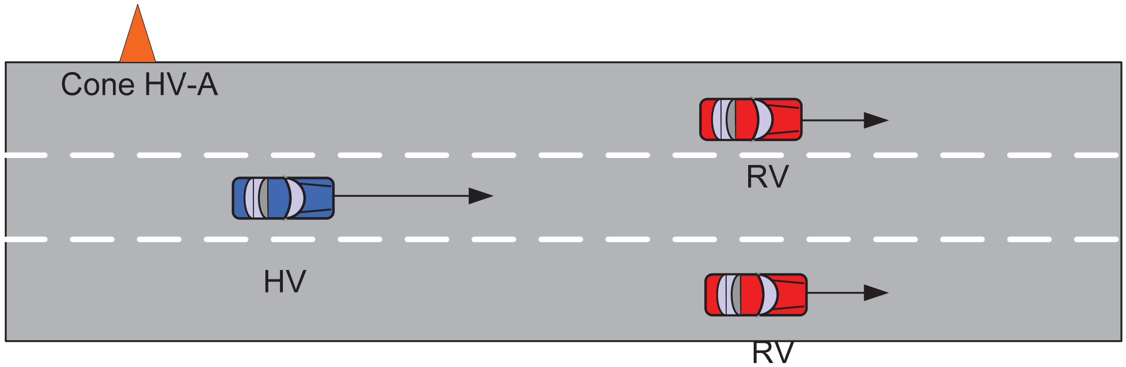

Figure 5-9: HV Drives Between Adjacent RVs

Cones with flags will be placed so the driver of the HV is aware of the vehicle's location in reference to the conflict point. These flags will be located by their distance from the starting point for the HV. It is assumed that flags will be placed using a L1 GPS handheld receiver. Alternate methods of flag location can be used. Flag locations are:

- A red flag is placed at the starting point where the HV and RVs begin their maneuvers (cone not shown)
- A yellow flag is placed at the point where the HV and RV reach the target speed (cone HV-A), at least 650 meters from the red flag

5.9.4 Driving Instructions

- The HV and RVs start at the red flag, the HV in the middle lane behind the RVs in the left and right adjacent lanes
- The RVs accelerate to reach a speed of 25 mph at which time the cruise control is set
- The initial headway between the RVs and the HV is 4 seconds
- The HV accelerates to reach a speed of 50 mph at which time the cruise control is set
- The HV tailgates the RVs
- After the HV passes between the RVs, all vehicles come to a controlled stop

5.9.5 Successful Criteria

None.

5.9.6 Unsuccessful Criteria

None.

5.9.7 Evaluation Criteria

Number of Valid Test Runs	HV Speed (mph)	RV Speed (mph)	Number of Successful Test Runs
2	50	25	N/A

5.10 Test Pass\Fail Recordings Table

Testing Comments:____
____
____

1									
3									
5									

[Note: The nominal range for each test run will be recomputed based on test run parameters.]

Vehicle Speed: Identical to longitudinal velocity

Vehicle Acceleration: Refers to longitudinal acceleration

FCW Range: The distance from the front of the HV FCW-equipped vehicle to the rear of RV vehicle

Nominal Range: The calculated range at which a warning alert is expected based on the testing parameters logged during each test run. Nominal range can be different for each test run

Maximum Range:	A calculated value which is equal to the nominal range + 10 percent of the nominal range
Minimum Range:	A calculated value which is equal to the nominal range - 10 percent of the nominal range
Actual Alert Range:	The actual range at which the warning alert was issued for a particular test run obtained from the test run log

6 BSW+LCW Objective Test Procedures

6.1 BSW+LCW –T1: LCW Warning, Left

6.1.1 Background

The Blind Spot Warning+Lane Change Warning (BSW+LCW) application gives a warning when the HV is signaling to turn or change lanes and a RV is currently occupying, or will soon be occupying, the blind zone on the corresponding side of the HV. This scenario tests the correct functioning of the BSW+LCW with two vehicles on a straight road, where the RV moves into the HV's blind spot. This test begins with the HV traveling at a constant speed in the right lane of an at least 2-lane road with its turn signals on. The RV will move into the HV's blind spot in the next lane to the left of the HV.

6.1.2 Test Assumptions

The HV is driving on a two-lane roadway, and the HV intends to change lanes. A RV is positioned in a way that the lane change of the HV would cause a dangerous situation. For safety, the HV does not actually change lanes at any time during this test.

6.1.3 Test Setup

Figure 6-1, below, shows vehicle positions for Test 1. The RV passes the HV on the left.

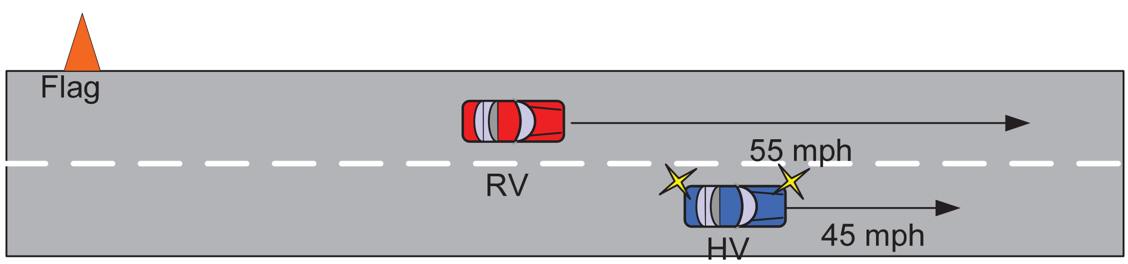

Figure 6-1: LCW Warn Test 1

Cones with flags will be placed so the drivers are aware of their locations with respect to the maneuvers that are being executed. These flags will be located by their distance from the starting point for the HV. It is assumed that flags will be placed using a L1 GPS handheld receiver. Alternate methods of flag location can be used. Flag locations are:

- A red flag is placed at the starting point where the HV and RV begin their maneuver

- A yellow flag is placed at the point where the RV reaches the target speed, which is 50 meters from the red flag (optional)

6.1.4 Driving Instruction

- The HV starts at the red flag in the right lane and accelerates to 45 mph
- When the HV is 50 meters ahead of the RV as shown by the TC application, the RV starts at the red flag in the left lane and accelerates to 55 mph after which time the cruise control will be set to 55 mph
- The HV activates its left turn signal once it issues a Blind Spot Advisory
- The RV maintains its speed, passing the HV on left side of HV, and moving ahead of the HV
- When the RV has passed the HV (the RV is classified as ahead left in HV's TC), both vehicles will come to a safe stop

6.1.5 Successful Criteria

- The HV receives an Advisory for the left blind zone when the RV enters the blind zone
- The HV receives a Warning when the left turn signal is activated, while the RV is occupying the left blind zone
- The HV Warning disappears after the RV has moved ahead of the HV
- The time delay between turn signal activation and LCW is within the range specified by the Table 6-1, below

Table 6-1: Alert Range for Test 6.1

	Warning Latency
Maximum	0.5 seconds
Nominal Value	0.1 seconds
Minimum	0.0 seconds

6.1.6 Unsuccessful Criteria

- The test is unsuccessful if any warning or advisory noted in the successful criteria above is missed
- The test fails if at least three out of eight runs fail

6.1.7 Evaluation Criteria

Number of Valid Test Runs	**Number of Instances HV Shows Warning:**		**Number of Successful Test Runs**
	Left	**Right**	
8	≥ 6	0	≥ 6

6.2 BSW+LCW – T2 LCW Warning, Right

6.2.1 Background

The BSW+LCW application provides a warning when the HV is signaling to turn or change lanes, and an RV is currently occupying, or will soon be occupying, the blind zone on the corresponding side of the HV.

6.2.2 Test Assumptions

The HV is driving on a multi-lane roadway, and the HV intends to change lanes. The RV's are positioned in a way that the lane change of the HV would cause a dangerous situation. For safety, the HV does not actually change lanes at any time during this test.

6.2.3 Test Setup

Figure 6-2, below, shows vehicle positions for Test 2. The RV passes the HV on the right.

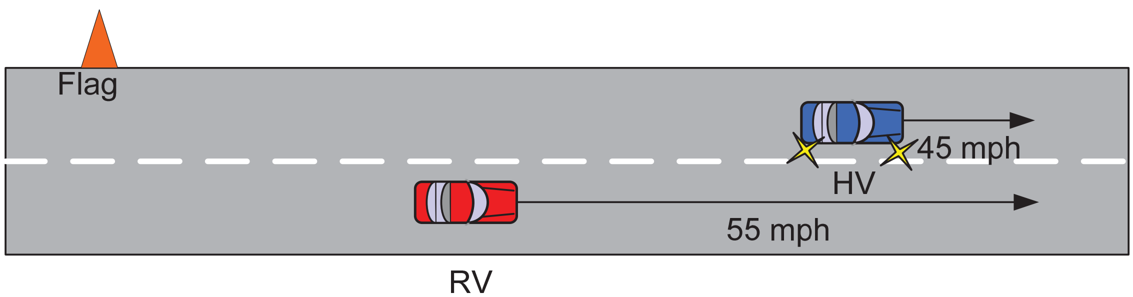

Figure 6-2: LCW Warn Test 2

Cones with flags will be placed so the drivers are aware of their locations with respect to the maneuvers that are being executed. These flags will be located by their distance from the starting point for the HV. It is assumed that flags will be placed using a L1 GPS handheld receiver. Alternate methods of flag location can be used. Flag locations are:

- A red flag is placed at the starting point where the RV begins its maneuver
- A yellow flag is placed at the point where the RV reaches the target speed, 50 meters from the red flag (optional)

6.2.4 Driving Instruction

- The HV starts at the red flag in the left lane and accelerates to 45 mph.
- After the HV is 50 meters ahead of the RV as shown by the TC application, the RV starts at the red flag in the right lane and accelerates to 55 mph after which the cruise control will be set to 55 mph.
- The HV activates its right turn signal once it issues a Blind Spot Advisory
- The RV maintains its speed, passing the HV on the right side of the HV, and moving ahead of the HV

- When the RV has passed the HV (the RV is classified as ahead right in the HV's TC), both vehicles will come to a safe stop

6.2.5 Successful Criteria

- The HV receives an advisory for the right blind zone when the RV enters the blind zone
- The HV receives a warning when the right turn signal is activated while the RV is occupying the right blind zone
- The HV warning disappears after the RV has moved ahead of the HV
- The time delay between turn signal activation and LCW is within the range specified by the Table 6-2, below

Table 6-2: Alert Range for Test 6.2

	Warning Latency
Maximum	0.5 seconds
Nominal Value	0.1 seconds
Minimum	0.0 seconds

6.2.6 Unsuccessful Criteria

- The test fails if any warning or advisory noted in the successful criteria above is missed
- The test fails if at least three out of eight runs fail

6.2.7 Evaluation Criteria

Number of Valid Test Runs	**Number of Instances HV Shows Warning:**		**Number of Successful Test Runs**
	Left	**Right**	
8	0	≥ 6	≥ 6

6.3 BSW+LCW – T3: LCW Warning, Right with Left BSW Advisory

6.3.1 Background

The BSW+LCW application provides a warning when the HV is signaling to turn or change lanes, and an RV is currently occupying, or will soon be occupying, the blind zone on the corresponding side of the HV. When different vehicles are occupying both left and right blind zones, a warning is given for the appropriate side according to the turn signal.

6.3.2 Test Assumptions

The HV is driving on a multi-lane roadway, and the HV intends to change lanes. The RVs are positioned in a way that the lane change of the HV would cause a dangerous situation. For safety, the HV does not actually change lanes at any time during this test.

6.3.3 Test Setup

Figure 6-3, below, shows vehicle positions for Test 3. RV-1 and RV-2 maintain position in blind zones of the HV.

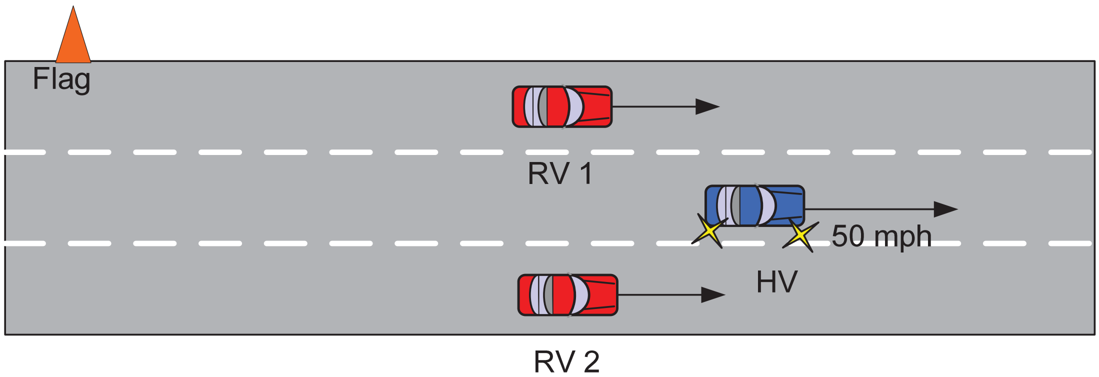

Figure 6-3: LCW Warn Test 3

6.3.4 Driving Instruction

- The HV, RV-1, and RV-2 start at the red flag: RV-1 in the left lane, HV in the middle lane, and RV-2 in the right lane. The vehicles accelerate to 50 mph after which time the HV's cruise control will be set to 50 mph.
- The vehicles will adjust their position so that the rear bumper of the HV is approximately less than one car length (3 meters ± 2 meters) ahead of both RV-1 and RV-2. Both RVs will adjust their speed until the correct position is reached. Both RVs maintain the same distance from the HV.
- After the HV receives an advisory for both blind zones for a period longer than 2 seconds, it will activate the right turn signal.
- All vehicles proceed until they reach the checkered flag after which time they will come to a safe stop in their respective lanes.

6.3.5 Successful Criteria

- The HV receives an advisory while no turn signal is activated and RV-1 and RV-2 are occupying the left- and right-blind zones, respectively
- The HV's right, blind zone advisory changes to warning when the right turn signal is activated and RV-2 remains in the HV's right blind zone
- The time delay between turn signal activation and LCW is within the range specified by the Table 6-3, below

Table 6-3: Alert Range for Test 6.3

	Warning Latency
Maximum	0.5 seconds
Nominal Value	0.1 seconds
Minimum	0.0 seconds

6.3.6 Unsuccessful Criteria

- A test is unsuccessful when any warning or advisory noted in the successful c criteria above is missed
- A test is unsuccessful when the warning latency is outside the range specified in the successful criteria
- The test fails if at least three out of eight runs fail

6.3.7 Evaluation Criteria

Number of Valid Test Runs	Number of instances HV shows Warning:		Number of Successful Test Runs
	Left	Right	
8	0	≥ 6	≥ 6

6.4 BSW+LCW – T4: BSW Advisory Alert, Left

6.4.1 Background

The BSW+LCW application provides an advisory when an RV enters the blind zone on either side of the HV.

6.4.2 Test Assumptions

The HV is driving normally, without intention to change lanes, near other moving vehicles, such as passing vehicles in another lane of traffic. The HV does not use turn signals at any time during this test.

6.4.3 Test Setup

Figure 6-4, below, shows the vehicle positions for Test 4. The RV passes the HV on the left.

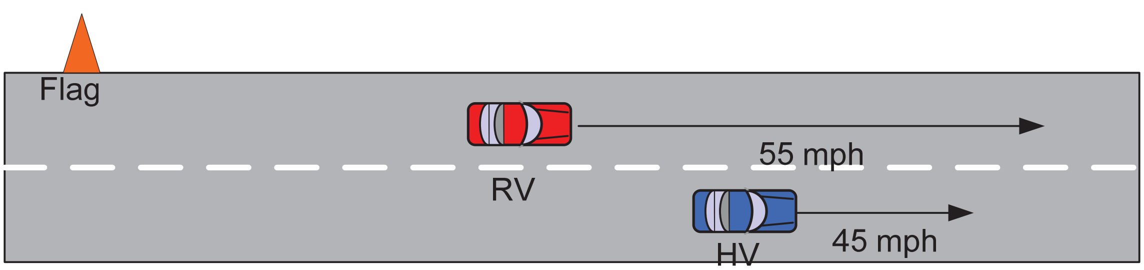

Figure 6-4: BSW Advisory Test 4

Cones with flags will be placed so the drivers are aware of their locations with respect to the maneuvers that are being executed. These flags will be located by their distance from the starting point for the HV. It is assumed that flags will be placed using a L1 GPS handheld receiver. Alternate methods of flag location can be used. Flag locations are:

- A red flag is placed at the starting point where the RV begins its maneuvers

- A yellow flag is placed at the point where the RV reaches the target speed, 50 meters from the red flag (optional)

6.4.4 Driving Instruction

- The HV starts at the red flag in the right lane and accelerates to 45 mph
- After the HV is 50 meters ahead of the RV as shown by the TC application, the RV starts at the red flag in the left lane and accelerates to 55 mph after which time the cruise control will be set to 55 mph
- The RV maintains its speed, passing the HV on the left side. The HV receives an Advisory when the RV enters the left Blind Zone.
- When the RV has passed the HV (the RV is classified as ahead left in the HV's TC), both vehicles will come to a safe stop

6.4.5 Successful Criteria

The HV receives an advisory for the left blind zone when passed by the RV on the left side.

6.4.6 Unsuccessful Criteria

- A test is unsuccessful when any warning is shown on the HV
- A test is unsuccessful when an advisory noted in the successful criteria above is missed
- The test fails if at least three out of eight runs fail

6.4.7 Evaluation Criteria

Number of Valid Test Runs	**Number of instances HV shows Advisory:**		**Number of Successful Test Runs**
	Left	**Right**	
8	≥ 6	0	≥ 6

6.5 BSW+LCW – T5: BSW Advisory Alert, Right

6.5.1 Background

The BSW+LCW application provides an advisory when the RV enters the blind zone on either side of the HV.

6.5.2 Test Assumptions

The HV is driving normally, without intention to change lanes, near other moving vehicles, such as passing vehicles in another lane of traffic. The HV does not use turn signals at any time during this test.

6.5.3 Test Setup

Figure 6-5, below, shows vehicle positions for Test 5. The RV passes the HV on the right.

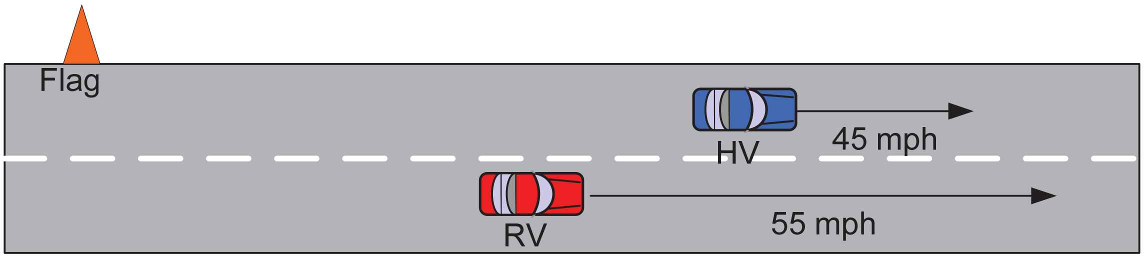

Figure 6-5: BSW Advisory Test 5

Cones with flags will be placed so the drivers are aware of their locations with respect to the maneuvers that are being executed. These flags will be located by their distance from the starting point for the HV. It is assumed that flags will be placed using a L1 GPS handheld receiver. Alternate methods of flag location can be used. Flag locations are:

- A red flag is placed at the starting point where the RV begins its maneuvers (cone not shown)
- A yellow flag is placed at the point where the RV reaches the target speed, 50 meters from the red flag (optional)

6.5.4 Driving Instruction

- The HV starts at the red flag in the left lane and accelerates to 45 mph
- After the HV is 50 meters ahead of the RV as shown by the TC application, the RV starts at the red flag in the right lane and accelerates to 55 mph after which the cruise control will be set to 55 mph
- The RV maintains its speed, passing the HV on the right side. The HV receives an advisory when the RV enters the right blind zone
- When the RV has passed the HV (the RV is classified as ahead right in the HV's TC), both vehicles will come to a safe stop

6.5.5 Successful Criteria

A test is successful when the HV receives an advisory for the right blind zone when passed by RV-2 on the right side.

