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DOT/FRA/ORD-22/07

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14. ABSTRACT
Phase 2 of the Rail Crossing Violation Warning (RCVW) application provides the means for equipped connected vehicles (CV) 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 CV Roadside-Based Subsystem (RBS) with track-circuit based train detection systems in place at active HRIs. The objective of this project was to build upon the RCVW proof of concept to make refinements to the software and hardware to achieve improved performance and enhanced system functionality. This project explored the use of enhanced Global Positioning System (GPS) solutions, OBD-II sourced vehicle data as additional input to the system, integration of the Institute of Electrical and Electronics Engineers (IEEE) 1570 serial signal preemption protocol for fail-safe train presence detection and an updated driver-vehicle interface.

15. SUBJECT TERMS
Rail Crossing Violation Warning, RCVW, connected vehicles, CV, Connected Automated Vehicles, CAV, Highway-Rail Intersection, Dedicated Short Range Communications, DSRC, signal phase and timing, SPaT, Map Data, MAP, Institute of Electrical and Electronics Engineers, IEEE

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LENGTH (APPROXIMATE)

1 inch (in) = 2.5 centimeters (cm)
1 foot (ft) = 30 centimeters (cm)
1 yard (yd) = 0.9 meter (m)
1 mile (mi) = 1.6 kilometers (km)

AREA (APPROXIMATE)

1 square inch (sq in, in^2) = 6.5 square centimeters (cm^2)
1 square foot (sq ft, ft^2) = 0.09 square meter (m^2)
1 square yard (sq yd, yd^2) = 0.8 square meter (m^2)
1 square mile (sq mi, mi^2) = 2.6 square kilometers (km^2)
1 acre = 0.4 hectare (he) = 4,000 square meters (m^2)

MASS - WEIGHT (APPROXIMATE)

1 ounce (oz) = 28 grams (gm)
1 pound (lb) = 0.45 kilogram (kg)
1 short ton = 2,000 pounds (lb) = 0.9 tonne (t)

VOLUME (APPROXIMATE)

1 teaspoon (tsp) = 5 milliliters (ml)
1 tablespoon (tbsp) = 15 milliliters (ml)
1 fluid ounce (fl oz) = 30 milliliters (ml)
1 cup (c) = 0.24 liter (l)
1 pint (pt) = 0.47 liter (l)
1 quart (qt) = 0.96 liter (l)
1 gallon (gal) = 3.8 liters (l)
1 cubic foot (cu ft, ft^3) = 0.03 cubic meter (m^3)
1 cubic yard (cu yd, yd^3) = 0.76 cubic meter (m^3)

TEMPERATURE (EXACT)

[(x-32)(5/9)] °F = y °C

METRIC TO ENGLISH

LENGTH (APPROXIMATE)

1 millimeter (mm) = 0.04 inch (in)
1 centimeter (cm) = 0.4 inch (in)
1 meter (m) = 3.3 feet (ft)
1 meter (m) = 1.1 yards (yd)
1 kilometer (km) = 0.6 mile (mi)

AREA (APPROXIMATE)

1 square centimeter (cm^2) = 0.16 square inch (sq in, in^2)
1 square meter (m^2) = 1.2 square yards (sq yd, yd^2)
1 square kilometer (km^2) = 0.4 square mile (sq mi, mi^2)
10,000 square meters (m^2) = 1 hectare (ha) = 2.5 acres

MASS - WEIGHT (APPROXIMATE)

1 gram (gm) = 0.036 ounce (oz)
1 kilogram (kg) = 2.2 pounds (lb)
1 tonne (t) = 1,000 kilograms (kg)
= 1.1 short tons

VOLUME (APPROXIMATE)

1 milliliter (ml) = 0.03 fluid ounce (fl oz)
1 liter (l) = 2.1 pints (pt)
1 liter (l) = 1.06 quarts (qt)
1 liter (l) = 0.26 gallon (gal)
1 cubic meter (m^3) = 36 cubic feet (cu ft, ft^3)
1 cubic meter (m^3) = 1.3 cubic yards (cu yd, yd^3)

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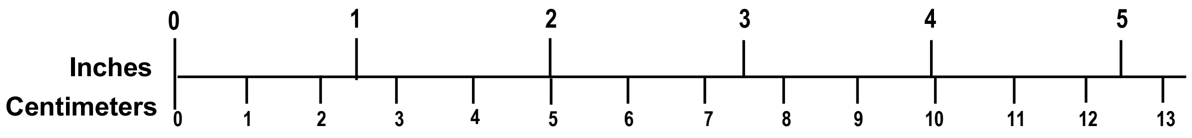

