Vehicle-to-Infrastructure Prototype Rail Crossing Violation Warning Application

Project Report

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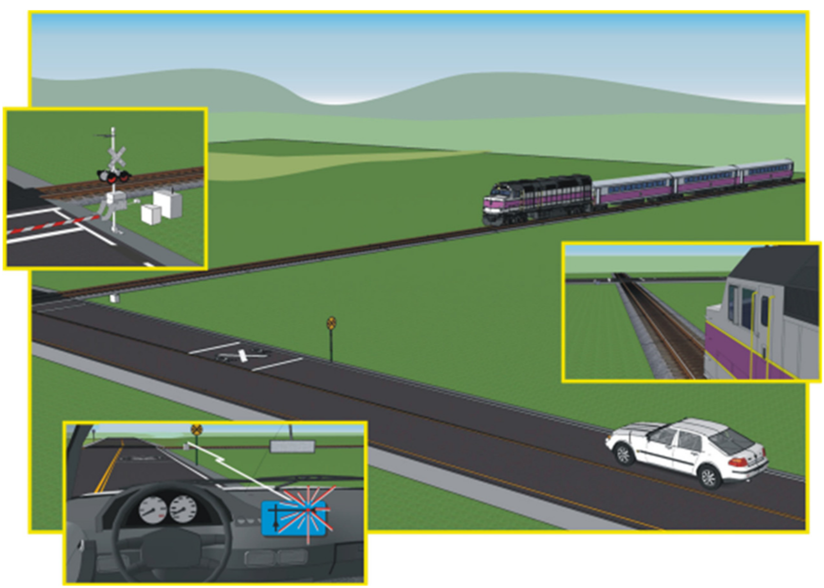
Final Report — September 5, 2017
FHWA-JPO-18-609



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U.S. Department of Transportation

Produced by The U.S. Department of Transportation

with

Support from Battelle under Contract DTFH-6112-D00040-5016

Federal Highway Administration
Federal Railroad Administration
John A. Volpe National Transportation Systems Center

Notice

Technical Report Documentation Page

1. Report No. FHWA-JPO-18-609	**2. Government Accession No.**	**3. Recipient's Catalog No.**
4. Title and Subtitle Prototype Rail Crossing Violation Warning Application Project Report		**5. Report Date** September 5, 2017
		6. Performing Organization Code Battelle
7. Author(s) David Neumeister, Gregory Zink, Alejandro Sanchez-Badillo		**8. Performing Organization Report No.**
9. Performing Organization Name and Address Battelle 505 King Avenue Columbus, Ohio 43201		**10. Work Unit No. (TRAIS)**
		11. Contract or Grant No. DTFH6112D00040-5016
12. Sponsoring Agency Name and Address Federal Highway Administration PO Box 268865 Oklahoma City, OK 73126-8865		**13. Type of Report and Period Covered** Final
		14. Sponsoring Agency Code FHWA

15. Supplementary Notes

Government Technical Monitor: Jared Withers, Federal Railroad Administration

16. Abstract

This report is the Project Report for the Rail Crossing Violation Warning (RCVW) safety application developed for the project on *Rail Crossing Violation Warning Application and Infrastructure Connection*, providing a means for equipped connected vehicles on approach to a Highway-Rail Intersection (HRI) to be warned of an imminent violation of an HRI active warning/protective system through the interconnection of a connected vehicle Roadside-Based Subsystem (RBS) with track-circuit based train detection systems in place at active HRIs.

The objective of this project was to utilize a Systems Engineering approach to design, develop, test, and evaluate a prototype Rail Crossing Violation Warning (RCVW) application in laboratory and field conditions. This project aimed to demonstrate the potential for leveraging real-time connected vehicle concepts and services to enhance and transform rail crossing safety.

17. Key Words Rail Crossing Violation Warning, RCVW, RCVW application, Highway-Rail Intersection, HRI	**18. Distribution statement** Unlimited.

19. Security Classif. (of this report) Unclassified	**20. Security Classif. (of this page)** Unclassified	**21. No. of Pages** 86	**22. Price**

Form DOT F 1700.7 (8-72) **Reproduction of completed page authorized**

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Executive Summary

This report summarizes the Rail Crossing Violation Warning (RCVW) application project. The project applied a Systems Engineering methodology to design, develop, test, and evaluate a prototype RCVW application, and demonstrated the potential for leveraging real-time connected vehicle concepts and services to enhance and transform rail crossing safety.

RCVW is a Vehicle-to-Interface (V2I) application that leverages the latest developments in connected vehicle components and technologies developed under previous U.S. DOT connected vehicle deployment projects, as well as expected deployment of connected vehicle technology in new cars. It consists of two physically separate subsystems: A Vehicle-Based Subsystem (VBS) installed in connected vehicles and a Roadside-Based Subsystem (RBS) integrated with roadside infrastructure at highway-railroad intersections (HRIs). Both subsystems are comprised of the same hardware and software components, such as a Computing Platform (CP) on which the RCVW software application executes, Dedicated Short-Range Communication (DSRC) radios, and a Global Positioning System (GPS) module. A unique component to the VBS is the Driver Visual Interface (DVI), which provides RCVW alerts and warnings to the vehicle operator.

The RCVW system provides real-time condition-based audible and visual alerting to vehicle operators to predict and warn drivers of predicted and imminent rail crossing violations for vehicles approaching or stopped within active rail crossings, respectively. The primary intended benefit for the RCVW application is the reduction in the frequency and severity of HRI safety-related incidents. However, the scalable and flexible design of the RCVW system affords potential future safety and mobility-related operational improvements, including reductions in emergency vehicle response times, improved traffic flow and routing efficiency with nearby traffic control devices, a reduction in energy consumption, and improved air quality.

Chapter 1 Project Report Summary

An urgent need exists for additional protections for vehicle drivers traversing HRIs beyond traditional active warning devices. The following statistics, from the United States Department of Transportation (U.S. DOT) Federal Railroad Administration (FRA) preliminary level crossing safety statistics for calendar year 2012, as presented in Chapter 3 of the RCVW ConOps document [1], provide a basis for the improvements sought by the prototype RCVW system developed and evaluated in this project:

- 1,840 HRI incidents involving motor vehicles and trains occurred at HRIs.
- These incidents involved 186 fatalities and 871 injuries.
- Damage to rail and track infrastructure amounted to $20.5 million.
- Roadway-vehicle damage costs were estimated at $13.5 million.
- Medical costs associated with injuries and losses of life were in the range of $645 million.

A review of FRA safety statistics since 2012, as presented in Table 1-1 below, do not reflect appreciable improvement in HRI incidents involving motor vehicles (excluding pedestrian and other categories), fatalities, or injuries.

Table 1-1. FRA Safety Statistics at HRIs from Calendar Years 2013-2016

Calendar Year	Motor Vehicle Incidents	Fatalities	Injuries
2013	1,896	232	977
2014	2,071	262	872
2015	1,863	233	1,045
2016	1,803	264	839

Source: Federal Railroad Administration Office of Safety Analysis Website (http://safetydata.fra.dot.gov)

The RCVW ConOps document [1] observes some additional important findings, which suggest that HRIs with traditional active HRI warning devices are no more effective than those with passive HRI warning devices and that drivers are often distracted when crossing HRIs:

- The number of incidents, injuries, and fatalities was effectively the same at HRIs equipped with active and passing warning devices.
- Injuries for autos and trucks at HRIs has been flat from 2008-2012
- A substantial percentage of light and heavy-duty vehicle operators do not look in either direction when crossing an HRI and/or are distracted by being engaged in tasks other than driving.

Distracted drivers may not notice they are approaching an HRI, fail to perceive activated warning devices, or not recognize that a train is approaching. Situational awareness of a vehicle operator may be challenged due to adverse atmospheric conditions, engagement with a myriad of distractions (including cell phone use or personal interactions), the influence of alcohol/drugs/medication, or impaired mental capacity due to fatigue or medical events. Existing warning devices are of limited effectiveness when a motorist's situational awareness is compromised because they do not communicate with roadway-vehicle systems.

Development of the RCVW application attempts to address this operational safety risk by enhancing the situational awareness of roadway-vehicle drivers when approaching or stopped within an active HRI by using in-vehicle multi-sensory warnings and alerts to overcome compromised situational awareness.

1.1 Document Identification

This project report documents the activities performed and results achieved over the course of development of the prototype Rail Crossing Violation Warning safety application for the project on "Rail Crossing Violation Warning Application and Infrastructure Connection". It is structured to help advance the body of knowledge related to the integration of active rail crossing warning preemption signaling for use toward the enhancement of rail crossing safety and other operational improvements. This report concludes with recommendations for improving the prototype to increase its performance and utility.

1.2 RCVW Project Overview

V2I HRI safety applications represent one of the latest additions to the U.S. DOT Connected Vehicle Program. This program is "a multimodal initiative that aims to enable safe, interoperable networked wireless communications among vehicles, the infrastructure, and portable personal communication devices to provide mobile related data services[1]." The suite of Intelligent Transportation Systems (ITS) elements incorporated within the Connected Vehicle concept aim to improve safety, facilitate mobility within the national transportation system, and reduce vehicle emissions via more efficient routing. A focus of this project was on development and application of ITS concepts appropriate for HRIs that employ track-circuit based signaling technology for train detection.

The RCVW project applied a Systems Engineering methodology to design, develop, test, and evaluate a prototype RCVW application, and demonstrated the potential for leveraging real-time connected vehicle concepts and services to enhance and transform rail crossing safety. Such a Connected Vehicle HRI safety application described in this Project Report did not previously exist.

1.2.1 Goals and Objectives

The RCVW system was developed to provide real-time, condition-based audible and visual alerting to vehicle operators to enhance situational awareness by predicting and warning drivers of imminent rail crossing violations for vehicles approaching or stopped within active rail crossings, respectively. The primary objective for the prototype RCVW application is the reduction in the frequency and severity of

[1] http://www.its.dot.gov/its_program/about_its.htm, accessed 5/30/2012.

HRI safety-related incidents. However, the scalable and flexible design of the RCVW system affords potential future safety, mobility, and environmental improvements.

The potential exists for future mobility-related improvements, if given the availability of accurate train arrival and HRI duration-of-occupancy information. One such improvement is the reduction in traffic congestion by optimizing traffic signal operation within the affected area. Another is the provision of alternate routes to emergency vehicles when feasible. Enhanced traffic flow, resulting from improvements in routing efficiency, may yield environmental improvements through reduced energy consumption and improvement of air quality via the reduction of harmful emissions.

The RCVW system is designed to take advantage of existing track-based train detection preemption signals for rapid deployment. Also, it is designed to be utilized by vehicles of all classes, thus making it deployable nationwide. It is intended that a deployed RCVW system will continually accrue benefits as an increasing number of roadway-vehicle drivers recognize its utility and adjust their driving behavior in response to its prompts.

1.2.2 Project Tasks

The Project was organized into nine primary tasks:

- Task 1. Develop Project Management Plan, and Provide Project Management
- Task 2. Support USDOT Outreach Efforts and Briefings
- Task 3. Coordinate with Other Related USDOT Connected Vehicle Activities
- Task 4. Review Concept of Operations Document
- Task 5. Review System Requirements Specification
- Task 6. Develop Architecture and Design Specification Documents
- Task 7. Build and Integrate RCVW Application and Infrastructure Connection
- Task 8. Test and Evaluation
- Task 9. Develop Final Project Report

This report is a deliverable for Task 9, Final Project Report.

1.2.3 Audience for the Document

The primary intended audience for this document is the U.S. DOT and stakeholders supporting integration and implementation of the RCVW application to include state DOT agencies and railroads, as well as traffic control, railroad, and vehicle equipment manufacturers.

1.2.4 Participants and Advisors

The project is sponsored by the FHWA Office of Operations and is a collaborative FRA-FHWA V2I safety research initiative focused on the development of a crash avoidance system specific. Jared Withers serves as the U.S. DOT Government Task Manager (GTM) with rail systems program support provided by Volpe National Transportation Systems Center staff.

This project was led by Battelle with support from the Texas A&M Transportation Institute (TTI) and Campbell Technology Corporation, Inc. (CTC). This project attempted to engage various stakeholders, including Crash Avoidance Metrics Partnership (CAMP), select vehicle manufacturers, and vendors developing vehicle infotainment system standards enabling display for and control of mobile phone (i.e., Apple and Google). A summary of these engagements is detailed below in Section 3.1.2 below.

1.3 Document Organization

This document consists of the following chapters and content.

Chapter 1. **Project Report Summary** provides a basis, scope, and overview of the project, including a description of goals and objectives, project tasks, document audience, and a list of project participants/advisors.

Chapter 2. **Referenced Documents** identifies the external documentation referenced within this document**.**

Chapter 3. **Summary of Results and Deliverables** includes:

- Summary of the Prototype RCVW project goals;
- Stakeholder Outreach and Engagement Approach;
- Prototype RCVW Conceptual Design;
- Prototype RCVW System Architecture and Design;
- Prototype RCVW DVI Display Warning and Alert Graphics and Annunciations;
- Prototype RCVW System Bench Test & Evaluation (BT&E) Summary; and
- Prototype RCVW System Field Test & Evaluation (FT&E) Summary

Chapter 4. **Conclusion and Future RCVW System and Application Enhancements** summarizes successes of the prototype RCVW system and application, presents lessons learned from integration and evaluation during FT&E, identifies potential future outreach opportunities, and summarizes potential enhancements and expanded functionality and capabilities for the RCVW system and application.

Appendix A. **List of Acronyms and Abbreviations** defines acronyms and abbreviations used in the document and project.

Chapter 2 Referenced Documents

Referenced Documentation

1. Vehicle-to-Infrastructure Rail Crossing Violation Warning Concept of Operations, Final Battelle Report Rev. F, March 31, 2016, FHWA-JPO-16-408.
2. Vehicle-to-Infrastructure Rail Crossing Violation Warning System Requirements Specification, Final Battelle Report Rev. 2, May 9, 2016, FHWA-JPO-16-409.
3. Vehicle-to-Infrastructure Rail Crossing Violation Warning Architecture and Design Specifications, Final Battelle Report Rev. 4, August 10, 2016, FHWA-JPO-16-410.
4. Vehicle-to-Infrastructure Rail Crossing Violation Warning Bench Test & Evaluation Plan, Final Rev. B, February 17, 2017, FHWA-JPO-17-TBD.
5. Vehicle-to-Infrastructure Rail Crossing Violation Warning Bench Test & Evaluation Report, Final Rev. B, March 31, 2017, FHWA-JPO-17-597.
6. Vehicle-to-Infrastructure Rail Crossing Violation Warning Field Test & Evaluation Plan, Final Rev. B, April 7, 2017, FHWA-JPO-17-TBD.
7. Vehicle-to-Infrastructure Rail Crossing Violation Warning Field Test & Evaluation Report, Final Rev. B, July 3, 2017, FHWA-JPO-18-607.

Chapter 3 Summary of Results and Deliverables

3.1 Prototype RCVW Application

3.1.1 Summary of Prototype RCVW Application Goals

The RCVW application provides a means for equipped roadway-vehicles on approach to a HRI be warned of an imminent violation of an HRI active warning/protective system. A warning, that is both timely and effective in alerting vehicle operators, who otherwise may be unaware of potential danger in their surroundings, is critical in the prevention of avoidable incidents.

The application is deployable at any HRI where benefit would be accrued by increasing situational awareness to minimize safety related incidents or improving the flow of roadway traffic.

The potential improvements offered by this HRI Connected Vehicle safety application are **safety**, **mobility**, and **environmental** related. Safety-related improvements are the primary goal for the prototype RCVW application project and, once deployed, could be measured by a reduction in the frequency and severity of HRI safety-related incidents, such as those cited in the safety statistics presented in the Chapter 1 Project Report Summary above.

The potential exists for future mobility-related improvements, given the availability of accurate train arrival and HRI duration-of-occupancy information. One improvement is the reduction in traffic congestion by optimizing traffic signal operation within the affected area. Another is the provision of alternate routes to emergency vehicles when feasible. Thus, the prototype RCVW system is designed to be modular and extensible to take advantage of these future benefits.

3.1.2 Stakeholder Outreach Summary and Engagement Approach

The Battelle Team engaged candidate stakeholders through a combination of e-mails and phone calls.

The following is an overview of opportunities that the Battelle Team used to engage with stakeholders and learn more of their needs.

3.1.2.1 CAMP Vehicle Safety Communications Consortium

Previous connected vehicle (CV) application demonstrations used external displays or speakers for visual or audible alerts to the driver. A request of this project was to integrate the RCVW application with a vehicle to use its display or other means integrated into the vehicle to alert the driver of violating an active rail crossing. CAMP was approached to discuss the possibility of integrating the RCVW in-vehicle application within vehicles to present warnings and alerts via Original Equipment Manufacturer (OEM) interfaces. CAMP was approached to see if they would support full integration with a vehicle, with the intent either of using the vehicle's current display or shaking the seat or steering wheel. CAMP expressed interest in the RCVW application, but was unwilling to share proprietary information needed to enable the RCVW system to be integrated with current in-vehicle systems as they were not identified as a partner or subcontractor early enough in the project.

For future CV application development projects requiring integration with existing in-vehicle subsystems, CAMP should be engaged during the proposal phase.

3.1.2.2 Automobile Manufacturers

In addition to reaching out to CAMP, Battelle contacted Ford to explore the possibility of integrating with the Ford Sync infotainment system. The Ford Sync system controls radio, navigation, and climate functions using voice commands or touch screen operation. The Ford Sync system also permits connectivity to mobile phones via Bluetooth for added features including telephony functions, music, and third-party applications like Yelp and Spotify. Battelle's intention was to create a mobile application for an Android device that would interface with the Ford Sync system to provide driver warnings and alerts using the existing user interface. During initial investigation into the available functionality supporting integration between the mobile phone and Ford Sync system, Battelle discovered that the options made available to developers were limited. For example, an application running in the background of the mobile phone could be classified only: 1) as a media application for music playback, or 2) as a messaging application. Battelle explored approaches to both options and found that neither afforded the relay of RCVW application information in an acceptably clear and concise manner, or in near-real time.

Battelle confirmed with Ford that, at the time of development of the RCVW application, no other options were available for warning and alerting the driver via the Ford Sync system. In the future, Ford may facilitate new or additional means of interacting with the Sync system to permit real time alerts on the vehicle display or interacting with the driver via other notification methods such as haptic seat motors or dashboard icons.

3.1.2.3 Vendors developing vehicle infotainment system standards enabling display for and control of mobile phone (Google and Apple)

As Ford has achieved via Sync, Apple and Google have each developed software for use by vehicle OEMs to allow seamless integration with each vendor's mobile phones.

Apple's CarPlay system mirrors a simple mobile phone interface on the vehicle's display and allows approved applications to run on the vehicle display. Currently the list of approved non-Apple applications is extremely short and is limited to media applications like Spotify or Amazon Music. Apple exercises authority over which applications will run in the CarPlay system, and restricts applications like Google Maps and Waze. To even begin developing an Apple CarPlay application, a prospective developer must apply to Apple for acceptance into the CarPlay developer network by describing the proposed application requiring CarPlay support. Battelle submitted an application request for the RCVW application to Apple, and was denied access to CarPlay. Denial rationale centered on concern that the application would distract drivers with additional alerts and warnings additional to those provided by the vehicle. The Apple CarPlay system was intentionally designed to be a vehicle infotainment interface for drivers to some of its cell phone application functionality and was not intended to relay real-time safety information to the driver. Unless Apple changes its stance, CV applications will not be allowed to interface with the CarPlay system.

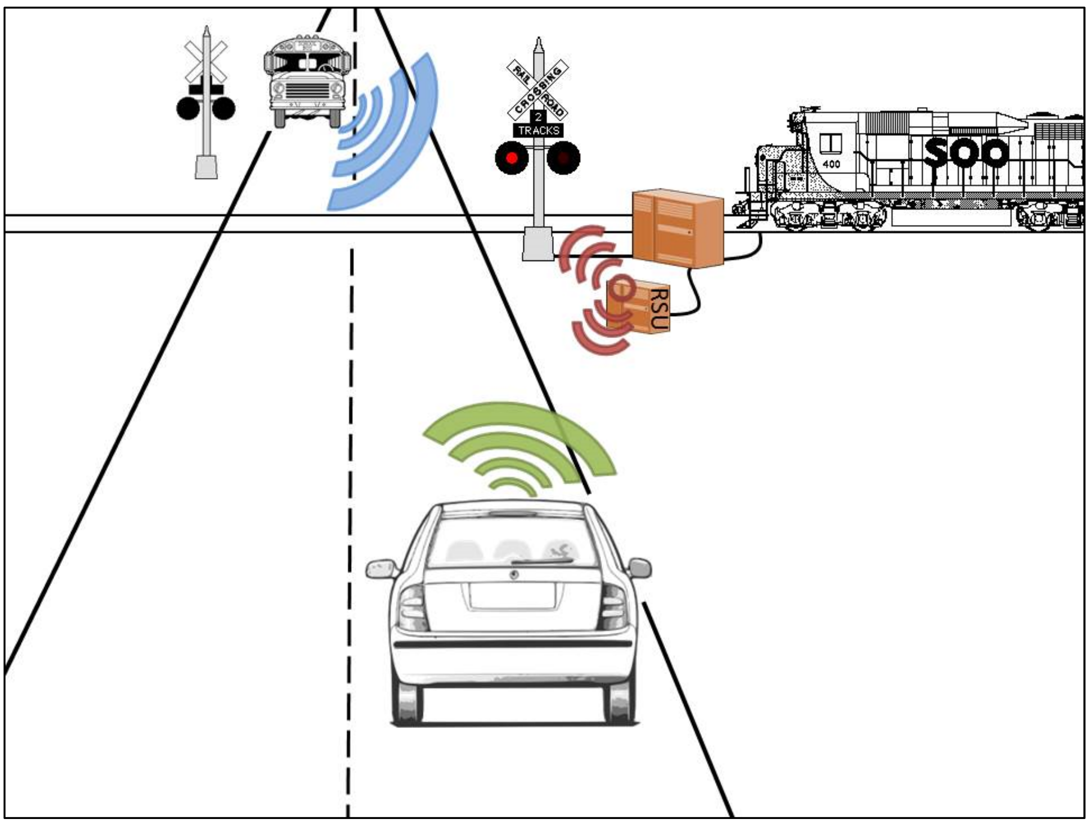
Google created a system called Android Auto, which integrates Android-powered cell phones to select vehicle infotainment systems. The Android Auto system is more open than Apple's CarPlay system in that a developer can create and test applications for Android Auto. However, Android Auto has similar limitations to the Ford Sync system. It allows only media and messaging type applications to interface the vehicle. Battelle was successful in the creation of an Android Auto application that did send messages for display by the vehicle infotainment display. However, those messages appeared like text messages do on a mobile phone. The notification area was small, and clearly would not command the driver's attention. Because the RCVW application is a real time CV safety application, it was determined by the development team that this integration did not meet the minimum requirements for notifying the driver of a violation of an active HRI. Battelle did contact Google regarding the possibility of obtaining additional functionality and control for the RCVW application, but was notified that Android Auto was not designed to support integration of vehicle safety applications.

3.1.3 Prototype RCVW System Conceptual Design

This section contains information from previous documents that describes the prototype RCVW system, including from the Cooperative Intersection Collision Avoidance Systems (CICAS)-V Phase I final report. This information was used to create the concept of operations scenarios and requirements for the RCVW project. This section reflects the concept of the prototype and does not accurately describe what was built and tested during the RCVW project. The requirements for the project, as well as traceability to the test cases used to verify them and the performance result, are presented in APPENDIX B. The design and architecture in 3.1.4 describes the system that was built and tested during the project.

3.1.3.1 Prototype RCVW System Concept

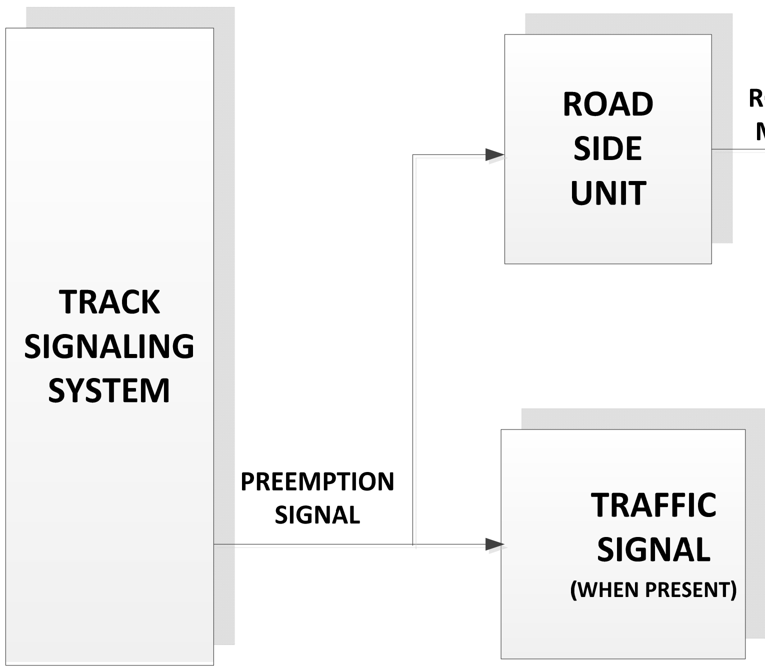
The RCVW System Concept is illustrated in Figure 3-1. This figure depicts an active HRI with an approaching train, activated rail warning devices, and a road side unit (RSU) communicating with connected vehicles approaching the HRI when a train is detected as approaching or present.



Source: John A. Volpe National Transportation Systems Center

Figure 3-1. RCVW Application Concept

A Conceptual Block Diagram of Integrated RCVW System Components is illustrated in Figure 3-2. This diagram summarizes how the preemption signal communicated from the track signaling system for a traffic signal (when present) is used by an RSU to generate a road side message to a connected roadway vehicle on-board unit (OBU).



Source: John A. Volpe National Transportation Systems Center

Figure 3-2. Conceptual Block Diagram of Integrated RCVW System Components

3.1.3.2 Prototype RCVW System Conceptual Architecture

<u>VBS</u>

The RCVW VBS was initially specified with Appendices C-1 and C-2 of the CICAS-V Phase I final report serving as a template. Figure 3-3 below presents an adaptation of the CICAS-V VBS to RCVW. Key details from the RCVW System Requirements Specification (SRS) [2] presented below represent the detailed revisions to VBS software programs that were necessary to implement RCVW.