6.5.6 Unsuccessful Criteria

- A test is unsuccessful if any warning is shown on the HV
- A test is unsuccessful if an advisory is noted in the successful criteria above is missed
- The test fails if at least three out of eight runs fail

6.5.7 Evaluation Criteria

Number of Valid Test Runs	Number of instances HV shows Advisory:		Number of Successful Test Runs
	Left	Right	
8	0	≥ 6	≥ 6

6.6 BSW+LCW – T6: No Warning or Advisory for RV Behind

6.6.1 Background

The BSW+LCW application is configured to only provide "inform" or "warning" for vehicles to the sides of the HV. No information or warning should be displayed when a RV is following directly behind the HV.

6.6.2 Test Assumptions

The HV and the RV are driving normally without intention to change lanes, with the RV following directly behind the HV.

6.6.3 Test Setup

Figure 6-6, below, shows vehicle positions for Test 6.

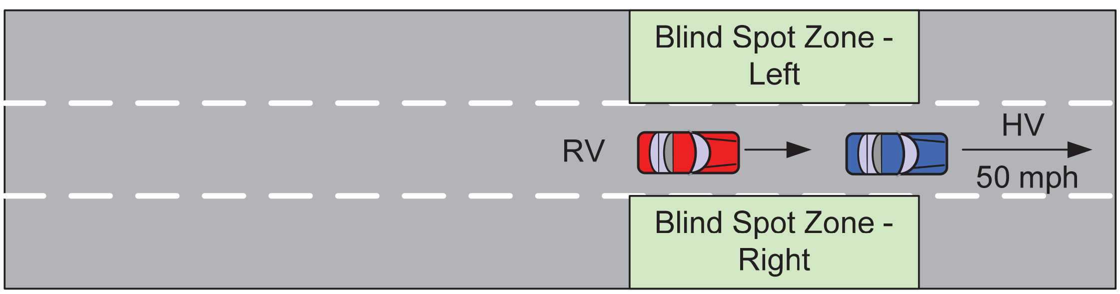

Figure 6-6: RV Behind HV Test 6

6.6.4 Driving Instruction

- The test begins with the HV and the RV stopped with the RV positioned directly behind the HV. Both vehicles are in "overdrive."
- The HV then accelerates to 50 mph in a straight line. The RV accelerates with the HV. Once the HV reaches 50 mph speed, the RV moves to less than 1 car length (3 meters ± 2 meters) from the HV's rear bumper. Refer to Figure 6-6.
- The RV maintains its position behind the HV for 5 seconds
- The test ends

6.6.5 Successful Criteria

None.

6.6.6 Unsuccessful Criteria

None.

6.6.7 Evaluation Criteria

Number of Valid Test Runs	Number of instances HV shows Advisory or Warning	Number of Successful Test Runs
2	0	N/A

6.7 BSW+LCW – T7: No Warning or Advisory for RV Far Right

6.7.1 Background

The BSW+LCW application is configured to only provide “inform” or “warning” for vehicles in the adjacent lanes of the HV. No information or warning should be displayed when a RV is two or more lanes separated from the HV.

6.7.2 Test Assumptions

The HV and the RV are driving normally without intention to change lanes, with the RV positioned behind and two lanes to the right of the HV.

6.7.3 Test Setup

Figure 6-7, below, shows vehicle positions for Test 7.

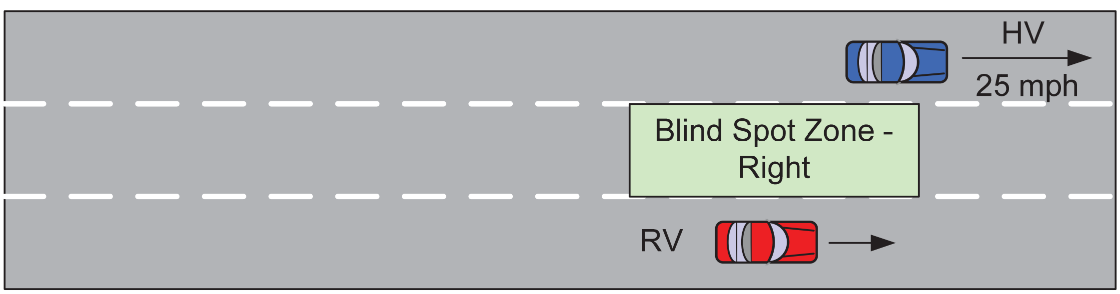

Figure 6-7: RV Far Right Test 7

6.7.4 Driving Instruction

- The test begins with the HV and the RV stopped with the RV positioned behind and two lanes to the right of the HV. Both vehicles are in “overdrive.”
- The HV then accelerates to 50 mph in a straight line. The RV accelerates with the HV. Once the HV reaches 50 mph, the RV moves to less than 1 car length (3 meters ± 2 meters) from the HV’s rear bumper, still two lanes to the right of the HV.
- The RV maintains its position behind right from the HV for 5 seconds
- The test ends

6.7.5 Successful Criteria

None.

6.7.6 Unsuccessful Criteria

None.

6.7.7 Evaluation Criteria

Number of Valid Test Runs	Number of Instances HV Shows Advisory or Warning	Number of Successful Test Runs
2	0	N/A

6.8 BSW+LCW – T8 LCW Warning in Curve, Right

6.8.1 Background

The BSW+LCW application provides a warning when the HV is signaling to turn or change lanes, and a RV is currently occupying, or will soon be occupying, the blind zone on the corresponding side of the HV. This particular scenario will test the ability of the system to give the correct warning when both vehicles drive on a curved road.

6.8.2 Test Assumptions

The HV is driving on a multi-lane roadway in a curve, and the HV intends to change lanes. The RV is positioned in a way that the lane change of the HV would cause a dangerous situation. For safety, the HV does not actually change lanes at any time during this test.

6.8.3 Test Setup

Figure 6-8, below, shows vehicle positions for Test 8.

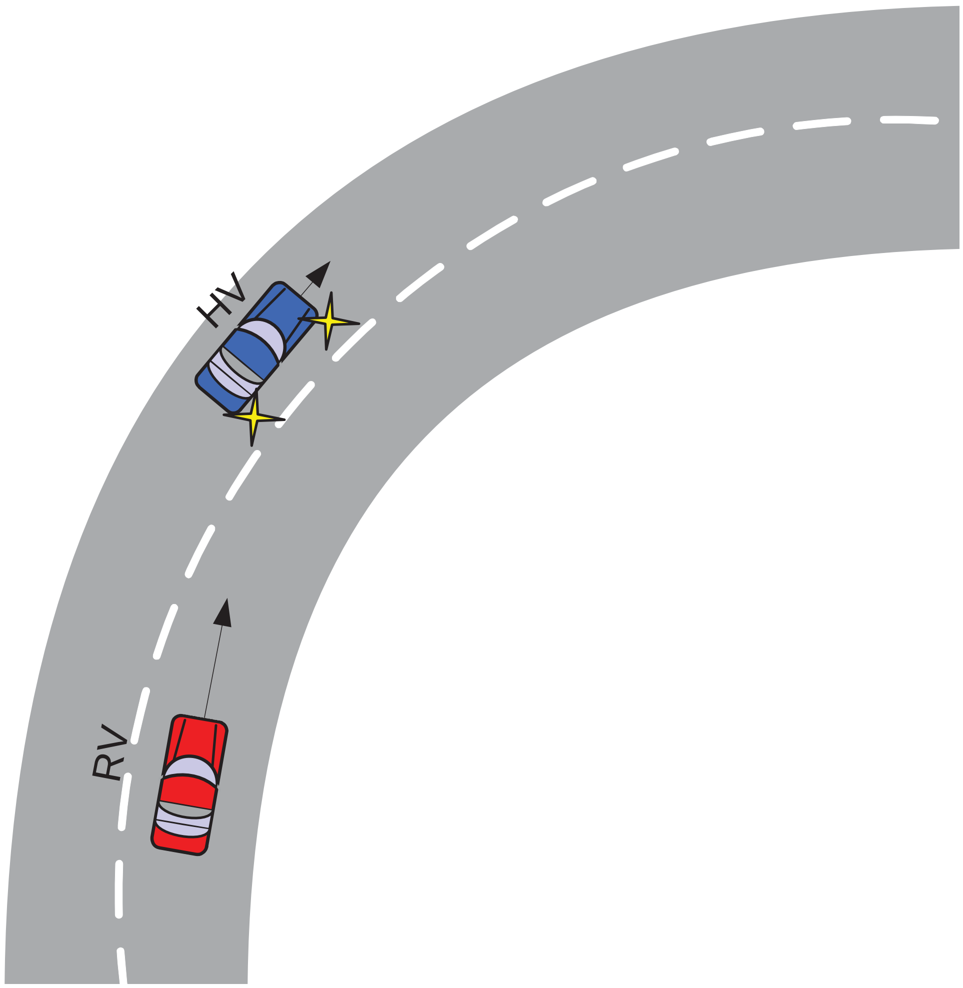

Figure 6-8: HV and RV in Curved Lane Test

6.8.4 Test Setup

Cones with flags will be placed so the driver of the HV and RV is aware of the vehicle’s location in reference to the required maneuvers. These flags will be located by their distance from the starting point for the HV and RV. It is assumed that flags will be placed using a L1, GPS handheld receiver. Alternate methods of flag location can be used. Flag locations are:

- A red flag is placed at the starting point where the HV and the RV begin their maneuvers (cone not shown)
- A yellow flag is placed at the point where the RV and the HV reaches the target speed, 150 meters from the red flag

6.8.5 Driving Instruction

- The HV starts at the red flag in the left lane and accelerates to 45 mph
- After the HV is 50 meters ahead of the RV as shown by the TC application, the RV starts at the red flag in the right lane and accelerates to 55 mph, after which time the cruise control will be set to 55 mph
- The HV activates its right turn signal once it issues a Blind Spot Advisory
- The RV maintains its speed, passing the HV on the right side of the HV, and moving ahead of the HV
- When the RV has passed the HV (the RV is classified as ahead right in the HV's TC), both vehicles will come to a safe stop

6.8.6 Successful Criteria

- The HV receives an advisory for the right blind zone when the RV enters the blind zone
- The HV receives a warning when the right turn signal is activated, while the RV is occupying the right blind zone
- The HV warning disappears after the RV has moved ahead of the HV
- The time delay between turn signal activation and LCW is within the range specified by the Table 6-4, below

Table 6-4: Alert Range for Test 6.8

	Warning Latency
Maximum	0.5 seconds
Nominal Value	0.1 seconds
Minimum	0.0 seconds

6.8.7 Unsuccessful Criteria

A run is unsuccessful if any of the conditions below occur:

- Any warning or advisory noted in the successful criteria above is missed
- Warning latency is outside the range specified in the successful criteria.
- Test fails if at least three out of eight runs fail

6.8.8 Evaluation Criteria

Number of Valid Test Runs	**Number of Instances HV Shows Warning:**		**Number of Successful Test Runs**
	Left	**Right**	
8	≥ 6	0	≥ 6

7 DNPW Objective Test Procedures

Do Not Pass Warning (DNPW) is a V2V communication-based safety feature that warns the driver of the HV when a slower moving vehicle (i.e., an Ahead Remote Vehicle, or ARV) cannot be safely passed using a passing zone potentially occupied by vehicles with the opposite direction of travel (i.e., an Oncoming Left Remote Vehicle, or OLRV). When a passing maneuver of an ARV is initiated (e.g., through the use of the left turn signal as a proxy only), the application determines the presence or absence of an OLRV in the passing zone of the adjacent lane. If the presence of an OLRV in the passing zone is detected, a warning is issued to the driver of the HV. The DNPW application can also be operated in an advisory mode that informs the driver that the passing zone is occupied without the use of the turn signal.

Sections 7.1 and 7.2 describe test scenarios for analyzing the consistency of the DNPW feature in warning the driver when a OLRV (stationary or moving) occupies the adjacent lane passing zone, where as Section 7.3 describes an optional test scenario where the DNPW feature is not expected to provide a warning. The test scenarios defined in Sections 7.1 and 7.2 are designed such that the HV encounters situations that should trigger a DNPW alert in a manner that meets the minimum performance requirements. The significant data from each test run is a comparison of the position (i.e., distance from the OLRV) at which the DNPW alert onset actually occurred (if it occurred) and the position at which the alerts were required to occur. Due to the variations in range, velocity, and acceleration of the HV, ARV, and OLRV vehicles when performing these tests, each individual test run may generate different alert onset ranges. Because of this, the nominal alert ranges should not be used as the pass/fail criteria for a test run. Rather, the alert ranges should be recomputed for each test run using the actual (achieved) range, velocity, and acceleration variables. For the DNPW feature, the maximum and minimum alert ranges are defined as ± 10 percent of the nominal alert range. The DNPW alert onset for an individual run should not occur outside of the allowable alert range.

7.1 DNPW-T1: Oncoming Remote Vehicle Occupies the Adjacent Lane

7.1.1 Background

This test is designed to evaluate two conditions:

- A DNPW advisory alert will occur when the HV is traveling along a two-lane road and cannot pass the ARV by entering an adjacent lane due to an OLRV that will be occupying the DNPW passing zone
- The DNPW advisory alert occurs within the ranges specified in Table 7-1

7.1.2 Test Assumptions

- The HV, ARV, and OLRV will remain in their respective lanes throughout the entire test
- No braking by the HV will occur during this test

7.1.3 Test Setup

Figure 7-1, below, shows the vehicle positions and test setup for Test 1.

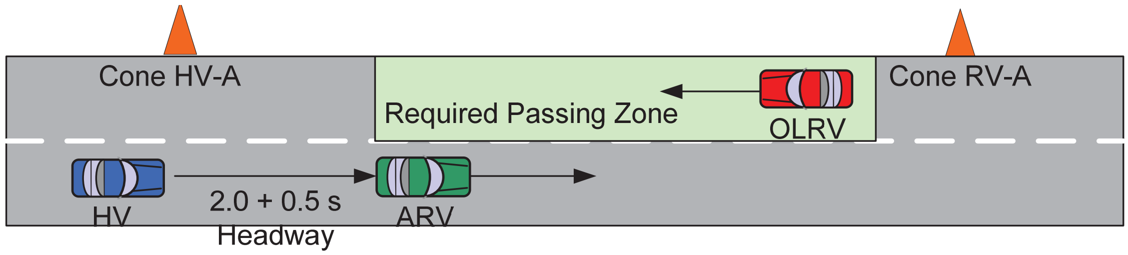

Figure 7-1: Attempt to Pass when OLRV Occupies the Adjacent Lane

Cones with flags will be placed so the drivers are aware of their locations with respect to the maneuvers that are being executed. These flags will be located by their distance from the starting point for the HV. It is assumed that flags will be placed using a L1 GPS handheld receiver. Alternate methods of flag location can be used. Flag locations are:

- A red flag placed at the starting point where the HV and the ARV begin their maneuver (cone not shown)
- A green flag is placed at the starting point where the OLRV starts its maneuver, 1000 meters from the red flag (cone not shown)
- A yellow flag placed at the point where the HV and ARV reach the target speed (cone HV-A), 100 meters from the red flag
- A yellow flag is placed at the point where the OLRV reaches its target speed, 100 meters from the green flag (cone RV-A)

7.1.4 Driving Instructions

- At the start of the test procedure, the HV and ARV will start from the red flag in the right lane
- The OLRV will start from the green flag in the adjacent lane (left lane from the HV and ARV perspective)
- The ARV will accelerate to a constant speed of 25/35 mph after which the cruise control will be set to 25/35 mph. At the same time, the OLRV will accelerate to a constant speed of 25/35 mph in the adjacent lane after which the cruise control will be set to 25/35 mph.
- The HV will follow behind the ARV and accelerate to a speed of 25/35 mph after which the cruise control will be set to 25/35 mph with an approximate headway of 2.0 seconds +/- 0.5 seconds (can be computed by multiplying the HV speed in m/s by the headway time)
- An advisory-based alert will be provided when the DNPW algorithm determines that the OLRV will be in the HV-required passing zone based on the dynamics of all vehicles involved in the test

- The test ends when the HV and OLRV pass each other in their respective lanes and the vehicles will come to a safe stop

For speeds exceeding 35 mph, the distances involved will likely exceed effective DSRC communication range at 17dBm between the HV and OLRV. If the system is tested at speeds exceeding 35 mph, this test should be qualified as an engineering test only. Advisory alert timing will be dictated by the initial communication between the HV and OLRV and may not be deterministic.

7.1.5 Successful Criteria

The DNPW algorithm is considered as functioning properly if 8 out of 10 runs (5 runs for each speed) are performed in adherence to the driving instructions described in Section 7.1.4, and the DNPW advisory alert occurs within the minimum and maximum ranges specified in Table 7-1.

7.1.6 Unsuccessful Criteria

A run is unsuccessful if any of the conditions below occur:

- A DNPW inform occurs outside the minimum and maximum ranges specified in Table 7-1
- The DNPW is missed such that the HV passes the OLRV and no inform is provided

7.1.7 Evaluation Criteria

Table 7-1: Estimated Alert Ranges for Test 7.1

	DNPW advisory (meters)
Maximum Range	373.8 / 540.1
Nominal Range	339.8 / 491,0
Minimum Range	305.8 / 441.9

Alert ranges provided as estimates only. Ranges will be recomputed based on actual data prior to final evaluation.

Number of Test Runs	HV speed (mph)	OLRV Speed (mph)	Number of successful test runs
5	25	25	≥ 8
5	35	35	

7.2 DNPW-T2: Stationary RV Occupies the HV Lane

7.2.1 Background

This test is designed to evaluate two conditions:

- A DNPW advisory alert will occur when the HV, traveling along a two-lane road, wishes to pass a stationary ARV but the adjacent lane is occupied by an OLRV positioned in the DNPW passing zone

- The DNPW advisory alert occurs within the ranges specified in Table 7-2

This test scenario shall include 30, 40, and 50 mph speed settings for the HV and OLRV, and a speed setting of 0 mph for the ARV.

7.2.2 Test Assumptions

- The HV, ARV, and OLRV will remain in their respective lanes throughout the entire test
- No braking by the HV will occur during this test

7.2.3 Test Setup

Figure 7-2, below, shows the vehicle positions and test setup for Test 2.

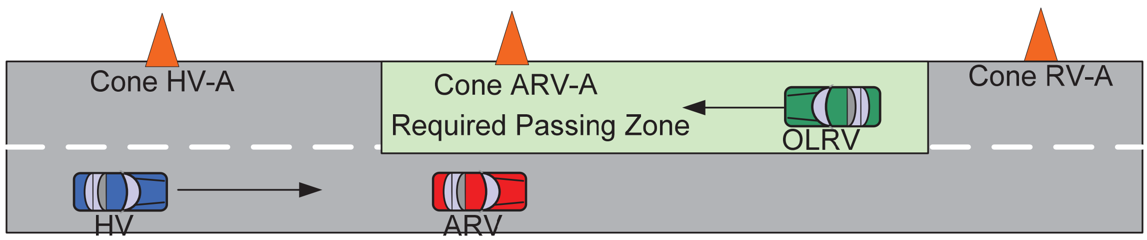

Figure 7-2: Attempt to Pass when a Stationary ARV Occupies Adjacent Lane

Cones with flags will be placed so the drivers are aware of their locations with respect to the maneuvers that are being executed. These flags will be located by their distance from the starting point for the HV. It is assumed that flags will be placed using a L1 GPS handheld receiver. Alternate methods of flag location can be used. Flag locations are:

- A red flag is placed at the starting point where the HV and the ARV begin their maneuvers (cone not shown)
- A green flag placed at the starting point where the OLRV starts its maneuver, 1000 meters from the red flag (cone not shown)
- A yellow flag is placed at the point where the HV reaches the target speed (cone HV-A), 100 meters from the red flag
- A yellow flag is placed at the point where the ARV will stop (cone ARV-A)

7.2.4 Driving Instructions

- At the beginning of the test procedure, the HV and ARV will start from the red flag in the right lane
- The OLRV will start from the green flag in the adjacent lane (left lane from the HV and ARV)
- The ARV will drive to the yellow flag and stop. At the same time, the OLRV will accelerate to a constant speed of 30 mph in the adjacent lane after which the cruise control will be set to 30 mph

- The HV will accelerate to a speed of 30 mph after which the cruise control will be set to 30 mph
- The test ends when the HV comes to a safe stop a maximum of 5 meters from the stationary ARV
- Repeat the abovementioned instructions for the HV and the ARV speeds of 40 and 50 mph

7.2.5 Successful Criteria

The DNPW algorithm is considered as functioning properly if four out of five runs are performed in adherence to the driving instructions described in Section 7.2.4, and the DNPW inform occurs within the minimum and maximum ranges specified in Table 7-2.