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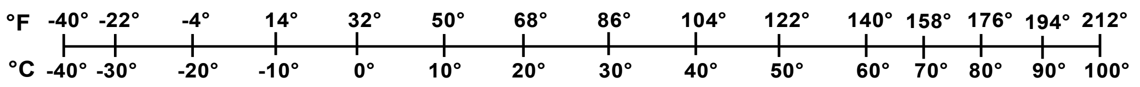

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Executive Summary

This report summarizes the Rail-Crossing Violation Warning Phase II (RCVW II) project from September 2018 to July 2021. This project builds upon prior proof-of-concept work performed by Battelle for the Federal Railroad Administration (FRA) and the Federal Highway Administration's Intelligent Transportation Systems – Joint Program Office. RCVW II enhances the RCVW's system robustness and incorporates new functionality.

The RCVW II system incorporates refinements to the software and hardware created during the Phase I RCVW project. These refinements improve performance and enhance system functionality. Performing the system design and development for RCVW II took place at Battelle Memorial Institute in Columbus, OH, from September 2018 to July 2020. The system demonstrates the potential for leveraging real-time connected vehicle (CV) concepts to enhance rail crossing safety.

In addition to an overall improvement to the RCVW algorithm, RCVW II incorporates the following refinements:

- Use of an Institute of Electrical and Electronics Engineers (IEEE) Standard[1] serial communication device, that provides a fail-safe and closed-loop response, to interface the preemption signal of a track-circuit-based train detection system to the Roadside-Based Subsystem (RBS)
- Use of Controller Area Network (CAN) bus to access vehicle status data as input to the Vehicle Based Subsystem (VBS)
- The improvement of the Global Navigation Satellite System's (GNSS) positional accuracy by using a dual phase Real-Time Kinematics (RTK) vehicle positioning system
- GNSS correction data broadcast over a Dedicated Short-Range Communications (DSRC) radio link
- Updated Driver-Vehicle Interface (DVI) visual and audio alerts based on published human factors design reports for CVs and in-vehicle safety applications

This report shows that a reliable system for enhancing safety at active highway-rail intersections (HRI) can be built using currently available technology and presents opportunities for future work with the goals of enhancing the overall system and achieving pilot.

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[1] IEEE Standard 1570-2002 (R2008): IEEE 1570 Standard for the Interface Between the Rail Subsystem and the Highway Subsystem at a Highway Rail Intersection (IEEE Standards Association, 2002).

1. Introduction

The U.S. Department of Transportation (DOT) is committed to the research and development of innovative technologies intended on making travel safer. Specifically, the connected vehicle (CV) initiative seeks to create applications and prototypes that rely on the exchange of safety-critical information from vehicle to vehicle (V2V) and between vehicle and infrastructure (V2I) using Dedicated Short-Range Communications (DSRC) radios. Beginning in 2015, the Federal Railroad Administration (FRA) and its subcontractors have been effective in producing a CV prototype called the Rail-Crossing Violation Warning (RCVW), which is designed to notify approaching drivers of an active rail crossing and warn them of a potential collision.

This report presents the results of the FRA funded RCVW Phase II (RCVW II) research project which builds upon the prior proof-of-concept work performed by Battelle for FRA and the Federal Highway Administration's Intelligent Transportation Systems – Joint Program Office. RCVW II enhances the original RCVW's system robustness and incorporates new functionality.

1.1 Background

An urgent need exists for additional protections for vehicle drivers traversing highway-rail intersections (HRI) beyond traditional active warning devices. Table 1 presents a review of FRA safety statistics since 2015[2] that does not reflect appreciable improvement in HRI incidents involving motor vehicles (i.e., excluding pedestrian and other categories), fatalities, or injuries.

Table 1. FRA Safety Statistics at HRIs from Calendar Years 2015–2020[3]

Calendar Year	Motor Vehicle Incident	Fatalities	Injuries
2015	1,926	188	991
2016	1,873	175	811
2017	1,952	193	799
2018	2,029	177	780
2019	2,041	193	780
2020	1,728	124	611

While active warning devices such as flashing lights, bells, and gates are effective at decreasing risk, these HRIs still account for roughly one-half of all crashes. The statistics also show that the top causes attributed to HRI crashes are distracted drivers and driver judgement errors

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[2] Source: Federal Railroad Administration Office of Safety Analysis website

[3] Data from 2020 appears to be lower than the previous years. This could be a result of the COVID-19 pandemic reduced vehicle volumes.