The safety application for RCVW is logically equivalent to a traffic control signal interfaced to a RBS, with minor modifications to the Driver Visual Interface (DVI).

As shown in Figure 3-3, the VBS is comprised of the following functional modules:

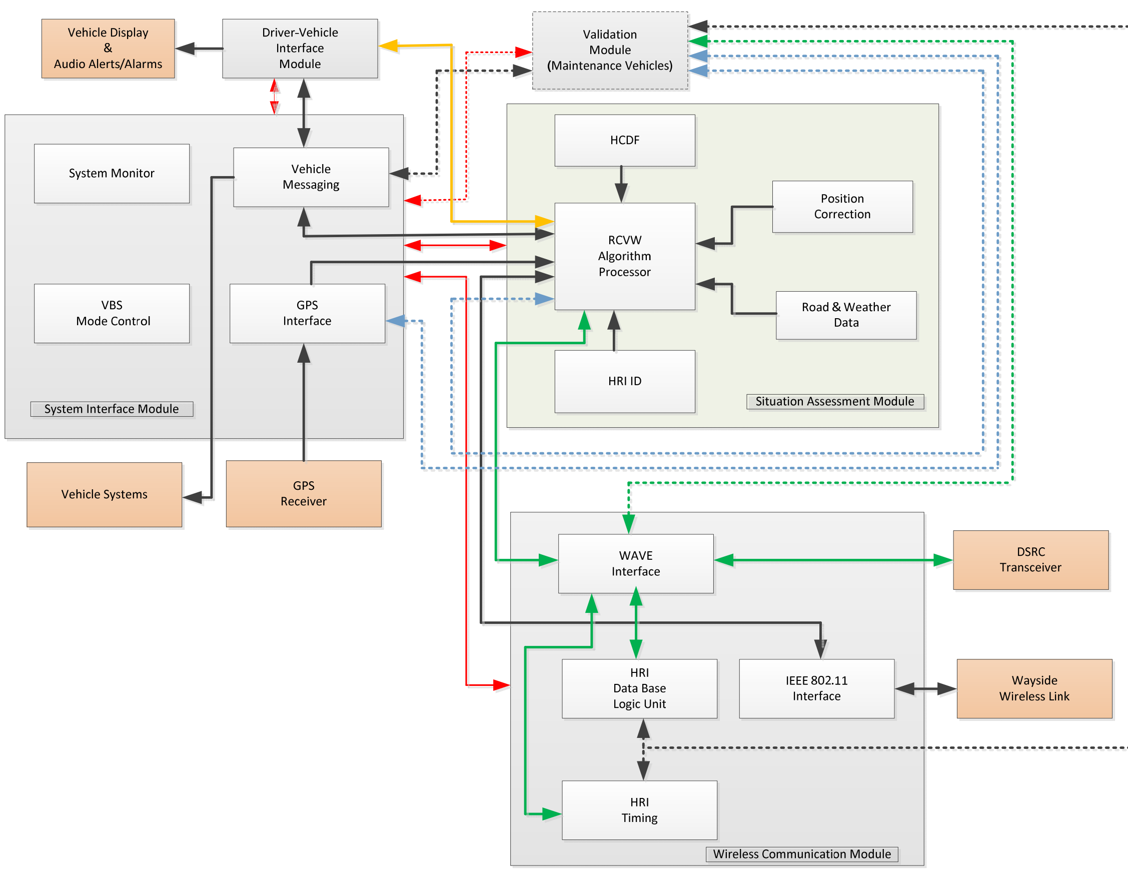
- Wireless Communication Module (WCM)
- VBS Validation Module (VVM) – required for maintenance vehicles
- Situation Assessment Module (SAM)
- System Interface Module (SIM)

- DVI Module (DVIM)

VBS System Interface Module

The SIM is the first module to be initialized when a vehicle is started and is responsible for wired communications between the VBS and all other physical in-vehicle devices. Upon startup, the SIM determines the proper operational mode for the VBS and transmits it to the other modules, as functionally represented by the “VBS Mode Control” block in Figure 3-3. Once operational, it periodically monitors the other VBS modules by requesting status and initiating corrective actions when necessary, as functionally represented by the “System Monitor” block in Figure 3-3. When a status message is received indicating an abnormality, or there is no response to the request, it initiates corrective actions.

For RCVW, the SIM manages the flow of messages between the SAM and the DVIM. The DVIM “echoes” messages back to the SIM. The SIM sends the “echoed” messages to the RBS, via the WCM, where they are stored for 48 hours.



Source: John A. Volpe National Transportation Systems Center

Figure 3-3. Adaption of CICAS-V VBS for RCVW

VBS Wireless Communication Module

The WCM provides the wireless link to/from the RBS. The functional requirements of the WCM are those stipulated in the IEEE suite of protocols addressing Wireless Access in Vehicular Environments (WAVE) and Dedicated Short-Range Communication (DSRC) specifications.

The WCM is initialized after receiving a signal from the SIM and will execute a Built-In Self-Test (BIST) after it is initialized. During normal operation, BIST routines are performed once per second. If a failure is detected, the WCM will report it to the SIM when polled. The WCM responds to status inquiries from the SIM with a message that indicates “normal function” or “failure detected”. The information flow for transmitted messages is:

SAM →SIM→WCM→ DSRC radio.

Received messages follow the reverse information flow and be authenticated in accordance with the WAVE protocol standards.

When the WCM receives the “echo” of a message sent to the DVIM by the SIM, the message enters the WAVE protocol stack. The message passes from layer to layer until it reaches the physical layer and is transmitted by the On-Board Unit (OBU).

VBS Situation Assessment Module

The SAM is the processing element of the VBS. The SAM for RCVW determines roadway vehicle:

- Speed
- Braking effectiveness
- Location with respect to the HRI

Braking effectiveness is a function of factors such as:

- Road-related (surface conditions and grade)
- Weather-related (rain, snow, sleet, temperature)
- Roadway vehicle performance specifications

The SAM is initialized by the SIM. The SAM executes a BIST routine after initialization. During normal operation, BIST routines are performed once per second.

The SAM validates RCVW-specific applications. An unsuccessful execution of the validation routine is followed by a second attempt. If the validation routine fails the second attempt, the SAM will transition to failure mode. The failure will be reported to the SIM when polled.

The SAM responds to status inquiries from the SIM with a status message that indicates either “normal function” or “errors detected.”

When a roadway vehicle is within DSRC range of an RBS in its database, the SAM expects to receive RBS broadcasts. If an RBS broadcast is not received, an error message is generated.

The SAM receives positioning correction data from the RBS.

While approaching an HRI, the SAM receives an HRI Configuration Data File (HCDF) from the RBS. If it does not receive one, it will retrieve a generic one from memory.

Using the above information, the SAM determines the likelihood of a roadway vehicle entering/crossing an HRI in violation of a RCVW. If it is predicted that a violation is about to occur, the SAM will issue a warning via the VBS DVI.

VBS Driver Visual Interface Module

The DVIM, which is initialized after receiving a signal from the SIM, controls the DVI display, audible, and/or haptic devices. The DVIM executes a BIST routine after being initialized. During normal operation, BIST routines are executed once per second. If a failure is detected, it is reported to the SIM when polled.

The DVIM will provide the driver with:

- Alerts – when it is detected that the RCVW system is not operating normally
- Warnings – when the HRI is active and a rail crossing violation is imminent or when a violation is in progress
- Multi-sensory warnings of potential impending violations
- VBS or RBS failure alerts.

VBS Validation Module

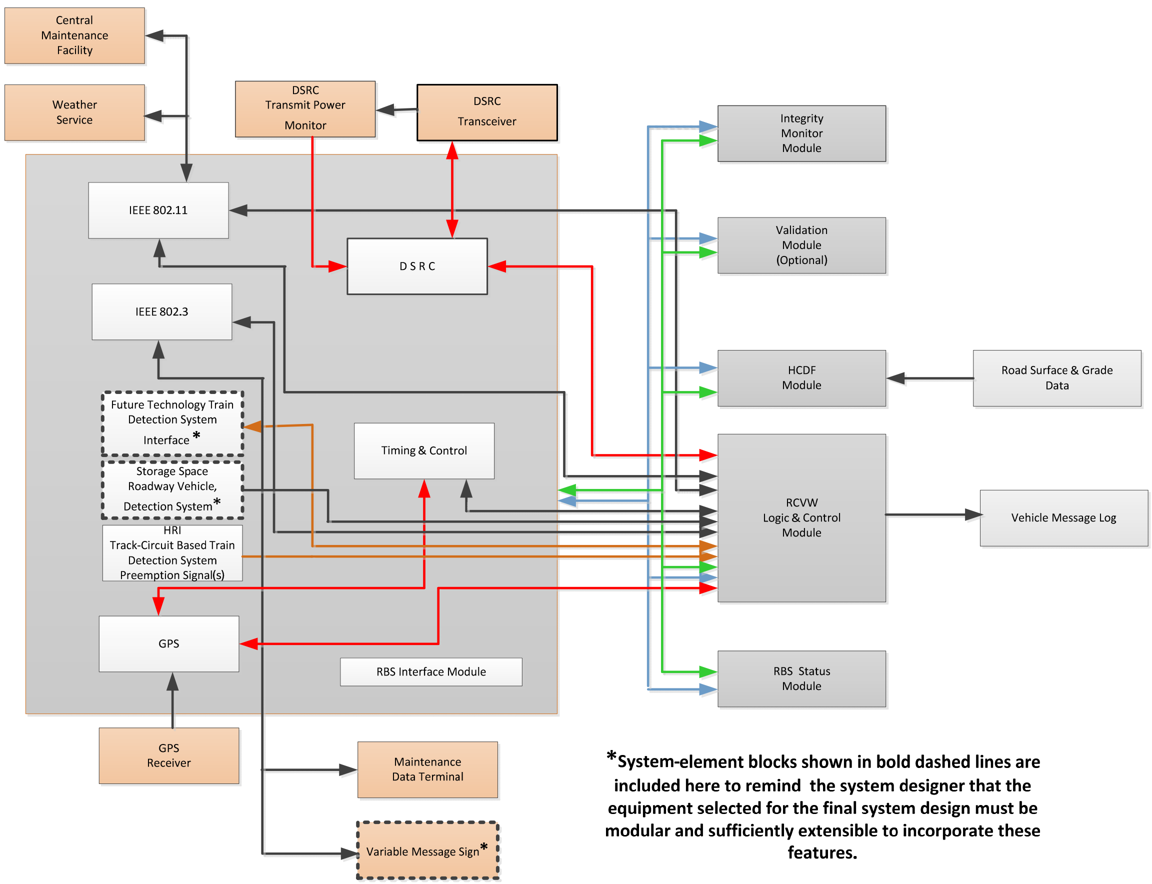
Maintenance vehicle VBS is to include a VVM. The VVM is used to evaluate DSRC radio performance and the accuracy and repeatability of Global Positioning System (GPS) derived positioning data.

The VVM is required to baseline the HCDF and initial operational testing of the RBS. It will be used subsequently for periodic validation of RBS operation and HCDF data accuracy. This functionality may be provided by stand-alone components.

<u>RBS</u>

Figure 3-4 presents the adaptation of CICAS-V RBS to RCVW. The RBS is comprised of the following functional modules (and required supporting devices):

- Integrity Module
- RBS Interface Module (RIM) provides interfaces for:
    - RSU
    - Industry standard unlicensed-band wireless transceivers (IEEE 802.3 & IEEE 802.11)
    - GPS
    - HRI track-circuit based controller
- RCVW Logic & Control Module (RLCM)
- HCDF Module
- RBS Status Module (RSM)
- RBS Validation Module (RVM)



Source: John A. Volpe National Transportation Systems Center

Figure 3-4. Adaptation of CICAS-V RBS for RCVW

RBS Integrity Module

The Integrity Module provides the monitor and control functions of the RBS. After initialization, the Integrity Module executes a BIST routine. Upon successfully completing the BIST routine, the Integrity Module initiates and monitors the subordinate RBS modules beginning with the RIM.

During Normal Operation Mode, the Integrity Module executes BIST routines once per second. The Integrity Module monitors each process and control routine in the system and will shut down or restart a routine when required. The Integrity Module performs its control function by periodically requesting status from each of the subordinate RBS modules. The modules respond with a status message that indicates either “normal function” or “error detected.”

Failure of a subordinate module to respond to a status request within 0.1 seconds is reported as an error. If the Integrity Module detects errors in two consecutive requests from a module, the Integrity Module declares it as having “failed” and the RBS transitions to Failure Mode. While in Failure Mode, the Integrity Module will attempt to restore the system. The first response of the Integrity Module is to shut down and restart the affected routine. If the first response fails to restore the system to normal operation, the next step is to reboot.

If rebooting fails to restore the system to normal operation, the RBS will remain in Failure Mode. The Integrity Module will report and record all software errors and hardware failures. The Integrity Module initiates the process to broadcast messages containing RBS status and HCDF revision level five times per second.

RBS RIM

The RIM interfaces and manages communications with all external devices. Messages to be transmitted by the DSRC radio or a roadside network, as well as transactions with a Maintenance Data Terminal (MDT), are routed via the RIM.

- Specific to the RCVW SRS [2], the RIM provides the electrical and connector interfaces to process up to four HRI controller preemption signals (four trains approaching) from a single HRI.
- The RIM formats messages that are to be transmitted by the DSRC radio to roadway vehicles in accordance with the IEEE 1609 suite of protocols.
- Messages sent to an MDT are formatted in accordance with the IEEE 802.3 standard.
- Messages sent via a roadside network are formatted and transmitted in accordance with industry standard wireless protocols.

The RIM receives data from the other RBS modules and devices, determines its destination, schedules the time of its broadcast, inserts it into its designated space within the appropriate ITS standard message format, and dispatches it to the appropriate device.

Messages that are to be received by the RSU are to be consistent with the suite of WAVE protocol standards. Messages transmitted by an MDT should be formatted in accordance with the IEEE 802.3 standard.

The RSU WAVE messages broadcast to OBUs includes the following types of information:

- Positioning correction data
- RBS operational status and software revision level
- HCDF
- HRI status (active or inactive)

There are two types of messages that can be received by the RBS from a roadway or maintenance vehicle VBS:

- Validation related messages: While in Validation Mode, the RBS receives validation messages from maintenance vehicles.
- Vehicle warning status message: When the VBS DVI issues a warning to the driver, the message is sent to the RBS, where it will be time-stamped and archived for 48 hours.

Validation related messages and heartbeat messages are forwarded to the RVM.

The RIM design allows parameter changes for each of the RBS modules without the need to recompile the software. The RIM receives up-to-date configurable parameter settings for each module and stores those settings for other modules to access. Upon request, the RIM sends configuration data.

RBS RCVW Logic and Control Module

The RLCM processes:

- Four HRI controller preemption signals (four trains approaching)
- Signals from two storage space roadway vehicle detection systems.

The RLCM is initialized by the Integrity Module. When the HRI status changes the RLCM initiates a change in status message directive. The directive is routed to the DSRC radio.

The RLCM initiates the HRI Active message.

RBS HCDF Module

The HCDF Module stores the geometric HRI description data and sends the data to the VBS via the RIM and RSU when directed to do so.

The HCDF Module is initialized by the Integrity Module.

When an HRI configuration changes and the HCDF data is revised to reflect the change, its revision level is updated. When the HCDF revision level is changed, an HCDF advisory message is created and sent to the Integrity Module.

RBS Status Module

The RBS Status Module (RSM) is initialized by the Integrity Module. The RSM requests status data from all modules having reportable status. The RSM also receives and stores driver-warning messages that were issued to a driver by the DVI.

When a Vehicle Status Data request is received, the module retrieves the data, formats a message, and sends it.

RBS Validation Module (Required for maintenance)

The RVM may be incorporated in:

- The RBS
- A system accessed via a roadside network
- The maintenance vehicle VBS

The RVM manages the RCVW testing that is conducted prior to the RBS being placed into service. Validation testing may also be performed as part of other scheduled maintenance activities. During validation testing, the RVM reviews the HCDF information, simulates inputs to the RLCM, monitors the messages that are sent to the maintenance vehicle VBS, and validates the required RSU signal reception area. The RVM manages simultaneous data input and processing from two sources of HRI-related data. The RVM, after having been initialized by the Integrity Module, performs the following tests:

- Coverage Mapping – The RVM evaluates the quality of the signal received from the maintenance vehicle OBU. The maintenance vehicle traverses all possible paths approaching and crossing the HRI. The RVM records the time when reception is acceptable and when it is not. The RVM correlates its time-stamped data with the time-stamped position data recorded by the maintenance vehicle VBS. This information is used to determine if the system is functioning as designed or needs to transition to Failure Mode.

- HRI Mapping – During its approach and crossing of the HRI, the maintenance vehicle acquires and records data. The RVM correlates the movement of the maintenance vehicle approaching and crossing the HRI with HRI reference points. The results are stored.
- Diagnostics and Logging – The RVM maintains a log of diagnostic messages created by RVM actions.

Upon request, the RVM retrieves validation data, formats it into a message, and sends it.

3.1.4 Prototype RCVW System Architecture and Design

3.1.4.1 Prototype RCVW System Functional Architecture for Implementation

System Overview and Context

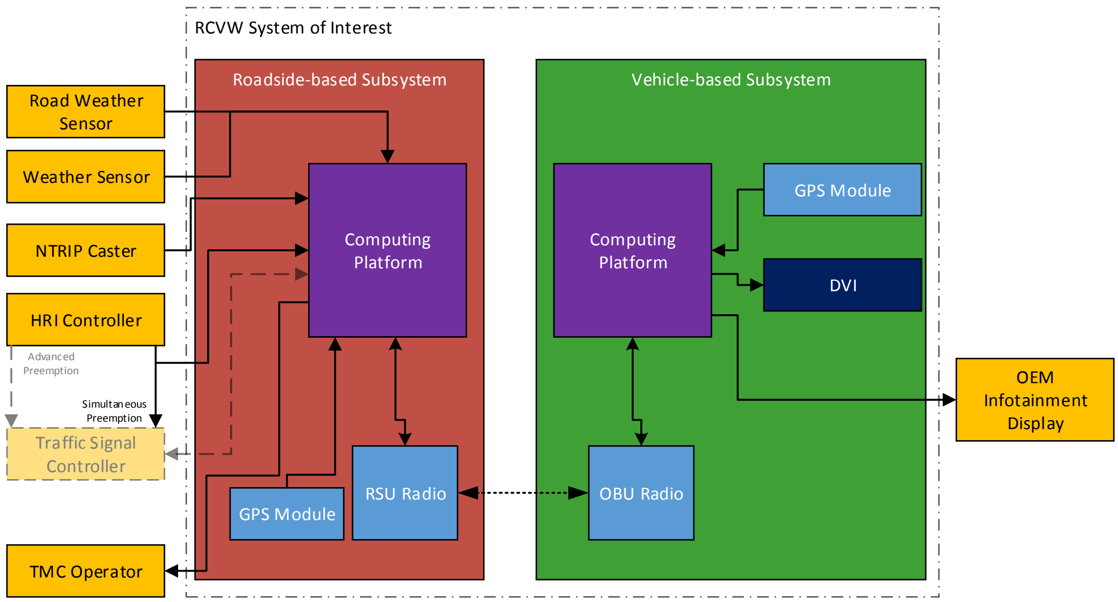
The RCVW system consists of two physically separate subsystems: A VBS installed in connected vehicles and a RBS integrated with roadside infrastructure at HRIs. Both subsystems possess common hardware and software components, as well as include unique components. The RCVW system includes the following components:

- CP: The heart of the RCVW system are its CPs, which control both RCVW subsystems. The RBS CP resides within an Integrated V2I Prototype (IVP) module.
- DSRC Radios – the VBS and RBS utilize DSRC radios (an OBU and an RSU, respectively) as a low-latency wireless communication method to connect the two subsystems.
- GPS – A GPS module resides within the VBS and RBS with capability provide real-time lane-level position data to the VBS CP and RBS CP, respectively.
- DVI – the RCVW interface to the connected vehicle driver provides the vehicle driver RCVW warnings and alerts.

Information from sources external to the RCVW system is accessed through an associated Transportation Message Exchange (TMX) plugin. This information includes weather, road weather (if available), and train detection signal status. The TMX software is Battelle's implementation of the V2I Hub which was developed for the IVP project to support infrastructure communications for CV applications. TMX is a singular communications platform with which a set of plugins are integrated to supply information to and receive information from deployed system components. The subset of TMX plugins created for the IVP project that are utilized for the RCVW project include: MAP, Signal Phase and Timing (SPAT), DSRC Message Forward, GPS, and Universal Time Code (UTC) plugins. Additional details on the IVP project and the plugins created can be found in the IVP Design and Integrated Vehicle-to-Infrastructure prototype IVP Interface Control Document (ICD) documents. The V2I reference implementation project will expand on the IVP project and provide software updates, hardware recommendations, deployment documentation, and training materials on system deployment. However, as of the time when the RCVW Architecture and Design was being developed, the V2I project had not produced documentation to reference. As a result, the RCVW system leveraged the IVP design and documentation.

RCVW System Architecture Overview

A high-level architectural view of the RCVW System is shown in Figure 3-5 below. Hardware components, their functionality, inputs, software, communications, and interface details are provided in the following sections of this document. Since the RCVW system was developed on top of the existing TMX software and hardware that were completed on the IVP project, the design of the RCVW system was constrained to that of the system created by the IVP project. The TMX (IVP) plugin architecture can be found in the referenced IVP Design document and IVP ICD document. For the following figures, the orange components are external entities to the RCVW system of interest. Entities with dashed lines and that are grayed out are external entities that were not implemented in the demonstration of the RCVW system.



Source: Battelle

Figure 3-5. RCVW System Architecture Overview

Figure 3-5 above shows the two subsystems that were built for the RCVW project: the RBS and the VBS. Both systems have a CP running the TMX software and interface with a DSRC radio, respectively. The RBS interfaces with external entities for input in creating the SAE J2735 messages that are transmitted to the VBS from the RBS RSU radio. The VBS receives SAE J2735 messages via the OBU radio and processes them in the RCVW plugin part of the VBS CP. The DVI delivers graphical and audible notifications to the operator. The DVI, which contains a small external display and speakers, is connected to the VBS via a HDMI connection. Figure 3-5 above depicts integration with OEM Infotainment Display. Although it was decided during the project that this feature would not be implemented, the OEM display remains a part of the overall RCVW System Architecture because the RCVW system possesses the capability to be integrated with a vehicle infotainment system once vehicle OEMs permit external systems to communicate and display safety critical information on vehicle infotainment displays.

Additional background on the concepts and requirements behind the RCVW architecture and its elements is provided in the RCVW ConOps [1], RCVW SRS [2], and System Architecture and Design [3] documents.

3.1.4.2 Prototype RCVW System Component Descriptions

<u>Computing Platform</u>

Identical CPs are employed by the VBS and RBS. Both CPs employ the TMX software developed for connected vehicle applications under the IVP project. The TMX software allows plugins to share information between each other in an IVP system and broadcast information via a DSRC radio. Utilizing the TMX facilitates a reduction in deployment time and effort through use of plugins developed under the IVP project. The VBS also uses the TMX as its main communication hub to receive DSRC messages from the RBS and make those messages available for other RCVW VBS plugins. The RCVW plugin on the VBS contains an application to use inputs supplied by other plugins, including J2735 MAP and SPAT, GPS, and weather information to determine when an RCVW warning or alert will be displayed.

Hardware

CP hardware was developed by Battelle, which consists of single board computer integrated with a DSRC radio. The CP possesses multiple communication channels including Bluetooth, Wi-Fi, Cellular, Ethernet, DSRC, and USB. The RCVW system utilizes the RS232, Ethernet, DSRC, and USB connections. The full specifications of the CP can be found in Appendix B of the RCVW Architecture & Design document [3].

DSRC Radio

The DSRC Radio transmits and receives messages in accordance to IEEE 802.11p and 1609.2 standards, and the J2735 message standards. Communications to the RSU are User Datagram Protocol (UDP) immediate forward-raw data payload messages, as defined in the RSU 4.0 specification. A sample MAP message is shown below in Figure 3-6.

Table 3-1 provides a listing of the RCVW message types.

The RCVW system utilizes SPAT, MAP, and RSA messages from the SAE J2735 message set. The MAP messages contain intersection geometry information, including the vehicle lanes and tracked vehicle lanes (train tracks) for the HRI. These messages are used by the VBS to fix its location within the HRI (i.e., the HRI Hazard Zone or HRI Approach Zone). The SPAT message contains the status of each lane entering the HRI. For example, at a simple HRI with vehicle lanes crossing a train track and no traffic intersection present, when the HRI is not active, the status of the vehicle lanes will be ‘permitted movement allowed’ and the tracked vehicle lane will be ‘stop and remain’. When the HRI is active, the status of the vehicle lanes will be ‘stop and remain’ and the tracked vehicle lane will be ‘permitted movement allowed’. SPAT information is used by the VBS to determine HRI status-based messaging. Weather information is transmitted from the RBS and to VBS using the RSA message. For more detail on the format of these messages, see the 2015 SAE J2735 Dedicated Short Range Communications Message Set Dictionary.

Version=0.5
Type=MAP
PSID=0xBFF0
Priority=7
TxMode=CONT
TxChannel=172
TxInterval=0
DeliveryStart=
DeliveryStop=
Signature=True
Encryption=False
Payload=3081DE8001108109000000000000001000830101A481C63081C3800102A11BA119A01080
0418054A3B8104CE3585DF82020D0681020040820102820207DB830306162184027D00850102A61
080041804FD888104CE35C39E82020CF68702016E880100A93C303A80020040A234A032A3300404
1C6BCDB304040420EC2B0404FAC8EC280404EF79F1210404EBC4FD660404E65310690404F9621
AA50404095B3F31AA3AA0383006A004800235293006A0048002010C3006A004800231383006A00
4800222113006A0048002010C3006A004800231483006A0048002221185021001

Source: LocomateUsersGuide_v1.26.pdf section D2

Figure 3-6. Map Data File to be Sent over UDP

Table 3-1. RCVW System DSRC Message Types

Common Message Name	PSID	Application	SAE J2735 message	DSRC Channel	DSRCmsgID
SPAT message	0x8003	RCVW	MSG_SignalPhaseAndTiming	172	0x8D
MAP message (aka GID)	0x8003	RCVW	MSG_MapData	172	0x87
RSA message	0x8000	RCVW	MSG_RoadServiceAnnouncement	178	0x30

Source: Battelle

GPS Receiver

UBlox NEO-7P, or similar, providing +/-2-meter accuracy.