7.2.6 Unsuccessful Criteria

- A DNPW warning outside the range calculated in the table below using run-specific variables results in run failure
- The DNPW warning system fails to provide two or more warnings before the OLRV passes the HV

7.2.7 Evaluation Criteria

Table 7-2: Estimated Alert Range for Test 7.2

Test Speed (mph)	Max Range for DNPW alert(m)	Nominal Range for DNPW alert(m)	Min Range for DNPW alert(m)	ARV Headway(s)
30	325.6	296	266.4	4
40	505.8	459.8	413.8	6
50	724.2	658.4	592.56	8

Alert ranges provided as estimates only. Ranges will be recomputed based on actual data prior to final evaluation. Suggested ARV headways provided as examples only. Results will vary based on test setup.

Number of Test Runs	HV Speed (mph)	OLRV Speed (mph)	Number of Successful Test Runs
5	30	30	≥ 4
5	40	40	≥ 4
5	50	50	≥4

7.3 DNPW-T3: Oncoming RV Does Not Occupy the Adjacent Lane (False Positive)

7.3.1 Background

This test determines if a DNPW will be suppressed if the HV that is traveling along a multiple-lane road wishes to pass a slower-moving ARV by entering an adjacent lane where an OLRV does not occupy the lane.

7.3.2 Test Assumptions

- The HV, ARV, and OLRV will remain in their respective lanes throughout the entire test
- No braking by the HV will occur during this test

7.3.3 Test Setup

Figure 7-3, below, shows the vehicle positions and test setup for Test 3.

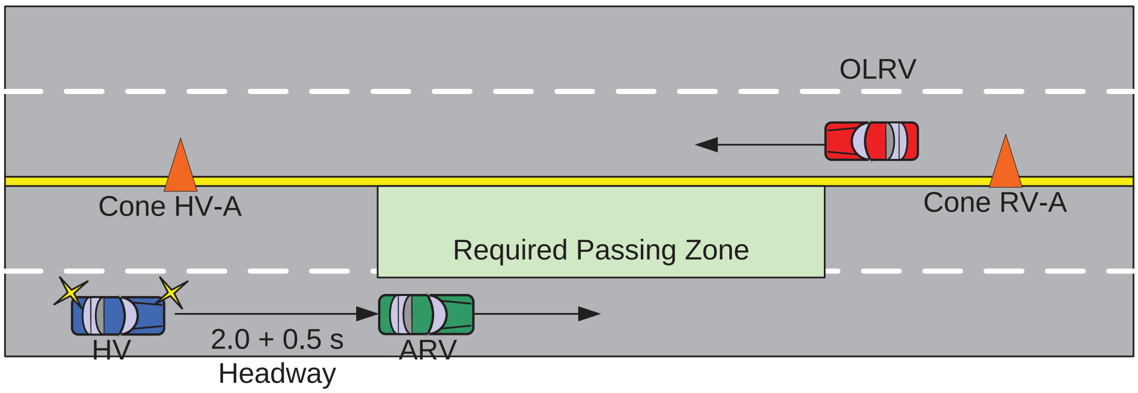

Figure 7-3: Attempt to Pass when RV Does Not Occupy Adjacent Lane

Cones with flags will be placed so the drivers are aware of their locations with respect to the maneuvers that are being executed. These flags will be located by their distance from the starting point for the HV. It is assumed that flags will be placed using a L1 GPS handheld receiver. Alternate methods of flag location can be used. Flag locations are:

- A red flag is placed at the starting point where the HV and the ARV begin their maneuvers (cone not shown)
- A green flag is placed at the starting point where OLRV starts its maneuver, 1200 meters from the red flag (cone not shown)
- A yellow flag is placed at the point where the HV and ARV reach the target speed (cone HV-A), 100 meters from the red flag
- A yellow flag is placed at the point where the OLRV will reach its target speed (cone RV-A)
- A checkered flag placed where the HV activates the left turn signal (cone HV-B), 50 meters from the yellow flag

7.3.4 Driving Instructions

- At the start of the test procedure, the HV and ARV will start from the red flag in the right lane
- The OLRV will start from the green flag two lanes over to the left from the HV and ARV

- The ARV will accelerate to a constant speed of 45 mph after which the cruise control will be set to 45 mph. At the same time, the OLRV will accelerate to a constant speed of 45 mph in the adjacent lane after which the cruise control will be set to 45 mph.
- The HV will follow behind the ARV and accelerate to a speed of 45 mph after which the cruise control will be set to 45 mph with an approximate headway of 2.0 seconds +/- 0.5 seconds (can be computed by multiplying the HV speed in m/s by the headway time)
- The HV will activate the left turn signal indicator after it reaches the checkered flag
- The test ends when the HV and OLRV pass each other in their respective lanes and the vehicles will come to a safe stop

7.3.5 Successful Criteria

None.

7.3.6 Unsuccessful Criteria

None.

7.3.7 Evaluation Criteria

Number of Test Runs	HV Speed (mph)	OLRV Speed (mph)	Number of Successful Test Runs
2	45	45	2

8 IMA Objective Test Procedures

The Intersection Movement Assist (IMA) is a V2V communication safety application that aims to prevent crashes in the intersection crash box at uncontrolled and stop-controlled intersections for straight-crossing path conflicts by issuing a warning to the driver of the HV in case a conflict is detected. The IMA has two levels of operation. The first level is an “INFORM” state that alerts the drivers of the vehicles involved that a potential conflict has been detected. The second level is the “WARN” state that alerts the drivers that a crash is likely to occur if corrective action is not taken. For the purpose of the test, only the WARN state will be evaluated. The INFORM state will be sometimes used to trigger an action in the HV.

The objective tests fall into two general scenarios: the HV is stopped while the RV is moving and both HV and RV are moving. All tests may be conducted at real-world intersections, although these intersections will be located at a restricted access facility such as a test track. The test intersections will have no buildings and have clear sightlines between the RV and the HV. In addition, there are scenarios where the HV’s view of the RV is obstructed by a parked vehicle.

The distances for INFORM and WARN are calculated in reference to the conflict point. The conflict point is the point in the intersection where the projected trajectories of the HV and the RV intersect. The placement of cones on the road will be measured from the stop bar on the lane, subtracting the offset of the conflict point from the stop bar from the distance.

8.1 General Driving Instructions

The drivers conducting the tests can select the rates of acceleration that allow the test to be conducted in safety. Whenever feasible, cruise control will be used to assist in achieving the target speed so that the results are reproducible. The drivers shall not touch the vehicle brake before a WARN occurs. If the driver touches the brake before the WARN is issued, the test will be considered invalid.

8.2 Test Assumptions

The assumptions in Section 1.4 are assumed to be true for all the IMA tests.

8.3 IMA-T1: Variable Speed Approaches, Stopped HV Enters Intersection with RV Approaching from Left

8.3.1 Background

The objective of this test is to determine whether an alert will be given when the HV is stopped at the intersection and then starts slowly moving forward when the RV passes the INFORM distance.

In this scenario, the HV is stopped with the gear in "drive" and the RV is approaching the intersection at constant speeds of 25 mph and 45 mph. When the RV passes the INFORM distance, the HV will get an INFORM. When the HV releases the brake, the HV will receive a WARN.

8.3.2 Test Setup

Figure 8-1, below, shows the vehicle positions and test setup for Test 1.

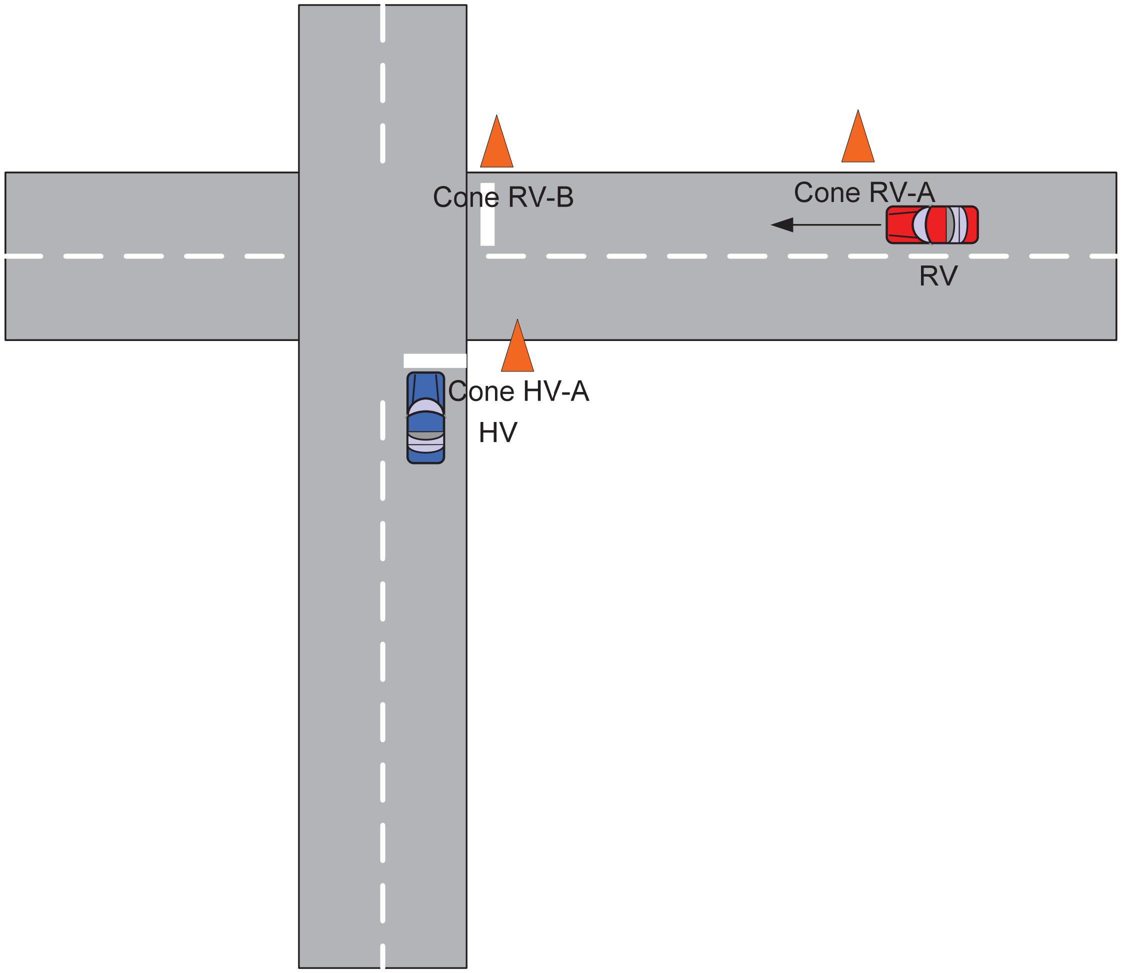

Figure 8-1: Test Setup for Variable Speed Approach Tests

Cones with flags will be placed so the driver of the RV is aware of the vehicle's location with respect to the required maneuvers. These flags will be located by their distance from the stop bar (cone HV-A and cone RV-B) including the offset of the stop bar from the conflict point. It is assumed that flags will be placed using a L1 GPS handheld receiver. Alternate methods of flag location can be used. Flag locations are:

- A green flag is placed at the upper right edge of the intersection box (cone RV-B)
- A red flag is placed at the point where the RV starts its maneuver, 300 meters from the green flag (cone not shown)
- A yellow flag is placed at the point where the RV reaches the target speed, 150 meters from the green flag (cone RV-A)
- A green flag is placed at the stop location of the HV, 1 meter from the lower right corner of the intersection box (cone HV-A)
- A checkered flag is placed where the HV starts to drive toward the intersection 50 meters from cone HV-A (cone not shown)

8.3.3 Driving Instructions

The test will be conducted in the following manner.

- The HV will start at the checkered flag and drive toward the intersection. The HV will stop at the green flag (cone HV-A) and park at the stop bar with the front bumper at the outer edge of the stop bar with the gear in "drive" and the parking brake engaged.
- The RV vehicle will begin at the green flag, 150 meters from the stop bar
- The driver will begin acceleration to the target test speed
- The driver will reach the targeted speed range before the vehicle reaches the yellow flag
- Cruise control will be set at the target test speed (20/30/40/50 mph)
- The driver will continue toward the stop bar at the target velocity
- The test observer in the RV will note behavior of the DVI and record state transitions from "OFF" to "INFORM"
- The test observer in the HV will observe and record if all available warning modalities occur
- The driver of the RV will continue at the test speed through the intersection and stop at any point after the intersection
- The driver of the RV will make a controlled stop of the vehicle after passing the intersection box

8.3.4 Successful Criteria

A valid WARN for the HV within ±10 percent of the nominal warning distance for the actual speed of the run, as specified in the Minimum Performance Requirements, for at least 4 out of 5 runs.

8.3.5 Unsuccessful Criteria

A run is unsuccessful if any of the conditions below occur:

- Any of the Alerts fail to generate
- Alerts are outside the warning range as specified in the successful criteria for three or more runs

8.3.6 Evaluation Criteria

RV Speed (mi/hr)	HV Speed	Maximal Range for IMA Alert (m)	Nominal Range for IMA Alert (m)	Minimal Range for IMA Alert	Number of Valid Tests	Number of Successful Tests to Pass
20	0	25.2	22.9	20.6	3	≥ 2
30	0	43.4	39.4	35.5	3	≥ 2

RV Speed (mi/hr)	HV Speed	Maximal Range for IMA Alert (m)	Nominal Range for IMA Alert (m)	Minimal Range for IMA Alert	Number of Valid Tests	Number of Successful Tests to Pass
40	0	65.3	59.4	53.4	3	≥ 2
50	0	100	82.7	74.4	3	≥ 2

The speed of the RV does not vary more than 2.5 mph from the test speed.

8.4 IMA-T2: HV Stopped at Intersection with RV Approaching from Right (False Positive)

8.4.1 Background

The objective of this test is to determine whether incorrect alerts will be avoided when the HV remains stopped at the intersection and the RV is moving through the intersection at a constant speed.

In this scenario, the HV is stopped with the gear in “drive” and the RV is approaching the intersection at a constant speed of 35 mph. When the RV passes the INFORM distance and the speed is above 35 mph, the HV will get an INFORM. No other warning should be given.

8.4.2 Test Setup

Figure 8-2, below, shows the vehicle positions and test setup for Test 2.

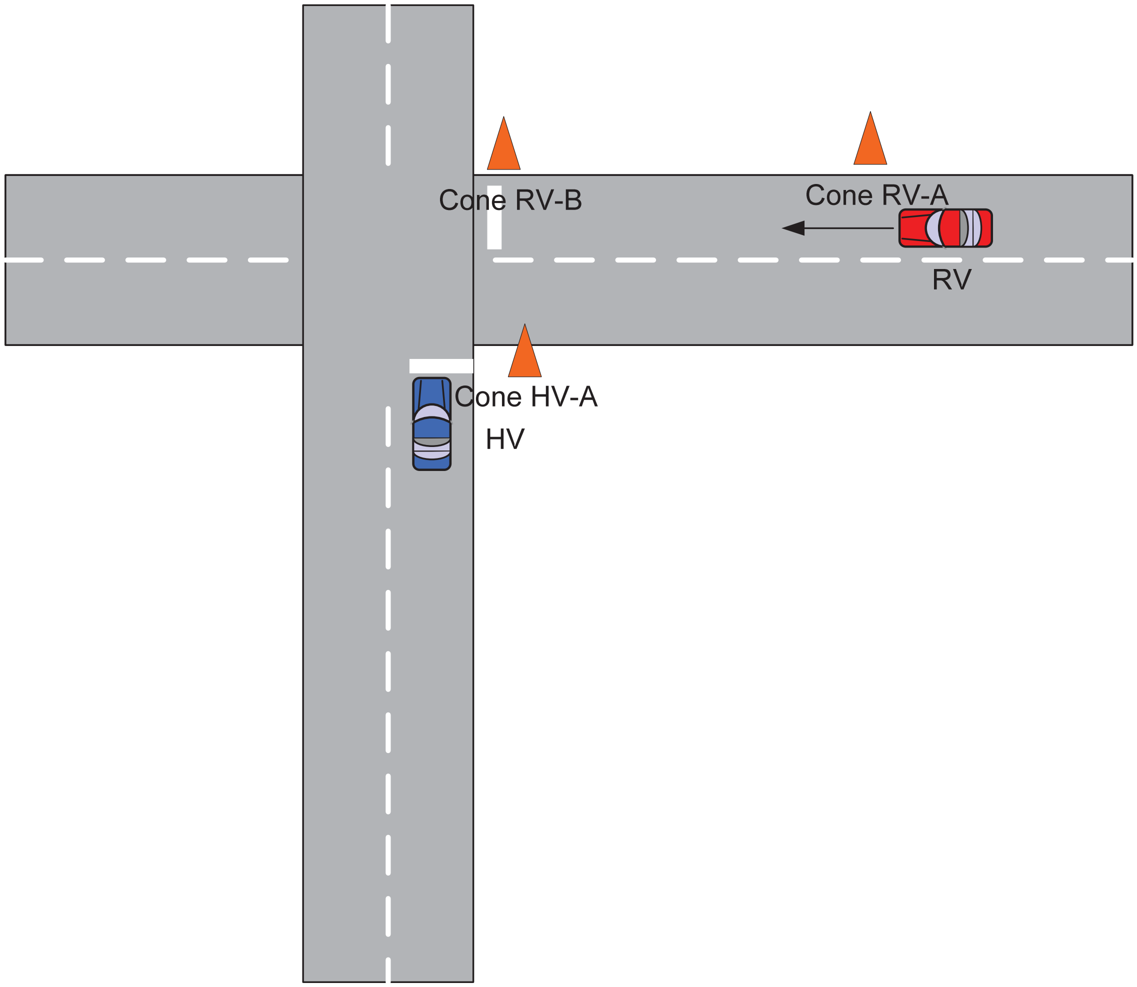

Figure 8-2: Test Setup for Stopped Vehicle False Positive Test

Cones with flags will be placed so the driver of the RV is aware of the vehicle's location with respect to the required maneuvers. These flags will be located by their distance from the stop bar (cone HV-A and cone RV-B) including the offset of the stop bar from the conflict point. It is assumed that flags will be placed using a L1 GPS handheld receiver. Alternate methods of flag location can be used. Flag locations are:

- A green flag is placed at the upper right edge of the intersection box (cone RV-B)
- A red flag is placed at the point where the RV starts its maneuver, 300 meters from the green flag (cone not shown)
- A yellow flag is placed at the point where the RV reaches the target speed, 150 meters from the green flag (cone RV-A)
- A green flag is placed at the stop location of the HV, 1 meter from the lower right corner of the intersection box (cone HV-A)
- A checkered flag where the HV starts to drive toward the intersection 50 meters from cone HV-A (cone not shown)

8.4.3 Driving Instructions

The test will be conducted in the following manner:

- The HV will start at the checkered flag and drive toward the intersection. The HV will stop at the green flag (cone HV-A) and park at the stop bar with the front bumper at the outer edge of the stop bar with the gear in “drive.” The driver has a foot on the brake.
- The RV will begin at the green flag, 150 meters from the stop bar
- The RV driver will begin acceleration to the target test speed
- The RV driver will reach the targeted speed range before the vehicle reaches the yellow flag
- The RV’s cruise control will be set at the target test speed (35, 50 mph)
- The RV driver will continue toward the stop bar at the target velocity
- The test observer in the RV will note behavior of the DVI and record state transitions from “OFF” to “INFORM”
- The test observer in the HV will observe and record if any warning modalities occur
- The driver of the RV will continue at the test speed through the intersection and stop at any point after the intersection
- The driver of the RV will make a controlled stop of the vehicle after passing the intersection box

8.4.4 Successful Criteria

None.