(Neumeister, D., 2019). Distracted drivers may not notice they are approaching an HRI, or 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 (e.g., 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 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.

1.2 Objectives

RCVW Phase I demonstrated a V2I-based technology intended for use at HRIs equipped with active warning devices (Neumeister, D., Zink, G., & Sanchez-Badillo, A., 2017). When a connected vehicle (CV) equipped with the RCVW system approaches an active HRI (i.e., the HRI Controller [HRIC] has activated the preemption signal) the system warns the driver if the Vehicle-Based Subsystem (VBS) predicts the driver is not taking sufficient action to prevent a violation.

The objectives of the RCVW II system were to make refinements to the software and hardware and transform the proof-of-concept prototype into a more reliable, accurate and widely applicable system. A Systems Engineering Methodology was applied to the design, development, testing, and evaluation stages of the project and demonstrated the potential for leveraging real-time CV concepts and services to enhance rail crossing safety.

The following modifications and enhancements were incorporated:

- Enhancements and modifications to the RCVW algorithm to include additional functionality such as an updated RCVW warning formula, vehicle deceleration rate values based on vehicle type, System Fault checks, configurable system parameters and a vehicle “snap-to-lane” function
- Updates of the systems to meet current CV standards, such as Society of Automotive Engineers (SAE) J2735-2016[4]
- Use of Institute of Electrical and Electronics Engineers (IEEE) 1570 serial communications device that provides a fail-safe interface between the device and highway sides of an HRI
- Use of Controller Area Network (CAN) bus vehicle data as input to the VBS
- Use of a dual phase Real-Time Kinematics (RTK) vehicle positioning system to improve Global Navigation Satellite System (GNSS) positional accuracy
- Use of DSRC technology to broadcast GNSS correction data

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[4] The standard SAE J2735-2016 was the latest version at the time of the project. SAE has since released an updated version of the standard which is SAE J2735-2020.

- Updates of Driver Vehicle Interface (DVI) visual and audio alerts based on published human factors design reports for CVs (see Section 2.4) and in-vehicle safety applications

1.3 Overall Approach

The approach was to:

- Acquire a better understanding of the state of the art CV projects and applications across the United States by staying abreast of related DOT CV activities and programs that could potentially impact the project
- Identify outreach opportunities to allow a broader dissemination of the RCVW project and its progress

These initial tasks facilitated an ensuing review of relevant changes to the CV and AV technologies to help better define the desired functionality for RCVW II.

The tasks were:

- An update of the design and architecture documentation and RCVW performance requirements
- A review of published human factors studies to update the visual and audio alerts
- A Positional Solution Comparative Analysis to identify the optimal GNSS system
- Developing and constructing the system hardware and software
- A controlled field test of the RCVW system

1.4 Scope

The RCVW II system is designed in accordance with the following:

- The system is installed in an HRI equipped with active warning devices such as gates, bells and or flashers.
- The HRI consists of a single train track.
- The HRI is perpendicular to the approach lane.
- No nearby traffic intersections are present.
- Information from the Roadside-Based Subsystem (RBS) is broadcasted over a DSRC radio.
- Information broadcasted from the RBS is received by an in-vehicle DSRC radio.

1.5 Organization of the Report

The report is organized as follows:

Section 1 provides background information on the project.

Section 2 describes the overall system and summarizes the results and deliverables.

Section 3 presents the project conclusions and future RCVW system and application enhancements.

Appendix A gives the RCVW system parameters.

Appendix B presents the field test and evaluation final report.

Appendix C gives the RCVW system requirements.

2. Summary of Results and Deliverables

2.1 Stakeholder Outreach and Coordination

To better develop and update the RCVW system design and architecture for RCVW II, stakeholder coordination input was needed. As an active member of the CV and automated vehicle (AV) community, the Battelle team participated in several workshops and webinars related to the following: CV/AV technologies and programs, engaged in communication with other contractors, stakeholders, and associated research/activities, and participated in seminars and conferences to present the RCVW II system and project efforts.