Software

The Operating System (OS) selected for the CP was Linux as it allows a flexible platform for product development due to it being open source and easily customized.

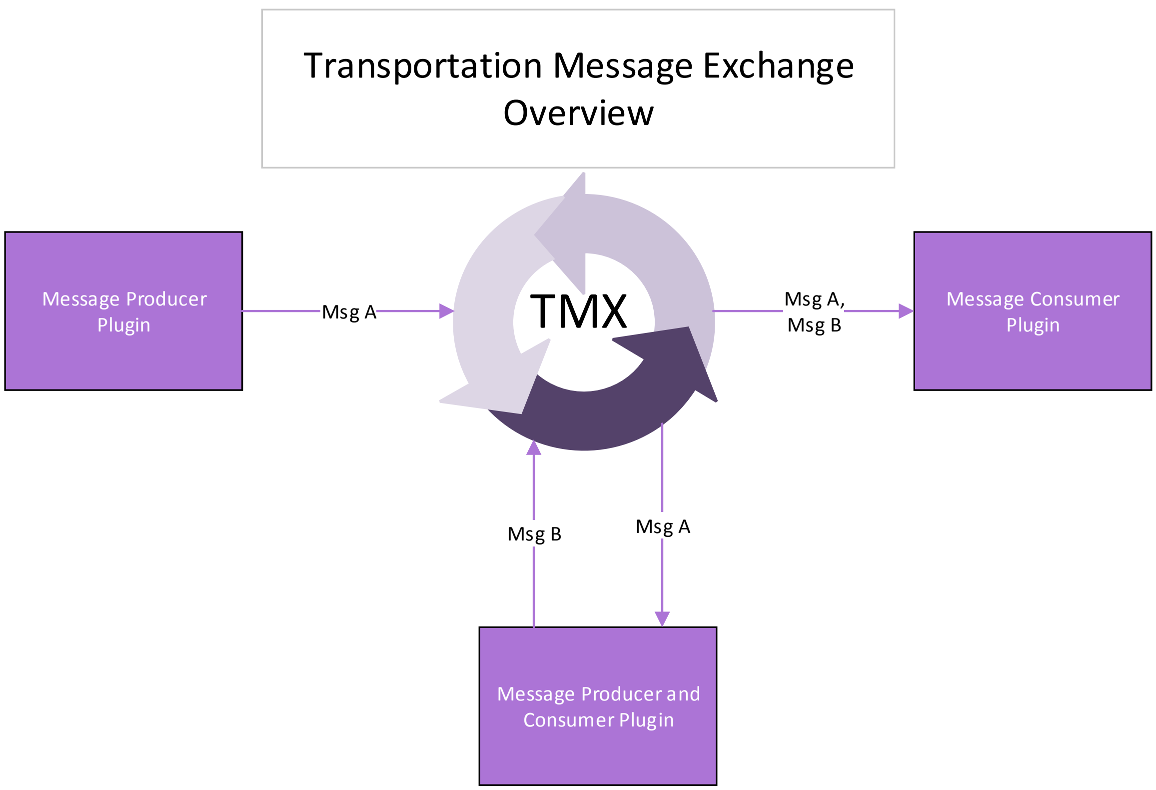
In addition to the OS layer, the RCVW design includes a common messaging framework for use across all connected vehicle projects. This common framework, TMX, is described in greater detail below.

Linux

The operating system running on the CPs is the most recent version of the Linux Ubuntu distribution with Long Term Support (LTS). At the time of development, the most recent version was 14.04, which is built on the 3.14.28 Linux kernel. The single board computer used in this product also provides a Board Support Package (BSP) with appropriate kernel modifications that permits custom hardware.

Transportation Message Exchange (TMX)

A common software platform was used in both RCVW subsystems. In both the VBS and RBS, the software developed was designed to make use of the TMX platform. The TMX platform is Battelle's implementation of the V2I Hub which was developed by Battelle to support the IVP project, and subsequently refined for use in other projects. A high-level overview diagram of the TMX platform is presented below in Figure 3-7.



Source: Battelle

Figure 3-7. Transportation Message Exchange (TMX) Overview

The system was developed using the TMX platform integrated with a set of loosely coupled plugins that communicate through the TMX hub. Each plugin is responsible for registering with the TMX hub. As part of registration, plugins notify the hub as to which message types the plugin will produce and transmit to the TMX. Each plugin additionally provides which message types it will request to receive from the TMX. Plugins can be either message producers, message consumers, or both. One key advantage of using the TMX platform as a foundation for building the RCVW system is that plugins developed by other projects can be leveraged, reducing the time of development and testing.

RCVW Design Overview

The HRI Hazard Zone, the area between the stop bars on either side of the grade crossing, is site-specific and static. Its geospatial description is determined, and stored, at the time of initial deployment of the RBS CP and communicated to the VBS CP for determining Rail Crossing Violation Warnings (RCVWs). The geospatial dimensions of the HRI Hazard Zone are a function of vehicle approach direction to the HRI, number of tracks, approach skew, and, where applicable, the type of active warning devices implemented at the HRI (e.g., two quadrant vs. four quadrant design). These same factors are used in determining the placement of warning gates and/or stop lines, as specified by the MUTCD and AREMA C&S Manual. The intention is that the HRI Hazard Zone and end of the HRI Approach Zone closely align with these rail warning markings and device placements. See Section 1.2 of the RCVW SRS document [2] for more detail and definitions of the HRI Hazard Zone and HRI Approach Zone.

For HRIs equipped with active warning devices and interconnected with traffic signal controllers at nearby intersections, a preemption signal is issued when an HRI is active. CFR Title 49 Part 234 specifies that this signal must be issued at least 20 seconds before train arrival. However, factors such as the roadway speed limit, railway speeds, design of the active warning devices, HRI hazard zone size (inclusive of number of tracks), placement of the HRI warning devices, and additional site-specific factors are considered in determining if more than 20 seconds is required.

As illustrated in Figure 3-5 above, the RBS CP relies on the HRI controller for receipt of the preemption signal. The RBS HRI Active message sequence is triggered upon receipt of this preemption signal. While the RBS CP will receive simultaneous preemption signaling from the HRI controller, it is designed to also accept advanced preemption signals through the Traffic Signal Controller (TSC). Although advanced preemption signaling is rarely expected to be available and is most reliably received directly from the HRI controller, the capability to accept this signaling through the TSC may present an attractive option for certain installations.

When the RBS receives a preemption signal, it will broadcast an HRI Active message. If a VBS is within the HRI Approach Zone, it may issue alerts, and, if necessary, RCVWs[2]. It is critical that the VBS receives timely HRI Active messages and issues actionable RCVWs.

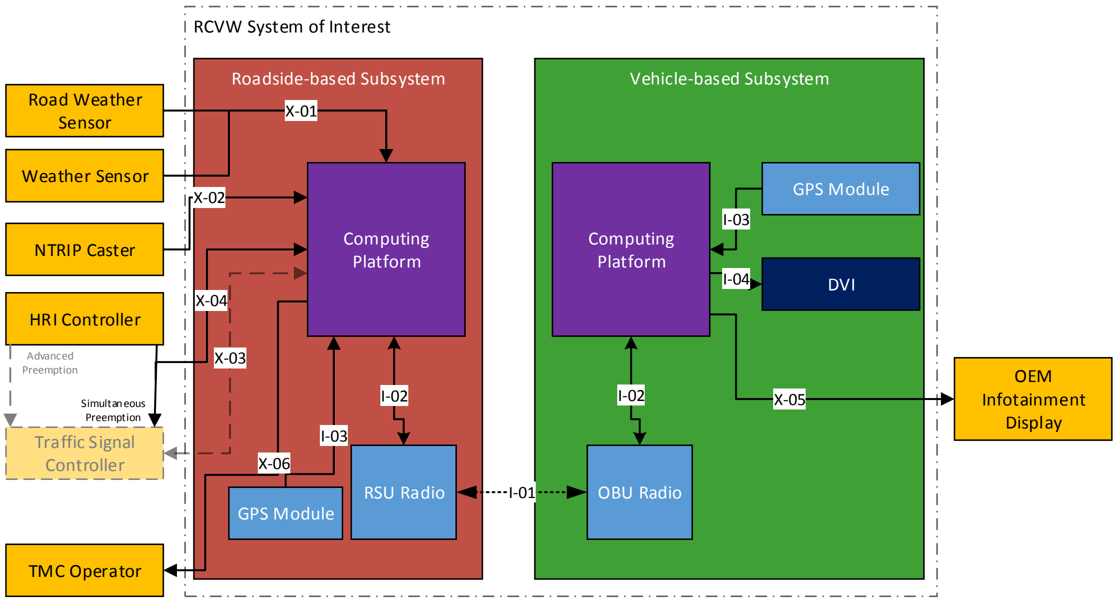
The VBS RCVW prediction algorithm will not change based on the availability of an advance preemption signal. The VBS RCVW algorithm is conservative in that it will not calculate or issue alerts or warnings for vehicles to proceed within the HRI Approach Zone when the HRI is active, regardless of vehicle-condition factors. In other words, it will not encourage vehicle operators to delay taking action to stop within the HRI Approach Zone when an HRI is active or contribute to the perception they can or should proceed (i.e., it effectively ignores virtual or actual “Dilemma Zones”). The “Dilemma Zone” is the area within which vehicle operators may become confused as to whether they should attempt to stop or proceed.

[2]RCVW warnings within this zone are determined by an algorithm executed by the VBS that considers factors including typical reaction time of an operator; assumed worst case positional inaccuracy; vehicle speed, and braking performance; road parameters; and weather.

System of RCVW Interfaces

The functional design of the RCVW Architecture is depicted in Figure 3-5 above. The functional decomposition of the RCVW is coincidently based on hardware boundaries.

The RCVW System is composed of two subsystems, with interfaces as depicted below in Figure 3-8. The RBS provides HRI attributes, road and weather conditions, and HRI status. The VBS determines and provides to the driver of the connected vehicle alerts, RCVWs, and clear HRI warnings.



Source: Battelle

Figure 3-8. RCVW System Overview with Interfaces

Table 3-2 below lists out each of the interfaces connecting the diagrammed subsystems, as well as the connections made to external systems.

Table 3-2. RCVW System Interfaces

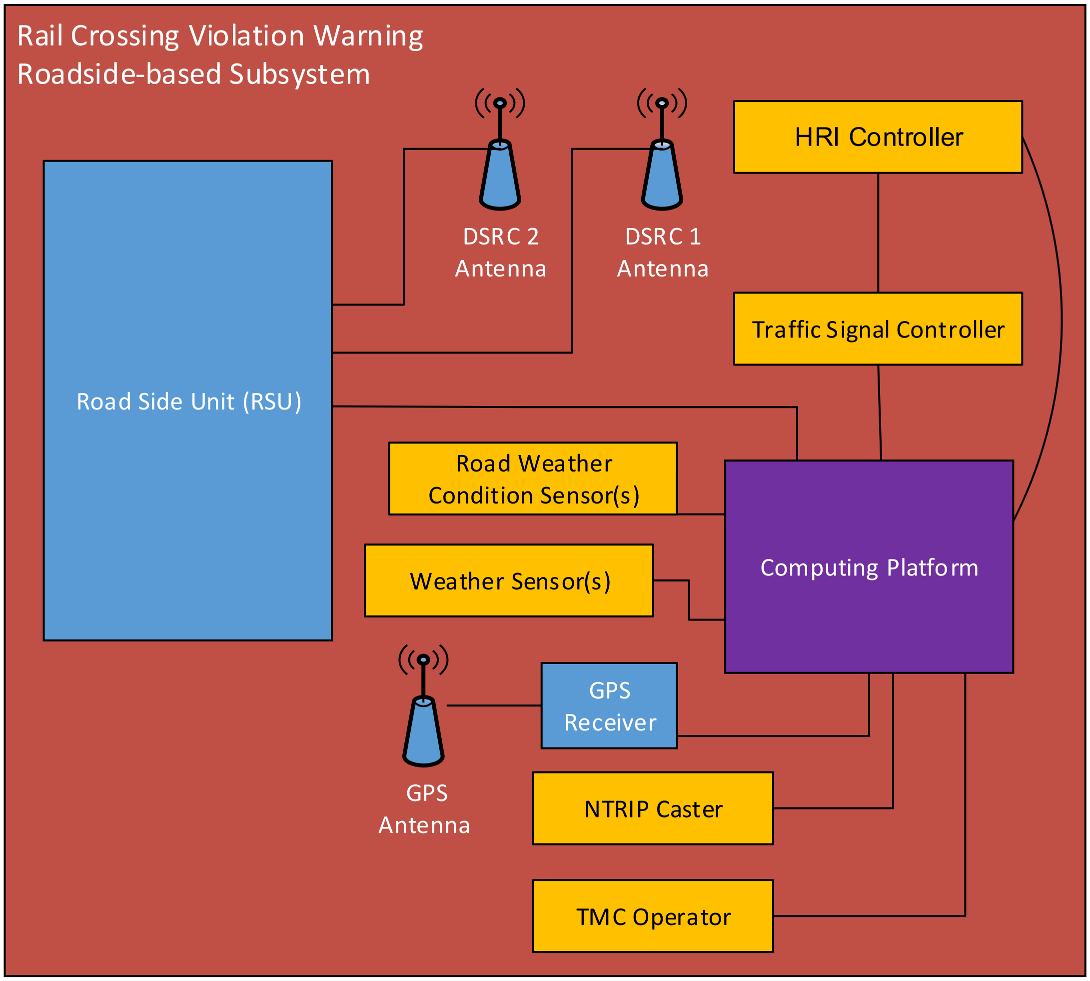
Interface Identifier	Interface Type	Exchanged information
I-01	DSRC	The RBS will send information to the VBS about the geographic layout of the HRI, local weather and road weather conditions, and HRI status. This information will be sent as MAP, RSA, and SPAT messages via DSRC.
I-02	TCP Socket	The RBS and VBS will have a socket connection to its DSRC radio to send and receive messages over DSRC.
I-03	TCP Socket	The RBS and VBS will have a socket connection to its GPS radio to receive position and time information
I-04	HDMI	The VBS will transmit warnings and alerts to DVI
X-01	NTCIP	The RBS will receive road weather and weather status information from weather and road weather sensors
X-02	TCP/IP	The RBS will receive NTRIP position correction information from an NTRIP caster network over a TCP/IP connection, and create RTCM messages that will be communicated via DSRC radio communications.
X-03	Signal Controller Status	The RBS IVP CP will receive the TSC status, which contains phase information needed to populate a SPAT message for the intersection. This information may also include the HRI preemption signal for potential use in future implementations not yet defined. **Note:** preemption signaling is, for RCVW purposes, received directly from the HRI controller.
X-04	Preemption Signal	The RBS IVP CP will receive the HRI preemption signal directly from the HRI controller
X-05	USB	The VBS will integrate with existing infotainment systems to display the alerts and warnings on an OEM display
X-06	Internet / Cellular	The RBS will send failure notifications to a Traffic Management Center (TMC) Operator.

Source: Battelle

Hardware Overview

Roadside-based Subsystem Hardware

A hardware block diagram for the RCVW RBS is shown in Figure 3-9. This figure identifies the main components and the associated interconnects that are required.



Source: Battelle

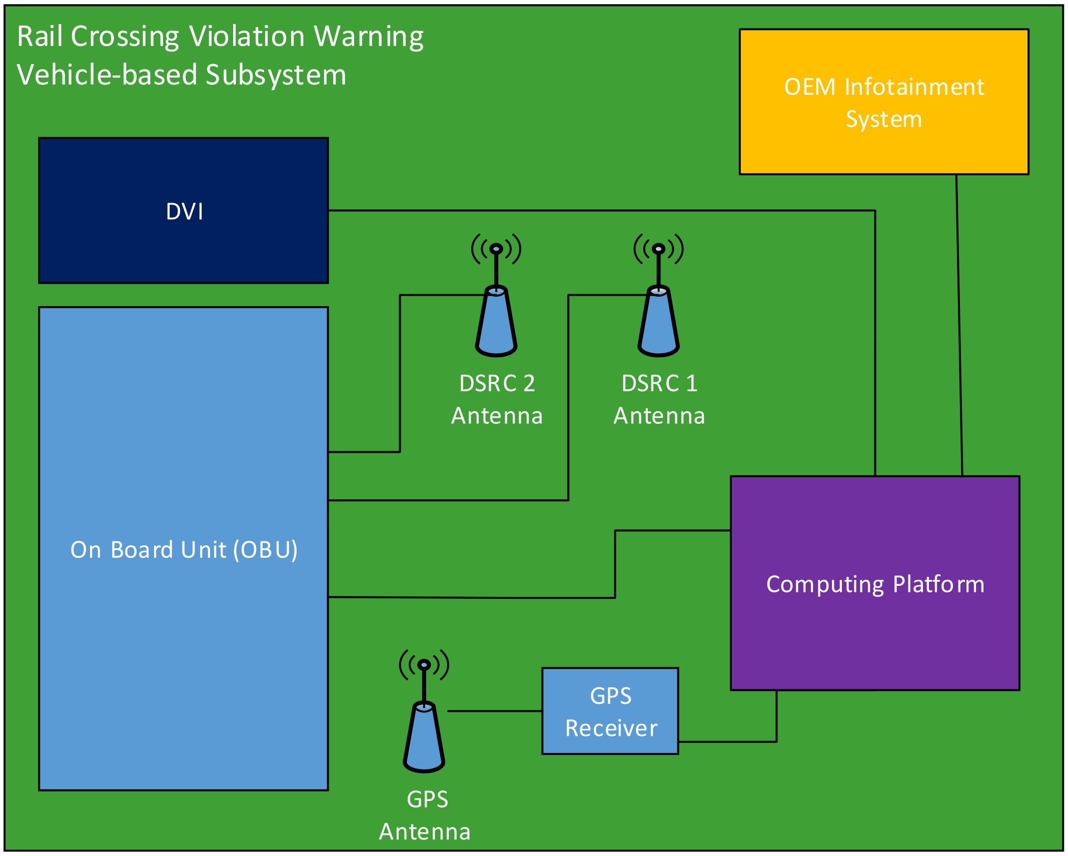
Figure 3-9. Roadside-based subsystem hardware block diagram.

- RCVW RBS Hardware includes:
  - Computing Platform
  - DSRC Radio
  - DSRC Antenna 1 and DSRC Antenna 2
  - Road Weather Condition and Weather Sensors
  - GPS Receiver

A more in-depth description of each hardware component is presented below.

Vehicle-based Subsystem Hardware

A hardware block diagram for the RCVW VBS is shown in Figure 3-10. This figure identifies the main components and the associated interconnections that are required.



Source: Battelle

Figure 3-10. Vehicle-based subsystem hardware block diagram.

- RCVW VBS hardware includes:
  - Computing Platform
  - DSRC Radio
  - DSRC Antenna 1 and DSRC Antenna 2
  - GPS Receiver and Antenna
  - DVI
  - OEM Infotainment System (originally planned, but not implemented due to limitations set by OEMs)

A more in-depth description of each hardware component is presented below.

Software Overview

Software applications for the RCVW system was developed for each of the two RCVW Subsystems. Both the RBS and VBS were built on a common hardware platform. Because of this common hardware, much of the software platform can also be the same for both subsystems.

At the heart of the RBS and VBS is a CP. It employs a Linux OS, which provides access to the underlying hardware components. Both subsystems also use a common software platform operating in tandem with the OS, which permits rapid development of the RCVW features and applications and leverages existing IVP project capabilities across the RCVW project. Additional details for the design of each software system are provided below.

3.1.4.3 Prototype RCVW System Inputs and Outputs and Components

RCVW Inputs and Outputs

There are five primary data input types to the RCVW system:

The first input type is HRI attributes, characteristics and geography that are transmitted in a SAE J2735 MAP message. The characteristics and attributes of the intersection include the lane types (pedestrian, vehicle, etc.), the permitted lane movements (straight, left turn, right turn, etc.), lane direction (approach or egress) and lane connection information all provide the best representation of the intersection to approaching vehicles. The MAP message contains all the HRI information necessary for a vehicle to place itself in the MAP. These messages are transmitted from the RBS RSU to the VBS OBU via DSRC.

The second is HRI status. The status, either active or inactive, is provided to the RBS by the HRI controller. The HRI status is transmitted by the RBS RSU via the SAE J2735 SPAT message. The SPAT information is used by the VBS RCVW application for determining when a RCVW alert/warning should be issued.

The third is GPS position and time. Position fix information to determine the position of the VBS in the HRI MAP is a required input for the RCVW algorithm. The position accuracy of the GPS must be sufficient to allow placement of the VBS within the lane information provided by the J2735 MAP message. Vehicle speed is used by the VBS HRI algorithm in addition to other parameters when determining if RCVW warnings and alerts should be displayed.

The fourth is the weather condition information. These data are communicated to the VBS via the RBS and are used in the RCVW prediction algorithm.

The fifth is vehicle type information. This information is provided via a configuration file into the VBS RCVW application for use in the RCVW prediction algorithm.

RCVW System

This section contains a detailed description of each RCVW subsystem along with the software and hardware that will be either developed or modified to support the determination of RCVWs for connected vehicles. See Section 3.1.4.2 above for a description of the DSRC radio hardware.

Vehicle-based Subsystem

The VBS is a collection of hardware and software to serve the purpose of alerting/warning the connected vehicle driver of imminent rail crossing violations.

Hardware

The hardware for the VBS consists of a computing platform and a driver visual interface.

Computing Platform. The CP serves as the central hub for all RCVW activity on the connected vehicle. This device communicates with the other RCVW subsystems as well as the external equipment on the connected vehicle. More details on the CP can be found in Chapter 4 of the RCVW Architecture & Design document [3].

Driver Visual Interface. The DVI for displaying and annunciating RCVWs is a commercial-off-the-shelf (COTS) external LCD display with speakers. Graphical alerts and warnings are presented to the vehicle driver via the high-resolution LCD display. For example, a system error alert is displayed if communications are not received from a “known” RBS. Similarly, a warning is displayed and annunciated if vehicle is on course to violate an active rail crossing or if the roadway vehicle is stopped within an active HRI hazard zone. DVI speakers possess an adjustable volume control allowing the driver to hear the audible annunciations inside a vehicle above ambient noise.

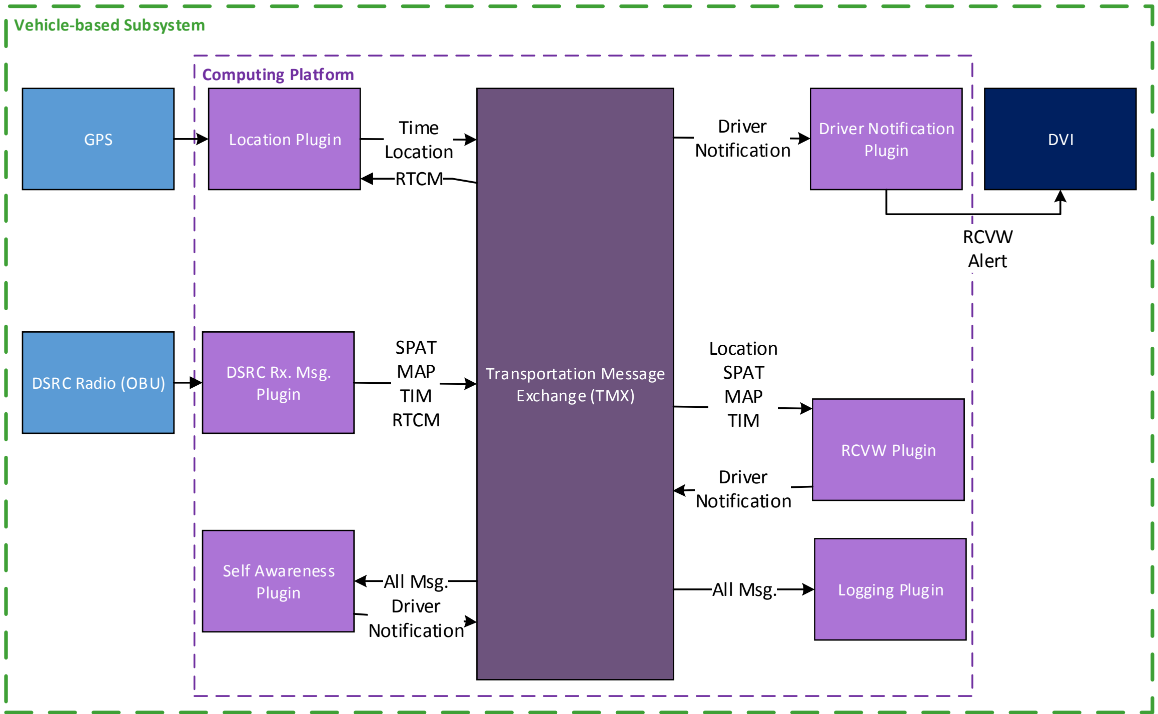
GPS. The GPS module is used to determine the position of the VBS. The position accuracy of the GPS must be sufficient to allow placement of the VBS within the lane information provided by the J2735 MAP message. The RCVW SRS document [2] specifies a R95 probability of less than or equal to 2 meters horizontal position as the required level of GPS accuracy to achieve lane-level positioning for the VBS. A U-blox NEO-7P chip was utilized to obtain the needed level of GPS accuracy. Although the RBS was designed to receive position correction information from an NTRIP caster network over a TCP/IP connection, and create RTCM messages that will be communicated to the VBS via DSRC radio communications, superior reliability and accuracy in position determination were previously observed to be supplied by the U-blox NEO-7P module when using SBAS. As a result, the VBS was configured for SBAS for RCVW FT&E testing.

OEM Infotainment System. The OEM Infotainment System is an in-vehicle system produced by the vehicle manufacturer that controls various non-safety critical functions like the radio and climate control. Most new vehicles are equipped with such systems. Examples of infotainment systems are the Ford Sync system, Chrysler UConnect, Android Auto and Apple CarPlay. Interface to these systems is supported by the VBS via a USB connection from the CP to the Infotainment System. However, for the reasons discussed above in Section 3.1.2, lack of adequate access or control of OEM Infotainment Systems evaluated, and support by candidate stakeholders, prevented the development and demonstration of an integrated solution inclusive of an OEM infotainment system which would meet the minimum requirements for acceptably notifying the driver of a violation of an active HRI.