8.4.5 Unsuccessful Criteria

None.

8.4.6 Evaluation Criteria

HV Speed (mph)	RV Speed (mph)	Number of Valid Test Runs	Number of Successful Test Runs
0	35	2	N/A
0	50	2	N/A

No additional validation requirements are necessary for this test

8.5 IMA-T3: Variable Speed Approaches, HV and RV Approaching Intersection from Cross Directions

8.5.1 Background

The objective of this test is to determine whether the alerts will be given for both the HV and the RV when both the HV and the RV are moving toward the intersection. This situation is encountered at uncontrolled intersections.

In this scenario, the HV is approaching the intersection at constant speeds of 15, 25, 35, and 45 mph. The RV will approach the intersection at speeds of 15, 25, and 35 mph. When the HV passes the warning distance, the HV will receive a WARN.

This test is the most complicated test for IMA since the movement of two vehicles has to be coordinated. Therefore, it is recommended to extensively rehearse this test beforehand.

8.5.2 Test Setup

Figure 8-3, below, shows the vehicle positions and test setup for Test 3.

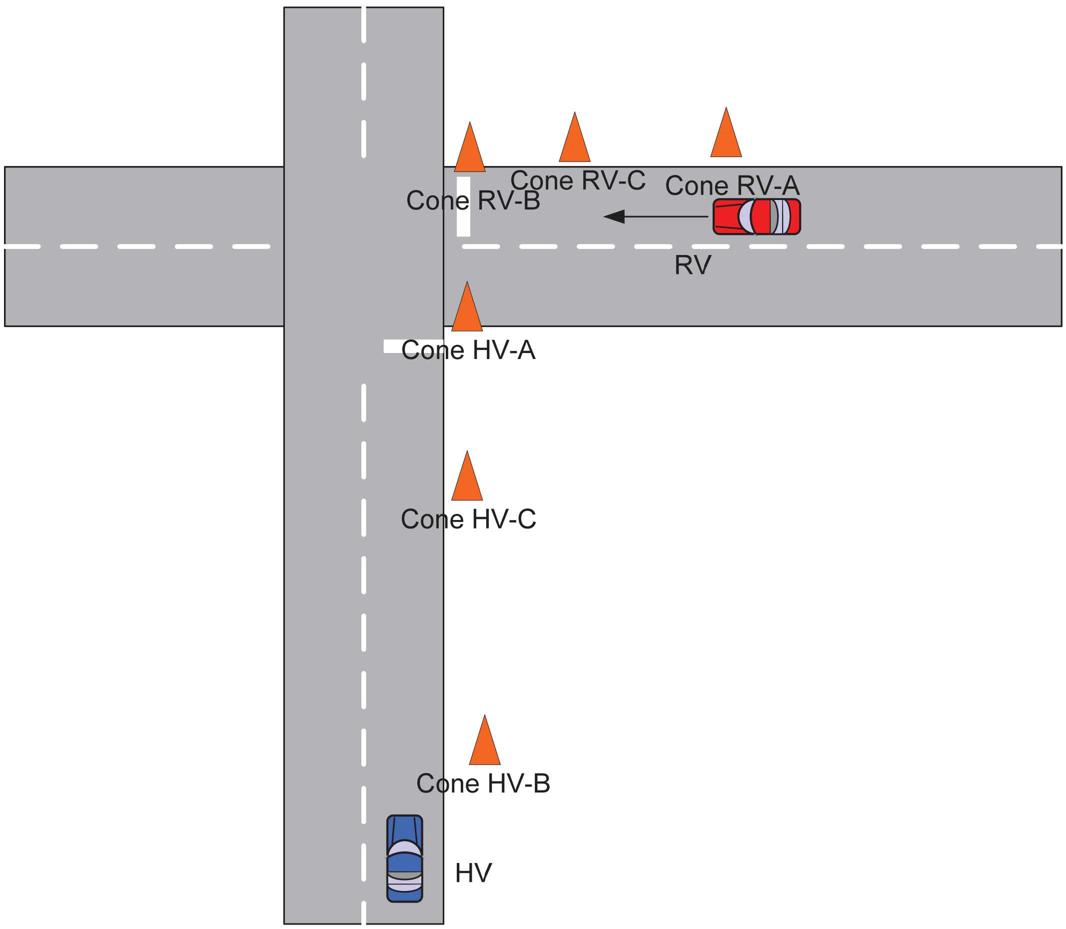

Figure 8-3: Test Setup for Variable Speed Approach Tests, Both Vehicles Moving

Cones with flags will be placed so the driver is aware of the vehicle's location in reference to the stop bar. These flags will be located by their distance from the stop bar. It is assumed that flags will be placed using a L1 GPS handheld receiver. Alternate methods of flag location can be used. Flag locations are:

- A green flag is placed at the lower right corner of the intersection box (cone HV-A)

- A red flag is placed at the point when the HV passes the flag, and the RV starts its maneuvers (cone HV-C). This point will be determined in the practice sessions.
- A yellow flag is placed where the HV is at target speed, 150 meters from the green flag (cone HV-B)
- A yellow flag is placed at the starting position for the RV (cone RV-A), 200 meters from cone RV-B
- A green flag is placed at the upper right corner of the intersection box (cone RV-B)
- A yellow flag is placed at the starting point for the RV approximately 150 meters from the green flag (cone RV-A). The exact location will be determined at the practice session.
- A checkered flag is placed where the RV must brake (cone RV-C), 16 meters from the green flag

Since this scenario has to coordinate the movement of two vehicles driving in crossing directions, a practice session will be scheduled to rehearse the maneuvers and timing at the actual testing location.

8.5.3 Driving Instructions

The test will be conducted in the following manner:

- For the tests at TRC, the HV will use the north loop to get up to speed and the flag for the starting location is omitted
- The HV driver will begin acceleration to the target test speed
- The HV will reach the targeted speed range before the vehicle reaches the yellow flag
- If cruise control is supported by the vehicle at the target speed, the driver will set the cruise control to the middle of the target range
- Before the HV reaches the checkered flag, the RV will accelerate to the target test speed, driving toward the intersection
- The drivers will continue toward the stop bar at the target velocity
- The test observers in the RV and the HV will note behavior of the DVI and record state transitions from “OFF” to “INFORM” to “WARN”
- The test observers in the HV and RV will observe and record if all available warning modalities occur
- Should a valid warning occur, the driver of the RV will make a controlled stop of the vehicle. Should a valid warning fail to occur, the driver of the RV begins braking at the checkered flag and comes to a stop before the stop bar. The driver of the HV will continue through the intersection and come to a safe stop.

8.5.4 Successful Criteria

A valid WARN for the HV within ±10 percent of the nominal warning distance for the actual speed of the run, as specified in the Minimum Performance Requirements.

8.5.5 Unsuccessful Criteria

A run is unsuccessful if any of the conditions below occur:

- WARN failed to generate
- The warning latency is outside the range specified in the Successful Criteria section for three or more runs

8.5.6 Evaluation Criteria

Number of Valid Test Runs	HV Speed (mph)	RV Speed (mph)	Number of Valid Runs	Max/Nominal, Min Warning Distance / m	Number of Successful Test Runs
2	15	15	2	17.5 / 15.9 / 14.3	
2	25	15	2	33.8 / 30.7 / 27.7	
2	25	25	2	33.8 / 30.7 / 27.7	
2	35	15	2	53.9 / 49 / 44.1	
2	35	25	2	53.9 / 49 / 44.1	
2	35	35	2	53.9 / 49 / 44.1	
2	45	15	2	77.7 / 70.6 / 63.5	
2	45	25	2	77.7 / 70.6 / 63.5	
2	45	35	2	77.7 / 70.6 / 63.5	
Total 18					Total ≥12

The vehicle speeds do not vary more than 5 mph from the target test speed. The test will be repeated until eight WARNs have been received to ensure that there have been eight valid runs. The data will be analyzed after the tests, and the first eight valid runs will be evaluated.

8.6 IMA-T4: HV and RV Approaching Intersection from Cross Directions (False Positive)

8.6.1 Background

The objective of this test is to determine whether the vehicles avoid giving unnecessary alerts when both the HV and the RV are moving toward the intersection. This situation is encountered at uncontrolled intersections. In this scenario, the HV and the RV are approaching the intersection at constant speeds of 25 mph. The HV will pass the intersection crash box before the RV passes the red flag.

8.6.2 Test Setup

Figure 8-4, below, shows the vehicle positions and test setup for Test 4.

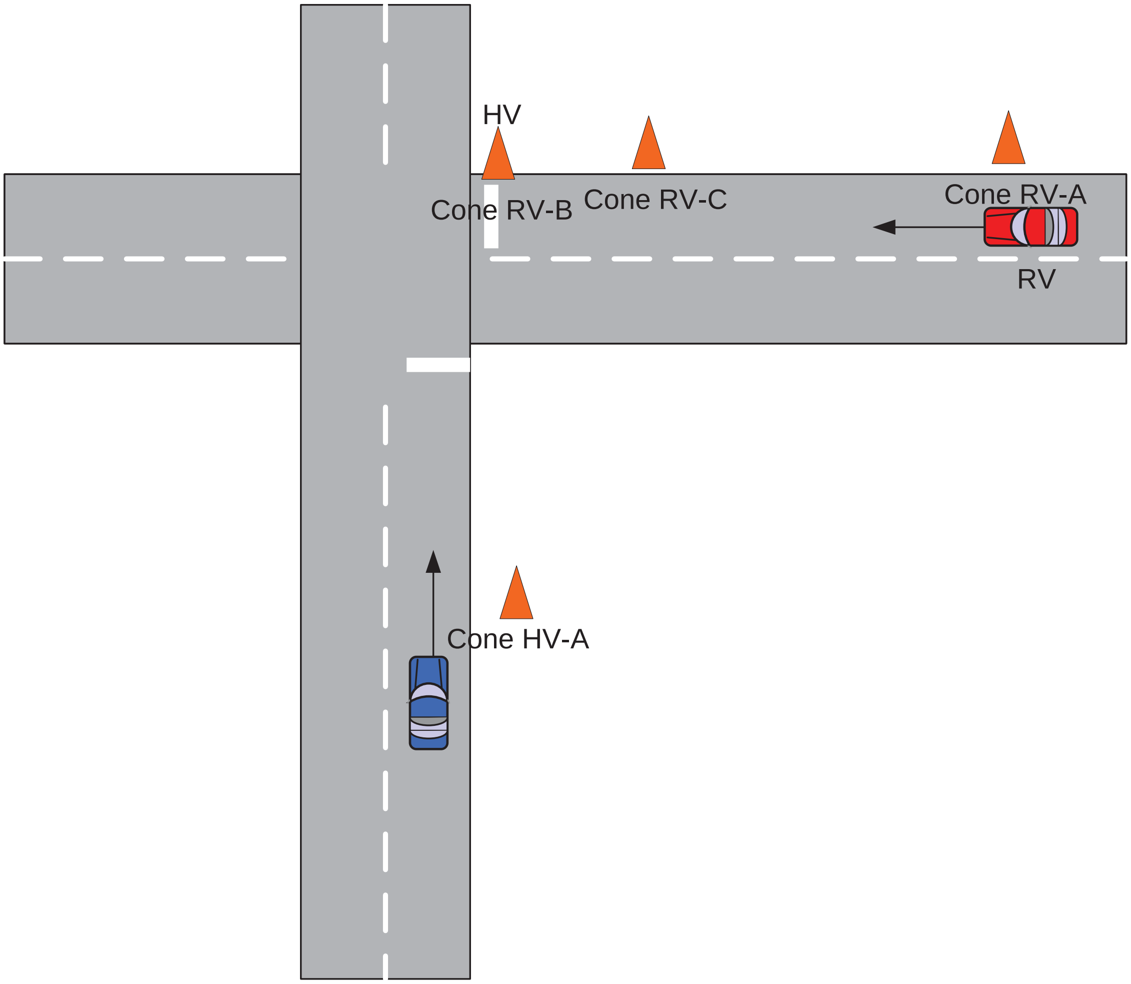

Figure 8-4: Test Setup for Intersection Approach False Positive Tests, Two Vehicles Moving

Cones with flags will be placed so the driver of the RV is aware of the vehicle's location in reference to the stop bar. These flags will be located by their distance from the stop bar. It is assumed that flags will be placed using a L1 GPS, handheld receiver. Alternate methods of flag location can be used. Flag locations are:

- A green flag is placed at the upper right corner of the intersection box (cone RV-B)
- A yellow flag is placed at the starting point for the RV 100 meters from the green flag (cone RV-A)
- A red flag is placed at the point where the passing of the HV signals the RV to start accelerating (cone HV-A), 50 meters from cone RV-B

8.6.3 Driving Instructions

The test will be conducted in the following manner:

- The driver of the HV will approach the intersection at the target test speed with the cruise control engaged
- Once the HV passes the red flag, the driver of the RV will begin acceleration to the target test speed
- The test observers in the HV and RV will observe and record if any available warning modalities occur
- The driver of the HV will make a controlled stop of the vehicle after passing the intersection. The driver of the RV will make a controlled stop after passing cone RV-C.

8.6.4 Successful Criteria

None.

8.6.5 Unsuccessful Criteria

None.

8.6.6 Evaluation Criteria

Number of Valid Test Runs	HV Speed (mph)	RV Speed (mph)	Number of Successful Test Runs
2	25	25	N/A

8.7 IMA-T5: HV Stopped, RV Moving, Open Intersection, Parked Vehicle, Warning

8.7.1 Background

This scenario will test whether the correct alerts are given when the line-of-sight between the HV and the RV is blocked by a parked car. In this scenario, the HV is stopped with the gear in DRIVE, and the RV is approaching the intersection at constant speeds of 35 mph. When the RV passes the INFORM distance at speeds greater than 30 mph, the HV will get an INFORM. When the HV releases the brake, the HV will receive a WARN.

8.7.2 Test Setup

Figure 8-5, below, shows the vehicle positions and test setup for Test 5.

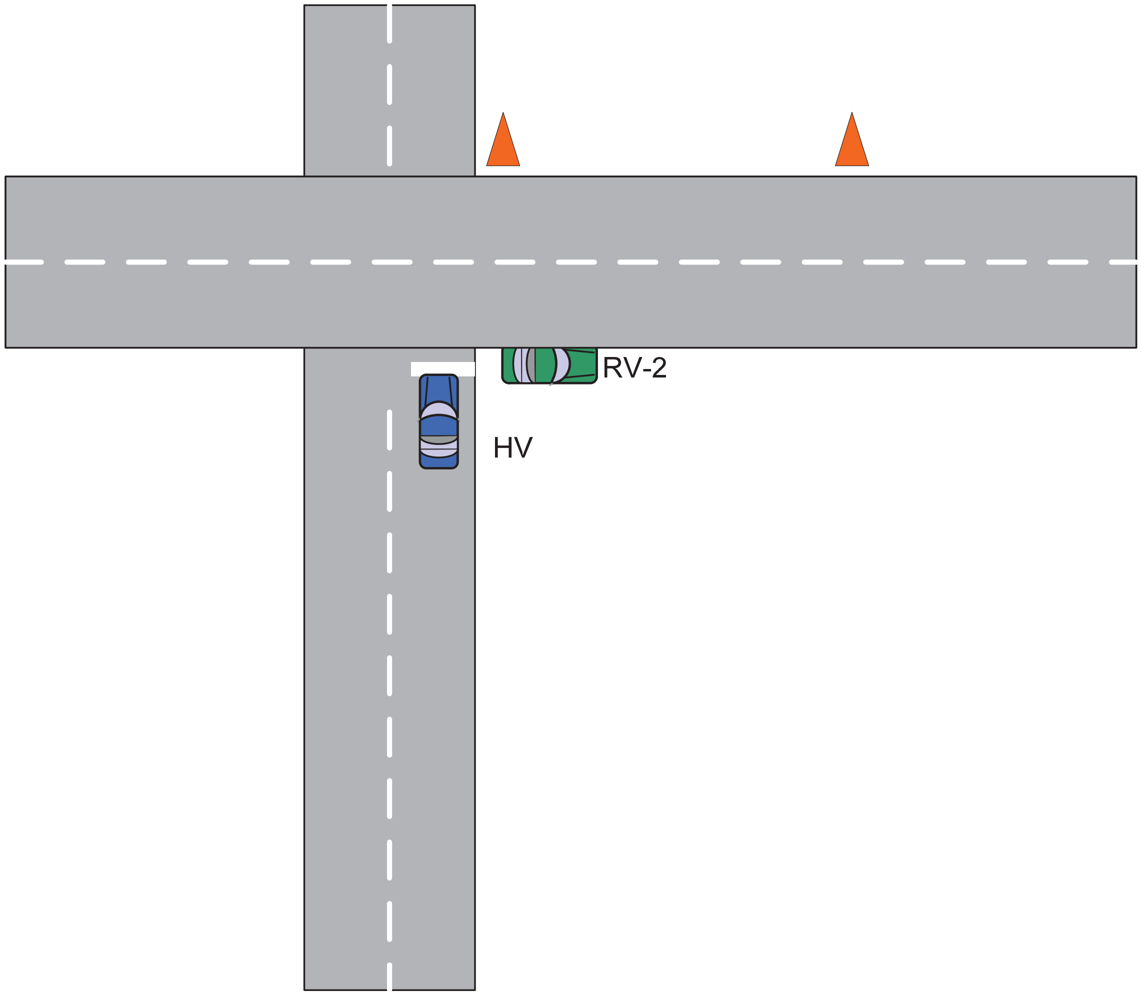

Figure 8-5: Test Setup for Blocking Vehicle Test

Cones with flags will be placed so the driver of the RV is aware of the vehicle's location with respect to the required maneuvers. These flags will be located by their distance from the stop bar (cone HV-A and cone RV-B) including the offset of the stop bar from the conflict point. It is assumed that flags will be placed using a L1 GPS handheld receiver. Alternate methods of flag location can be used. Flag locations are:

- A green flag is placed at the upper right edge of the intersection box (cone RV-B)
- A red flag is placed at the point where the RV starts its maneuver, 150 meters from the green flag (cone not shown)
- A yellow flag is placed at the point where the RV reaches the target speed, 100 meters from the green flag (cone RV-A)
- A green flag is placed at the stop location of the HV. The HV will be parked so that the view of the driver to the RV is obstructed for the duration of the approach at least until the warning distance for the RV.
- A checkered flag is placed where the HV starts to drive toward the intersection 50 meters from cone HV-A (cone not shown)

- A cone without a flag is placed at the position where the blocking vehicle (RV-2) is parked, 10 meters from cone RV-B (cone not shown). The blocking vehicle will be parked such that the left tires are to the right of the right lane boundary.

8.7.3 Driving Instructions

The test will be conducted in the following manner:

- The HV will start at the checkered flag and drive toward the intersection. The HV will stop at the green flag (cone HV-A) and park at the stop bar with the front bumper at the outer edge of the stop bar with the gear in DRIVE and the parking brake engaged. The driver has the foot on the brake.
- The RV will begin at the green flag, 150 meters from the stop bar
- The RV driver will begin acceleration to the target test speed
- The RV driver will reach the targeted speed range before the vehicle reaches the yellow flag
- The RV's cruise control will be set at the target test speed (20/30/40/50 mph)
- The RV's driver will continue toward the stop bar at the target velocity
- The test observer in the RV will note behavior of the DVI and record state transitions from "OFF" to "INFORM"
- When the RV passes the warning cone, the driver of the HV will take a foot off the brake
- The test observer in the HV will observe and record if all available warning modalities occur
- The driver of the RV will continue at the test speed through the intersection and stop at any point after the intersection
- The driver of the RV will make a controlled stop of the vehicle after passing the intersection box

8.7.4 Successful Criteria

A valid WARN for the HV within ±10 percent of the nominal warning distance for the actual speed of the run, as specified in the Minimum Performance Requirements, for at least 4 out of 5 runs.