2.1.1 Workshops and Webinars

On December 18, 2018, the team attended the National Operations Center of Excellence's (NOCoE) webinar Transforming the Transportation Industry with Cooperative Research Mobility Applications (CARMA) (National Operations Center of Excellence, 2018). The webinar introduced CARMA and showcased its plugins and features. One takeaway of particular interest from this webinar was to learn the CARMA "Yield" functionality, which is defined as slowing down a trailing cooperating CV to avoid a collision. In RCVW II, a similar functionality could be included where a lead vehicle equipped with RCVW II communicates the "HRI Active" to trailing, cooperating CVs so that they could reduce their speed by using a Coordinated Adaptive Cruise Control functionality. This functionality is out-of-scope for the current project, but knowledge of it provided an awareness of an opportunity to ensure that a revised RCVW design should be extensible so that additional functionality can be easily implemented.

In April 2019, the team attended the joint FHWA and FRA webinar on Autonomous and Connected Vehicles at Rail Crossings. The webinar presented an update of the RCVW project as well as a study on Railroad Considerations for Connected and Automated Vehicle Interaction with HRIs. Questions from the audience served as a refresher to the team into the general public perception of the system and provided guidance into future outreach and coordination events.

On October 2019, the team participated in the SAE Vehicle to Everything (V2X) Core Technical Committee which covers the SAE J2735 standard. The purpose of the meeting was to review the modifications to the standard for the SAE J2735-2020 version of the specification. The team was able to learn and become familiar with the standard related to extended support of the C-V2X functionality and discussed the RCVW signaling solution for rail crossings directly with the committee chairperson.

2.1.2 Outreach Activities

The goals for the outreach activities were:

1. To let the stakeholder know that these technologies are advancing
2. To receive feedback regarding the system requirements development
3. Encourage railroads to engage with highway stakeholders to develop standards and practices related to these types of communications

FRA and the Battelle team participated in the railroad conferences presented in Table 2 and provided an overview of the RCVW Part II project.

Table 2. Stakeholder Engagement Conferences

Conference	Sponsor Entity	Location	Date
Joint Rail Conference on Railroad Engineering	American Society of Mechanical Engineers (ASME)	Snowbird, UT	March 2019
Rail Crossing Committee Meeting	Association of American Railroads (AAR)	Columbus, OH	June 2019
Rail Conference	American Public Transportation Association (APTA)	Toronto, ON (Canada)	June 23, 2019
Railway Interchange	American Railway Engineering Maintenance-of-Way Association (AREMA)	Minneapolis, MN	September 22, 2019

2.2 RCVW System Description and Updated Functionality

The RCVW system leverages the components and technologies developed under previous DOT CV deployment projects, including additional capabilities to enhance the safety of CVs at HRIs. The goal of the system is to increase the awareness of a driver approaching an HRI taking into consideration the vehicle speed and position, driver actions (i.e., deceleration rate and reaction times), and efficacy of in-vehicle alerts.

This section provides the RCVW system description and updated functionality. Appendix C presents the requirements for the project.

2.2.1 RCVW System Concept

1. An HRI equipped with the RCVW system constantly broadcasts over DSRC the following HRI-specific data:
    a. Map Data (MAP) which includes approach zone and HRI geometry
    b. Signal Phase and Timing (SPaT) data which includes HRI status (i.e., whether an HRI is active or not)
    c. Radio Technical Commission for Maritime Services (RTCM) corrections (to be used by a vehicle onboard Global Positioning System [GPS])
2. A vehicle equipped with the RCVW system enters the range of a known RBS (i.e., defined by the Distance to HRI parameter [see Appendix A] and its VBS begins processing the HRI-specific data it receives. At this point, System Fault processing initiates. See Section 2.2.2.
3. The vehicle enters the approach lane (MAP).

4. If the vehicle VBS receives and processes data from the RBS indicating that the HRI is not active, no alerts or warnings are issued, and the system continues to process the received data.
5. If the vehicle continues within the approach lane, and its VBS receives and processes data indicating that the HRI is active, the system will:
    a. Issue an audio and graphic alert to inform the driver of an active HRI ahead
    b. Continually determine the vehicle position relative to the HRI
    c. Correlate vehicle speed and performance parameters versus position with respect to the HRI to assess the probability of a violation
    d. Issue an audio and graphic warning if a violation is likely imminent (i.e., system algorithm detects that the vehicle's distance to the HRI is not sufficient to allow the vehicle to stop before reaching the stop bar, when applying nominal braking, at its current speed).
    e. Continue to correlate vehicle speed and performance parameters versus position with respect to the HRI to determine whether the driver is responding to the in-vehicle warnings. If the driver performs corrective actions (i.e., braking), it will extinguish the warning message and revert to an inform alert (i.e., if the HRI is still active) or extinguishes all alerts when HRI is no longer active.