Software

The software for the VBS generates alerts, predicted RCVWs, and clear HRI warnings to the driver of a connected vehicle.

The RCVW application was designed to interface with the TMX software platform. The logic required to perform the needed functions was developed as a set of plugins. Each plugin will perform a single discrete function. The diagram in Figure 3-11, illustrates the plugins, including how they interact with RCVW system components.



Source: Battelle

Figure 3-11. Vehicle-based Subsystem Software Design

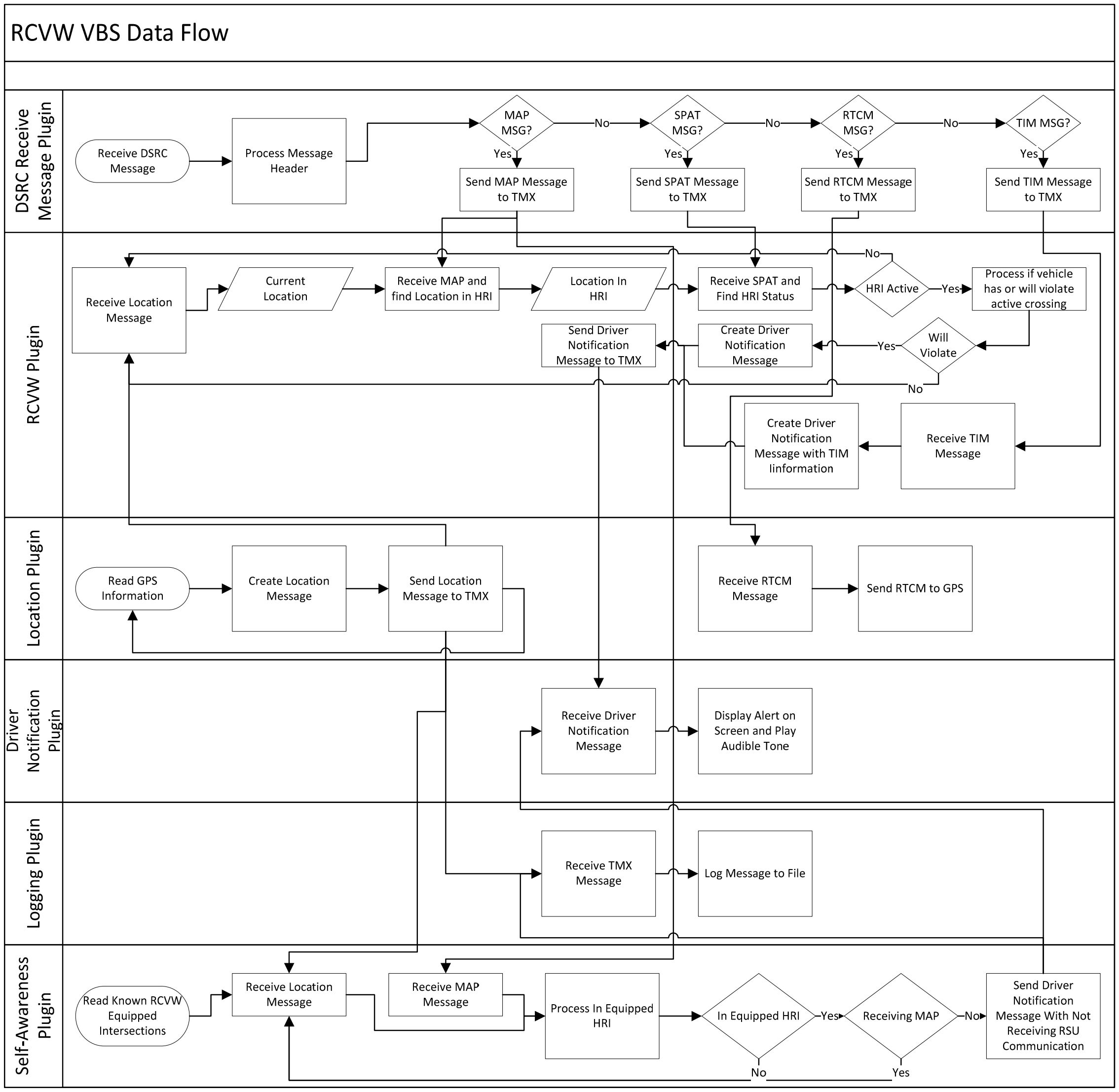
Table 3-3, below, provides a brief description of each plugin and its associated data exchange. The internal format of the messages is described in the Integrated Vehicle-to-Infrastructure Prototype Design document's IVP JSON Message Structure section.

Table 3-3. RCVW System VBS TMX Plugins

Plugin	Description	Plugin Input	Plugin Output
Location Plugin	This plugin will interact with the GPS hardware and provide the current location and time information to the rest of the system. The location plugin will also correct the GPS location information by using correction information from the J2735 RTCM message.	Output stream from GPS receiver RTCM message	Location Message
DSRC Receive Message Plugin	The DSRC Receive Message plugin is responsible for taking messages received via the DSRC radio and relaying those to the rest of the system.	Messages from DSRC Radio	SPAT Message MAP Message RSA Message RTCM Message
Driver Notification Plugin	The Driver Notification plugin will be responsible for alerting/warning the vehicle driver in an audible fashion through an external speaker and displaying visual alerts to the driver through the LCD, via visual and audible cues.	RCVW Warning Clear HRI RCVW System Failure	Suitable audio output annunciated via DVI speakers Events shown on driver display
Logging Plugin	The Local Logging plugin will monitor the state of the system and record the state information to the local system for later review.	All Messages	Data logged to local filesystem
RCVW Plugin	The RCVW Plugin uses an application to process information from VBS support plugins and the CP to determine if and when to issue driver warnings and alerts.	SPAT Message MAP Message RSA Message Location Message	Driver Notification Message
Self Awareness Plugin	The Self Awareness Plugin will monitor the VBS' location against a known set of RBS'. When the VBS detects that it is in a RBS zone, it will notify the driver if it doesn't receive a message from the RBS.	All Messages	Driver Notification

Source: Battelle

Figure 3-12 below shows the applications and each application's data flow inside the RCVW VBS system. To simplify the diagram, the TMX core message router is not shown. Plugins that produce and send messages to TMX have a line to the consumer of those messages. Additional details regarding the RCVW application for the VBS are described below.



Source: Battelle

Figure 3-12. RCVW VBS Applications Data Flow

VBS Support Plugins. The RCVW application plugin is supported by a suite of plugins designed to interface with the TMX platform. The Location plugin allows the GPS position to be augmented using correction data from the RTCM J2735 message. The DSRC Receive Message plugin acts as the interface to the DSRC Radio and converts the received J2735 messages into a common format used by the TMX platform. The Driver Notification Plugin is responsible for both issuing visual and audible warnings and alerts to the driver and uses notification outputs from the RCVW plugin application to do so.

Self Awareness Plugin. The VBS Self Awareness Plugin notifies the driver with an alert when the VBS is on track to intercept an HRI and is within nominal DSRC reception range of a “known” RBS-equipped HRI” and has not received any messages. The alert from the Self Awareness Plugin notifies the driver that the RBS is not operating properly, so the driver can proceed with caution.

RCVW Application Plugin. The RCVW application plugin continuously executes the RCVW algorithm and actively monitors DSRC MAP messages received. Based on the receipt of the MAP message from the RBS and the current vehicle location provided by the Location plugin, the RCVW application plugin will determine if a vehicle is approaching an HRI, and its location relative to the HRI. When the vehicle is determined to be on approach and within range of the HRI, the application plugin receives the HRI Hazard Zone geospatial information and computes the HRI Approach Zone for a vehicle based on typical operator response time, vehicle characteristics, and instantaneous location and speed. The distance derived by the HRI Approach Zone ensures that the driver is provided a timely warning in the event of imminent predicted rail crossing violations. The RCVW application plugin monitors the received SPAT messages for the HRI Active status. When a vehicle is within the HRI Approach Zone of an active HRI, the RCVW application plugin will determine if an alert/warning is needed to alert the vehicle operator of a potential RCVW.

Roadside-based Subsystem

The RBS is responsible for monitoring and reporting the status and condition of the HRI. The RBS will wirelessly transmit to approaching vehicles specific details regarding the physical layout of the intersection, weather-related road conditions, and HRI status.

Hardware

The RBS consists of the following hardware:

- Computing Platform (CP) to include:
  - Interface(s) to receive HRI status
  - Bi-directional interface(s) with roadway traffic controller(s) (if present)
  - Interface(s) to receive weather and road weather sensor data
  - Interface to internet to receive RTCM correction information
  - GPS
- Weather sensors
- Other external components can be interfaced into the RBS, like road weather sensors, by utilizing V2I Hub plugins which communicate to those components. These components were not implemented or demonstrated during this project.

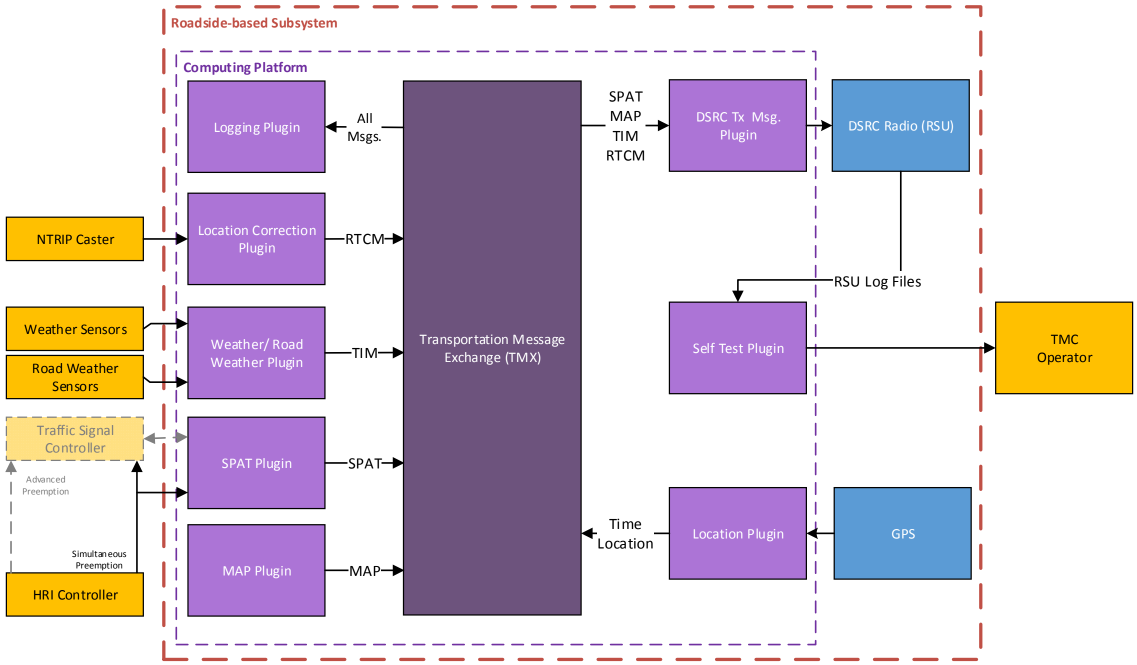
It communicates with RCVW VBS-equipped connected vehicles as well as the external equipment associated with RCVW prediction at the HRI. The RBS CP will be an instance of the CP as described in Chapter 4 of the RCVW Architecture & Design document [3].

Train Detection Signal. The train detection system is the source of the HRI status within the RCVW SPAT message. The HRI Active message is initiated exclusively by the preemption/train detection signal from the HRI controller.

Software

The RBS software is designed to provide supporting information to the RCVW plugin operating on the VBS. The RBS will provide detailed information about the intersection so that the VBS may determine if an RCVW should be presented to the driver. Key information exchanged will include a message providing detailed roadway geometry for the intersection, weather-related road conditions, and HRI status.

The RBS software is designed to interface with the TMX software platform as a set of plugins. Each plugin performs a single discrete function. To the extent practical, common functionality between the two subsystems utilizes the same plugins. The diagram below in Figure 3-13 provides a block diagram showing the design of the software.



Source: Battelle

Figure 3-13. Roadside-based Subsystem Software Design

3.1.4.4 Prototype RCVW System Plugins and Data Flows

The core plugins in the RBS provide situational information for the intersection. Both the MAP and SPAT plugins were developed for the IVP project and were used to the maximum extent practical. Required modifications to the SPAT system included adding functionality to monitor the preemption signal status to set the lane status to stop and remain so when the HRI is active. The remaining plugins support the primary task of providing the other required information. Table 3-4 below outlines each plugin used in the RBS along, with the messages produced and consumed by each plugin.

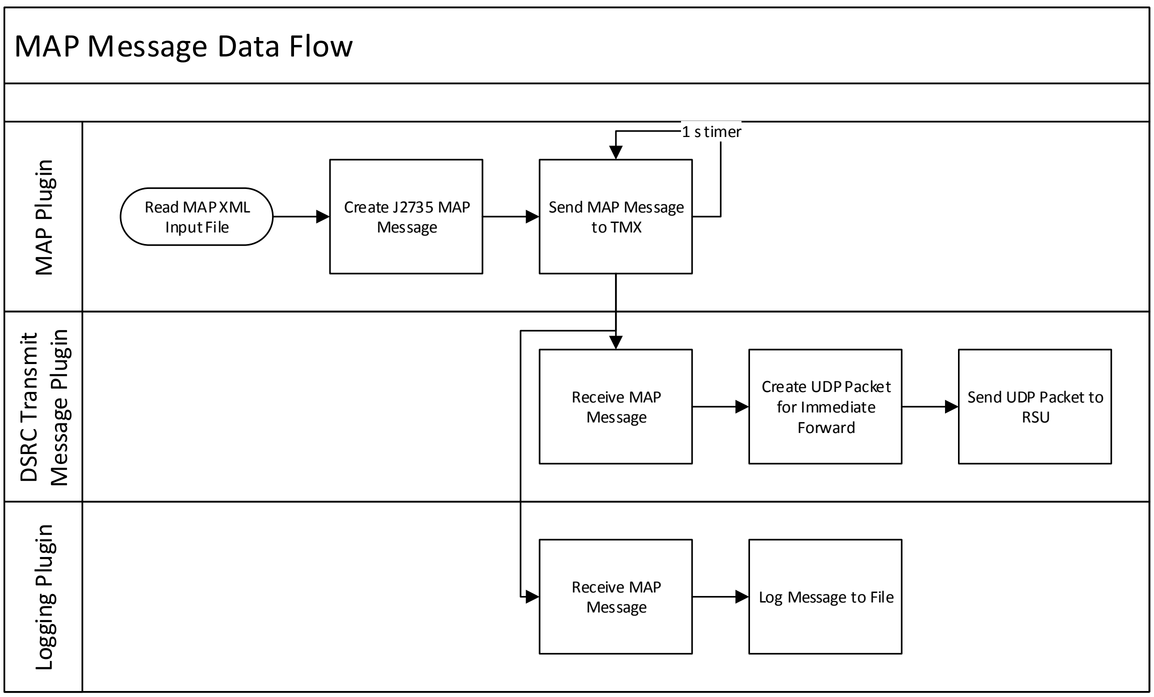
Table 3-4. RCVW System RBS TMX Plugins

Plugin	Description	Plugin Input	Plugin Output
MAP Plugin	The MAP plugin will be responsible for generating the appropriate MAP message for the specific intersection.	HRI geometry loaded from filesystem	MAP Message
SPAT Plugin	The SPAT plugin is responsible for interfacing with the HRI controller and generating SPAT messages containing the status of the HRI. The SPAT plugin is also responsible for interfacing to the TSC.	Output from HRI signal controller	SPAT Message
DSRC Transmit Message Plugin	The DSRC Transmit Message Plugin is responsible for taking internal messages flagged for transmission and ensuring they are sent out via the DSRC radio.	SPAT Message MAP Message RSA Message RTCM Message	Input to DSRC radio to send appropriate message
Weather / Road Weather Plugin	This plugin will interact with external weather and road weather sensor hardware and provide the current local weather related road conditions.	Output stream from RWIS sensors	RSA Message containing Weather Report
Location Plugin	This plugin will interact with a GPS receiver and supply the system with location and time information.	GPS NEMA Sentences	Time and Location Information
Location Correction Plugin	This plugin will interact with a state-wide NTRIP Caster network and receive correction information	Location Correction Information	RTCM Message
Logging Plugin	The Local Logging plugin will monitor the state of the system and record the state information to the local system for later review.	All Messages	Data logged to local filesystem
Self-Test Plugin	The Self-Test Plugin will monitor the RBS' log files for any failures, and notify a TMC Operator of those failures.	RBS Log Files	SMS or Email

Source: Battelle

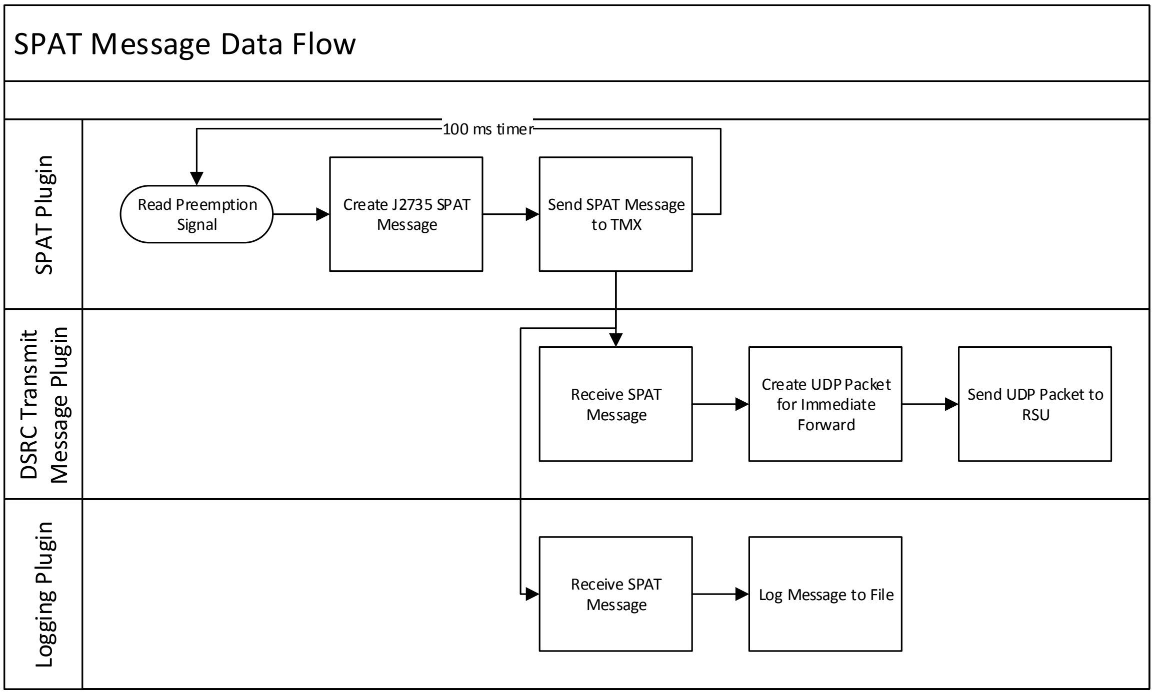
MAP and SPAT Plugins. The MAP and SPAT plugins work in concert to provide the information needed by approaching vehicles to determine whether a warning or alert should be issued given the current situation. The MAP message provides the geographic context for which the SPAT Message information is applied. The content of a MAP message is used by the VBS CP to construct a detailed layout of each element of the roadway approach to the HRI. The RCVW application analyzes the MAP information to determine if the vehicle is within the HRI Approach Zone and where specifically the vehicle is located relative to the HRI. The intersection used for FT&E and demonstration possessed a unique MAP message prepared and configured so that the MAP plugin would broadcast its unique information. The data flow in the RCVW VBS system can be found in Figure 3-12. Figure 3-14 shows the flow of the MAP message in the RCVW RBS system.

If the HRI is not adjacent to a preempted highway intersection, the RBS will only produce SPAT messages containing the HRI active status information for the HRI. When the HRI is in proximity to a preempted highway intersection, the RBS may be configured to send two types of SPAT messages; one containing the HRI active for the HRI, and a second containing the signal phase and timing information for the highway intersection. The RBS will likewise be configured to send MAP messages containing HRI and highway intersection details. Even though the HRIC can also send its preemption signal to the TSC of the highway intersection, the two systems will be treated independently by the RBS. The SPAT message for the HRI contains the HRI active signal state as “event status”. The SPAT message contains an intersection ID that is used to correlate the SPAT message to its MAP message. The VBS uses both MAP and SPAT messages to determine “event status” (i.e. stop and remain, protected movement allowed, permissive movement allowed, protected clearance allowed, etc.) of a lane in the MAP message. For the RCVW project, event status “stop and remain” is used as the trigger for HRI active. Figure 3-15 shows the flow of the SPAT message in the RCVW RBS system.



Source: Battelle

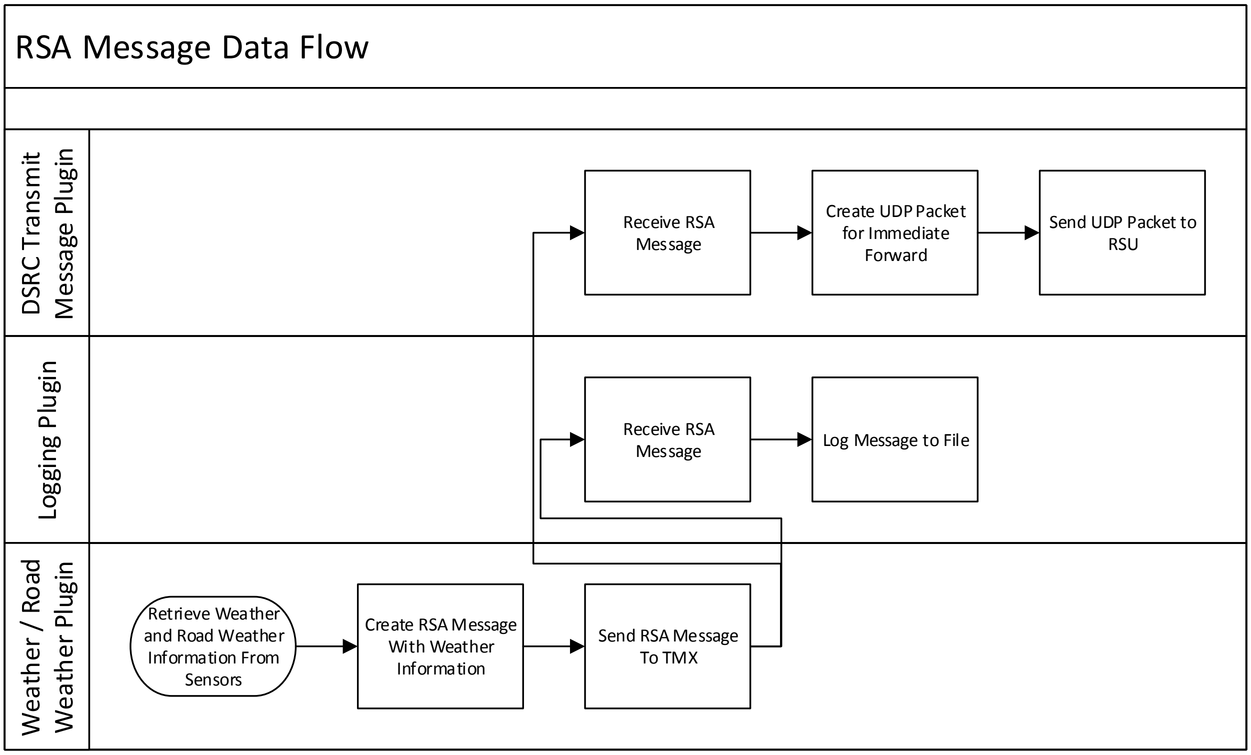
Figure 3-14. MAP Message Data Flow



Source: Battelle

Figure 3-15. SPAT Message Data Flow

Weather / Road Weather Plugin. The Weather / Road Weather plugin interfaces with weather and road weather sensors, either locally over an NTCIP connection or remotely via an internet connection depending on what devices are available at the intersection. This plugin retrieves all weather information available and creates a RSA message containing the weather report, which includes pavement condition, precipitation type, and precipitation rate. Weather/road report information is supplied by the RBS to the VBS for use in determining the timing of an RCVW warning or alert. The data flow of the RSA message produced by the Weather / Road Weather Plugin is found in Figure 3-16.