8.7.5 Unsuccessful Criteria

A run is unsuccessful if any of the conditions below occur:

- Any of the alerts fail to generate
- Alerts are outside the warning range as specified in the successful criteria for three or more runs

8.7.6 Evaluation Criteria

RV Speed (mi/hr)	HV Speed	Maximal Range for IMA Alert (m)	Nominal Range for IMA Alert (m)	Minimal Range for IMA Alert	Number of Valid Tests	Number of Successful Tests to Pass
20	0	25.2	22.9	20.6	3	≥ 2
30	0	43.4	39.4	35.5	3	≥ 2
40	0	65.3	59.4	53.4	3	≥ 2
50	0	100	82.7	74.4	3	≥ 2

The speed of the vehicles does not vary more than 2.5 mph from the test speed. The RV passing the flag will be indicated in the HV by the presence of an INFORM.

9 CLW Objective Test Procedures

The operational goal of Control Loss Warning (CLW) as defined in the Concept of Operations is to warn the driver who is about to enter a zone where another driver has recently lost control of his vehicle. The application targets a subset of crashes involving poor road conditions.

Correspondingly, to pass this objective test, the system must warn the driver when at least one nearby vehicle has lost control. The control loss event is defined as at least one of the vehicle’s Antilock Brake System (ABS), Electronics Stability Control (ESC), or Traction Control (TC) systems being activated for a time duration longer than that as specified in the Minimum Performance Requirements. The following scenarios are selected to cover the typical CLW cases with the RV in the same lane/left lane/right lane, traveling in the same or opposite direction ahead of the HV. Two speed settings—30 mph and 40 mph—are selected as a moderate and appropriate representative speeds for CLW objective testing.

9.1 CLW –T1: HV at Constant Speed with CLW RV in Same Lane ahead in Same Travel Direction

9.1.1 Background

This test is to verify that the CLW system will issue a warning when the control loss event of a vehicle within its forward-path and direction of travel has occurred. The primary objective of the CLW system is to enhance driver awareness of potential hazards via wireless communication amongst similarly equipped vehicles

An illustration of this test procedure is shown in Figure 9-1.

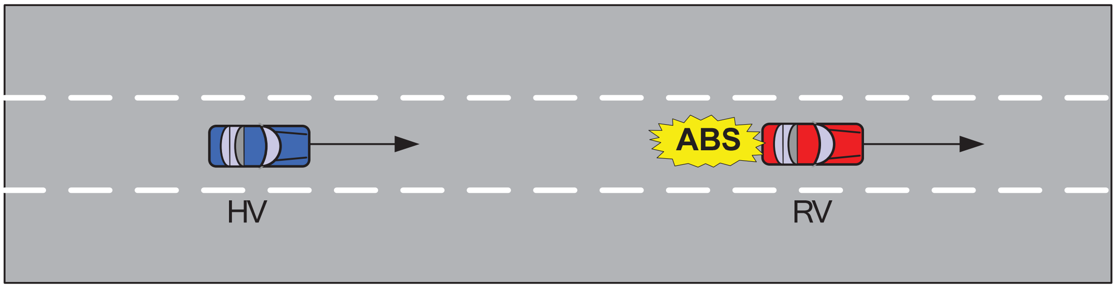

Figure 9-1: RV in Same Lane

9.1.2 Test Assumptions

None.

9.1.3 Test Setup

Cones with flags will be placed so the driver of the HV is aware of the vehicle's location in reference to the required maneuvers. These flags will be located by their distance from the starting point for the HV. It is assumed that flags will be placed using a L1 GPS handheld receiver. Alternate methods of flag location can be used. Flag locations are:

- Red flags placed at the starting point where the HV and RV begin their maneuver (flags not shown in the figure)

9.1.4 CLW Specific Initial Conditions

- CLW event activation shall last longer than 400 ms
- Headway between the HV and RV should be at least 2 seconds until the RV begins a CLW event activation

9.1.5 Driving Instructions

- The RV starts at the red flag, accelerates to 40 mph, and maintains this speed in the center lane
- The HV starts at the red flag, accelerates to 40 mph, and maintains this speed in the center lane, with at least a two-second headway to the RV
- Once the RV test observer and the HV test observer communicate to each other that 40 mph is maintained, the RV performs a CLW event activation and then stops
- The HV observes whether a warning is issued and comes to a stop

9.1.6 Successful Criteria

The HV issues a warning to the driver within the maximum latency as specified in the Minimum Performance Requirements CLW application section for at least 6 out of 8 test runs.

9.1.7 Unsuccessful Criteria

The test is unsuccessful if the warning is missed or issued outside the time range specified in the successful criteria for three or more out of eight test runs.

9.1.8 Evaluation Criteria

Number of Valid Test Runs	HV Speed (mph)	RV Speed (mph)	Number of Successful Test Runs
8	40	40	≥6

9.2 CLW –T2: HV at Constant Speed with CLW RV in Second Right Lane (False Positive)

9.2.1 Background

This test is to verify that the CLW system will NOT issue a warning when the control loss event of a vehicle outside of its forward-path (including immediate adjacent lanes) and direction of travel has occurred. An illustration of this test procedure is shown Figure 9-2.

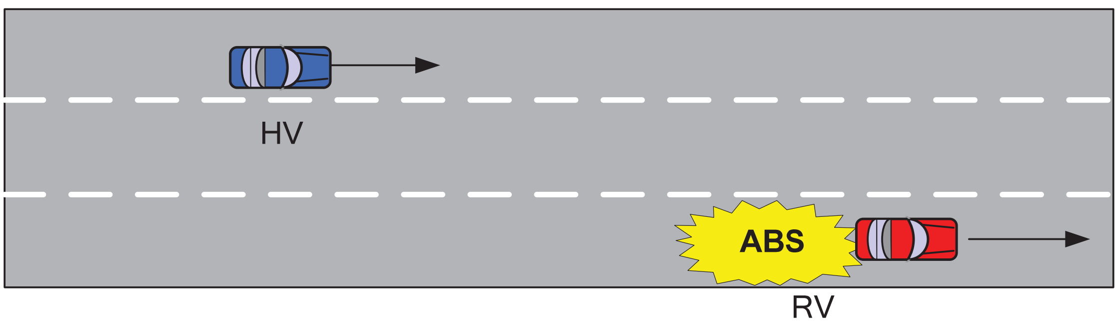

Figure 9-2: RV in Same Lane

9.2.2 Test Assumptions

None.

9.2.3 Test Setup

Cones with flags will be placed so the driver of the HV is aware of the vehicle's location in reference to the required maneuvers. These flags will be located by their distance from the starting point for the HV. It is assumed that flags will be placed using a L1 GPS handheld receiver. Alternate methods of flag location can be used.

Flag locations are: red flags placed at the starting point where the HV and RV begin their maneuver (flags not shown in the figure).

9.2.4 CLW Specific Initial Conditions

- A CLW event shall be activated longer than 400 ms

- Headway between the HV and RV should be 2 seconds until the RV begins a CLW event activation

9.2.5 Driving Instructions

- The RV starts at the red flag, accelerates to 30 mph and maintains this speed in the right lane (right of the center lane).
- The RV's cruise control is set to 30 mph
- The HV starts at the red flag, accelerates to 30 mph, and maintains this speed in the left lane (left of the center lane), with at least 2 seconds headway to the RV
- Once the RV test observer and the HV test observer communicate to each other that 30 mph is maintained, the RV performs a CLW event activation and then stops
- The HV observes whether a warning is issued and comes to a safe stop in its lane of travel

9.2.6 Successful Criteria

None.

9.2.7 Unsuccessful Criteria

None.

9.2.8 Evaluation Criteria

Number of Valid Test Runs	HV Speed (mph)	RV Speed (mph)	Number of Successful Test Runs
2	30	30	N/A

9.3 CLW –T3: HV at Constant Speed with CLW RV in Adjacent Lane Ahead in Opposite Travel Direction

9.3.1 Background

This test is to verify that the CLW system will issue a warning when the CLW event of a vehicle within its forward path and opposite direction of travel has been activated. The primary objective of the CLW system is to enhance driver awareness of potential hazards via wireless communication amongst similarly equipped vehicles. An illustration of this test procedure is shown in Figure 9-3.

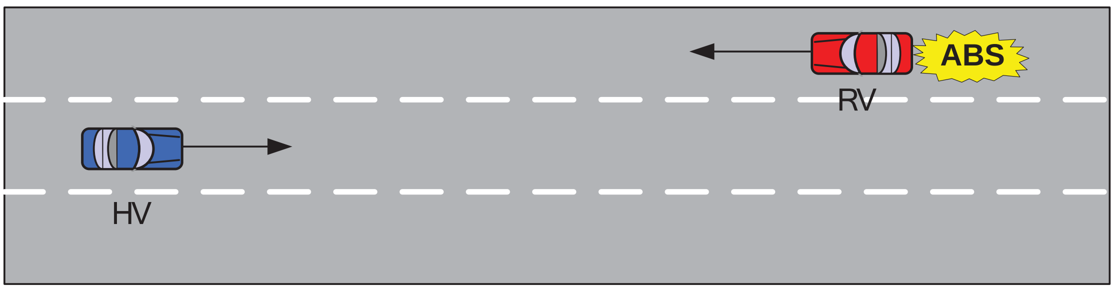

Figure 9-3: HV and RV in Opposite Directions

9.3.2 Test Assumptions

None.

9.3.3 Test Setup

Cones with flags will be placed so the driver of the HV is aware of the vehicle's location in reference to the required maneuvers. These flags will be located by their distance from the starting point for the HV. It is assumed that flags will be placed using a L1 GPS handheld receiver. Alternate methods of flag location can be used. Flag locations are:

- Red flags placed at the starting point where the HV and RV begin their respective maneuvers (flags not shown in the figure), 500 meters from each other

9.3.4 CLW Specific Initial Conditions

CLW event activation shall occur longer than 400 ms.

9.3.5 Driving Instructions

- The RV starts at the red flag, accelerates to 30 mph and maintains this speed in the left lane, approaching the HV
- The HV starts at the red flag, accelerates to 30 mph and maintains this speed in the center lane
- Once the RV test observer and the HV test observer communicate to each other that 30 mph is maintained at approximately a 150 meter headway, the RV performs a CLW event activation and then stops
- The HV observes whether a warning is issued and comes to a safe stop

9.3.6 Successful Criteria

The HV issues a warning to the driver within the maximum latency as specified in the Minimum Performance Requirements CLW application section for at least six out of eight test runs.

9.3.7 Unsuccessful Criteria

The test is unsuccessful if the warning is missed or issued outside the time range specified in the successful criteria for three or more out of eight test runs.

9.3.8 Evaluation Criteria

Number of Valid Test Runs	HV Speed (mph)	RV Speed (mph)	Number of Successful Test Runs
8	30	30	≥6

10 Test Procedure Results Form

Name of Test			
Conditions and Data Collected			
Date (GMT)	Time (GMT)	Weather	Wet / Dry
Driver	Observer		
Nominal test speed			
Nominal headway (if applicable)			
Other Conditions for Test Validity			
Collected Data Files	Log File HV		
Config File	Log File RV		

Results					
Test Run Number	Observer Speed Recorded	Warning Received?	Test Appeared Valid?	Warning appears correct	Appeared to Pass or Fail
1	____mph	Y / N	Y / N	Y / N	Pass /Fail

Name of Test					
Conditions and Data Collected					
2	____mph	Y / N	Y / N	Y / N	Pass /Fail
3	____mph	Y / N	Y / N	Y / N	Pass /Fail
4	____mph	Y / N	Y / N	Y / N	Pass /Fail
5	____mph	Y / N	Y / N	Y / N	Pass /Fail
6	____mph	Y / N	Y / N	Y / N	Pass /Fail
7	____mph	Y / N	Y / N	Y / N	Pass /Fail
8	____mph	Y / N	Y / N	Y / N	Pass /Fail

11 References

[1] Crash Avoidance Metrics Partnership, *"Development and Validation of Functional Definitions and Evaluation Procedures For Collision Warning/Avoidance Systems,"* NTHSA Technical Report DOT HS 808 964, August 1999.

[2] CAMP VSC2 Consortium, *"Vehicle Safety Communications – Applications (VSC-A) Final Report: Appendix C-1 – Minimum Performance Requirements,"* Appendix Volume 1, NHTSA Publication, 2011.

[3] CAMP VSC2 Consortium, *"Vehicle Safety Communications – Applications (VSC-A) Final Report: Appendix C-3 – Objective Testing Results,"* Appendix Volume 1, NHTSA Publication, 2011.

VSC-A Final Report: Appendix C-3

Objective Testing Results

List of Acronyms

BSW	Blind Spot Warning
BSW+LCW	Blind Spot Warning+Lane Change Warning
CAMP	Crash Avoidance Metrics Partnership
CAN	Controller Area Network
CLW	Control Loss Warning
CPU	Central Processing Unit
DMU	Dynamics Measurement Unit
DNPW	Do Not Pass Warning
DSRC	Dedicated Short Range Communications
DVI	Driver Vehicle Interface
DVIN	Driver Vehicle Interface Notifier
ECDSA	Elliptic Curve Digital Signature Algorithm
ECU	Electronic Control Unit
EEBL	Emergency Electronic Brake Lights
EGUI	Engineering Graphical User Interface
FCW	Forward Collision Warning
GPS	Global Positioning System
GUI	Graphical User Interface
HV	Host Vehicle
ID	Identifier
IMA	Intersection Movement Assist
ITS	Intelligent Transportation Systems
JPO	Joint Program Office
LCW	Lane Change Warning
MPR	Minimum Performance Requirements
NHTSA	National Highway Traffic Safety Administration
OEM	Original Equipment Manufacturer
OLRV	Oncoming Left Remote Vehicle
OTA	Over-the-Air
OTP	Objective Test Procedure(s)

RITA	Research and Innovative Technology Administration
RV	Remote Vehicle
SP	Single Point (Relative Positioning)
TC	Target Classification
TRC	Transportation Research Center
USDOT	United States Department of Transportation
VDA	Vehicle Dynamics Area
VOD	Verify on Demand
VRTC	Vehicle Research & Testing Center
VSC	Vehicle Safety Communications
VSC2	Vehicle Safety Communications 2
VSC-A	Vehicle Safety Communications – Applications
V-V or V2V	Vehicle-to-Vehicle
WSU	Wireless Safety Unit

Table of Contents

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1 Introduction

1.1 Purpose

This report describes the results of the Objective Test Procedure (OTP) testing in the VSC-A Project that took place from June 1, 2009, to June 3, 2009, at the Transportation Research Center (TRC) in East Liberty, Ohio. This project activity served to test the performance of the applications and to ascertain their performance according to the VSC-A Minimum Performance Requirements [3].

1.2 Organization of the Report

The report will briefly describe each application that was tested, the test facilities, along with scenarios in which each application was tested. The exact tests and the test setup procedures can be found in Objective Test Procedures and Plan appendix [4] in the VSC-A Final Report for the VSC-A Project. Finally, the results of the objective tests as determined by the analysis by the individual automotive Original Equipment Manufacturers (OEMs) in the VSC-A Project will also be listed.

2 Applications and System Configuration

2.1 Applications

The applications that were tested in the objective tests were:

- Emergency Electronic Brake Lights (EEBL)
- Blind Spot Warning+Lane Change Warning (BSW+LCW)
- Forward Collision Warning (FCW)
- Do Not Pass Warning (DNPW)
- Intersection Movement Assist (IMA)
- Control Loss Warning (CLW)

The following paragraphs contain a brief description of the applications. A more detailed description can be found in the Test Bed System Development appendix of the VSC-A Final Report [2].

<u>Emergency Electronic Brake Lights (EEBL):</u>

The EEBL application enables a vehicle to broadcast a self-generated emergency brake event to the surrounding vehicles. Upon receiving such event information, the Host Vehicle (HV) determines the relevance of the event and then provides a warning to the driver, if appropriate. This application is particularly useful when the driver's line-of-sight is obstructed by other vehicles or bad weather conditions (e.g., fog, heavy rain).

Blind Spot Warning+Lane Change Warning (BSW+LCW):

The BSW+LCW application will warn the driver of the HV if the blind spot zone into which the HV intends to switch is, or will soon be, occupied by another vehicle traveling in the same direction and that a lane change is not safe. Moreover, the application provides advisory information to the driver whenever a vehicle in an adjacent lane is positioned in a blind spot zone of the HV. A lane change attempt is based, only as a proxy, upon the HV's turn signal initiation.

Forward Collision Warning (FCW):

The FCW application issues a warning to the driver of the HV in case of an impending rear-end collision with a vehicle ahead in traffic in the same lane and direction of travel. FCW will help drivers avoid or mitigate rear-end vehicle collisions in the forward path of travel.

Do Not Pass Warning (DNPW):

The DNPW application warns the driver when a slower moving vehicle cannot be safely passed using a passing zone which is occupied by vehicles with the opposite direction of travel. When a passing maneuver is initiated through the use of the left turn signal, only as a proxy, the application determines the presence or absence of an on-coming Remote Vehicle (RV) in the passing zone of the adjacent lane. If the presence of an on-coming vehicle in the passing zone is detected, a warning is issued to the driver. The DNPW application can also be operated in an advisory mode that informs the driver that the passing zone is occupied without the use of the proxy turn signal.

Intersection Movement Assist (IMA):

The IMA application warns the driver of a HV when it is not safe to enter an intersection due to high-collision probability with other RVs. Initially, IMA is intended to help drivers avoid or mitigate vehicle collisions at stop-sign controlled and uncontrolled intersections.

Control Loss Warning (CLW):

The CLW application enables a vehicle to broadcast a self-generated, control-loss event to surrounding vehicles. Upon receiving such event information, the HV determines the relevance of the event and, if appropriate, provides a warning to the driver.

2.2 System Configuration

All the configuration information for the applications in the objective testing was stored in a configuration file. The configuration file contains information about speed and distance thresholds, positioning, communications, security, and other parameters necessary for the functioning of the system. The important settings for communication, positioning, and security used in the objective testing default configuration are:

Communications Configuration

- All vehicle-to-vehicle (V2V) applications were enabled
- 1609.4 channel switching was enabled with a 10 Hz message transmission rate and 20 dBm transmission power

- The data rate for the channel was set at 6 Mbit/second

<u>Security Configuration</u>

- Security was enabled and configured for Elliptic Curve Digital Signature Algorithm (ECDSA) with Verify on Demand (VoD)
- Privacy was enabled with full identification randomization including the sender identification (ID)
- Certificates were attached with each message and certifications changed randomly every 5 to 10 minutes

<u>Positioning</u>

- Single Point (SP) relative positioning was enabled
- Position coasting was enabled to support short Global Positioning System (GPS) and communication outages

3 Objective Testing Facilities and Organization

3.1 Facilities

The objective testing used both the Skid Pad, a 26 meter by 1097 meter straight road with 5 lanes with a lane width of 4.3 meters (Figure 1), and the Vehicle Dynamics Area (VDA), a 200,000 square meter asphalt pad with acceleration loops at each end (Figure 2).