Figure 1 illustrates the RCVW system concept.

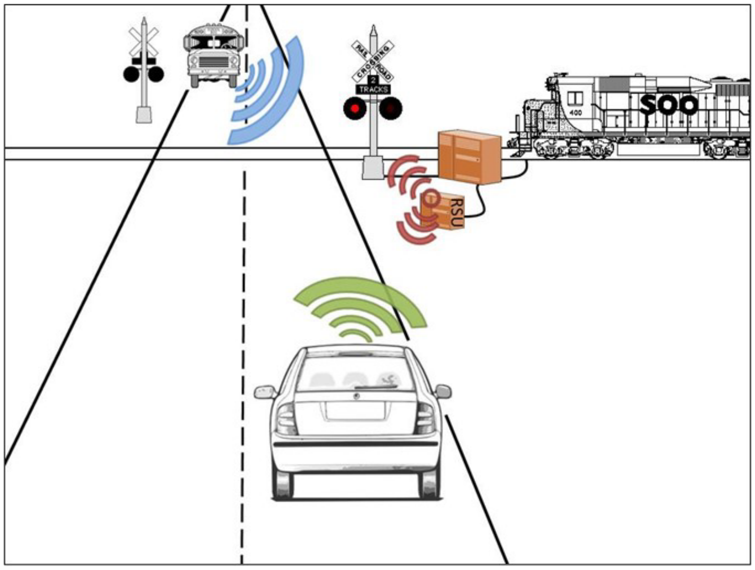

Figure 1. RCVW Application Concept

2.2.2 RCVW System Fault Checks

The RCVW II project implemented the following System Fault checks.

Loss of DSRC Data (System Fault Condition)

1. A vehicle equipped with the RCVW system is within the range of a known RBS (i.e., defined by the Distance to HRI parameter [see Appendix A]) and its VBS begins processing the HRI-specific data it receives.
2. If the system fails to receive DSRC over a set time (e.g., Message Expiration parameter [see Appendix A]), a one-time System Fault audio message and a System Fault graphic message is presented to the driver. The graphic message remains on screen until DSRC data is restored. At this point, the RCVW resumes normal operation.
3. The fault graphic message is removed once the vehicle is outside the range of the RBS or when DSRC data is restored. At this point, the RCVW system resumes normal operation.

Note: The communication range as well as the Message Expiration values are configurable parameters of the system.

Loss of MAP/SPaT Data (System Fault Condition)

1. A vehicle equipped with the RCVW system is within the communication range of a known RBS (i.e., defined by the Distance to HRI parameter [see Appendix A] where the RBS is constantly broadcasting HRI-specific specific data (e.g., MAP, SPaT, and RTCM corrections).
2. The vehicle enters the approach lane (MAP) and it begins processing the HRI-specific data it is receiving.
3. If the system fails to receive MAP and/or SPaT data over a set period of time (i.e., Message Expiration parameter [see Appendix A]), it presents a one-time System Fault audio message and a persistent System Fault graphic message to the driver.
4. The fault graphic message is removed once the vehicle is outside the range of the RBS or reception of SPaT or MAP data is restored. At this point, the RCVW system resumes normal operation.

Degraded GPS - GPS Module Position Solution (System Fault Condition)

1. A vehicle equipped with the RCVW system is within the communication range of a known RBS (i.e., defined by the Distance to HRI parameter [see Appendix A] where the RBS is constantly broadcasting HRI-specific specific data [MAP, SPaT and RTCM corrections]).
2. If the RCVW GPS module fails to receive RTCM corrections or its position algorithm does not reach or loses its RTK solution (i.e., this means that the GPS module is not able to completely determine its position algorithm and as a result, is not able to calculate the most accurate position), the DVI presents a one-time System Fault audio message and a persistent System Fault graphic message to the driver.
3. The fault graphic message is removed once the vehicle is outside the range of the RBS or the GPS module reaches an RTK solution. At this point, the RCVW system resumes normal operation.