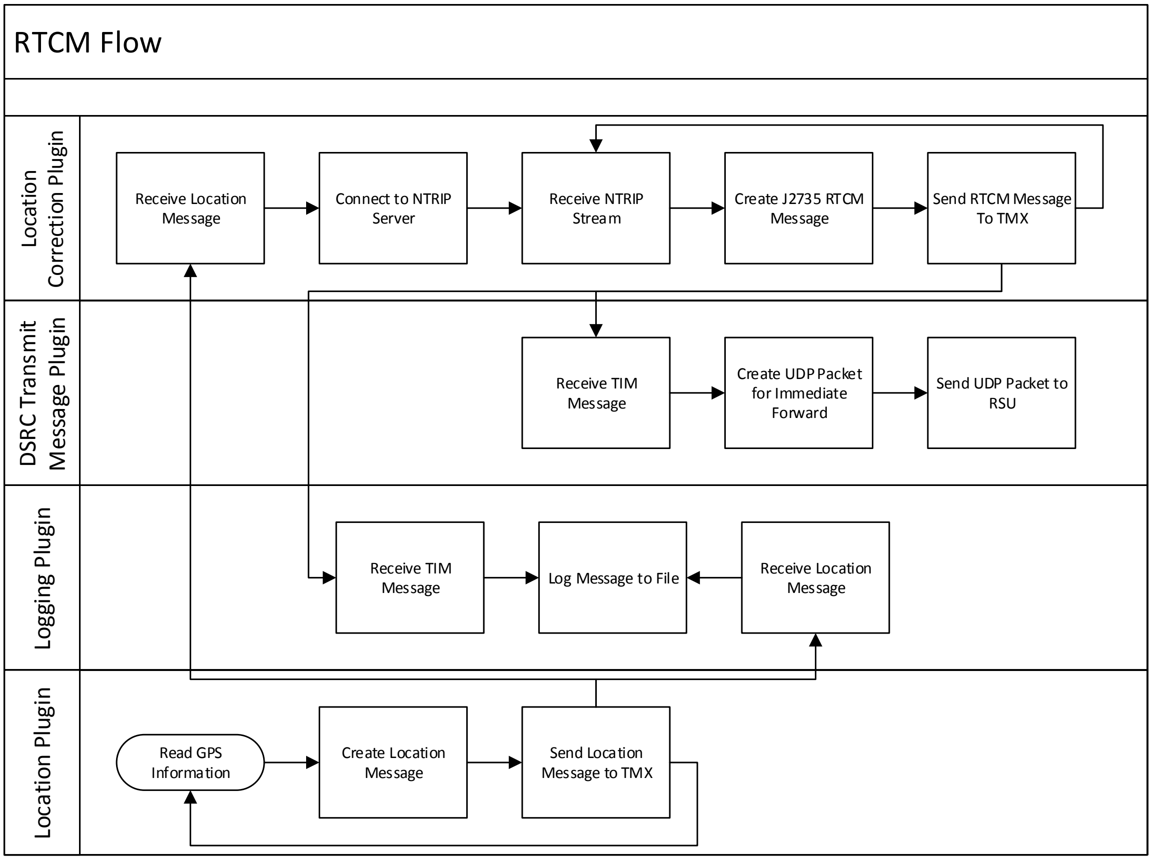


Source: Battelle

Figure 3-16. RSA Message Data Flow

Self-Test Plugin. The Self-Test plugin communicates with the RBS to get failure information from the RBS' log files. If a connection cannot be made to the RSU, a network failure notification is to be sent to the TMC Operator. If the Self-Test plugin finds a failure logged in the RBS's log files, the Self-Test plugin will send a notification to the TMC Operator of that failure. The notifications can be sent via email or text via short message service (SMS) depending on the deployment infrastructure.

Location and Location Correction Plugins. The Location plugin receives NEMA-0183 GPGGA and NEMA-0182 GPVTG messages produced by the RBS GPS module, and parses the information into location and time messages that can be used by the plugins in the RBS computing platform. The RCVW system utilizes the current Location Correction Plugin that was created for the IVP project. The Location Correction Plugin communicates with a state-wide position correction information system, and receives periodic location correction information. The Location Correction Plugin generates a J2735 RTCM message with the provided correction information, and sends that message into the computing platform to be subsequently forwarded to the DSRC Radio by the DSRC Transmit Message Plugin. Figure 3-17 diagrams the data flow of the RTCM message produced by the Location Correction Plugin.



Source: Battelle

Figure 3-17. RTCM Message Data Flow

3.1.5 Prototype RCVW DVI Display Warning and Alert Graphics and Annunciations

The RCVW VBS presents audible and visual notifications to warn the driver of two events via the DVI: 1) the predicted violation of an active HRI by an approaching vehicle (or RCVW warning), and 2) to clear the HRI when the vehicle is stopped within it (or Clear HRI warning).

An RCVW warning is displayed and annunciated via the DVI when the VBS determines that the vehicle cannot be stopped with non-emergency braking prior to entering the active HRI under the current conditions (e.g., decelerate at a rate to prevent HRI penetration). This warning will persist until adequate corrective action (e.g., braking) is taken to prevent active HRI penetration or until the HRI status changes to not active, while the vehicle continues its approach. The RCVW warning graphic displayed is presented below in Figure 3-18.

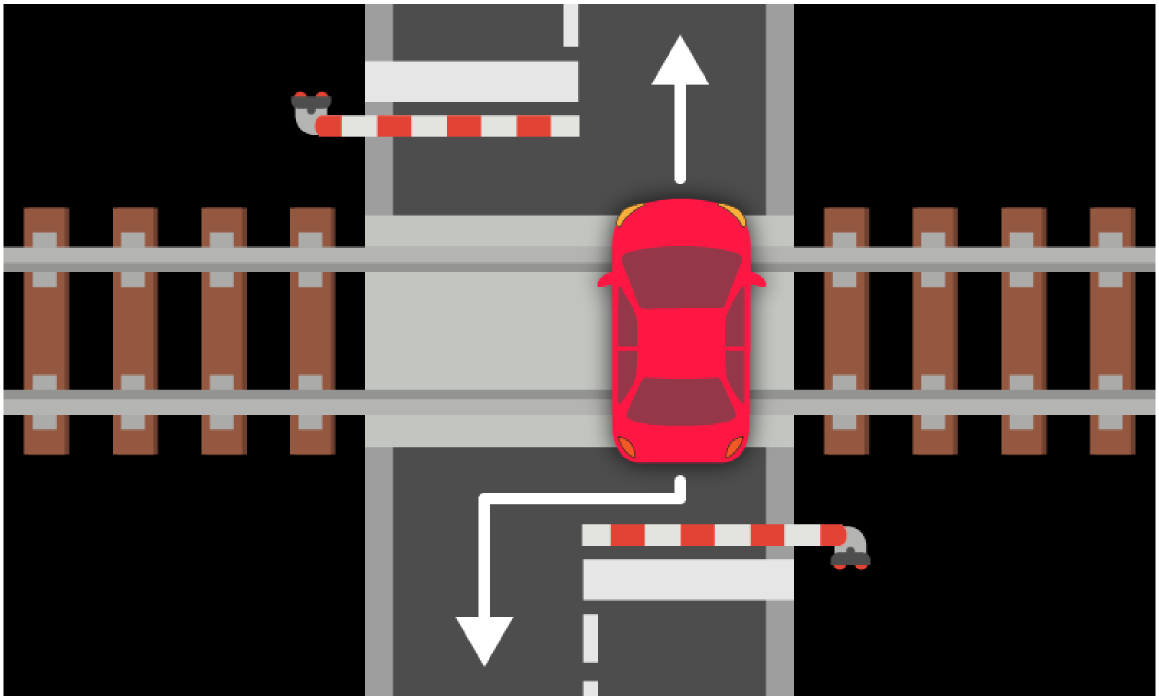
This graphic is animated such that the light red and dark red “lights” alternately illuminate at 500ms to emulate railroad grade crossing flashing lights. An associated audible “train horn” annunciation is periodically sounded. This “train horn” sound was chosen due to the urgency it conveys and how readily its meaning is likely to be understood by most drivers, perhaps even negating the need for a driver to look at the DVI display.

Source: Battelle

Figure 3-18. Rail Crossing Violation Warning (RCVW) Warning

A Clear HRI warning is displayed and annunciated via the DVI when the VBS detects that the vehicle is stopped within an active HRI. This warning aims to prevent a vehicle-train collision by encouraging the vehicle driver to exit the HRI immediately and by any means necessary, prior to interception by a train. This associated graphic and audible warning are distinguishable from the RCVW warning, attempts to convey urgency for action, and specifies possible actions via the graphic. The Clear HRI warning graphic displayed is presented below in Figure 3-19.

This graphic presents a bird's eye view of a vehicle stopped on railroad tracks within an HRI. The vehicle is colored red to indicate it is in danger and the arrows shown are animated and flash at 500ms to convey to the driver to take immediate action to exit the HRI in any available direction (including in reverse). An associated audible of 4 rapid, high pitch beeps are sounded at the initiation of this warning.



Source: Battelle

Figure 3-19 Clear HRI Warning

When applicable, one of three possible system error graphics may be displayed on the DVI. Any of these error messages are intended to inform the vehicle operator that RCVW is degraded and to imply that the system should not be relied upon for accurate warnings and alerts. The RCVW system will not present warnings when a system error is detected. The three degraded states represented by system error graphics include when an expected message is not received by the VBS from the RBS RSU, such as MAP or SPAT data, or when GPS communications are lost by the VBS. Each of these system errors utilize the base graphic shown below in Figure 3-20.

For testing and evaluation purposes, presented beneath the "SYSTEM ERROR" message was a more specific message presented in smaller font and in lower case (i.e., "MAP data not received," "SPAT data not received," or "GPS data not received").

Source: Battelle

Figure 3-20 Sample RCVW System Error Screen

3.1.6 Prototype RCVW System Bench Test & Evaluation (BT&E) Summary

Bench testing was conducted in accordance with the *Vehicle-to-Infrastructure Rail Crossing Violation Warning Bench Test & Evaluation Plan* document [4]. Testing was designed to verify and demonstrate that the Prototype RCVW system has the functionality and performance capabilities necessary to deliver the features described in the project Concept of Operations document [1] and that the system meets its functional and performance requirements described in the project's System Requirements Specification document [2]. The RCVW system design is described in the Architecture and Design Specifications document [3].

The results presented throughout the remainder of this section are a summary of the details found in the BT&E Report [5]. Details such as the test setup and individual results of each test case and requirement assessed can be found in this document and are not presented here.

3.1.6.1 RCVW BT&E Participation

BT&E testing was conducted by Battelle in its Columbus, Ohio 11-7-110 laboratory on 2/22/17, 3/2/17, and 3/3/17. Additional inspection-oriented tests were performed on 3/6/17.

Test execution of the simulation scripts was conducted primarily by three Battelle staff. All three staff, as well as other development staff, participated in the investigations into unexpected behaviors/bugs detected in testing. Following test execution, log files were reviewed and compared with hand recorded data sheets based on time, and calculated script input data, for evidence of proper/expected detection and alerting, congruence of events within the timeline as observed, and evidence of anomalies. In addition, the log files were reviewed to confirm that messaging was being communicated/received at the required frequency under the specified conditions.

3.1.6.2 RCVW BT&E Test Setup

The following equipment and communication details summarize the configuration used in support of conducting RCVW BT&E testing:

VBS:

- Battelle Common Computing Platform (CCP) M/N: RCVW VBS 1; S/N: 5171-22
- HDMI display
- Mobile Mark SMW-30X antenna - supplying a GPS antenna and 2 DSRC antennas

Note: The CCP and Display are shown within the red shape in Figure 3-21 below.

RBS:

- Boundary Devices single board computer in metal enclosure on which the TMX core with RCVW application is loaded (RCVW-RBS)
- Cohda MK5 RSU (M/N: CWP-RSU-MK05-WW00101; S/N: 04E54801541C)
- Linksys Power over Ethernet device: to power and permit communications between the RCVW-RBS and RSU
- Preemption circuit: high-isolation switch to interrupt 12V DC power through a digital I/O converter, feeding a high/low signal to the RCVW-RBS as a USB input – used to simulate the signal that would be received from a Highway-Rail Intersection Controller (HRIC)
- *Note:* All components except the preemption circuit are shown within the light green shape, while the preemption circuit is within the dark green shape in Figure 3-21 below.

Visualization:

- Arada OBU housing a GPS receiver (U-blox EVK-7P) and DSRC radio (Arada Locomate Mini2) that uses Bluetooth to communicate with CV Inspector, and associated GPS and DSRC antennas, powered by USB
- Samsung Android Tablet running CV Inspector visualization software showing MAP zones and phase (preemption status) and vehicle position

Note: The above components less the antennas are shown within the orange shape in Figure 3-21 below.

Simulation and Data Collection:

- Laptop running TMX Portal and scripting software that communicates with VBS via Ethernet (to feed simulated vehicle behavior, including time, position, and speed) and accesses log files.

Note: The laptop is out of view but connects to the RCVW system via the switch shown to the left of the Linksys Power over Ethernet (PoE) device in the light green shape in Figure 3-21 below.

Observation Timing:

- Android Phone running application to display time in seconds from cellular network (for recording alert status changes on VBS display for post-processing reconciliation with log files). This is shown in the blue shape in Figure 3-21 below.

Source: Battelle

Figure 3-21. RCVW BT&E Test Setup Configuration

3.1.6.3 RCVW BT&E Testing Approach

The heart of BT&E were scenario-based test cases (i.e., those numbered 2.#.#). These test cases were executed using prepared scripts in conjunction with the test setup configuration described above. In BT&E, because RCVW equipment components were tested in a laboratory setting, it was necessary to simulate vehicle behavior prior to and following RCVW alerts under conditions specified by the BT&E test cases.

Except in test case 2.1.0 - during which a preemption signal was not issued, and with specified additions for select test cases, the assumptions used and sequence of the scripting were the same across all script-based tests performed, as follows:

- Simulated a constant velocity (speed specified in the test case) of the vehicle from the start of its advancement toward the Approach Zone (the Approach Zone MAP length was 908 meters) and throughout vehicle travel through the Approach Zone to the point when the RCVW alert was issued

- Each script either began with the preemption signal active for cases where the signal was to be active upon vehicle entry into the Approach Zone, or upon reaching a calculated point in the approach (i.e., ¾ point, midpoint, or close to the HRI Hazard Zone).
- *Note:* It was quickly determined that using a reference point relative to the full length of the Approach Zone would not yield different results from the preemption signal being active at entry because nearly all RCVW alerts were received within the final 25% or so of the Approach Zone. For this reason, a ¾ point, midpoint, and ¼ point warning distance was calculated as a percentage of when the RCVW would have been issued.
- A constant, vehicle type-based deceleration rate was simulated to begin after the established slow or fast driver response time duration and maintained until the vehicle stopped
- Grade was held constant across test cases at zero degrees of incline/decline (i.e., level)
- Other multipliers were held constant across test cases, as specified below

Besides MAP length, the other key details that were input into the algorithm and simulation scripts – either directly or based upon calculated results from the equations described next - included:

- The associated Vehicle Stopping Effectiveness (VSE) for the specified vehicle type (0.70 for type A/passenger car and 0.56 for type B/single unit box truck)
- Pavement Condition Reduction (PCR) percentage (i.e., weather: 1.0 for dry, 0.6 for rain, and 0.45 for snow) and associated IT IS codes (4617 for dry, 4885 for rain, and 4868 for snow)
- Driver Response Time (DRT) – inclusive of perception and reaction times (1.0 seconds for fast – all types, 1.5 seconds for slow response of vehicle types A and B, and 2.0 or 2.5 seconds for slow response of vehicle type C)
- Vehicle-based Deceleration Rate in Dry Pavement Condition for the simulated vehicle behavior only (4.572 m/s^2 for type A, 3.658 m/s^2 for type B, and 3.886 m/s^2 for type C)

RCVW prediction algorithm equations:

- Vehicle Stopping Distance = V^2 /{ 2 * 9.8m/s^2 * VSE * PCR * [COS(incline deg) + SIN(incline deg.)]}
- Total Stopping Distance = (DRT * V) + Vehicle Stopping Distance
- Warning Distance = Total Stopping Distance * Safety Offset Multiplier * Preemption Multiplier

  Note: The Safety Offset Multiplier and Preemption Multiplier are factors that can be applied to the Warning Distance equation to permit adjustment of when the vehicle operator will be warned relative to the calculated Total Stopping Distance. Using values of 1.0 for both multipliers means that the Warning Distance is the same as the Total Stopping Distance.

  Note: The intent of the Safety Offset Multiplier is to permit, by using values greater than 1.0, earlier warnings than the Total Stopping Distance in the interest of enhancing safety. The Safety Offset Multiplier used in BT&E testing was 1.5 for all test cases.

Note: The intent of the Preemption Multiplier is to permit, by using values less than 1.0, later (delayed) warnings than would otherwise be provided based on the Total Stopping Distance as potentially adjusted by the Safety Offset Multiplier. This factor is provided for use on an as-needed basis during deployment to effectively offset any excessively long preemption signal setting. The Preemption Multiplier used in BT&E testing was 1.0 for all test cases.

Simulation script equations:

- Warning % of Lane (used for giving observers a 'heads up') = (Warning Distance / Approach Zone Length) * 100
- Start Location for Deceleration (in distance from end of Approach Zone) = Warning Distance – (Simulated DRT * V)
  - *Note:* The simulated DRT was the same as the DRT used in the RCVW prediction algorithm for each test case. Thus, for test cases that had the same inputs but which differed only in DRT no significant difference in stop distance was observed because the warning distance was automatically shortened for faster response. During Field Test and Evaluation (FT&E), the plan is to hold the DRT used in the prediction algorithm at 1.5 seconds, but vary DRT.
- Estimated Stop Distance (used as an expectation for what should be observed) = Start Location for Deceleration – ((V^2 / 2) / (deceleration rate / PCR))

Table 3-5 below summarizes the conditions and inputs for each of the scenario-based test cases executed using scripts.

Table 3-5. Summary of the Scenario-Based BT&E Test Cases

Test Case Number	CV Location at Preemption Signal Detection	CV Speed at Approach Entry	CV Response (Sec) type | speed | time A | Slow | 1.5 A | Fast | 1.0 B | Slow | 1.5 B | Fast | 1.0 C | Slow | 2, 2.5 C | Fast | 1.0	Vehicle Stopping Effectiveness (VSE) • Type A = 0.700 • **Type B = 0.560** • ***Type C = 0.595***	Pavement Condition Reduction % (IT IS Code) •Dry = 0% / 4617 •Rainy = 40% / 4885 •Snow = 55% / 4868	RCVW State
2.1.0	N/A (no Preemption Signal)	50 mph	None	Type A	Dry	Normal
2.1.1	Start of Approach	50 mph	None	Type A	Dry	Normal
2.2.1.A	Start of Approach	50 mph	Slow	Type A	Dry	Normal
2.2.1.B	Start of Approach	15 mph	Slow	Type A	Dry	Normal
2.2.1.C	Start of Approach	20 mph	Slow	Type A	Dry	Normal
2.2.1.D	Start of Approach	25 mph	Slow	Type A	Dry	Normal
2.2.1.E	Start of Approach	30 mph	Slow	Type A	Dry	Normal
2.2.1.F	Start of Approach	35 mph	Slow	Type A	Dry	Normal
2.2.1.G	Start of Approach	40 mph	Slow	Type A	Dry	Normal
2.2.1.H	Start of Approach	45 mph	Slow	Type A	Dry	Normal
2.2.1.I	Start of Approach	55 mph	Slow	Type A	Dry	Normal
2.2.1.J	Start of Approach	60mph	Slow	Type A	Dry	Normal
2.2.1.K	Start of Approach	65 mph	Slow	Type A	Dry	Normal
2.2.1.L	Start of Approach	70 mph	Slow	Type A	Dry	Normal
2.2.1.M	Start of Approach but Preemption Signal removed at Midpoint	50 mph	Slow	Type A	Dry	Normal
2.2.2	Start of Approach	50 mph	Slow	**Type B**	Dry	Normal
2.2.3	Start of Approach	50 mph	Slow	***Type C***	Dry	Normal
2.2.4.A	Start of Approach	50 mph	Slow	Type A	Rain	Normal
2.2.4.B	Start of Approach	15 mph	Slow	Type A	Rain	Normal
2.2.4.C	Start of Approach	20 mph	Slow	Type A	Rain	Normal
2.2.4.D	Start of Approach	25 mph	Slow	Type A	Rain	Normal
2.2.4.E	Start of Approach	30 mph	Slow	Type A	Rain	Normal
2.2.4.F	Start of Approach	35 mph	Slow	Type A	Rain	Normal
2.2.4.G	Start of Approach	40 mph	Slow	Type A	Rain	Normal
2.2.4.H	Start of Approach	45 mph	Slow	Type A	Rain	Normal
2.2.4.I	Start of Approach	55 mph	Slow	Type A	Rain	Normal
2.2.4.J	Start of Approach	60mph	Slow	Type A	Rain	Normal
2.2.4.K	Start of Approach	65 mph	Slow	Type A	Rain	Normal

Test Case Number	CV Location at Preemption Signal Detection	CV Speed at Approach Entry	CV Response (Sec) type | speed | time A | Slow | 1.5 A | Fast | 1.0 B | Slow | 1.5 B | Fast | 1.0 C | Slow | 2, 2.5 C | Fast | 1.0	Vehicle Stopping Effectiveness (VSE) • Type A = 0.700 • **Type B = 0.560** • ***Type C = 0.595***	Pavement Condition Reduction % (IT IS Code) •Dry = 0% / 4617 •Rainy = 40% / 4885 •Snow = 55% / 4868	RCVW State
2.2.4.L	Start of Approach	70 mph	Slow	Type A	Rain	Normal
2.2.5.A	Start of Approach	50 mph	Slow	Type A	Snow	Normal
2.2.5.B	Start of Approach	15 mph	Slow	Type A	Snow	Normal
2.2.5.C	Start of Approach	20 mph	Slow	Type A	Snow	Normal
2.2.5.D	Start of Approach	25 mph	Slow	Type A	Snow	Normal
2.2.5.E	Start of Approach	30 mph	Slow	Type A	Snow	Normal
2.2.5.F	Start of Approach	35 mph	Slow	Type A	Snow	Normal
2.2.5.G	Start of Approach	40 mph	Slow	Type A	Snow	Normal
2.2.5.H	Start of Approach	45 mph	Slow	Type A	Snow	Normal
2.2.5.I	Start of Approach	55 mph	Slow	Type A	Snow	Normal
2.2.5.J	Start of Approach	60mph	Slow	Type A	Snow	Normal
2.2.5.K	Start of Approach	65 mph	Slow	Type A	Snow	Normal
2.2.5.L	Start of Approach	70 mph	Slow	Type A	Snow	Normal
2.2.6	¾ Point	50 mph	Slow	Type A	Dry	Normal
2.2.7	Midpoint	50 mph	Slow	Type A	Dry	Normal
2.2.8	Near HRI Hazard Zone	50 mph	Slow	Type A	Dry	Normal
2.3.1	Start of Approach	50 mph	Fast	Type A	Dry	Normal
2.3.2	Start of Approach	50 mph	Fast	**Type B**	Dry	Normal
2.3.3	Start of Approach	50 mph	Fast	***Type C***	Dry	Normal
2.3.4	Start of Approach	50 mph	Fast	Type A	Rain	Normal
2.3.5	Start of Approach	50 mph	Fast	Type A	Snow	Normal
2.3.6	¾ Point	50 mph	Fast	Type A	Dry	Normal
2.3.7	Midpoint	50 mph	Fast	Type A	Dry	Normal
2.3.8	Near HRI Hazard Zone	50 mph	Fast	Type A	Dry	Normal
2.3.9	Start of Approach	50 mph	Fast (Adequate), then subsequent RCVW (Inadequate action)	Type A	Dry	Normal
2.5.1	Stopped on tracks	N/A	Clears tracks	Type A	Dry	Normal
2.6.1	Start of Approach	50 mph	Not factored	Type A	Dry	Fault – DSRC
2.6.2	Start of Approach	50 mph	Not factored	Type A	Dry	Fault – GPS
2.6.3	Start of Approach	50 mph	Not factored	Type A	Dry	Fault - HRIC

Source: Battelle

Note: Because the configured area of the Approach Zone is effectively equivalent to that of the area within which DSRC communications are received when approaching the HRI, test case 2.4.1 is no different than 2.2.1.A. For this reason, this test case was deemed unnecessary and was not performed.

Note: “type” or “Vehicle #” in the Table 3-5 header above means the following:

- Type A = Passenger Car
- Type B = Box Truck
- Type C = Tractor-trailer

3.1.6.4 Summary of Prototype RCVW BT&E System Testing Performance

A detailed account of all BT&E testing and results can be found in the RCVW BT&E Report [5], and performance by requirement can be found in APPENDIX B. In summary, all BT&E test cases passed and all requirements evaluated were confirmed to be met, with one exception: test case 1.1.8 was rated as failed because requirement RBS-18 was not met. See the second in Table 3-6 below for more detail.

Generally, the simulated vehicle was observed to stop within the Approach Zone for all simulated scenarios in the range 2.2.1.X-2.3.8, except for 2.2.4.C and 2.2.5.B (see below) plus test cases 2.2.7, 2.2.8, and 2.3.6-2.3.8, where the vehicle stopped in or beyond the HRI Hazard Zone.

Test cases 2.2.6-2.2.8 and 2.3.6-2.3.8 differ from each other only in DRT time, but all present an RCVW within the distance needed to safely stop using normal deceleration rates. Based on the way these tests were performed, this is expected behavior. Test cases 2.2.4.C and 2.2.5.B resulted in the vehicle penetrating the HRI Hazard Zone and stopping in it; however, the vehicle would actually have stopped short of the HRI. The vehicle was observed to penetrate the HRI because the simulation input process used required an approximation that allows for an up to 1% error (i.e., the vehicle is simulated to stop up to 30 feet later than it would have without this limitation).

3.1.6.5 Summary of BT&E Detected Issues and Resolution Status

All issues detected during BT&E that impacted upon the key functionality and requirements for RCVW were resolved prior to, and re-confirmed during, FT&E. For a list of the issues resolved, refer to Table 2 of the RCVW BT&E Report [5]. Table 3-6 below presents issues detected during BT&E that are planned for resolution in a different or future project.

Table 3-6. Summary of RCVW BT&E Detected Issues and Resolution Status

Date	Category	Issue	Resolution Status
2/22/17	Display Graphic / Audible	The RCVW “Clear HRI” audible (beeps series) plays only once at the start of the warning. If a vehicle is stopped within the Hazard Zone, it is recommended that this series of beeps should cycle/repeat every so often until the condition no longer exists (the graphic does persistently flash while conditions apply).	**3/3/17 Open**. This and other functionality associated with the DVI can be easily modified when the RCVW system is readied for production.
3/3/17	Alerting / Logic	While running 1.1.8, observed that the TMX core restarted but the plugins (including the HRI status plugin) are not resetting when connectivity is regained via USB connection being reestablished. It was also found that there is no logging of the TMX core failure.	**3/3/17 Open**. This appears to be a bug in the V2I hub software produced on the IVP project. This has been relayed to the V2I Reference Implementation development team for action.

Source: Battelle

3.1.7 Prototype RCVW System Field Test & Evaluation (FT&E) Summary

Field testing was conducted in accordance with the RCVW FT&E Plan document [6]. As with bench testing, field testing was designed to verify and demonstrate that the prototype RCVW system has the functionality and performance capabilities necessary to deliver the features described in the project Concept of Operations document [1] and that the system meets its functional and performance requirements described in the project's System Requirements Specification document [2]. Likewise, the RCVW system design can be found in the Architecture and Design Specifications document [3].