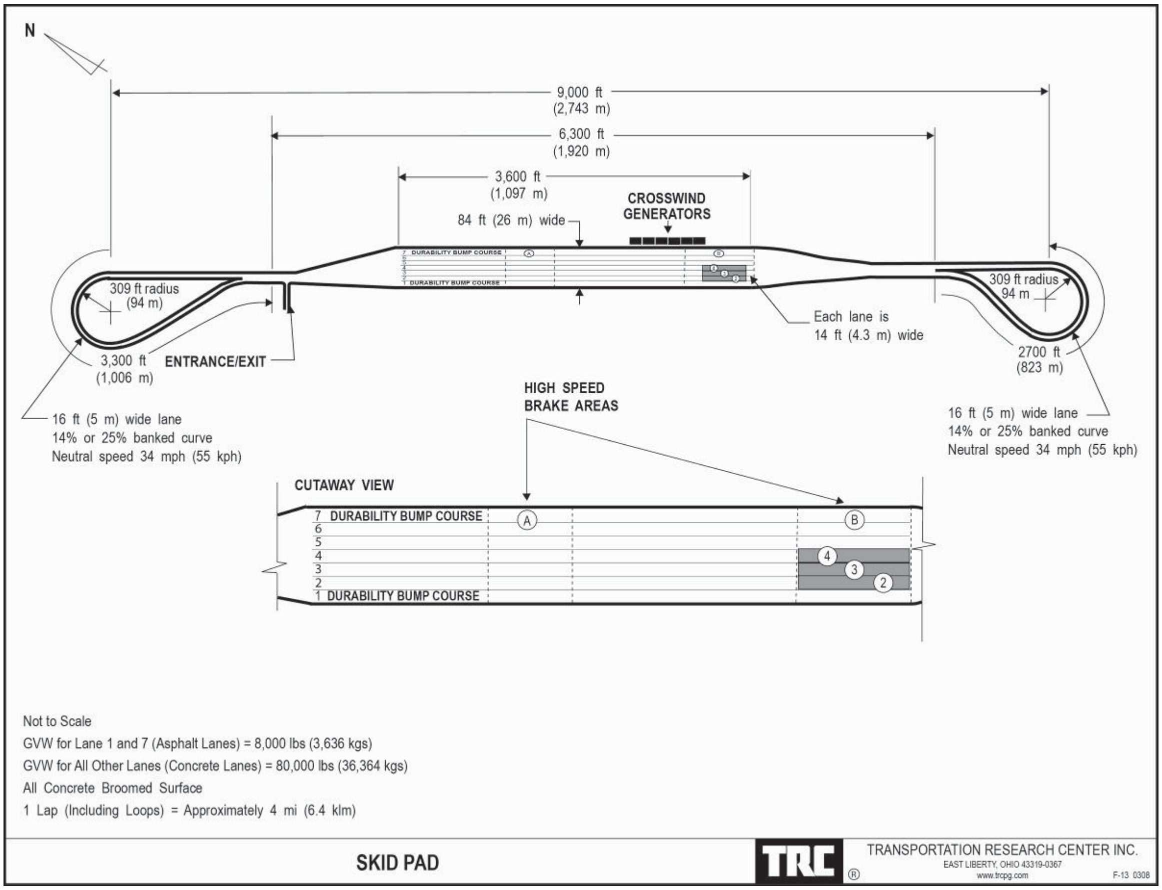

Figure 1: Skid Pad

The tests performed on the skid pad included the EEBL (with the exception of the curve tests), FCW (with the exception of the curve tests), BSW+LCW (with the exception of the curve tests), and DNPW warning applications.

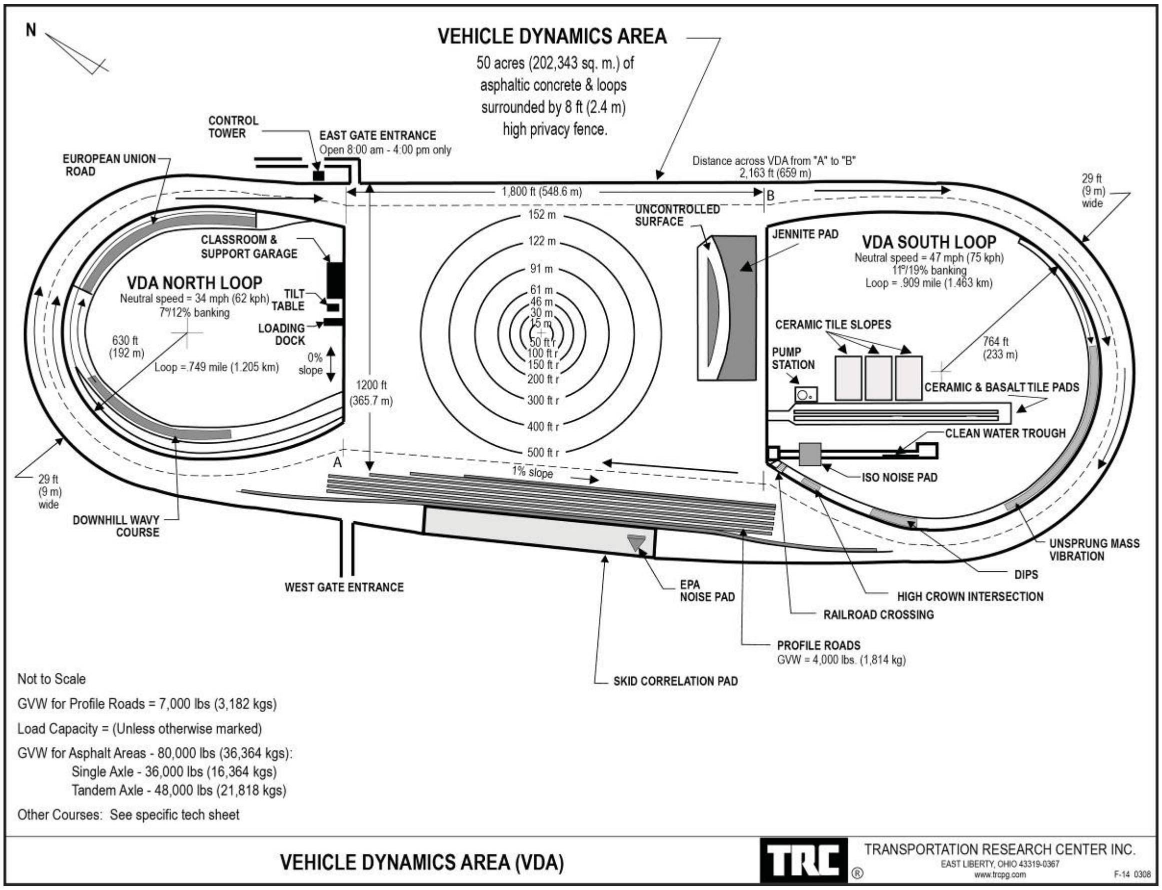

Figure 2: Vehicle Dynamics Area

On the VDA, an intersection was set up in the middle of the area at the 300 foot radius line using traffic cones. The Jennite Pad was used for the CLW test scenarios, and the VDA South Loop was used for the curve tests for the EEBL, FCW, and BSW+LCW applications.

3.2 Organization

The OEMs transported the vehicles to TRC for inspection the weekend prior to testing. Inspection by the Vehicle Research & Test Center (VRTC) was a mandatory requirement for the vehicles to drive on the testing facilities. On the morning of the first testing day, the Skid Pad was laid out with cones and flags according to the setup procedures in [4]. The tests started on the afternoon of the first day of testing on the Skid Pad and continued there on the morning of the second day. On the afternoon of the second day testing began on the VDA. Weather conditions were sunny and dry for all testing days.

Testing on the Skid Pad was conducted using all five lanes with two scenarios being run in parallel. Testing on the VDA used the intersection for the IMA application with one vehicle using the VDA north loop to get up to the required test speed. The VDA south loop was used for the curve scenarios with multiple tests run in parallel. The Jennite Pad was used for the CLW application.

4 Data Recording

The data that was collected during the OTP testing was recorded both in a data logging and visualization tool called and as a scenario recording in the DENSO Wireless Safety Unit (WSU). Figure 3 shows an example of the primary screen of the data logging and visualization tool that was used for the objective testing. The screen is divided into four quadrants:

- Quadrant 1: Contains a birds-eye view which is a graphical representation of the location of the HV, centered at (0,0) and the RVs that the HV is in communication with. In addition to plotting the HV and RV(s) locations, the ability to plot their path history points and predicted paths is also supported.
- Quadrant 2: Contains the camera data which consists of a single image, as shown below, or up to four images multiplexed together. The applicable RV track number(s) will be overlaid onto the displayed image when the single image mode is selected.
- Quadrant 3: Contains the HV's vehicle sensor data, Dynamics Measurement Unit (DMU) data, and GPS data.
- Quadrant 4: Contains the RV track data as determined by the Target Classification (TC) core module.

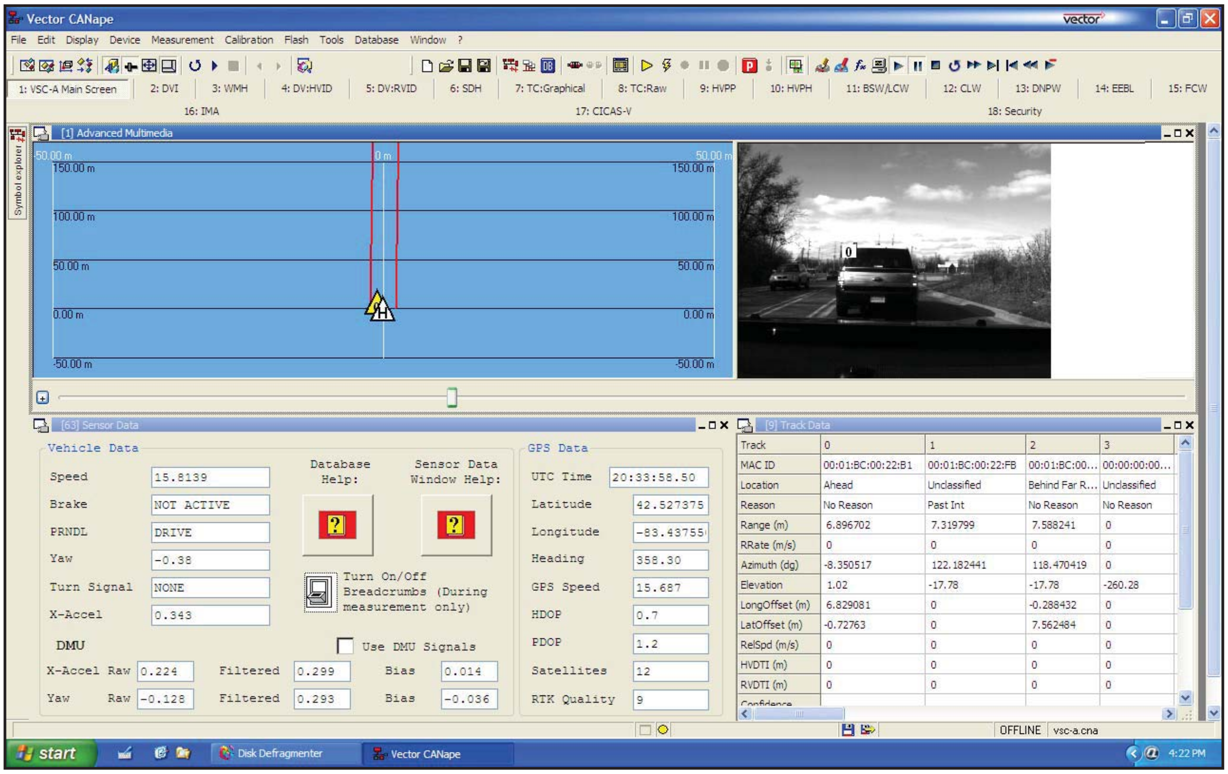

Figure 3: Example Layout Screen for OTP Testing

Early on it was decided that, due to the potential Central Processing Unit (CPU) usage requirements required by the WSU to simultaneously support both the on-board

Engineering Graphical User Interface (EGUI) and the data logging and visualization tool, support for the EGUI screens would be provided in the data logging and visualization tool. This was done as a risk containment measure due to the usefulness and critical nature of the data contained in the EGUI screens and, to ensure access to this data while only requiring a single tool to run on the WSU during the OTP testing. Thus, avoiding potential impact to the performance of the safety applications. Figure 4 shows an example of the DNPW EGUI application screen, supported in the data logging and visualization tool.

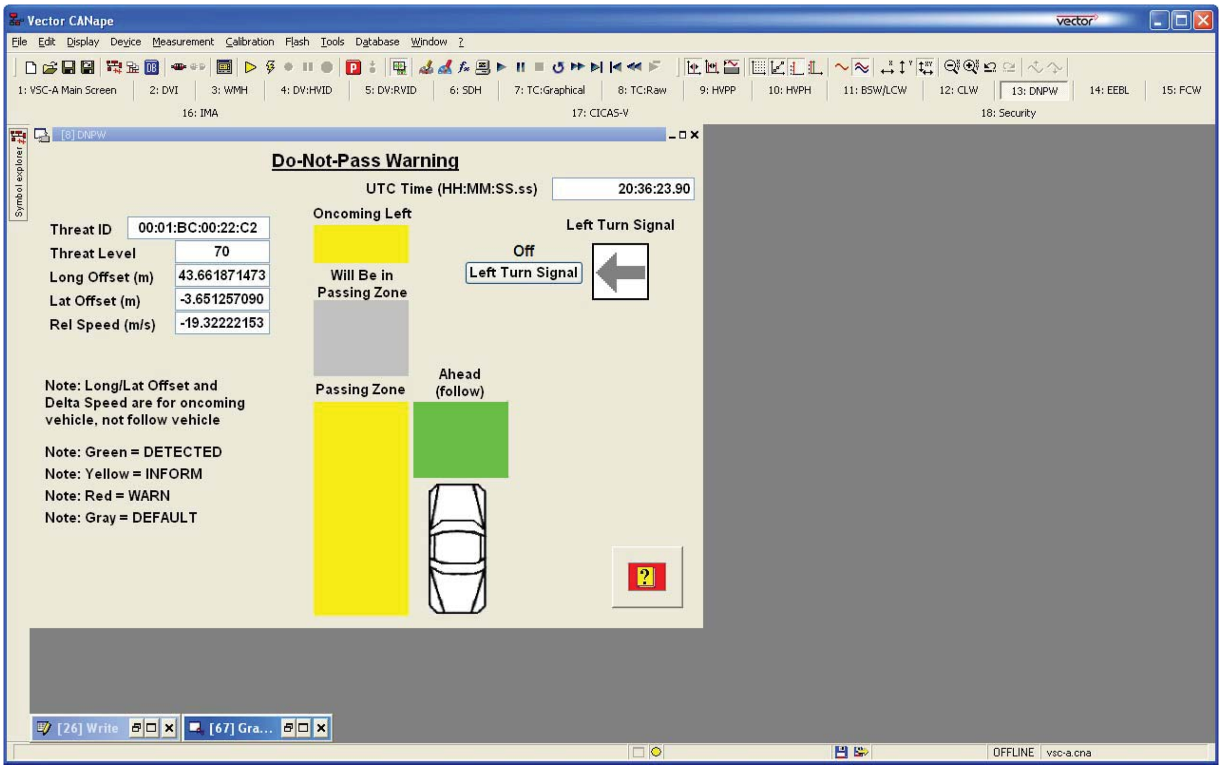

Figure 4: Example Layout for the DNPW EGUI in the Visualization Tool

Figure 5 shows the data logging and visualization tool screen for the IMA application followed by Figure 6 which shows the analysis screen used for the analysis of the IMA application. Analysis of the test results was the other primary usage of the data logging and visualization tool. The screens for the other applications look similar.

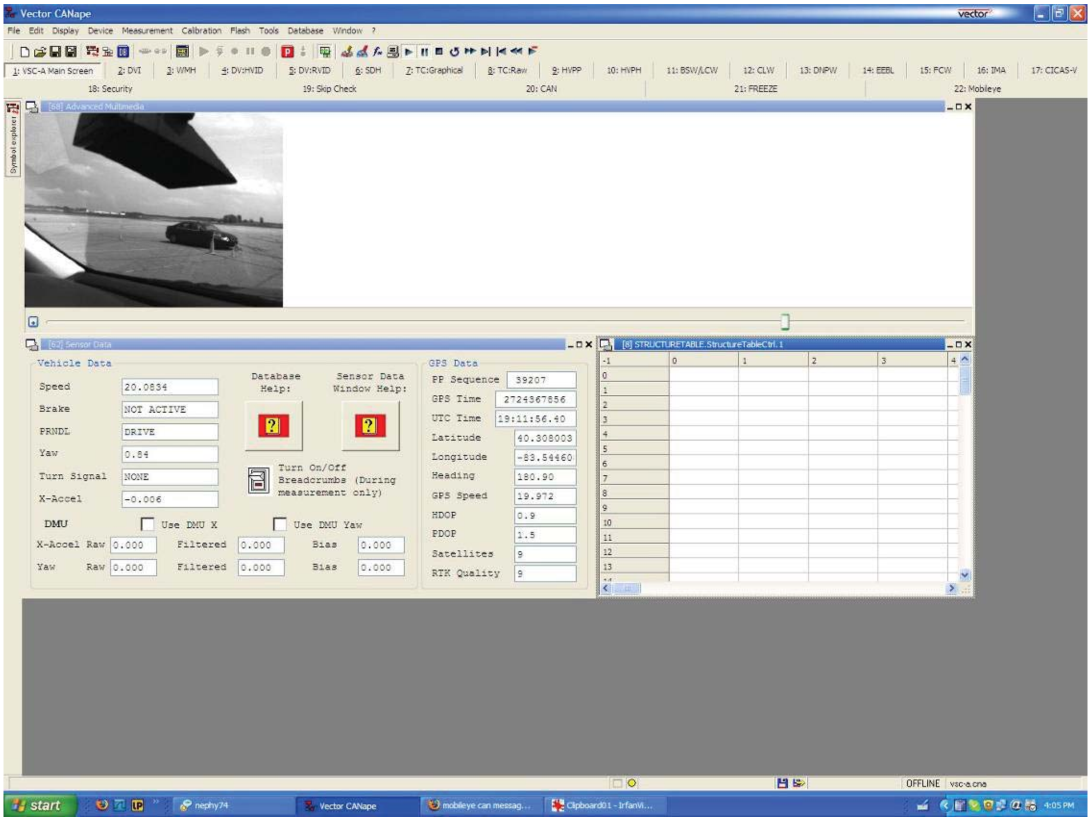

Figure 5: Recording Screen for IMA in the Visualization Tool

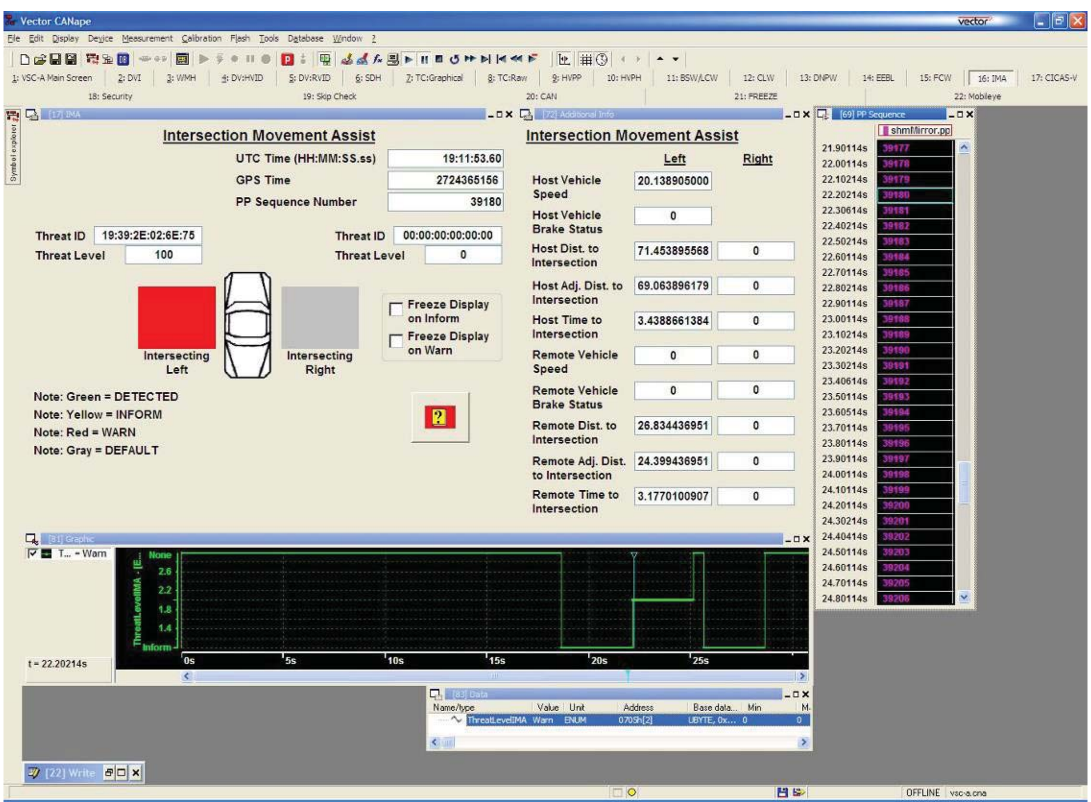

Figure 6: Analysis Screen in the Visualization Tool for IMA OTP Analysis

5 Objective Test Results

5.1 Overview

The objective tests included both true positive tests where the objective was to get a warning and false positive tests where the system was supposed to not issue a warning since it was not necessary. The complete list of tests, the speeds for the runs, and the number of runs for each test is shown in Table 1. True positive tests had successful/unsuccessful criteria associated with them to gauge the performance of the application to successfully warn the driver of a detected threat. False positive tests were not evaluated for that purpose since they did not measure the performance of the application with regard to warning latencies, etc. The number of runs per test varied. In general, true positive tests had eight (8) or ten (10) runs, whereas false positive tests had two (2) runs. If multiple speed combinations were tested in one scenario, the number of runs was adjusted to keep the overall number of runs manageable.