Degraded GPS—GPS Rate Check/GPS Loss (System Fault Condition)

4. A vehicle equipped with the RCVW system is constantly receiving GPS location messages from its GPS module.
5. If the system's reception rate of GPS location messages from the GPS module falls below a minimum specified value (i.e., due to loss of GPS signal or GPS module communication issues), it presents a one-time System Fault audio message and a persistent System Fault graphic message to the driver.
6. The fault graphic message is removed once the vehicle's reception rate of GPS location messages from the GPS module is above the minimum specified value (i.e., V2 Minimum Location Frequency parameter [see Appendix A]). At this point, the RCVW system resumes normal operation.

Loss of IEEE 1570 Heartbeat

1. A vehicle equipped with the RCVW system is within the range of a known RBS (i.e., defined by the Distance to HRI parameter [see Appendix A]) where the RBS is constantly broadcasting HRI-specific specific data (MAP, SPaT, and RTCM corrections).
2. If the system's RBS is configured to receive HRI status from an IEEE 1570 device, and fails to receive the "Heartbeat" signal from the IEEE 1570 device over a set period of time, the vehicle system presents a one-time System Fault audio message and a System Fault graphic message to the driver.
3. The fault message is removed once the vehicle is outside the range of the RBS or the heartbeat message is restored. At this point, the RCVW system resumes normal operation.

2.2.3 Vehicle "Snap-to-Lane" Function

The "Snap-to-Lane" function detects when the vehicle location data is deviating excessively from the approach lane (MAP) and automatically "Snaps" the vehicle back to the lane based on its previous heading. The functionality can be better understood by the following sequence:

1. A vehicle equipped with the RCVW system enters the communication range of a known RBS (i.e., defined by the Distance to HRI parameter [see Appendix A]) where the RBS is constantly broadcasting HRI-specific specific data (MAP, SPaT, and RTCM corrections).
2. The vehicle enters the approach lane (MAP).
3. The vehicle location data begins to drift and positions the vehicle outside a pre-defined area in the MAP.
4. The system detects this drift and "Snaps" the vehicle location back to the lane based on its previous heading.

Note: During this process, the RCVW system continues its normal operation.

2.2.4 System Configurable Parameters

The RCVW II system incorporates a series of system configurable parameters used by the algorithm to generate warnings and alerts. These parameters allow a configuration of the system depending on several factors such as vehicle type, deceleration, antenna location, vehicle length, and road grade. Appendix A provides a full description of these parameters. These parameters also allow for fine tuning the system by modifying specific values such as Application Latency or Communication Latency.

In Phase I of the RCVW project, the stopping distance formula (see Figure 2) was employed to determine if the in-vehicle system is required to issue an alert to a driver approaching an active HRI (Neumeister, D., Zink, G., & Sanchez-Badillo, A., 2017). This formula included the speed of the vehicle (v), the coefficient of friction of the surface (μ), the acceleration of gravity (g), and the driver reaction time (t_R).

$$D_{stop} = vt_R + \frac{v^2}{2\mu g}$$

Figure 2. RCVW Phase I Warning Formula

A flaw with this approach was that the coefficient of friction is not easily determined since it varies depending on the road surface and tire material, design, and wear. Also, weather and road grades were not considered in this formula.

The RCVW II system, now uses the current American Association of State and Highway Transportation Officials (AASHTO) Green Book (American Association of State and Highway Transportation Officials, 2018) Stopping Sight Distance formula seen in Figure 3 (i.e., modified to include additional information unique to the current implementation).

$$D_{Stop} = E_P + E_N + (0.278) * v * (t_R + t_C + t_A) + \frac{(0.039 * v^2)}{((\alpha/g) + G)}$$

Figure 3. RCVW II Warning Formula

Where:

D_{Stop} = distance in meters

- E_P = GPS error in meters
- E_N = antenna placement in meters
- V = speed meters per second (m/s)
- t_R = perception-reaction time in seconds
- t_C = communication latency in seconds
- t_A = application latency in seconds
- a = acceleration in meters per second per second
- G = grade, rise/run meters per meter
- g = acceleration of gravity 9.8 meters per second per second