Because a single site visit at a single intersection was used for FT&E, conditions such as grade, weather/road weather, and intersection approach geometry (to challenge line of sight) was not variable. However, different weather/pavement conditions were simulated during BT&E. For FT&E, the grade was flat and the weather/pavement conditions were warm and dry, which represents fairly ideal conditions for stopping distance. It was, however, windy (a notable tailwind was observed in the second testing day). Other than this variable atmospheric weather condition, the conditions were unchanged across FT&E testing which did permit performance comparisons to be made.

The results presented throughout the remainder of this section are a summary of the details found in the Field Test & Evaluation Report [7]. Details such as the test setup and individual results of each test case and requirement assessed can be found in this document and are not presented here.

3.1.7.1 RCVW FT&E Participation

Except where noted, results described within this document were based on testing executed by Battelle, TTI, and CTC at the Texas A&M Riverside (RELLIS) Campus Testing Area in Bryan, Texas on April 24-26, 2017.

Prior to test execution, CTC and TTI staff installed and integrated Battelle RCVW and CTC equipment at the TTI rail crossing test site. Battelle's RBS V2I Hub computer, PoE Injector, and USB I/O converter (see bottom portion of light green area in Figure 3-22 below), plus CTC's x-RPS™ Processor, Expansion, and Flasher Modules (see dark green area in Figure 3-22 below), were housed within with TTI's traffic signal controller cabinet. CTC additionally provided a simulated railroad relay test switch that enabled a Battelle team member to activate and deactivate the preemption signal away from the cabinet and on demand. TTI mounted the RBS RSU on a nearby pole located adjacent to the HRI. See top portion of light green area in Figure 3-22 below.

> **Note:** The colors outlining RCVW equipment in below corresponds to those used in Figure 1 of the V2I RCVW Bench Test & Evaluation Report [5] for consistency.

TTI provided a Honda EU2000i generator, which powered the above roadside equipment, the CTC-provided rail crossing flashing lights that were pole-mounted below a crossbuck sign at the HRI and directed toward the approaching vehicle (see Figure 3-23 below), and additional equipment used for test visualization including Battelle' s Arada OBU and Samsung Tablet running CV Inspector.

> **Note:** Although commonly used flashing lights and crossbuck signage were installed in a manner typically deployed at an HRI, the height of the signs/lights was 2 feet lower than standard due to limitations of the pole used. This did not impact upon the testing. The lights provided an indication of the HRI state and were visible to the vehicle driver throughout its approach.

Note: The iron rails that appear in Figure 3-23 below, which run parallel to the approach zone, are not a part of the test configuration. In this testing configuration, the railroad tracks are virtual and would align perpendicular to the direction of the Approach Zone arrow vector – bisecting the HRI Hazard Zone polygon.

Battelle staff installed the VBS equipment described below, including the magnetic mount multi-antenna outlined in red in Figure 3-24 below, and assisted in final integration of the roadside equipment, including the signal connection and grounding between the CTC x-RPS™ Processor Module and USB I/O converter, which transformed the preemption signal to the RCVW-RBS as a USB input.

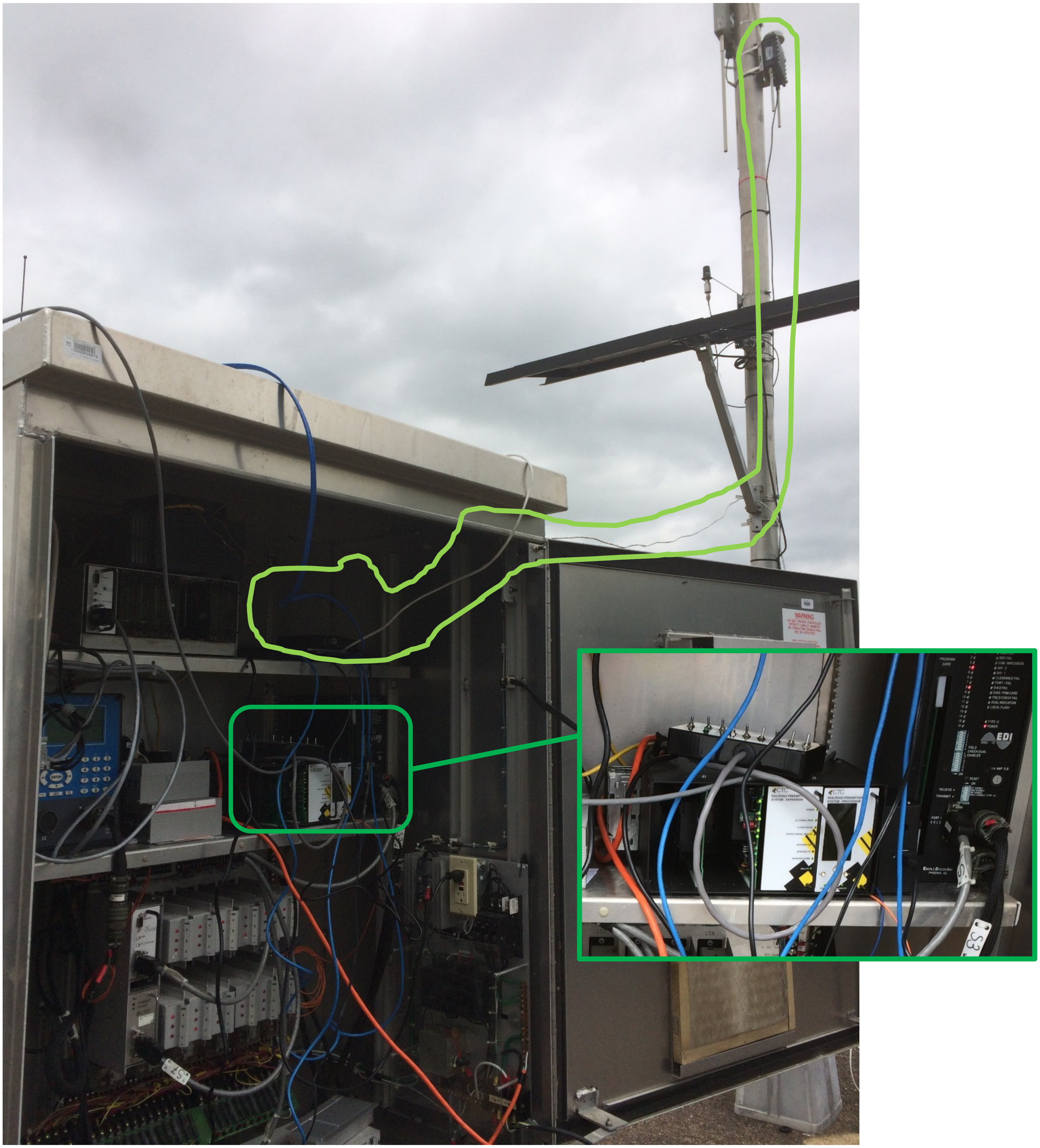
Table 3-7 below summarizes test team personnel location and responsibilities, including data collection details. The control station was located near the roadside controller cabinet in which the RCVW RBS was integrated.

Table 3-7. Test Team Locations and Responsibilities for Scenario-Based FT&E Test Cases

Location	Responsibility	Action	Collection
CV	Driver	• Accelerate CV to specified initial approach speed and set with cruise control (Type A) • Apply a steady braking response at the specified vehicle type-based deceleration rate until the vehicle stops after a pre-coordinated response delay (perception component of DRT) upon RCVW issuance (displayed/annunciated and called out by CV observer)	None
CV	Observer	• Monitor VBS display and notify CV driver of RCVW warning • Collect data specified • Maintain radio communication between tests to relay/receive observation data and to coordinate and prepare for the next test • Video documentation	• Record test start time • Record Approach Zone entry (for tests when HRI is active) • Record RCVW warning ON and OFF times • Record Error message ON and OFF times, if applicable • Record any oddities or situations for future resolution
Control Station	Test Director	• Coordinate test sequence • Monitor CV Inspector • Video documentation	• Lead reconciliation after tests
Control Station	Algorithm Observer	• Control preemption signal activation/de-activation • Monitor algorithm performance for errors and communicate any anomalies	• Record time of preemption switch ON/OFF (where applicable) • Collect log files

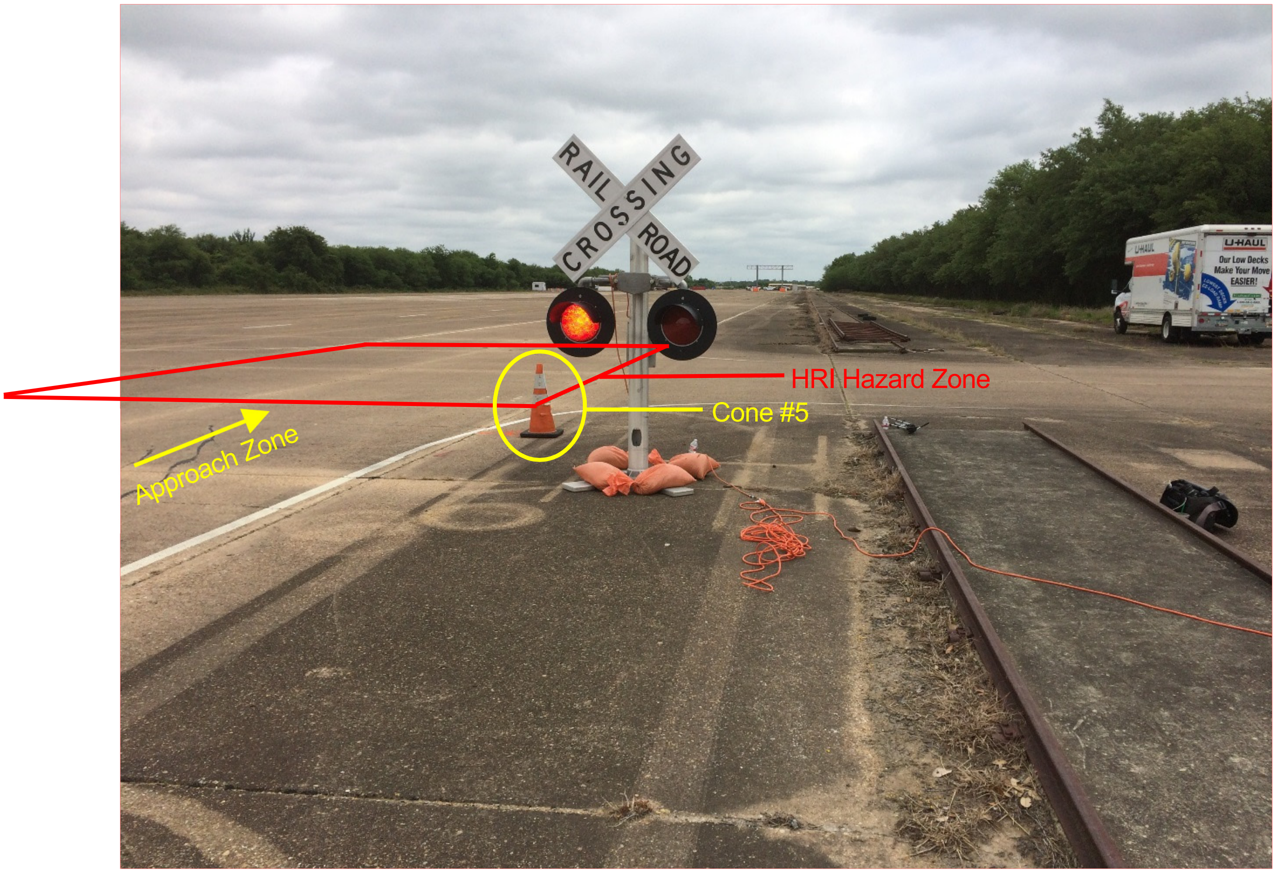
Location	Responsibility	Action	Collection
Roadway Observer 1	Data Collection at anticipated RCVW Activation	See collection	Collect time vehicle passes RCVW Activation point (vehicle passes Cone #2)
Roadway Observer 2	Data Collection at HRI entry and stop point	See collection	Collect time vehicle passes HRI entry (passes Cone #5, if applicable) and/or location the vehicle stops

Source: Battelle



Source: Battelle

Figure 3-22. Signal Controller Cabinet



Source: Battelle

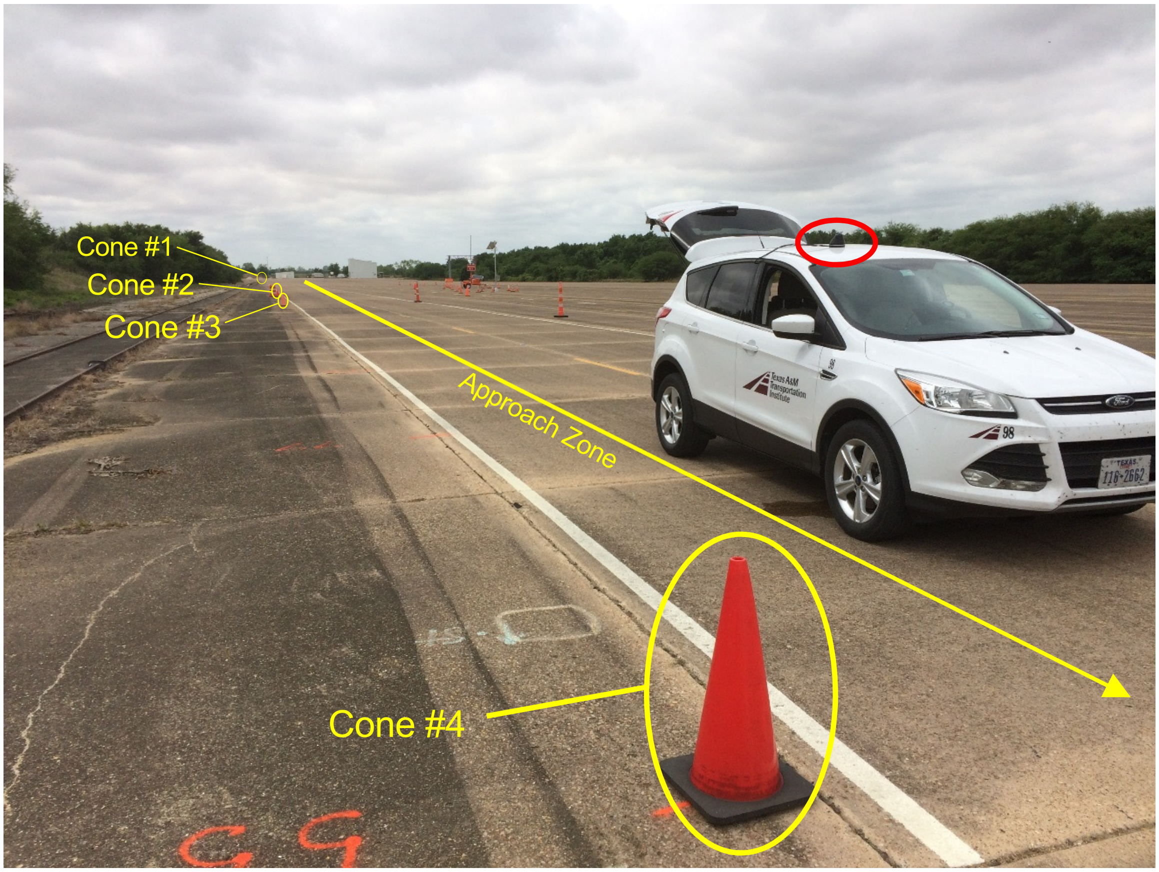
Figure 3-23. Rail Crossing Crossbuck Sign and Flashing Lights

Test execution was conducted by seven team members: three from Battelle, two from TTI, and two from CTC. All scenario-based testing was observed by the client and client representatives.

One Battelle team member directed the testing, monitored the CV Inspector tool, and lead reconciliation efforts after each test. A second Battelle team member was responsible of watching the VBS display, notifying the CV driver of an RCVW warning, collecting times when HDMI display alerts annunciated and stopped annunciating, collecting vehicle stop time, participated in reconciliation, and noting anomalies observed during each test. A third Battelle team member controlled preemption signal activation/de activation, monitored algorithm operation, and collected log files for reconciliation.

One TTI team member was dedicated to operating the vehicle, which typically involved driving the vehicle straight along the approach, applying cruise control to establish and maintain the initial approach speed (except tests involving the Type B box truck), and attempting to initiate and maintain deceleration in accordance with target response times and rates. The Type A passenger vehicle shown in Figure 3-24 and the Type B box truck shown in Figure 3-23 were made available by TTI. Prior to each test, a second TTI team member measured and marked (with water soluble paint) all reference cone locations where: 1) a RCVW warning was predicted to display (typically Cone #2 per the V2I RCVW Field Test & Evaluation Plan [6]), 2) where a driver response was predicted to initiate a response (typically Cone #3 per the RCVW FT&E Plan [6]), and 3) the location where the vehicle was predicted to stop (typically Cone #4 per the V2I RCVW Field Test & Evaluation Plan [6]). This team member was positioned adjacent to Cone #2 to record the time of vehicle passage for each applicable test case. See Figure 3-24 below for the cone locations used to support Test Case 2.2.1.A.

CTC staff monitored its rail-side equipment and recorded the time at which the vehicle stopped short of or traversed the stop bar (see Cone #5 in Figure 3-23, which is located at the stop bar, or transition between the Approach Zone and the HRI Hazard Zone), for applicable test cases.



Source: Battelle

Figure 3-24. Type A Vehicle Stopped in the Approach Zone Short of the HRI Hazard Zone

At the conclusion of the scenario-based field tests, Battelle retrieved log files and compared them with hand recorded data sheets based on time for evidence of: 1) proper/expected detection and alerting, 2) congruence of events within the timeline as observed, and 3) evidence of anomalies. In addition, TMX core log files were reviewed to confirm that messaging was communicated/received at the required frequency under the specified conditions.

Additional non-scenario type tests were conducted during FT&E, as follows:

- Test Case 1.1.10 (lower power mode verification) was conducted by Battelle team members on 4/24/17 at RELLIS in Bryan, Texas.
- Data for Test Case 1.1.9 (vehicle-based horizontal position accuracy verification) were collected in the overnight period between 4/26/17 and 4/27/17. TTI assisted Battelle in obtaining power and positioning the Common Computing Platform (CCP) and multi-antenna

including GPS at the National Geodetic Survey (NGS) “SMETANA” marker PID:BM0048 (see Figure 3-25 below) at RELLIS in Bryan, Texas. The CCP was placed in a cooler to avoid damage from the elements, and alternating current power was extended to power it from a nearby building.

Source: TTI

Figure 3-25. SMETANA NGS marker used for Test Case 1.1.9

Test Case 1.1.11 (failure alert, logging, and notification verification) and regression testing of script-based Test Case 2.6.1 were conducted by Battelle on May 16, 2017 at Battelle’s campus in Columbus, Ohio.

3.1.7.2 RCVW FT&E Test Setup

The following sections describe the layout of equipment and connections used for the RCVW VBS and RBS components.

The RCVW RBS produced SAE J2735 MAP and SPAT messages to support the RCVW VBS algorithms used to provide warnings to the driver. The J2735 MAP file contained the Approach Zone geometry for the mock- equipped HRI, while the J2735 SPAT message communicated the HRI activity status (i.e., whether a train was present).

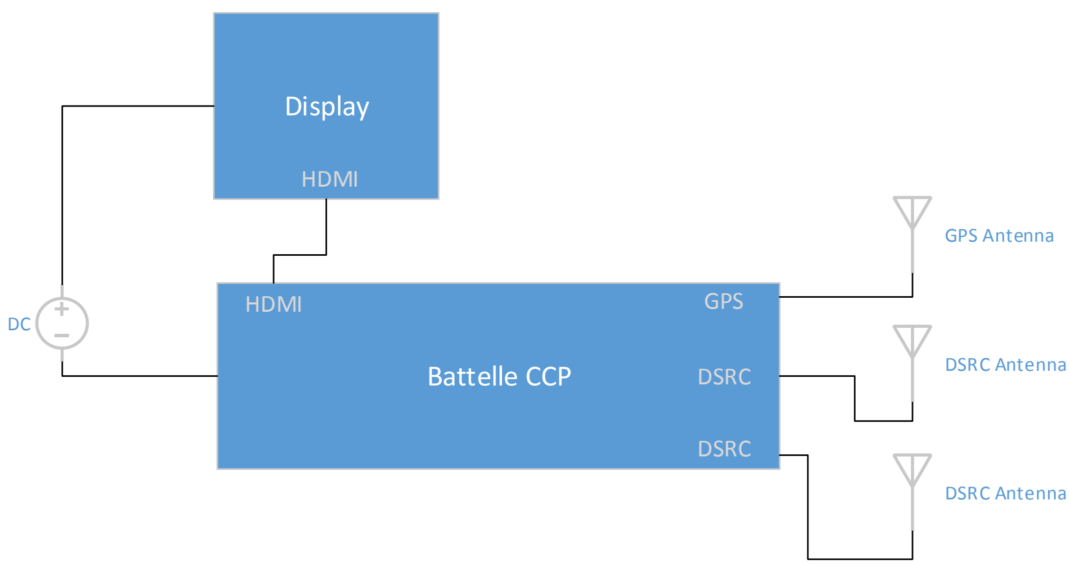
VBS Equipment:

- Battelle CCP (M/N: RCVW VBS 1; S/N: 5171-22) running V2I Hub with the following plugins installed
  - CohdaInterface
  - EventLoggingPlugin
  - Location
  - RCVW
- HDMI display
- Mobile Mark SMW-30X antenna with magnetic mount - supplying a GPS antenna and 2 DSRC antennas

Figure 3-26 below presents the physical setup for the VBS installed in the vehicle. A photo of the CCP and Display are shown within the red shape in Figure 1 of the V2I RCVW Bench Test & Evaluation Report [5].

VBS Connections:

- The display in the vehicle was attached to the windshield by using a suction cup mount.
- The display and Battelle's CCP were powered by the 12 Volt DC feed from the car's cigarette lighter socket
- The antenna was placed on the roof of the vehicle and attached using its magnetic mount
- Connecting cables were guided thru a rear window and connected to each respective Fakra connector ports on the CCP



Source: Battelle

Figure 3-26. Physical Setup of VBS

RBS Equipment:

- Boundary Devices Nitrogen MX6_Max single board computer in metal enclosure on which the V2I Hub with the following RCVW application plugins loaded (RCVW-RBS):
    - BIST Plugin
    - CohdaBsmReceiver
    - Weather
    - MAP
    - HRI Status (SPAT)
    - DSRC Message Manager
- Cohda MK5 DSRC RSU 4.0 (M/N: CWP-RSU-MK05-WW00101; S/N: 04E54801541C)
- Linksys LACPI30 PoE Injector to supply the RSU with power and communications
- ACCES I/O USB-IDIO-16T for receiving the preemption signal and converting to USB input
- Network switch permitting simultaneous interconnectivity between the Cohda RSU and Boundary Devices Nitrogen MX6_Max. The use of a network switch also allowed a laptop, external to the system, to be connected to monitor the system during testing.

Figure 3-27 below presents the physical setup for the RBS subsystem and its connections with the rail equipment. A photo of the V2I Hub computer, RSU, and PoE Injector are shown within the light green shape in Figure 1 of the V2I RCVW Bench Test & Evaluation Report [5]. The I/O device is shown within the dark green shape in Figure 1 of the V2I RCVW Bench Test & Evaluation Report [5]. The network switch is shown next to the PoE Injector just outside of the light green shape in Figure 1 of the V2I RCVW Bench Test & Evaluation Report [5].

RBS Connections:

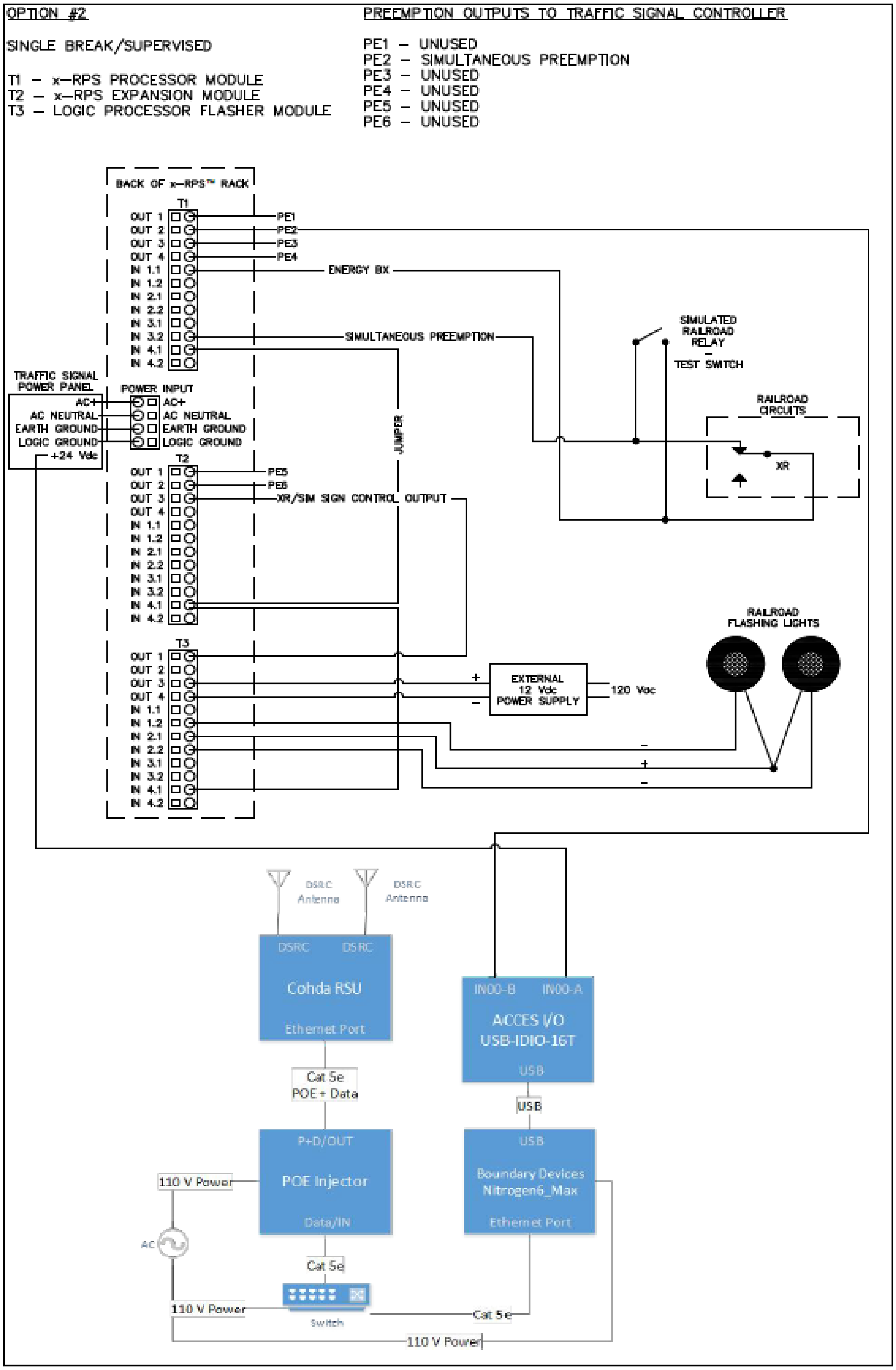
- The Boundary Devices Nitrogen MX6_Max, network switch and PoE injector received its power from the power outlet located within the signal controller cabinet (supplied from generator power, as described above)
- DSRC and GPS antennas were connected to the RSU
- Ethernet cables were interconnected as follows:
    - Boundary Devices Nitrogen MX6_Max into the network switch
    - PoE Injector Data / IN port to the network switch
    - PoE Injector P+D / OUT port to the RSU
- A simulated +24 Volt DC track-circuit-detection signal was connected to IN00-A input of the ACCES I/O USB-IDIO-16T
- A simulated -24 Volt DC ground-true simultaneous preemption signal from the CTC x-RPS™ Processor Module (Out 2) was connected to IN00 side B input of the ACCES I/O USB-IDIO-16T

Rail Equipment:

- CTC x-RPS™ Processor Module – process the simultaneous preemption signal and relay HRI state to RCVW RBS I/O module and to x-RPS™ modules controlling the Railroad Flashing Lights
- CTC x-RPS™ Expansion Module
- CTC x-RPS™ Logic Processor Flasher Module –with the Expansion Module that controls the Railroad Flashing Lights based on the HRI state from the Processor Module
- Simulated Railroad Relay and Test Switch
- Railroad Flashing Lights
- Crossbucks (not electronic)

Rail Connections:

- As shown in Figure 3-27 below.