The evaluation of the test runs was conducted by each OEM responsible for the application. In general, the purpose of the test was to measure the consistency of the warning, rather than the absolute warning timing. The reasons for this methodology are:

- This demonstrates the ability of the system to support any warning timing that is chosen
- The absence of a real Driver-Vehicle Interface (DVI) so only the time where the system gives the signal to the DVI Notifier (DVIN) can be used as an objective measure
- The applications were developed to demonstrate the capabilities of the system with an emphasis on interoperability, so the warning timings were not optimized

For the reasons listed above, the warning timings ***do not represent*** the warning timings that will be implemented in the final version of the applications for use with naïve drivers.

True positive tests that passed at least six (6) out of eight (8) or eight (8) out of ten (10) runs were classified as successful, otherwise they were deemed unsuccessful. As can be seen from Table 1, all the true positive tests were successful. The false positive tests were not evaluated for success or failure, but all the false positive tests were successful in the sense that no warning was issued. Please refer to [4] for the details of each test identified in the 'Test Scenario' column of Table 1.

Table 1: Test Scenarios and Results

Test Scenario	Description	Speeds	Number of Runs	Type of Test	Result
EEBL-T1	HV at constant speed with decelerating RV in same lane	50	8	True positive	Successful

Test Scenario	Description	Speeds	Number of Runs	Type of Test	Result
EEBL-T2	HV at constant speed with decelerating RV in left lane on curve	50	8	True positive	Successful
EEBL-T3	HV at constant speed with decelerating RV in same lane and obstructing vehicle in between	50	8	True positive	Successful
EEBL-T4	HV at constant speed with mild-decelerating RV in same lane	50	2	False positive	N/A
EEBL-T5	HV at constant speed with decelerating RV in 2nd right lane	50	2	False positive	N/A
FCW-T1	HV travel at a constant speed/RV stopped	50	10	True positive	Successful
FCW-T2	HV travel behind RV1/RV1 travel behind RV2/RV2 stopped	50	10	True positive	Successful
FCW-T3	HV drive on a curve\RV stopped at the curve	50	8	True positive	Successful
FCW-T4	HV tailgate RV	50	2	False positive	N/A
FCW-T5	HV follows RV/RV brakes hard	40	10	True positive	Successful
FCW-T6	HV driving into a curved right lane/RV stopped in the left curved lane	50	2	False positive	N/A
FCW-T7	HV travels behind a slower RV	50	10	True positive	Successful
FCW-T8	HV changes lanes behind a stopped RV	50	8	True positive	Successful
FCW-T9	HV approaches two RVs in left and right adjacent lanes and passes between them	50	2	False positive	N/A
BSW/LCW-T1	LCW Warning, Left	50	8	True positive	Successful

Test Scenario	Description	Speeds	Number of Runs	Type of Test	Result
BSW/LCW-T2	LCW Warning, Right	50	8	True positive	Successful
BSW/LCW-T3	LCW Warning, Right with Left BSW Advisory	50	9	True positive	Successful
BSW/LCW-T4	BSW Advisory Alert, Left	50	8	True positive	Successful
BSW/LCW-T5	BSW Advisory Alert, Right	50	8	True positive	Successful
BSW/LCW-T6	No Warning or Advisory for RV behind	50	2	False positive	N/A
BSW/LCW-T7	No Warning or Advisory for RV far Right	50	2	False positive	N/A
BSW/LCW T8	LCW Warning in Curve, Right	35	8	True positive	Successful
DNPW-T1	Attempt to pass with oncoming RV in adjacent lane	25/35	10	True positive	Successful
DNPW-T2	Attempt to pass with stopped RV in adjacent lane	30/40	10	True positive	Successful
DNPW-T3	Attempt to pass with oncoming RV not in adjacent lane	45	2	False positive	N/A
IMA-T1	Variable speed approaches with stopped HV/moving RV/open intersection	20/30/40/50	12	True positive	Successful
IMA-T2	Stopped HV/moving RV/open intersection	35/50	4	False positive	N/A
IMA-T3	Variable speed approaches with moving HV/moving RV/open intersection	15/25/35/45	16	True positive	Successful
IMA-T4	Moving HV/moving RV/open intersection	25	4	False positive	N/A

Test Scenario	Description	Speeds	Number of Runs	Type of Test	Result
IMA-T5	Stopped HV/moving RV/open intersection/parked vehicle	20/30/40/50	12	True positive	Successful
CLW-T1	HV at constant speed with CLW RV in same lane ahead in same travel direction	40	8	True positive	Successful
CLW-T2	HV at constant speed with CLW RV in 2nd right lane	30	2	False positive	N/A
CLW-T3	HV at constant speed with CLW RV in adjacent lane ahead in opposite travel direction	30	12	True positive	Successful

5.2 Results by Application

5.2.1 Emergency Electronic Brake Light (EEBL)

For the EEBL application to pass the true positive tests (EEBL-T1, EEBL-T2 and EEBL-T3), the warning had to come within the latency specified in the minimum performance requirements [3]. Table 2 shows the overall results of the EEBL testing excluding failed test runs.

Table 2: Overall Results of the True Positive EEBL Tests

Warning Latency (s)	
Maximum	0.377
Average	0.271
Minimum	0.065

In the following tables, the results of the individual runs for each test are listed.

5.2.1.1 EEBL Test 1

Table 3: EEBL Test 1 Results

Run	Latency (s)	Result
1	0.373	Pass
2	0.372	Pass
3	0.377	Pass

Run	Latency (s)	Result
4	0.065	Pass
5	0.241	Pass
6	0.272	Pass
7	0.274	Pass
8	0.269	Pass

5.2.1.2 EEBL Test 2

Table 4: EEBL Test 2 Results

Run	Latency (s)	Result
1	1.618	Fail: delay
2	0.308	Pass
3	0.220	Pass
4	0.320	Pass
5	0.315	Pass
6	0.218	Pass
7	0.316	Pass
8	0.219	Pass

5.2.1.3 EEBL Test 3

Table 5: EEBL Test 3 Results

Run	Latency (s)	Result
1	0.374	Pass
2	0.272	Pass
3	0.272	Pass
4	0.374	Pass
5	0.171	Pass
6	0.173	Pass
7	0.273	Pass
8	0.172	Pass

5.2.1.4 EEBL Test 4

Table 6: EEBL Test 4 Results

Run	RV Acceleration (m/s^2)	Result
1	-1.98	No Warning (False positive)
2	-2.72	No Warning (False positive)

5.2.1.5 EEBL Test 5

Table 7: EEBL Test 5 Results

Run	RV Acceleration (m/s^2)	Result
1	-7.68	No Warning (False positive)
2	-6.91	No Warning (False positive)

5.2.2 Blind Spot Warning+Lane Change Warning

For the BSW+LCW application to pass the true positive tests (BSW+LCW-T1 – T5 and T8), the warning had to come within the latency specified in the minimum performance requirements for the BSW+LCW application. All the individual runs in every scenario passed, so the application was successful. In Table 8, Table 9, Table 10, Table 11, Table 12, and Table 15, the results for each true positive test scenario are listed.

5.2.2.1 BSW+LCW Test 1

Table 8: BSW+LCW Test 1 Results

Run	HV Speed (mph)	RV Speed (mph)	Latency (ms)	Result
1	45.7	54.5	148	Pass
2	45.8	54.5	146	Pass
3	45.7	53.4	114	Pass
4	45.7	55.0	103	Pass
5	45.8	53.2	90	Pass
6	45.9	55.0	102	Pass
7	45.8	53.3	104	Pass
8	45.8	54.1	87	Pass

5.2.2.2 BSW+LCW Test 2

Table 9: BSW+LCW Test 2 Results

Run	HV Speed (mph)	RV Speed (mph)	Latency (ms)	Result
1	45.7	53.6	102	Pass
2	45.8	53.6	56	Pass
3	45.8	54.4	91	Pass
4	45.7	53.8	214	Pass
5	45.8	54.8	256	Pass
6	45.9	54.2	176	Pass
7	45.6	54.2	93	Pass
8	45.8	54.5	132	Pass

5.2.2.3 BSW+LCW Test 3

Table 10: BSW+LCW Test 3 Results

Run	HV Speed (mph)	RV Speed (mph)	Latency (ms)	Result
1	45.7	53.6	102	Pass
2	50.8	50.1	104	Pass
3	49.8	48.7	114	Pass
4	49.8	48.7	137	Pass
5	50.6	49.7	91	Pass
6	50.2	48.3	136	Pass
7	50.5	49.3	137	Pass
8	49.4	47.9	80	Pass
9	49.8	48.5	133	Pass

Note: The HV speed in Run 1 was lower than desired, which led to adding an additional run in case the first run was not valid.

5.2.2.4 BSW+LCW Test 4

The scenarios Test 4 and Test 5 do not have warning latencies associated with them since in those scenarios only an advisory was given to alert the driver of the HV that a vehicle was in the HV's blind spot.

Table 11: BSW+LCW Test 4 Results

Run	HV Speed (mph)	RV Speed (mph)	Latency (ms)	Result
1	45.8	54.4	N/A	Pass
2	45.9	54.2	N/A	Pass
3	45.8	53.8	N/A	Pass
4	45.9	54.0	N/A	Pass

Run	HV Speed (mph)	RV Speed (mph)	Latency (ms)	Result
5	45.7	53.9	N/A	Pass
6	45.8	53.0	N/A	Pass
7	45.6	54.1	N/A	Pass
8	45.7	54.7	N/A	Pass

5.2.2.5 BSW+LCW Test 5

Table 12: BSW+LCW Test 5 Results

Run	HV Speed (mph)	RV Speed (mph)	Latency (ms)	Result
1	45.8	53.9	N/A	Pass
2	45.8	53.9	N/A	Pass
3	45.8	55.0	N/A	Pass
4	45.8	55.2	N/A	Pass
5	45.8	55.5	N/A	Pass
6	45.8	54.5	N/A	Pass
7	45.7	53.5	N/A	Pass
8	45.8	54.6	N/A	Pass

5.2.2.6 BSW+LCW Test 6

Table 13: BSW+LCW Test 6 Results

Run	Result
1	N/A (False Positive)
2	N/A (False Positive)

5.2.2.7 BSW+LCW Test 7

Table 14: BSW+LCW Test 7 Results

Run	Result
1	N/A (False Positive)
2	N/A (False Positive)

5.2.2.8 BSW+LCW Test 8

Table 15: BSW+LCW Test 8 Results

Run	HV Speed (mph)	RV Speed (mph)	Latency (ms)	Result
1	35.6	45.1	140	Pass
2	35.6	45.1	170	Pass
3	35.6	45.2	196	Pass
4	35.6	44.6	120	Pass

Run	HV Speed (mph)	RV Speed (mph)	Latency (ms)	Result
5	35.6	44.5	32	Pass
6	35.6	44.1	144	Pass
7	35.4	44.7	53	Pass
8	35.6	45.3	56	Pass

5.2.3 Forward Collision Warning

For the FCW application to pass, the warning had to come between the maximum and minimum alert range that was calculated for each run [4]. As can be seen from the test results tables, the application was successful in all the true positive test scenarios (Test 1-3, Test 5, Test 7-8).

5.2.3.1 FCW Test 1

Table 16: FCW Test 1 Results

	Actual Values at Alert Onset				Calculated Run-Specific Alert Ranges					
Run	**HV Speed**	**HV Accel**	**RV Speed**	**RV Accel**	**Maximum (meters)**	**Nominal (meters)**	**Minimum (meters)**	**Actual Alert Range (meters)**	**Pass/Fail**	**Headway**
FCW T1	50 mph 22.35 m/s	0 g	0 mph	0 g	93.7	85.2	76.7			6.71
1	49.70 mph 22.21 m/s	0 g	0 mph	0 g	92.8	84.4	75.9	84	Pass	6.80
2	50.0 mph 22.35 m/s	0 g	0 mph	0 g	93.7	85.2	77.7	86	Pass	6.83
3	49.68 mph 22.21 m/s	0 g	0 mph	0 g	91.7	83.4	75.0	85	Pass	6.76
4	50.31	0 g	0 mph	0 g	94.1	85.5	77.0	85	Pass	6.80

	Actual Values at Alert Onset				Calculated Run-Specific Alert Ranges					
Run	HV Speed	HV Accel	RV Speed	RV Accel	Maximum (meters)	Nominal (meters)	Minimum (meters)	Actual Alert Range (meters)	Pass/Fail	Headway
	mph 22.49 m/s									
5	49.69 mph 22.21 m/s	0 g	0 mph	0 g	92.8	84.4	75.9	85	Pass	6.80
6	49.50 mph 22.13 m/s	0 g	0 mph	0 g	93.1	84.6	76.2	80	Pass (A # of communication outages from the RV)	6.82
7	49.84 mph 22.28 m/s	0 g	0 mph	0 g	93.9	85.4	76.8	83	Pass	6.73
8	49.75 mph 22.24 m/s	0 g	0 mph	0 g	92.7	84.3	75.9	82	Pass (A # of communication outages from the RV)	6.79
9	50.35 mph 22.51 m/s	0 g	0 mph	0 g	93.2	84.7	76.3	85	Pass	6.66
10	49.71	0 g	0 mph	0 g	91.7	83.3	75.0	84	Pass	6.75

	Actual Values at Alert Onset				Calculated Run-Specific Alert Ranges					
Run	HV Speed	HV Accel	RV Speed	RV Accel	Maximum (meters)	Nominal (meters)	Minimum (meters)	Actual Alert Range (meters)	Pass/Fail	Headway
	mph 22.22 m/s									

5.2.3.2 FCW Test 2

Table 17: FCW Test 2 Results

	Actual Values at Alert Onset				Calculated Run-Specific Alert Ranges					
Run	HV Speed	HV Accel	RV Speed	RV Accel	Maximum (meters)	Nominal (meters)	Minimum (meters)	Actual Alert Range (meters)	Pass/Fail	Headway
FCW-T2	50 mph 22.35 m/s	0 g	0 mph	0 g	93.7	85.2	76.7			6.71
1	47.40 mph	0g	0 mph	0 g	85.0	78.0	70.2	78	Pass	7.08

	Actual Values at Alert Onset				Calculated Run-Specific Alert Ranges					
Run	HV Speed	HV Accel	RV Speed	RV Accel	Maximum (meters)	Nominal (meters)	Minimum (meters)	Actual Alert Range (meters)	Pass/Fail	Headway
	21.19 m/s									
2	49.78 mph 22.25 m/s	0 g	0 mph	0 g	94.0	85.5	76.9	85	Pass	6.74
3	49.78 mph 22.25 m/s	0 g	0 mph	0 g	94.0	85.5	76.9	83	Pass (A # of communication outages from the RV)	6.74
4	50.4 mph 22.41 m/s	0 g	0 mph	0 g	93.5	85.0	76.5	85	Pass	6.69
5	49.57 mph	0 g	0 mph	0 g	91.9	83.5	75.2	84	Pass	6.77

	Actual Values at Alert Onset				Calculated Run-Specific Alert Ranges					
Run	**HV Speed**	**HV Accel**	**RV Speed**	**RV Accel**	**Maximum (meters)**	**Nominal (meters)**	**Minimum (meters)**	**Actual Alert Range (meters)**	**Pass/Fail**	**Headway**
	22.16 m/s									
6	49.36 mph 22.06 m/s	0 g	0 mph	0 g	92.2	83.8	75.4	84	Pass	6.80
7	50.10 mph 22.39 m/s	0 g	0 mph	0 g	93.6	85.1	76.6	86	Pass	6.70
8	49.51 mph 22.13 m/s	0 g	0 mph	0 g	92.0	83.6	75.2	82	Pass	6.78
9	49.45 mph	0 g	0 mph	0 g	92.1	83.7	75.3	83	Pass	6.79

	Actual Values at Alert Onset				Calculated Run-Specific Alert Ranges					
Run	**HV Speed**	**HV Accel**	**RV Speed**	**RV Accel**	**Maximum (meters)**	**Nominal (meters)**	**Minimum (meters)**	**Actual Alert Range (meters)**	**Pass/Fail**	**Headway**
	22.11 m/s									
10	49.64 mph 22.19 m/s	0g	0 mph	0 g	91.8	83.4	75.1	85	Pass	6.76

5.2.3.3 FCW Test 3

Table 18: FCW Test 3 Results

	Actual Values at Alert Onset				Calculated Run-Specific Alert Ranges					
Run	**HV Speed**	**HV Accel**	**RV Speed**	**RV Accel**	**Maximum (meters)**	**Nominal (meters)**	**Minimum (meters)**	**Actual Alert Range (meters)**	**Pass/Fail**	**Headway**
FCW-T3	50 mph 22.35 m/s	0 g	0 mph	0 g	93.7	85.2	76.7			6.71
1	49.81 mph 22.27 m/s	0 g	0 mph	0 g	94.0	85.4	76.9	85	Pass	6.74
2	50.70 mph 22.66 m/s	0 g	0 mph	0 g	95.2	86.5	77.9	87	Pass	6.62
3	49.30 mph 22.04	0 g	0 mph	0 g	92.3	83.9	75.5	82	Pass	6.81

	Actual Values at Alert Onset				Calculated Run-Specific Alert Ranges					
Run	HV Speed	HV Accel	RV Speed	RV Accel	Maximum (meters)	Nominal (meters)	Minimum (meters)	Actual Alert Range (meters)	Pass/Fail	Headway
	m/s									
4	49.60 mph 22.17 m/s	0 g	0 mph	0 g	91.8	83.5	75.1	85	Pass	6.77
5	50.40 mph 22.53 m/s	0 g	0 mph	0 g	95.6	86.9	78.2	86	Pass	6.66
6	49.68 mph 22.21 m/s	0 g	0 mph	0 g	91.7	83.4	75.0	85	Pass	6.75
7	49.68 mph 22.21	0 g	0 mph	0 g	91.7	83.4	75.0	85	Pass	6.75

	Actual Values at Alert Onset				Calculated Run-Specific Alert Ranges					
Run	**HV Speed**	**HV Accel**	**RV Speed**	**RV Accel**	**Maximum (meters)**	**Nominal (meters)**	**Minimum (meters)**	**Actual Alert Range (meters)**	**Pass/Fail**	**Headway**
	m/s									
8	49.75 mph 22.24 m/s	0 g	0 mph	0 g	91.6	83.3	75.0	85	Pass	6.75

5.2.3.4 FCW Test 4

Table 19: FCW Test 4 Results

	Actual Values at Alert Onset				Calculated Run-Specific Alert Ranges					
Run	**HV Speed**	**HV Accel**	**RV Speed**	**RV Accel**	**Maximum (meters)**	**Nominal (meters)**	**Minimum (meters)**	**Actual Alert Range (meters)**	**Pass/Fail**	**Headway**
FCW-T4	50 mph 22.35 m/s	0 g	50 mph 22.35 m/s	0 g						0.5 s (11 meters)
1	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Fail (The test setup did not meet the test	N/A

	Actual Values at Alert Onset				Calculated Run-Specific Alert Ranges					
Run	HV Speed	HV Accel	RV Speed	RV Accel	Maximum (meters)	Nominal (meters)	Minimum (meters)	Actual Alert Range (meters)	Pass/Fail	Headway
									criteria)	
2	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Pass	N/A
3	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Pass	N/A