Source: CTC and Battelle

Figure 3-27. Physical Setup of RBS and Rail Equipment

Other Equipment for Visualization:

- Arada OBU housing a GPS receiver (U-Blox EVK-7P) and DSRC radio (Arada Locomate Mini2) that uses Bluetooth to communicate with CV Inspector, and associated GPS and DSRC antennas, powered by USB
- Samsung Android Tablet running CV Inspector visualization software showing MAP zones and phase (preemption status) and vehicle position

Note: The above components less the antennas are shown within the orange shape in Figure 1 of the V2I RCVW Bench Test & Evaluation Report [5].

Other Equipment for Observation Timing:

- Android Phone running Digital Clock application (developed by Light Dot Net) to display time in seconds for all manual observations. This is shown in the blue shape in Figure 1 of the V2I RCVW Bench Test & Evaluation Report [5].

3.1.7.3 RCVW FT&E Testing Approach

The primary focus of FT&E was to assess the performance of the RCVW system on a subset of the scenario-based test cases performed in BT&E. Table 3-8 below summarizes the 2.X.X-numbered scenario-based test cases conducted. These tests were performed in a closed loop environment in which the RCVW system was integrated into surrogate infrastructure. All scenario-based tests used a real vehicle driven towards a mock equipped HRI, configured as described above.

A total of 16 scenario-based test cases were performed, eleven of which were performed twice or more each. In addition, 6 unplanned tests were performed ad hoc upon client request, which were aimed at assessing the level of nuisance alerting observed under specified challenging circumstances with the vehicle in the Approach Zone heading toward the HRI (two tests) and with the vehicle stopped at various locations near/within the HRI Hazard Zone (four tests).

Except as noted, the following parameters applied across all scenario-based test cases:

- The Type A CV used in all scenario test cases except Test Case 2.2.2 was a Ford Escape with Anti-Lock Braking System (ABS) and cruise control, while the Type B CV used for Test Case 2.2.2 was a 20-foot U-Haul box truck without ABS braking or cruise control.
- The CV started its approach at approximately 2,000 feet (600 m) away from the HRI
- The Approach Zone MAP length was 1,923 feet (586 m)
- The initial CV approach speed attained near the start of the Approach Zone and maintained throughout the approach to the point when the RCVW alert was issued was set at 50 mph, except for Test Cases 2.2.1.E and 2.1.1.L, where initial approach speed was set at 30 mph and 70 mph, respectively. Due to the short distance of landscape in advance of the length of the Approach Zone (ingress MAP lane), the specified initial approach speed was often not reached until about 100 m into the Approach Zone. The inability to reach the initial approach speed prior to Approach Zone entry had no impact on the location at which the RCVW warning was issued or the vehicle response.

- All scenario-based test cases began with the HRI in the active state (i.e., preemption signal low prior to vehicle entry into the Approach Zone), except those for which the HRI was specified to become active with the vehicle on approach with less than the full warning distance remaining. Specified warning point-based distance included the ¾ warning point, (Test Cases 2.2.6 and 2.3.6), the warning midpoint (Test Cases 2.2.7 and 2.3.7), or the ¼ warning point (Test Cases 2.2.8 and 2.3.8).

- Five traffic cones were used along the Approach Zone, as specified in the test cases comprising the V2I RCVW FT&E Plan [4] and this report for reference and future reconciliation with our system logs.
    - Cone #1: Approach Zone entry
    - Cone #2: Expected point of RCVW Activation
    - Cone #3: Expected start of vehicle deceleration
    - Cone #4: Expected vehicle stopping point
    - Cone #5: Stop Bar at HRI (i.e., transition between the Approach Zone and HRI Hazard Zone)

  Note: Cone #1 and Cone #5 remained in the same position throughout the tests, while the other cones were re-positioned prior to the beginning of each test in accordance with the location specified for the next test case. Although Cone #2 passage was expected to be pretty close to the time at which the VBS display annunciated an RCVW warning (given that initial approach speed could easily be achieved and maintained using cruise control), there was no expectation that the vehicle would be observed to start decelerating or come to a stop precisely at Cones #3 and #4, respectively, given the anticipated control difficulty with applying an accurately timed braking response, including a steady rate of deceleration throughout the slow to stop regime.

- Elevation details are optional in the SAE J2735 message set and were not populated for the MAP used in FT&E at RELLIS. The RCVW application continuously calculates the inclination/declination (grade) based on node elevation details for use in the stopping distance algorithm. However, it is designed to assign a default value of zero degrees of inclination/declination (i.e., level grade) when elevation details are not available in the MAP nodes. Use of a level grade for FT&E was confirmed to be assumed by the algorithm. Subsequent verification testing in Columbus, Ohio on 5/12/17 confirmed that elevation details available in a MAP are received by the VBS from the RBS for use as grade input(s) to the RCVW prediction algorithms.

- Other settings and multipliers were held constant across test cases, as specified below

- The associated VSE for Vehicle Type A was 0.70 and for Vehicle Type B was 0.56. The applicable value was configured prior to each test, as specified.

- PCR percentage (i.e., weather: 1.0 for dry, 0.6 for rain, and 0.45 for snow) is based upon associated International Traveler Information Systems (ITIS) codes (4617 for dry, 4885 for rain, and 4868 for snow). An active internet connection was not available at the RELLIS testing site, which impacted the receipt of weather related information directly from a weather source. However, the system is designed to assign a default value of 1.0 (dry) for pavement condition reduction when weather related information is not received, and use of this weather assumption was confirmed. Subsequent verification testing in Columbus, Ohio on 5/12/17 confirmed that when the RBS possesses an ITIS code, that code is populated in the SAE J2735 RSA message sent to and received by the VBS from the RBS.

The parameters used as inputs to the RCVW prediction algorithm equations were exactly the same as those used in BT&E (see above), except the Safety Offset Multiplier differed. The Safety Offset Multiplier used initially in FT&E testing was 1.5 – the same value used in BT&E. However, after practice runs, it was observed that the vehicle was always stopping beyond the calculated stop distance – even after achieving some level of control was established over DRT and the vehicle deceleration rate. The reason for this is not clear, but may be indicative of combined system latencies, different coefficient of friction of the surface, and/or impact of wind force (typically observed to be aligned as a tailwind). Trial and error, as well as subsequent testing, suggested that the safety offset should be set at 1.75. This configurable setting change was the only one that differed from settings used in BT&E.

Table 3-8 below summarizes the conditions and inputs for each of the scenario-based test cases executed in FT&E.

Seven other requirements were confirmed via means other than scenario-based testing conducted at RELLIS, as follows:

- Requirements RBS-8 and RBS-9 were confirmed via non-scenario-based test case 1.1.10 (Low Power Mode Verification) on 4/24/17 at RELLIS, prior to scenario-based testing.
- Requirement VBS-5 was verified by collecting data for test case 1.1.9 (Vehicle-Based Horizontal Position Accuracy Verification) in the overnight period between 4/26/17 and 4/27/17 at RELLIS. Subsequent data analysis in Columbus, Ohio verified the requirement.
- Requirements RBS-10 and RBS-17 were verified through non-scenario-based test case 1.1.11 (Failure Alert, Logging, and Notification Verification) conducted in Columbus, Ohio following testing conducted at RELLIS on 5/16/17.
- Requirements RBS-16 and RBS-19 were confirmed via regression testing of scenario-based test case 2.6.1 in a simulated laboratory environment (same configuration used for BT&E testing) in Columbus, Ohio following testing conducted at RELLIS on 5/16/17.

Table 3-8. Distinctive conditions for the Scenario-Based FT&E Test Cases

Test Case Number	CV Location at Preemption Signal Detection	CV Initial Approach Speed	CV Driver Response Time (Sec)** Spd / Time Slow / 1.5 Fast / 1.0	Vehicle Type*** Vehicle Stopping Effectiveness (VSE) • Type A = 0.70 • Type B = 0.56	Pavement Condition Reduction % (ITIS) •Dry = 0% (4617)	RCVW State
2.1.0	N/A (no Preemption Signal)	50 mph	None	Type A	Dry	Normal
2.1.1	Start of Approach Zone	50 mph	None	Type A	Dry	Normal
2.2.1.A	Start of Approach Zone	50 mph	Slow	Type A	Dry	Normal
2.2.1.E	Start of Approach Zone	30 mph	Slow	Type A	Dry	Normal
2.2.1.L	Start of Approach Zone	70 mph	Slow	Type A	Dry	Normal
2.2.2	Start of Approach Zone	50 mph	Slow	Type B	Dry	Normal
2.2.6*	¾ Warning Point	50 mph	Slow	Type A	Dry	Normal
2.2.7*	Warning Midpoint	50 mph	Slow	Type A	Dry	Normal
2.2.8*	¼ Warning Point	50 mph	Slow	Type A	Dry	Normal
2.3.1	Start of Approach Zone	50 mph	Fast	Type A	Dry	Normal
2.3.6*	¾ Warning Point	50 mph	Fast	Type A	Dry	Normal
2.3.7*	Warning Midpoint	50 mph	Fast	Type A	Dry	Normal
2.3.8*	¼ Warning Point	50 mph	Fast	Type A	Dry	Normal
2.3.9	Start of Approach Zone	50 mph, then 20 mph	Fast (Adequate), then subsequent RCVW (Inadequate action)	Type A	Dry	Normal
2.5.1	Stopped on tracks	N/A	Clears tracks	Type A	Dry	Normal
2.6.1	Start of Approach Zone	50 mph	Not factored	Type A	Dry	Fault – DSRC

Source: Battelle

* **Note:** These test cases intentionally present a "late" RCVW warning. The CV location referenced is the percentage of remaining Approach Zone distance available relative to the distance at which the CV would have received an RCVW warning at the prevailing conditions if the preemption signal was available sooner.

** **Note:** Except where marked "None," the target deceleration rate following driver response time (a combination of perception time and reaction time) is 4.572 m/s^2 (15 $ft./s^2$) for Type A and 3.658 m/s^2 (12 $ft./s^2$) for Type B vehicles. The figures presented in each of the test cases in the next chapter include driver/vehicle response reference locations (Cones #2, #3, and #4) based on driver response time and these constant deceleration rates applied.

*** **Note:** "Vehicle Type" in the Table 3-8 header above means the following:

- Type A = Passenger Car
- Type B = Box Truck

3.1.7.4 Summary of Prototype RCVW System FT&E Performance

A detailed account of all FT&E test results can be found in the RCVW FT&E Report [7]], and performance by requirement can be found in APPENDIX B. In summary, all test cases passed and all requirements evaluated were confirmed to be met, with two exceptions: 1) requirement RBS-13 was deemed not applicable and 2) requirement RBS-17 was not confirmed as met in the RCVW FT&E Report.

RBS-13 requires that secure communication protocols not adversely impact the performance of the safety application in providing timely alerts. This requirement was rated as not applicable because a secure communication protocol was not used. The RCVW system under test did not employ SCMS, as it was not operational at the time of the test. When SCMS is available, this requirement will technically apply to the RSU. For RCVW, no secure communication protocols were used to transmit data (socket communication over USB for the preemption, UDP socket communication over Ethernet for communication to RSU). Therefore, the performance impact via the use of secure communications could not be assessed.

RBS-17 requires that the RBS shall conduct self-diagnostics and report status and/or failures to a centralized control center. Although the functionality is present to permit this feature, this requirement could not be confirmed because Battelle was unable to setup an SMTP server to connect with to demonstrate that the Linux syslog would send an email when an error is detected. For this reason, the requirement is rated as not met.

Across the scenarios focused on detecting violations with the CV approach the HRI (i.e., Test Cases 2.1.X-2.3.X), the RCVW system was found to always reliably warn the driver when the vehicle was approaching the active crossing at a speed calculated to be too fast for the stopping distance remaining at the prevailing conditions (using the calculations and parameters described above). This permitted the driver to safely decelerate and stop both vehicle types before reaching the crossing – except in some cases when the warning was intentionally delivered late.

Performance of the RCVW System beyond metrics identified by the requirements was additionally assessed. Again, more complete details of these assessments can be found within the RCVW FT&E Report [7]. The following bullets summarize the performance investigated, with sub-bullets presenting a summary of findings:

- Warning Distance Performance and the Safety Offset (via use of the TMXcore log files)
    - Initially, a safety offset of 1.5 was used (the same value used in BT&E). Except in the first iteration of test case 2.2.1.A, the RCVW warning was issued 10-15 meters later than expected for all test cases executed with this setting.
    - When a safety offset of 2.0 was used, the results of test case 2.2.1.L produced a warning substantially sooner than expected.
    - Ultimately, a safety offset of 1.75 was found to most closely provide warnings when/where they were predicted and this setting was used for all FT&E tests except test case 2.1.1 (as it is not impacted by this setting). Using this setting across test cases featuring differing combinations of conditions (including vehicle type and approach speed), however, in some cases yielded warnings with varying advance responses that differed relative to predicted warning points. For example:
        - Moderately earlier than expected warnings at between 7 and 17 meters in advance of the predicted distance were observed for test cases 2.2.1.A, 2.2.1.E, and 2.3.1
        - Slightly later than anticipated warnings were observed during the box truck test iterations (test case 2.2.2) at around 2 meters and 7 meters late, though these slightly late warnings did not impact the ability of the vehicle to stop within the predicted stopping distance.

        - Although most tests produced moderately early warnings when using a safety offset of 1.75, test case 2.2.1.L (conducted at 70 mph) produced a warning significantly earlier than anticipated.

    This variability can in part be explained by the limitations involved when using TMXcore log file details for such an exercise. The biggest limitations are that:

        - the TMX Core log file records presenting state changes (i.e., HRI Active / RCVW issued) contain an accurate timestamp of each event but do not contain location details – so location must be captured from an adjacent record with position details
        - in addition to GPS position fix updates being communicated to the RCVW application at only ~4Hz or ~250ms (despite this is four times the required frequency, each position recorded will be over 5.5 meters from the last at 50 mph), this location information is subject to capture no earlier than by the next TMX core record to receive and log it, which introduces a ~170ms error potential. The constructive time error of both can be up to ~420ms. This would have a greater impact on warning distance the faster the vehicle is travelling (at 30 mph, the warning can be late/early up to 18.5 ft., while at 70 mph this error would correspond up to a 43.1 ft. discrepancy).

    Recommended enhancements to address these limitations are addressed in Section 3.1.7.5 (Logging section) and Section 4.4. (final bullet) below.

    - A means to adjust the stopping distance algorithm calculation for prevailing conditions and system performance, such as through use of an offset(s), is necessary. The field environment indeed presented factors impacting warning distance and stopping distance that were not present in the simulated scripts used for BT&E, such as the coefficient of friction and the impact of wind force (see section 3.1.7.3 above). However, the best method for calibrating the algorithm needs further investigation as the factors impacting warning and stopping distance in the field environment are not fully understood. Separate from the logging factors and road and weather conditions mentioned above (which impacted the logging, but not RCVW condition detection and alerting), factors that may possibly have contributed to the need to adjust the safety offset include:
        - latency in communications between the RBS (RSU) and VBS (OBU),
        - internal processing latency within the RCVW algorithm executed on the VBS, and
        - the frequency of GPS position updates.

    It is unclear what impact these factors or others may have upon the warning algorithm and whether these are predictably constant under differing conditions for a given/all vehicle type(s) such that they can be accounted for during a calibration period. Understanding this better would permit determination of the best relationship the offsets should have to the core stopping distance calculation, including whether these offsets should be expressed as terms to be added rather than multipliers to be factored.

- Driver Response and Deceleration Profile
    - Although the driver did not necessarily brake at a constant deceleration rate, and some test cases revealed more response variability than others, an analysis of the driver response across test cases verified approximate achievement on average of the assumed deceleration rate for the Type A vehicle.
    - Characterization of the driver response for the Type B vehicle test case revealed achievement of a noticeably better than assumed deceleration rate, which permitted the vehicle to stop earlier than predicted despite being warned slightly later than anticipated.

- Not surprisingly, the exceptions included test cases where the HRI active state was activated when the vehicle approaching the HRI at the ¼ warning point and midpoint of the normal distance needed to safely stop (Test Cases 2.2.7, 2.2.8, 2.3.7, and 2.3.8). However, the driver safely stopped the vehicle faster than predicted and short of the HRI Hazard Zone in all iterations of late warnings issued at the ¾ warning point (Test Cases 2.2.6 and 2.3.6).

- Faults, Stopped in the HRI, and Ad Hoc Nuisance Testing
  - Fault conditions and scenarios in which the vehicle was stopped in the HRI reliably produced annunciations of the proper alerts and warnings.
  - The RCVW system did not issue improper warnings/messaging or nuisance alerts – aside from the first two iterations of Test Case 2.2.2 when GPS and DSRC communication issues were noted, relating to placement of the GPS/DSRC multi-antenna
  - In addition to Test Case 1.1.9 (which focused on static GPS accuracy), six ad hoc tests static and dynamic tests were conducted to challenge GPS accuracy-based alerting in the Approach Zone and along the HRI envelope to evaluate RCVW performance relative to nuisance alerts. The nature of these tests is described within the Summary of RCVW Performance section of the RCVW FT&E Report [7]. Although it would not have been surprising to observe inappropriate warnings outside of the HRI Hazard Zone or lack of warnings within the HRI Hazard Zone on occasion over a 5-minute period, only appropriate warnings appeared in all of these tests.

- TMX Log File Timestamps and Observed Event Timestamps
  - Logged and hand-collected event data on the DVI typically matched within 1 second. This included passage times for vehicle entry into Approach Zone with the HRI active (and the Intersection Active message displayed), when RCVW warnings were issued and cleared, and when errors were displayed.
  - Manually-collected timestamp data for when the vehicle antenna passed the predicted warning point (Cone #2) does not correlate as closely with TMX core log timestamps for when the 'Rail Crossing Violation Warning' state change as the observed DVI RCVW warning issued timestamp. About half of the presented results match within 0-1 seconds, but three test cases show a differential of 2-3 seconds.
  - A larger and positive discrepancy in time between the Cone #2 observed passage time (later) as compared with the DVI RCVW warning issuance timestamp discrepancy with the TMX log 'Rail Crossing Violation Warning' state change timestamp should not be surprising given that the Cone #2 distance was calculated using a safety offset of 1.5. It is also worth mentioning that the Cone #2 observation position is challenging with regard to accurately capturing the timestamp of when a vehicle antenna – travelling at typically 50 mph - passes a marked location broadside.
  - FT&E setup and execution did reveal some minor bugs, anomalies, and opportunities for potential refinements. These are summarized below in Section 3.1.7.5 and Section 4.4.

3.1.7.5 Summary of FT&E Detected Issues and Resolution Status

The following detected issue, anomalies, and potential refinement opportunities were identified during FT&E.

Detected Issue

- During vehicle positioning for Test Case 2.2.2, while the vehicle was driven along an egress lane away from the HRI, there were observed instances when a 'MAP not received' error graphic was displayed on the DVI. This is expected behavior due to the DSRC antennas not having a clear line of sight to the

RBS RSU. When the error condition resolved (i.e., DSRC communications restored) the graphical portion of the error message cleared and was replaced by the ‘System Ready’ symbol as expected, however the text from the error graphic remained visible beneath the ‘System Ready’ graphic until a DVI state change occurred. This issue is being addressed as part of work on another project and, once the code change is verified to be corrected, will be used to update the RCVW code.

Observed Anomalies

- An audible “Warning” sound was heard while the vehicle was stopped within the HRI Hazard Zone in addition to, but well after, annunciation of the proper audible alert and graphic (i.e., series of 4 beeps and ‘Clear HRI’ graphic). It is not clear what triggered this audible, and it should not be heard. This anomaly was experienced only once throughout FT&E, and not during a test. Further testing of the application during future work should monitor for this anomaly and address if experienced more frequently.

- In Test Case 2.2.7 Iteration #1, the RCVW system did not record a ‘Clear RCVW Alert’ message in the logging, although this alert was observed to clear on the DVI and all other state changes in this test case were correctly logged. In all other test cases, the logging shows the ‘Clear RCVW Alert’ message in addition to the rest of the state change. This behavior may possibly be the result of a GPS position update timing issue and/or a loss of communication between threads. This anomaly was experienced only once during FT&E. Future work should monitor for this anomaly and address if experienced more frequently.

Potential Refinements in Future Work

Application Logic

- During Test Case 2.3.6 Iterations #1 and #2, it was observed that the ‘Intersection Active’ graphic appeared upon entry and within the HRI Hazard Zone. This messaging should appear only within the Approach Zone (MAP lane). The observed behavior was confirmed via a review of the TMX core log files.
    - **Note:** In both iterations, the log files reported this message as the vehicle traversed the HRI Hazard Zone with the HRI inactive (with the preemption switch being set to inactive while the vehicle was stopped short of the stop bar after stopping short of the HRI Hazard Zone).
- During Test Case 2.6.1 Iteration #4, the same “horn” audible associated with RCVW warnings sounded while the error graphic remained with the vehicle moving toward the HRI within the Approach Zone at a point of approximately 500 feet upstream of the HRI Hazard Zone. This audible should only sound in conjunction with the RCVW warning, and should not sound when the system is in an error state.
- Test Case 2.5.1 Iteration #2 was conducted differently from Iteration #1. In this iteration, after receiving a ‘Clear HRI’ warning in the HRI Hazard Zone, the vehicle backed out of the HRI into the Approach Zone (i.e., ingress MAP lane) and received an RCVW warning while moving away from the HRI. Currently, the RCVW application does not use heading to determine that the vehicle is approaching or departing the HRI, but rather relies upon vehicle position and speed within the MAP ingress/egress lanes. If deployed without modification, this approach exposes the vehicle operator to nuisance and/or incorrect warnings when an equipped vehicle enters an ingress while exiting the HRI Hazard Zone as well as when a vehicle’s position creeps into a nearby ingress lane even though the vehicle is travelling away from the HRI in an egress lane. A potential refinement would be the addition of vehicle heading in the establishment criteria for RCVW warnings to avoid this problem.

  - **Note:** Additionally, it would be beneficial as part of future work to organize discussion(s) with the MAP group about an approach to defining the intersection and possibly components in the intersection. Presently, MAP covers ingress/egress lanes only.

Logging

- A review of Tmxcore log files is needed to remove unnecessary logging information, such as “speedtime” and “prevspeedtime”, and to add useful information such as the value of the “safety offset”, and update the format of the reported values such as representing when a vehicle is within the Approach Zone, HRI, or the egress lane by true or false methods. The current programming requires determination of vehicle position within these zones through manual interpretation of numerical values. These changes would support more efficient and effective reconciliation activities.

Chapter 4 Conclusion and Future RCVW System and Application Enhancements

4.1 Summary of Prototype RCVW Successes

Observed Field Testing of the prototype RCVW system demonstrated the potential for leveraging the latest developments in connected vehicle technology and connecting to existing active grade crossing infrastructure to enhance and transform rail crossing safety to real-time warnings to drivers who may be distracted or who might otherwise not recognize they are approaching an HRI with activated warning devices when a train is approaching. This RCVW project has helped to advance the body of knowledge related to development and deployment of such a RCVW system.

Key successes achieved by the prototype RCVW system included:

- Successful integration with “HRIC” by simulating closure of HRIC XR relay contacts
- Low power draw of RCVW roadside equipment, making it a good platform for remote locations which may require the use of alternate power sources and conditional sleep cycles
- Reliable warnings in scenarios and conditions tested, and continued performance but appropriate DVI alerting when the RCVW system is degraded (i.e., when MAP message is not received)
- Low/no nuisance alerting in the approach or in HRI areas in formal testing and ad hoc testing during FT&E
- The RBS is designed to interface directly to an HRIC. The RCVW application does not require a TSC to be present
- RCVW architecture is modular and extensible and serves as a solid platform from which to make enhancements, expand functionality, and potentially further leverage CV data
- RCVW system is compliant with applicable standards, including SAE J2735 and other IEEE/SAE standards
- Although Security Credential Management System (SCMS) was not employed, no Personally Identifiable Information (PII) is at risk and information communicated via DSRC is reasonably secured

Nonetheless, designing, prototyping, and test and evaluation of the Prototype RCVW system revealed opportunities for enhancements and improvements. The remaining sections of this chapter summarize the lessons learned, further outreach, and enhancements and expansion of the RCVW system functions and capabilities that will facilitate a more robust and deployable system.

4.2 Lessons Learned from Integration and Evaluation during FT&E

- **Safety offset calibration** - A means to adjust the stopping distance algorithm calculation for prevailing conditions and system performance, such as through use of an offset(s), is necessary. The field environment indeed presented factors impacting warning distance and stopping distance that were not present in the simulated scripts used for BT&E, such as the coefficient of friction and the impact of wind force. However, the best method for calibrating the algorithm needs further investigation as the factors impacting warning and stopping distance in the field environment are not fully understood. See additional details in sections 3.1.7.3 and 3.1.7.4 above.
- **Grounding during integration of the RBS** – It is critical to understand the grounding system in the controller cabinet with which the RBS is integrated.
- **Integration with vehicle infotainment systems** - Per Section 3.1.2 above, it is presently not the intent of OEMs and vendors controlling vehicle infotainment systems to allow control and access to those system for presenting vehicle operators safety alerts and warnings that may be potentially ambiguous, conflicting, or distracting. The limited support provided did not permit adequate access or control of OEM Infotainment Systems to present drivers RCVW warnings. However, infotainment systems and other existing vehicle interfaces are constantly under development and opportunities for OEM vehicle integration with RCVW may be simplified in the future.

4.3 Potential Additional Outreach Opportunities

The following outreach opportunities should be planned to facilitate a more robust, deployable RCVW system that will be embraced by the railroad, vehicle manufacturer, and ultimately the vehicle operator:

- Reengage CAMP to understand likely OEM equipment and after-market devices that will be in or supported by vehicle manufacturers so that further RCVW development can be aimed at using inputs and presenting feedback on that equipment, possibly even having the equipment host TMX.
- Encourage the MAP group to develop and provide guidance/rules on within-intersection/HRI lane and geometry specifications (see Section 3.1.7.5 above).
- Attempt to engage, if advantageous, the railroads to make them aware of the RCVW system and its benefits, as well as potentially explore safety opportunities the RCVW platform affords to railroad stakeholders.

4.4 Potential RCVW System Enhancements and Expansion of RCVW Functions and Capabilities

In addition to the potential refinements listed in Section 3.1.7.5 above, the following enhancements and expanded functions and capabilities derive from development of the RCVW system and application as well as integration and evaluation:

- Research & Study vehicle position solution advancements
  - Better position performance may be needed for a high-performing RCVW application. Determination of a fix from a warm start takes only seconds, but from a cold start can take a few minutes or more – especially if the GPS has not had a fix for an extended period of time. Multi/different position sources may not be limited in this way. Although accuracy tests in FT&E revealed good performance, the testing conditions were ideal relative to line of sight. Multi-path errors for crossings in some urban areas or in natural canyons would be less likely to produce acceptable and resilient position accuracy using a single source GNSS/GPS.
    - Evaluate alternate GPS correction methods (RTCM, SBAS, RTK)
    - Evaluate multi-GNSS solutions (GPS + GLONASS/Galileo/BeiDou/NAVIC)
    - Evaluate multi-source solutions (GNSS + INS, GNSS + Cellular triangulation)
  - Implementation of Active Error Checking (use HDOP/PDOP/VDOP, snap-to-map)
  - Employ directionality into the consideration for alerting to prevent nuisance alerting possibilities, e.g., when backing-up away from an HRI.
- Better understand and characterize the environmental factors (and sensitivity of them) impacting upon the safety offset setting choice and considerations for modifying and/or adjusting the preemption and safety offset multipliers so that guidance can be issued for calibration during RCVW deployment, to include simultaneous expanded weather conditions testing to include wind speed/direction, more dramatic grades, different pavement types, etc.
- Confirm communications to TMC of fault conditions – this was not tested in BT&E or FT&E.
- Potentially explore dashboard of CV conformance status/details (webpage via the Cloud) – perhaps of RCVWs and vehicle response behavior to support studies of high-accident HRIs equipped with RCVW.
- Alternate Integration of RCVW RBS at remote HRIs and/or where a traffic signal controller cabinet is not available, to potentially include alternate power source impacts on RCVW RBS and system performance.
- RCVW application ConOps scenario future expansion
  - Dilemma zone scenarios – perhaps suppress warning if vehicle cannot stop if it is unlikely that train will actually collide
  - Scenarios with nearby traffic intersection – harmonization of RCVW alerting to consider traffic signal(s), which may employ queue clearing phasing/timing and/or non-simultaneous preemption signaling
  - More variations of HRI – angled approaches, different gating/staggered gating, multiple tracks with multiple trains, and parallel approaches (to include mobility considerations)
  - Any scenarios lending themselves to presented alerts for automated vehicles or for CV vehicles operating with automated vehicles around (i.e., multiple connected vehicles)

- More environmental condition scenarios – both to confirm the detection and alerting algorithms as well as to better characterize how offsets can best be calibrated

- The current implementation of the RCVW system considers vehicle length in the determination of when to detect or – more importantly – when to no longer detect and annunciate RCVW warnings. Ideally, the application would obtain and use vehicle length in these determinations to fully protect all vehicle class/types. Longer vehicles (buses, trucks, etc.) can remain endangered in the HRI long after the front of the vehicle is no longer endangered. This will also be an important consideration in the implementation of 'dilemma zone' enhancements if undertaken, as the length of the vehicle must be considered when determining at what point to no longer issue warnings to drivers approaching an HRI that becomes active when they are close to passage.

- Possible integration of RCVW with other CV applications (such as electronic braking, forward collision warning, curve speed warning, etc.) and pedestrian applications (mobile pedestrians and bicyclists – for places like Portland), to include prioritization of interface messaging and warnings and additional ConOps scenarios.

- Per Section 4.3 above, revisit attempts to investigate the state of the art in OEM equipment and after-market devices to assess and, if warranted, attempt integration of RCVW with devices that will be in or supported by vehicle manufacturers. Success in doing so would provide an avenue for further RCVW development aimed at using inputs and presenting feedback on that equipment, possibly even having the equipment host TMX.

- Human factors study of display graphics and annunciations to include frequency of looping annunciations, characteristics of audible annunciations (frequency, sound, volume, etc.), and characteristics of graphics (how best to convey information, conformity with vehicle standards, best practice experience), this would particularly include 'bus graphic' and 'intersection active' modifications.

- Optimizing/assuring necessary RCVW system performance. Although performance could be characterized through the execution of test cases multiple times, BT&E and FT&E testing for this prototype system and application was strictly limited to requirements verification. Validation of the robustness of the system would require a longer-term deployment and evaluation and this should be considered as part of future work.

- Exploration of architectural changes of the RCVW system or RCVW application needed to support efficient deployment.

- Develop an RCVW Project Description that can be used as a briefing by DOT and its representatives when engaging stakeholders, such as those referenced above in Section 4.3 and others.

- In addition to conducting a review of Tmxcore log files to remove unnecessary logging information, and adding useful information (see Section 3.1.7.5 Logging, above), the frequency with which data are logged should be re-evaluated and - where necessary to support valuable post-processing assessments - made more frequent to prevent the sort of approximation errors experienced in post-processing performance analyses described in Section 3.1.7.4 bullets above.

APPENDIX A. List of Acronyms and Abbreviations

ABS	Anti-Lock Braking System
AREMA	American Railway Engineering and Maintenance-of-Way Association
BIST	Built-In Self-Test
BT&E	Bench Test and Evaluation (a phase of RCVW testing and evaluation)
C&S	Communication and Signals Manual
CAMP	Crash Avoidance Metrics Partnership
CCP	Common Computing Platform
CICAS	Cooperative Intersection Collision Avoidance Systems
ConOps	Concept of Operations
COTS	Commercial-Off-The-Shelf
CP	Computing Platform
CTC	Campbell Technology Corporation, Inc.
CV	Connected Vehicle
DOT	State Department of Transportation
DRT	Driver Response Time
DSRC	Dedicated Short-Range Communication
DVI	Driver Vehicle Interface
DVIM	DVI Module
FRA	Federal Railroad Administration
FT&E	Field Testing and Evaluation (a phase of RCVW testing and evaluation)
GID	Geometric Intersection Description
GNSS	Global Navigation Satellite Systems
GPS	Global Positioning System
GTM	Government Task Manager
HCDF	HRI Configuration Data File
HRI	Highway-Rail Intersection
HRIC	HRI Controller
ICD	Interface Control Document
ITIS	International Traveler Information Systems
ITS	Intelligent Transportation Systems

IVP	Integrated V2I Prototype
MAP	Roadway Geometry and Attribute Data (a.k.a., GID)
MUTCD	Manual on Uniformed Traffic Control Devices
NGS	National Geodetic Survey
NTRIP	Network Transport of RTCM via Internet Protocol
OBU	On-board Unit (DSRC radio in VBS)
OEM	Original Equipment Manufacturer
OS	Operating System
PCR	Pavement Condition Reduction
PII	Personally Identifiable Information
PoE	Power over Ethernet
RBS	Roadside-based Subsystem (an RCVW subsystem)
RCVW	Rail Crossing Violation Warning (warning message)
RSU	Roadside Unit (DSRC radio in RBS)
RTCM	Radio Technical Commission for Maritime Services
SCMS	Security Credential Management System
SMS	Short Message Service (text message)
SPAT	Signal Phase and Timing
SRS	Systems Requirement Specification
TMC	Traffic Management Center
TMX	Transportation Message Exchange
TSC	Traffic Signal Controller
TTI	Texas A&M Transportation Institute
U.S. DOT	United States Department of Transportation
VBS	Vehicle-based Subsystem (an RCVW subsystem)
VSE	Vehicle Stopping Effectiveness
V2I	Vehicle to Infrastructure
WAVE	Wireless Access in Vehicular Environments

APPENDIX B. RCVW Requirements Traceability Matrix and Results

Table B-1 below presents the RCVW system requirements, test cases in which they were verified, and the testing result. Discrete tests are designated with 1.#.# numbering, while scenario-based test cases (simulated scripts in the BT&E and using an equipped vehicle and infrastructure in FT&E) are designated with 2.#.# numbering. Some discrete test cases were conducted only in BT&E and others only in FT&E. Those test cases conducted only in BT&E are denoted with "Evaluated in BT&E" before the test case number. All scenario-based test cases were conducted in BT&E, with a subset of those test cases conducted in FT&E. Scenario test cases share the same number between BT&E and FT&E, and although all scenario test cases were conducted in BT&E only the test cases conducted in FT&E are listed below. The two scenario-based tests conducted in BT&E that were not repeated in FT&E are 2.2.1.M (RBS-5) and 2.6.2 (VBS-19), and this is recognized within the matrix.

Table B-1. RCVW Requirements Traceability Matrix

RCVW Rqmt No.	System / SubSystem	Requirement	RCVW BT&E and FT&E Test Cases		Met?
			Discrete Tests	Scenario-Based	
RCVW-1	RCVW System	The system shall include a vehicle-based subsystem component and a roadside-based subsystem component.	Evaluated in BT&E 1.1.1		YES
RCVW-2	RCVW System	The system shall interoperate with current infrastructure safety systems (e.g. traffic control and Train Approaching warning devices) in accordance with NEMA TS 2-2003 v02.06	Evaluated in BT&E 1.1.1		YES
RCVW-3	RCVW System	The system shall be modular and sufficiently extensible to address all design objectives defined in this SRS.	Evaluated in BT&E 1.1.1		YES
RCVW-4	RCVW System	The system shall employ track circuit based train detection system preemption signal(s) to trigger the HRI Active message		2.1.0, 2.1.1, 2.2.1.A, 2.2.1.E, 2.2.1.L, 2.2.2, 2.2.6, 2.2.7, 2.2.8, 2.3.1, 2.3.6, 2.3.7, 2.3.8, 2.3.9, 2.5.1	YES
RCVW-5	RCVW System	The only point(s) of connection between the system and the track-circuit based train detection system shall be the preemption signal(s)	Evaluated in BT&E 1.1.1		YES
RCVW-7	RCVW System	The vehicle-based subsystem OBU and roadside-based subsystem RSU shall communicate using DSRC in compliance with SAE J2735-20015, IEEE 1609, SAE J2739, and SAE J2450 (ITIS) Standards.	Evaluated in BT&E 1.1.2		YES
RCVW-8	RCVW System	All "over-the-road" licensed vehicles (i.e., vehicles of all vehicle classes) are included.		2.1.1, 2.2.1.A, 2.2.1.E, 2.2.1.L, 2.2.2, 2.2.6, 2.2.7, 2.2.8, 2.3.1, 2.3.6, 2.3.7, 2.3.8, 2.3.9, 2.5.1, 2.6.1/2.6.3	YES

RCVW Rqmt No.	System / SubSystem	Requirement	RCVW BT&E and FT&E Test Cases		Met?
			Discrete Tests	Scenario-Based	
RCVW-11	RCVW System	The system shall be compliant with Connected Vehicle Personally Identifiable Information (PII) standards and guidelines	Evaluated in BT&E 1.1.4		YES
VBS-1	Vehicle-Based Subsystem (VBS)	The vehicle-based subsystem DVI shall have the capability to produce alerts suitable for all licensed drivers.	Evaluated in BT&E 1.1.3		YES
VBS-2	Vehicle-Based Subsystem (VBS)	The vehicle-based subsystem DVI shall have a human-machine interface (HMI) that is configurable to be audible, visual, both, or neither by the driver	Evaluated in BT&E 1.1.3		YES
VBS-3	Vehicle-Based Subsystem (VBS)	The vehicle-based subsystem DVI will display alerts that are consistent with the Connected Vehicle Human Factors Guidelines.	Evaluated in BT&E 1.1.3		YES
VBS-4	Vehicle-Based Subsystem (VBS)	The vehicle-based subsystem DVI shall produce alerts that can be implemented in all vehicle classes and types equipped with appropriate connected vehicle technologies. Note: vehicle-specific installation procedures may be required.		2.1.1, 2.2.1.A, 2.2.1.E, 2.2.1.L, 2.2.2, 2.2.6, 2.2.7, 2.2.8, 2.3.1, 2.3.6, 2.3.7, 2.3.8, 2.3.9, 2.5.1, 2.6.1/2.6.3	YES
VBS-5	Vehicle-Based Subsystem (VBS)	The vehicle-based subsystem shall receive and process roadside-based subsystem GPS correction data to achieve a R95 probability of horizontal position accuracy of less than or equal to 2 meters.	1.1.9		YES
VBS-6	Vehicle-Based Subsystem (VBS)	The vehicle-based subsystem shall process HRI configuration (GID) data that describes the geographic composition of the intersection.		2.1.1, 2.2.1.A, 2.2.1.E, 2.2.1.L, 2.2.2, 2.2.6, 2.2.7, 2.2.8, 2.3.1, 2.3.6, 2.3.7, 2.3.8, 2.3.9, 2.5.1	YES
VBS-7	Vehicle-Based Subsystem (VBS)	The vehicle-based subsystem shall be able to provide direction specific alerts. Note: For clarity, the application shall be able to provide alerts to vehicles approaching the HRI and not alert vehicles departing the HRI.		2.1.1, 2.2.1.A, 2.2.1.E, 2.2.1.L, 2.2.2, 2.2.6, 2.2.7, 2.2.8, 2.3.1, 2.3.6, 2.3.7, 2.3.8, 2.3.9, 2.5.1	YES
VBS-8	Vehicle-Based Subsystem (VBS)	The system shall utilize an integrated HMI (DVI) installed by an OEM or an aftermarket mobile device to provide alerts to vehicle operators.	Evaluated in BT&E 1.1.1		YES
VBS-9a	Vehicle-Based Subsystem (VBS)	The vehicle-based subsystem shall not interfere with any of the onboard safety systems, especially automotive industry autonomous safety systems	Evaluated in BT&E 1.1.1		YES
VBS-9b	Vehicle-Based Subsystem (VBS)	The vehicle-based subsystem shall not interfere with any existing infrastructure subsystems (traffic control and HRI warning systems)	Evaluated in BT&E 1.1.7		YES
VBS-10	Vehicle-Based Subsystem (VBS)	The vehicle-based subsystem shall determine if the vehicle is within the HRI Hazard Zone and/or the HRI Approach Zone.		2.1.0, 2.1.1, 2.2.1.A, 2.2.1.E, 2.2.1.L, 2.2.2, 2.2.6, 2.2.7, 2.2.8, 2.3.1, 2.3.6, 2.3.7, 2.3.8, 2.3.9, 2.5.1, 2.6.1/2.6.3	YES

RCVW Rqmt No.	System / SubSystem	Requirement	RCVW BT&E and FT&E Test Cases		Met?
			Discrete Tests	Scenario-Based	
VBS-11	Vehicle-Based Subsystem (VBS)	The vehicle-based subsystem shall issue warnings when the HRI is active and the vehicle is stopped within the HRI Hazard Zone or when the vehicle is within the HRI Approach Zone and the vehicle is not decelerating sufficiently to stop safely before the HRI Hazard Zone.		2.1.1, 2.2.1.A, 2.2.1.E, 2.2.1.L, 2.2.2, 2.2.6, 2.2.7, 2.2.8, 2.3.1, 2.3.6, 2.3.7, 2.3.8, 2.3.9, 2.5.1	YES
VBS-12	Vehicle-Based Subsystem (VBS)	The vehicle-based subsystem shall receive and process weather data from the roadside-based subsystem.		2.1.0, 2.1.1, 2.2.1.A, 2.2.1.E, 2.2.1.L, 2.2.2, 2.2.6, 2.2.7, 2.2.8, 2.3.1, 2.3.6, 2.3.7, 2.3.8, 2.3.9, 2.5.1	YES
VBS-13	Vehicle-Based Subsystem (VBS)	The vehicle-based subsystem shall receive and process road-related data including grade, surface material, etc. from the roadside-based subsystem.		2.1.0, 2.1.1, 2.2.1.A, 2.2.1.E, 2.2.1.L, 2.2.2, 2.2.6, 2.2.7, 2.2.8, 2.3.1, 2.3.6, 2.3.7, 2.3.8, 2.3.9, 2.5.1	YES
VBS-14	Vehicle-Based Subsystem (VBS)	The vehicle-based subsystem shall process the HRI Active message in the context of its position with respect to the HRI, its instantaneous speed, vehicle parameters, weather data, and road parameters to determine if an RCVW should be issued		2.1.1, 2.2.1.A, 2.2.1.E, 2.2.1.L, 2.2.2, 2.2.6, 2.2.7, 2.2.8, 2.3.1, 2.3.6, 2.3.7, 2.3.8, 2.3.9, 2.5.1	YES
VBS-15	Vehicle-Based Subsystem (VBS)	The distance from the HRI when a warning is presented to the vehicle operator shall be a function of: typical operator reaction time, vehicle characteristics (i.e., vehicle class), roadway parameters (i.e., grade and surface), weather conditions, and vehicle telematics (i.e., speed and heading of the vehicle).		2.1.1, 2.2.1.A, 2.2.1.E, 2.2.1.L, 2.2.2, 2.2.6, 2.2.7, 2.2.8, 2.3.1, 2.3.6, 2.3.7, 2.3.8, 2.3.9	YES
VBS-16	Vehicle-Based Subsystem (VBS)	The vehicle-based subsystem shall not provide warnings when it is not inside the HRI Hazard Zone or HRI Approach Zone		2.1.1, 2.2.1.A, 2.2.1.E, 2.2.1.L, 2.2.2, 2.2.6, 2.2.7, 2.2.8, 2.3.1, 2.3.6, 2.3.7, 2.3.8, 2.3.9, 2.5.1	YES
VBS-17	Vehicle-Based Subsystem (VBS)	The vehicle-based subsystem DVI shall issue an emphatic RCVW if a vehicle is positioned in the HRI Hazard Zone when a train is approaching,		2.5.1	YES
VBS-18	Vehicle-Based Subsystem (VBS)	The vehicle-based subsystem DVI shall inform the vehicle operator when the RCVW system is not functioning in "normal" operations mode.		2.6.1/2.6.2/2.6.3	YES
VBS-19	Vehicle-Based Subsystem (VBS)	The vehicle-based subsystem DVI shall inform the vehicle operator when the on-board unit cannot provide positional information.	Evaluated in BT&E 2.6.2		YES

RCVW Rqmt No.	System / SubSystem	Requirement	RCVW BT&E and FT&E Test Cases		Met?
			Discrete Tests	Scenario-Based	
VBS-20	Vehicle-Based Subsystem (VBS)	The vehicle-based subsystem shall have a means for informing the vehicle operator when it does not receive a Service Announcement from a "known" HRI roadside-based subsystem		2.6.1	YES
RBS-1	Roadside-Based Subsystem (RBS)	The application shall communicate using DSRC in compliance with SAE J2735-20015, IEEE 1609, SAE J2739, and SAE J2450 (ITIS) Standards.	Evaluated in BT&E 1.1.2		YES
RBS-2	Roadside-Based Subsystem (RBS)	The roadside-based subsystem shall operate using 60 Hz 115VAC power as the primary power source.	Evaluated in BT&E 1.1.1		YES
RBS-3	Roadside-Based Subsystem (RBS)	The infrastructure-based DSRC equipment shall be compliant with the IVP Reference platform. Note: If available, the equipment could alternatively be compliant with V2I Reference Implementation.	Evaluated in BT&E 1.1.1		
RBS-4	Roadside-Based Subsystem (RBS)	The roadside-based subsystem shall broadcast the HRI Active message 10 times per second when an associated HRI controller activates a preemption signal.		2.1.1, 2.2.1.A, 2.2.1.E, 2.2.1.L, 2.2.2, 2.2.6, 2.2.7, 2.2.8, 2.3.1, 2.3.6, 2.3.7, 2.3.8, 2.3.9, 2.5.1	YES
RBS-5	Roadside-Based Subsystem (RBS)	The roadside-based subsystem shall stop broadcasting the HRI Active message when the HRI controller deactivates the preemption signal(s)	Evaluated in BT&E 2.2.1 Iteration #2 (2.2.1.M)		YES
RBS-6	Roadside-Based Subsystem (RBS)	The roadside-based subsystem shall broadcast the Service Announcement once per second		2.1.0, 2.1.1, 2.2.1.A, 2.2.1.E, 2.2.1.L, 2.2.2, 2.2.6, 2.2.7, 2.2.8, 2.3.1, 2.3.6, 2.3.7, 2.3.8, 2.3.9, 2.5.1	YES
RBS-7	Roadside-Based Subsystem (RBS)	The roadside-based subsystem shall broadcast the HCDF and weather data once per second		2.1.0, 2.1.1, 2.2.1.A, 2.2.1.E, 2.2.1.L, 2.2.2, 2.2.6, 2.2.7, 2.2.8, 2.3.1, 2.3.6, 2.3.7, 2.3.8, 2.3.9, 2.5.1	YES
RBS-8	Roadside-Based Subsystem (RBS)	The roadside-based subsystem RSU shall transition to a lower energy consuming state when no trains and no connected vehicles are present	1.1.10		YES
RBS-9	Roadside-Based Subsystem (RBS)	The roadside-based subsystem shall resume normal operations when trains or connected vehicles are present.	1.1.10		YES
RBS-10	Roadside-Based Subsystem (RBS)	The roadside-based subsystem shall execute periodic BIST, which includes a default mode that, if possible - depending on the nature of the failure, informs the driver via the vehicle-based subsystem when critical components are offline.	1.1.11		YES (via 2.6.1)
RBS-11	Roadside-Based Subsystem (RBS)	The roadside-based subsystem shall employ methods to prevent unauthorized physical and cyber access.	Evaluated in BT&E 1.1.5		YES
RBS-12	Roadside-Based Subsystem (RBS)	The V2I communication shall implement security as defined by IEEE 1609 Standards for Wireless Access in the Vehicular Environment (WAVE). For clarity, a unique security solution will not be developed for this project, but the available security solution provided by U.S. DOT for V2I communications will be exercised.	Evaluated in BT&E 1.1.2		YES

RCVW Rqmt No.	System / SubSystem	Requirement	RCVW BT&E and FT&E Test Cases		Met?
			Discrete Tests	Scenario-Based	
RBS-13	Roadside-Based Subsystem (RBS)	Secure-communication protocols shall not adversely impact the performance of the safety application with respect to the ability to provide alerts in a timely manner		2.1.0, 2.1.1, 2.2.1.A, 2.2.1.E, 2.2.1.L, 2.2.2, 2.2.6, 2.2.7, 2.2.8, 2.3.1, 2.3.6, 2.3.7, 2.3.8, 2.3.9, 2.5.1	NA
RBS-14	Roadside-Based Subsystem (RBS)	The roadside-based subsystem shall provide to the vehicle-based subsystem: current weather and visibility conditions, when available, and road related parameters		2.1.0, 2.1.1, 2.2.1.A, 2.2.1.E, 2.2.1.L, 2.2.2, 2.2.6, 2.2.7, 2.2.8, 2.3.1, 2.3.6, 2.3.7, 2.3.8, 2.3.9, 2.5.1	YES
RBS-15	Roadside-Based Subsystem (RBS)	The roadside-based subsystem shall comply with the environmental requirements cited in Chapter 3 with the exception that the roadside equipment employed as part of the project will be tested in a controlled and semi-controlled environment and may be prototype in nature and may not comply with the temperature and vibration requirements.	Evaluated in BT&E 1.1.6, but will be updated when information is received from Cohda re: SAE J1113.		YES (PARTIAL)
RBS-16	Roadside-Based Subsystem (RBS)	The roadside-based subsystem shall identify and log system failures to the extent that it is practicable		2.6.1/2.6.3	YES
RBS-17	Roadside-Based Subsystem (RBS)	The roadside-based subsystem shall conduct self-diagnostic testing diagnosis and report status and/or failure to a centralized control center.	1.1.11		NO
RBS-18	Roadside-Based Subsystem (RBS)	The roadside-based subsystem shall incorporate self-recovering routines in order to recover from a major system failure associated with firmware/software systems.	Evaluated in BT&E 1.1.8		NO
RBS-19	Roadside-Based Subsystem (RBS)	Application and system logs (for example messages received from vehicle-based subsystem OBUs regarding roadside-based subsystem RSUs that failed to transmit Service Announcements) will be timestamped using an internally consistent mechanism (e.g., GPS or UTC time) and maintained until reported to a Central Maintenance Facility		2.6.1/2.6.3	YES

Source: Battelle

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