5.2.3.5 FCW Test 5

Table 20: FCW Test 5 Results

	Actual Values at Alert Onset				Calculated Run-Specific Alert Ranges					
Run	HV Speed	HV Accel	RV Speed	RV Accel	Maximum (meters)	Nominal (meters)	Minimum (meters)	Actual Alert Range (meters)	Pass/Fail	Headway
FCW -T5	40 mph 17.88 m/s	0 g	17.88 mph	-0.5 g	57.5	52.3	47.1			4
1	39.47 mph 17.64168 m/s	0g	38.48 mph 17.2m/s	-0.48 g	45.8	41.7	37.5	41	Pass	2.489

	Actual Values at Alert Onset				Calculated Run-Specific Alert Ranges					
Run	**HV Speed**	**HV Accel**	**RV Speed**	**RV Accel**	**Maximum (meters)**	**Nominal (meters)**	**Minimum (meters)**	**Actual Alert Range (meters)**	**Pass/Fail**	**Headway**
2	40.63 mph 18.18 m/s	0g	38.57 mph 17.24 m/s	-0.53 g	52.6	47.8	43.0	48	Pass	2.86
3	39.82 mph 17.80 m/s	0g	38.50 mph 17.21 m/s	-0.557 g	52.9	48.0	43.2	47	Pass	2.92
4	39.61 mph 17.71 m/s	0 g	38.12 mph 17.04 m/s	-0.589 g	55.6	50.5	45.5	51	Pass	3.33
5	39.31 mph 17.57 m/s	0g	38.72 mph 17.31 m/s	-0.454	52.3	47.6	42.8	47	Pass	3.24
6	39.50 mph	0g	38.61 mph	-0.41g	29.6	26.9	24.2	27	Pass	1.53

	Actual Values at Alert Onset				Calculated Run-Specific Alert Ranges					
Run	HV Speed	HV Accel	RV Speed	RV Accel	Maximum (meters)	Nominal (meters)	Minimum (meters)	Actual Alert Range (meters)	Pass/Fail	way
	17.66 m/s		17.26 m/s							
7	40.79 mph 18.23 m/s	0g	38.46 mph 17.19 m/s	-0.42 g	26.4	24.0	21.6	24	Pass	1.32
8	39.54 mph 17.68 m/s	0g	38.64 mph 17.27 m/s	-0.41 g	36.6	33.3	30.0	34	Pass	1.92
9	39.93 mph 17.85 m/s	0g	38.75 mph 17.32 m/s	-0.36 g	33.1	30.1	27.0	30	Pass	1.74
10	38.93 mph 17.40 m/s	0g	38.95 mph 17.41 m/s	-0.49	40.0	36.4	32.8	36	Pass	2.13

5.2.3.6 FCW Test 6

Table 21: FCW Test 6 Results

Run	Actual Values at Alert Onset				Calculated Run-Specific Alert Ranges					
	HV Speed	HV Accel	RV Speed	RV Accel	Maximum (meters)	Nominal (meters)	Minimum (meters)	Actual Alert Range (meters)	Pass/Fail	Headway
FCW-T6	50 mph 22.35 m/s	0 g	0 mph	0 g						
1	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Pass	N/A
2	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Pass	N/A

5.2.3.7 FCW Test 7

Table 22: FCW Test 7 Results

Run	Actual Values at Alert Onset				Calculated Run-Specific Alert Ranges					
	HV Speed	HV Accel	RV Speed	RV Accel	Maximum (meters)	Nominal (meters)	Minimum (meters)	Actual Alert Range (meters)	Pass/Fail	Headway
FCW-T7	50 mph 22.35 m/s	0 g	25 mph 11.18 m/s	0 g	31.0	28.2	25.4			6.71
1	47.74	0 g	24.09 mph	0 g	28.9	26.3	23.7	28	Pass	7.03

	Actual Values at Alert Onset				Calculated Run-Specific Alert Ranges					
Run	HV Speed	HV Accel	RV Speed	RV Accel	Maximum (meters)	Nominal (meters)	Minimum (meters)	Actual Alert Range (meters)	Pass/Fail	Headway
	mph 21.34 m/s		10.77 m/s							
2	47.14 mph 21.07 m/s	0 g	23.62 mph 10.56 m/s`	0 g	28.6	26.0	23.4	27	Pass	7.12
3	47.82 mph 21.38 m/s	0 g	23.85 mph 10.66 m/s	0 g	29.5	26.8	24.1	28	Pass	7.02
4	47.77 mph 21.35 m/s	0 g	23.76 mph 10.62 m/s	0 g	29.2	26.6	23.9	27	Pass	7.02
5	48.68 mph	0 g	23.89 mph 10.71 m/s	0 g	30.1	27.3	24.6	30	Pass	6.89

	Actual Values at Alert Onset				Calculated Run-Specific Alert Ranges					
Run	**HV Speed**	**HV Accel**	**RV Speed**	**RV Accel**	**Maximum (meters)**	**Nominal (meters)**	**Minimum (meters)**	**Actual Alert Range (meters)**	**Pass/Fail**	**Headway**
	21.76 m/s									
6	50.57 mph 22.60 m/s	0 g	23.83 mph 10.65 m/s	0 g	33.5	30.5	27.4	31	Pass	6.64
7	49.63 mph 22.19 m/s	0 g	24.21 mph 10.82 m/s	0 g	31.2	28.4	25.5	30	Pass	6.76
8	47.50 mph 21.23 m/s	0 g	24.50 mph 10.95 m/s	0 g	28.2	25.6	23.0	27	Pass	7.07
9	49.21 mph 22.00	0 g	23.20 mph 10.37 m/s	0 g	32.0	29.1	26.2	30	Pass	6.82

	Actual Values at Alert Onset				Calculated Run-Specific Alert Ranges					
Run	HV Speed	HV Accel	RV Speed	RV Accel	Maximum (meters)	Nominal (meters)	Minimum (meters)	Actual Alert Range (meters)	Pass/Fail	Headway
	m/s									
10	48.76 mph 21.79 m/s	0 g	23.74 mph 10.61 m/s	0 g	30.9	28.1	25.3	30	Pass	6.88

5.2.3.8 FCW Test 8

Table 23: FCW Test 8 Results

	Actual Values at Alert Onset				Calculated Run-Specific Alert Ranges					
Run	HV Speed	HV Accel	RV Speed	RV Accel	Maximum (meters)	Nominal (meters)	Minimum (meters)	Actual Alert Range (meters)	Pass/Fail	Headway
FCW-T8	50 mph 22.35 m/s	0 g	0 mph	0 g	93.7	85.2	76.7			6.71

	Actual Values at Alert Onset				Calculated Run-Specific Alert Ranges					
Run	**HV Speed**	**HV Accel**	**RV Speed**	**RV Accel**	**Maximum (meters)**	**Nominal (meters)**	**Minimum (meters)**	**Actual Alert Range (meters)**	**Pass/Fail**	**Headway**
1	49.52 mph 22.18 m/s	0g	0 mph	0 g	92.4	84.0	75.6	80	Pass (A # of communication outages from the RV)	5.20
2	49.78 mph 22.25 m/s	0g	0 mph	0 g	93.1	84.6	76.2	84	Pass	5.30
3	49.52 mph 22.14 m/s	0 g	0 mph	0 g	91.5	83.2	74.8	79	Pass	5.56
4	49.78 mph 22.25 m/s	0 g	0 mph	0 g	93.9	85.4	76.9	83	Pass	5.44

	Actual Values at Alert Onset				Calculated Run-Specific Alert Ranges					
Run	**HV Speed**	**HV Accel**	**RV Speed**	**RV Accel**	**Maximum (meters)**	**Nominal (meters)**	**Minimum (meters)**	**Actual Alert Range (meters)**	**Pass/Fail**	**Headway**
5	49.37 mph 22.07 m/s	0 g	0 mph	0 g	91.8	83.5	75.1	83	Pass	5.48
6	49.78 mph 22.25 m/s	0 g	0 mph	0 g	93.1	84.6	76.2	82	Pass (A # of communication outages from the RV)	5.38
7	49.52 mph 22.14 m/s	0 g	0 mph	0 g	91.7	83.4	75.0	84	Pass (A # of communication outages from the RV)	5.47
8	49.45 mph 22.11 m/s	0 g	0 mph	0 g	93.1	84.6	76.2	84	Pass	5.43

5.2.3.9 FCW Test 9

Table 24: FCW Test 9 Results

	Actual Values at Alert Onset				Calculated Run-Specific Alert Ranges					
Run	HV Speed	HV Accel	RV Speed	RV Accel	Maximum (meters)	Nominal (meters)	Minimum (meters)	Actual Alert Range (meters)	Pass/Fail	Headway
FCW-T10	50 mph 22.35 m/s	0 g	RV1 RV2 25 mph 11.18 m/s	0 g						
1	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Pass	N/A
2	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Pass	N/A

5.2.4 Do Not Pass Warning

For the DNPW feature, the maximum and minimum alert ranges are defined as ± 10 percent of the nominal alert range [4]. The DNPW alert onset for an individual run should not occur outside of the allowable alert range.

5.2.4.1 DNPW Test 1

Table 25: DNPW Test 1 Results

DNPW-T1	HV Speed (m/s)	ARV Speed (m/s)	OLRV Speed (m/s)	OLRV Long Distance (m)	Advisory Activation Distance Actual (HV-OLRV) (m)	Advisory Activation Distance Calculated (HV-OLRV) (m)	%Error (Act-Calc)	%Error (Actual Average)	Std Deviation (m)	Pass/Fail (Error < 10%)
1	11.5	11.5	11.7	330.1	330.1	350.8	5.9	1.8	12.4	Pass
3	12.3	12.1	11.6	355.5	355.5	369.2	3.7	5.7		Pass
4	12.8	12.5	11.6	337.1	337.1	352.0	4.2	0.3		Pass*
5	12.1	11.4	11.6	321.8	321.8	336.6	4.4	4.2		Pass
7	15.5	15.7	15.7	487.7	487.7	493.2	1.1	2.7	19.8	Pass
8	15.6	15.8	15.7	503.1	503.1	509.9	1.3	4.7		Pass
9	15.9	15.3	15.7	448.8	448.8	451.5	0.6	6.5		Pass
10	15.2	15.7	15.7	481.4	481.4	488.4	1.4	0.2		Pass

*Test passed error boundary, but Oncoming Left Remote Vehicle (OLRV) speed slightly outside of recommended range.

5.2.4.2 DNPW Test 2

Table 26: DNPW Test 2 Results

DNPW-T2 Run	HV Speed (m/s)	OLRV Speed (m/s)	ARV Long Distance (m)	HV-ARV Headway (s)	OLRV Long Distance (m)	Advisory Activation Distance Actual (HV-ARV) (m)	Advisory Activation Distance Calculated (HV-ARV) (m)	%Error (Act-Calc)	%Error (Actual Average)	Std Deviation (m)	Pass/Fail (Error < 10%)
1	13.0	13.3	154.2	11.9	333.5	154.2	156.0	1.2	0.3	0.4	Pass
3	13.0	13.3	154.8	11.9	373.2	154.8	156.0	0.8	0.1		Pass
4	13.0	13.3	154.3	11.9	279.7	154.3	156.0	1.1	0.2		Pass
5	13.0	13.3	155.2	11.9	307.1	155.2	156.0	0.5	0.4		Pass

DNPW -T2 Run	HV Speed (m/s)	OLRV Speed (m/s)	ARV Long Distance (m)	HV-ARV Headway (s)	OLRV Long Distance (m)	Advisory Activation Distance Actual (HV-ARV) (m)	Advisory Activation Distance Calculated (HV-ARV) (m)	%Error (Act-Calc)	%Error (Actual Average)	Std Deviation (m)	Pass/Fail (Error < 10%)
6	16.8	19.3	200.1	11.9	448.1	200.1	201.6	0.7	1.4	1.7	Pass*
7	17.0	19.3	203.6	12.0	450.5	203.6	204.0	0.2	0.3		Pass*
8	17.1	19.2	204.6	12.0	304.2	204.6	205.2	0.3	0.8		Pass*
10	17.1	19.4	203.7	11.9	450.4	203.7	205.2	0.7	0.3		Pass*
11	21.3	22.8	256.2	12.0	527.6	256.2	255.6	0.2	0.5	2.8	Pass
12	21.9	22.6	256.9	11.7	553.6	256.9	262.8	2.2	0.3		Pass
14	21.6	23.1	254.8	11.8	622.0	254.8	259.2	1.7	1.1		Pass
15	22.0	23.1	262.3	11.9	664.4	262.3	264.0	0.6	1.8		Pass

*Test passed error boundary, but OLRV speed slightly outside of recommended range.

5.2.4.3 DNPW Test 3

Table 27: DNPW Test 3 Results

DNPW-T3 Run	Comments
1	False positive test. No threat detected. No alert provided. Test passed.
2	False positive test. No threat detected. No alert provided. Test passed.

5.2.5 Intersection Movement Assist (IMA)

For the IMA application to pass, the warning distance determined from the test runs had to be within ±10 percent of the nominal warning distance for the actual speed of the run specified in the minimum performance requirements [3]. As can be seen from the results tables, the application passed all the true positive tests (Test 1, 3, 5).

5.2.5.1 IMA Test 1

Table 28: IMA Test 1 Results

Run	Remote Speed (mph)	Actual Warning Distance (m)	Nominal Warning Distance (m)	Delta (%)	Pass/Fail
RV Target Speed (mph): 20					
1	18.32	20.01	20.4	2	Pass
RV Target Speed (mph): 30					
2	28.57	36.18	36.9	2	Pass
3	28.48	35.87	36.7	2.2	Pass
RV Target Speed (mph): 40					
4	38.32	54.73	55.8	2	Pass
5	38.34	54.32	55.8	3	Pass
RV Target Speed (mph):50					
6	47.67	75.89	77.0	1.5	Pass
7	47.65	75.54	76.9	2	Pass
RV Target Speed (mph): 50	Brake release test				
8	47.58	Special Criteria	Special Criteria	< 200 ms	Pass
9	47.53	Special Criteria	Special Criteria	< 200 ms	Pass

The initial setup for the IMA Test 1 test has the parking brake engaged and the foot of the driver of the HV off the brake pedal. To show the full functionality of the system, two runs were added (run 8 and 9) where the driver of the HV released the brake pedal when the RV entered the warning zone.

5.2.5.2 IMA Test 2

Table 29: IMA Test 2 Results

Run	Valid?	Remote Speed (mps)	Remote Speed (mph)	Warning Issued?	Pass/Fail
RV Target Speed (mph): 35					
1	Yes	14.71	32.91	No	Pass
2	No - RV Speed	14.45	32.32	No	N/A

5.2.5.3 IMA Test 3

Table 30: IMA Test 3 Results

Run	Target Speeds (mph)	Valid?	Host Speed (mph)	Remote Speed (mph)	Actual Warning Distance (m)	Nominal Warning Distance (m)	Delta (%)	Pass/Fail
	HV: 15 RV: 15							
1		Yes	14.97	13.69	15.85	15.85	0	Pass
2		Yes	14.41	15.43	14.95	15.12	1	Pass
3		Yes	14.97	13.15	15.43	15.85	3	Pass
	HV: 25 RV: 15							
4		Yes	24.85	13.15	29.45	30.49	3	Pass
5		Yes	24.92	14.12	30.45	30.60	0.5	Pass
	HV: 25 RV: 25							
6		Yes	24.85	21.21	29.72	30.49	3	Pass
7		Yes	24.85	24.43	29.79	30.49	2	Pass
8		Yes	24.99	22.39	30.25	30.72	2	Pass
	HV: 35 RV: 15							
9		Yes	34.92	13.29	48.08	48.82	2	Pass
10		Yes	34.85	14.14	47.62	48.68	2	Pass
	HV: 35 RV: 25							

Run	Target Speeds (mph)	Valid?	Host Speed (mph)	Remote Speed (mph)	Actual Warning Distance (m)	Nominal Warning Distance (m)	Delta (%)	Pass/Fail
12		Yes	35.05	21.79	48.59	49.09	1	Pass
14		Yes	34.85	21.09	47.79	48.68	2	Pass
15		Yes	34.78	24.11	48.09	48.55	1	Pass
	HV: 35 RV: 35							
16		Yes	34.92	30.20	48.41	48.82	1	Pass
18		Yes	34.85	31.79	47.7	48.68	2	Pass
19		Yes	35.05	32.84	48.32	49.09	2	Pass
20		Yes	34.92	34.38	48.81	48.82	0	Pass
	HV: 45 RV: 15							
21		Yes	44.92	18.01	68.91	70.43	2	Pass
22		Yes	45.05	17.13	69.06	70.74	2	Pass
	HV: 45 RV: 25							
23		Yes	44.98	22.39	70.37	70.59	0	Pass
24		Yes	45.05	24.40	70.19	70.74	1	Pass
	HV: 45 RV: 35							
27		Yes	44.92	31.97	69.52	70.43	1	Pass

5.2.5.4 IMA Test 4

Table 31: IMA Test 4 Results

Run	Host Speed (mph)	Remote Speed (mph)	Warning/Inform Issued?	RV DTI when HV crosses Intersection (m)	Pass/Fail
Target Speed (mph): HV: 25, RV: 25 mph					
1	24.92	22.95	None	84.8	Pass
2	24.92	27.54	None	68.25	Pass
4	24.85	22.68	None	41.61	Pass
6	24.99	24.67	None	40.46	Pass

5.2.5.5 IMA Test 5

Table 32: IMA Test 5 Results

Run	Remote Speed (mph)	Actual Warning Distance (m)	Nominal Warning Distance (m)	Delta (%)	Pass/Fail
RV Target Speed (mph): 20					
1	19.08	21	21.54	3	Pass
2	19.08	21	21.54	3	Pass
RV Target Speed (mph): 30					
3	27.92	34.7	35.71	3	Pass
4	27.92	35.77	35.71	0	Pass
RV Target Speed (mph): 40					
5	37.69	54.26	54.47	0	Pass
6	37.67	53.58	54.43	2	Pass
RV Target Speed (mph):50					
7	47.65	75.7	76.92	2	Pass
8	47.67	75.35	76.97	2	Pass

5.2.6 Control Loss Warning (CLW)

For the CLW application to pass, the maximum warning latency had to be smaller than the maximum latency specified in the minimum performance requirements [3]. As can be seen from the results table, the application was successful in all the true positive scenarios (Test 1 and Test 3).

5.2.6.1 CLW Test 1

Table 33: CLW Test 1 Results

Run	Latency (s)	Result
1	0.20837	Pass
2	0.02743	Pass

Run	Latency (s)	Result
3	0.12078	Pass
4	0.11833	Pass
5	0.12267	Pass
6	0.12367	Pass
7	0.02225	Pass
8	0.11523	Pass

5.2.6.2 CLW Test 2

Table 34: CLW Test 2 Results

Run	Latency (s)	Result
1	N/A	No Warning (False Positive)
2	N/A	No Warning (False Positive)

5.2.6.3 CLW Test 3

Table 35: CLW Test 3 Results

Run	Latency (s)	Result
1	0.16503	Pass
2	0.16682	Pass
3	0.15787	Pass
4	0.15691	Pass
5	0.15866	Pass
6	0.1637	Pass
7	0.16175	Pass
8	0.16693	Pass
9	0.15951	Pass
10	0.15722	Pass
11	0.15752	Pass
12	0.16658	Pass

6 References

[1] CAMP VSC2 Consortium, *"Vehicle Safety Communications – Applications (VSC-A) Final Report,"* NHTSA Publication, 2011.

[2] CAMP VSC2 Consortium, *"Vehicle Safety Communications – Applications (VSC-A) Final Report: Appendix B-1 – Test Bed System Development,"* Appendix Volume 1, NHTSA Publication, 2011.

[3] CAMP VSC2 Consortium, *"Vehicle Safety Communications – Applications (VSC-A) Final Report: Appendix C-1 – Minimum Performance Requirements,"* Appendix Volume 1, NHTSA Publication, 2011.

[4] CAMP VSC2 Consortium, *"Vehicle Safety Communications – Applications (VSC-A) Final Report: Appendix C-2 – Objective Test Procedures and Plan,"* Appendix Volume 1, NHTSA Publication, 2011.

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