The Green Book suggests a standard perception-reaction time of 2.5 seconds which covers 90 percent of all drivers at simple to moderately complex driving situations. It also covers situations that are more complex or critical and has guidelines for increasing this time to anywhere from 3 seconds to 9.1 seconds depending on the environment. A comfortable deceleration rate of 3.4 m/s^2 also covers 90 percent of all drivers in both dry and wet conditions given current road surface tire, and vehicle technologies. This deceleration rate was used as a standard for light vehicles. Considerations were given to decrease the deceleration rate for heavy and light trucks. The deceleration rates used are based on the current Federal Motor Vehicle Safety Standards (FMVSS) 121 and FMVSS 135.[5] These values are set and can be updated in the RCVW system by means of the system parameters found in Appendix A. A ratio between the AASHTO guidelines for stopping sight distance and the FMVSS requirement for passenger cars in ideal conditions was calculated and the same ratio was used to generate recommended deceleration values to use for light and heavy trucks. The following are the deceleration rates used in RCVW II:

- Light Vehicle (i.e., vehicles with a Gross Vehicle Weight Rating [GVWR] of 10,000 pounds or less): 3.4 m/s^2
- Light Truck (i.e., vehicles with a GVWR of 10,001 pounds to 26,000 pounds): 2.148 m/s^2
- Heavy Truck (i.e., vehicles with a GVWR of more than 26,000 pounds): 2.322 m/s^2

Appendix B presents more information regarding the calculations used to determine deceleration rates.

2.3 RCVW Architecture and Design

The RCVW system consists of two physically separate subsystems: a VBS installed in vehicles and an RBS integrated with roadside infrastructure at HRIs. Both subsystems share some common hardware and software components, as well as include unique components. The RCVW system was developed on top of the existing V2I Hub software (United States Department of Transportation, 2021). V2I Hub is a singular communication platform with a set of integrated plugins to supply and receive information from deployed system components. Each plugin is responsible for registering with the V2I Hub as well as providing which message types it will request to receive. Plugins can be either message producers, message consumers or both. One key advantage of using the V2I Hub 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

The following is an overview of the RCVW hardware and software used by both subsystems. Specific details regarding the hardware used for the current RCVW system (such as part number, manufacturer and model) can be found in the RCVW II field test report in Appendix B.

Computing Platform

The heart of the RCVW system is the computer platform (CP). Each RBS and VBS is controlled by its own CP. The V2I Hub software resides within the RBS and VBS CPs. The CP was chosen from commercial options that were available during the design phase. The need to use a common

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[5] FMVSS Guide requirements for vehicle stopping distance, standards 121 and 135.

CP for both RBS and VBS RCVW systems dictated that the CP would require high-speed Ethernet, TIA/EIA-422/485, Digital Input/Output (DIO), Universal Serial Bus (USB), high-speed CAN, and DVI interfaces. Whereas the previous version of RCVW also required integrated Bluetooth, Wi-Fi, DSRC, and/or cellular networking. This release simplifies the design of the CP by decoupling the necessary wireless communication, namely GNSS and DSRC, into external hardware models. The Operating System (OS) selected for the CP is Linux version 16.04 built on the 4.15.0-29 Linux kernel as it allows a flexible platform for product development due to it being open source and easily customized. A common OS is used in both RCVW subsystems, which is designed to make use of the V2I Hub platform.

DSRC Radio

The DSRC radio transmits and receives messages in accordance with the IEEE 802.11p,[6] 1609.2,[7] and SAE J2735[8] message standards. Communications from the CP to the DSRC radio is done via the User Datagram Protocol (UDP) defined in the RSU 4.1 specification (Federal Highway Administration, 2017).

The RCVW system utilizes SPaT, MAP and RTCM-correction messages from the SAE J2735 message set. The MAP messages contain the intersection geometry including the vehicle lanes and tracked vehicle lanes (e.g., train tracks) for the HRI. These messages are used by the VBS to fix the location of a vehicle within an HRI (i.e., the HRI Hazard Zone or HRI Approach Zone). The SPaT message contains the status of each lane in the HRI. For example, at a simple HRI with vehicle lanes crossing a single set of train tracks and no nearby traffic intersection, 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 will be used by the VBS to determine HRI status-based messaging. The RTCM-correction message contains the differential GNSS information, including RTKs, to be used by the VBS position solution.

GNSS Module

A multi-band GNSS module with built-in RTK technology resides within the VBS to provide real-time lane-level position data. A similar device resides within the RBS to provide RTCM corrections to be broadcasted over DSRC.

2.3.1 RCVW System Architecture Overview

Figure 4 shows a high-level architectural overview of the RCVW system. The RBS and the VBS subsystems have a CP running the V2I Hub software interfaced with a DSRC radio. The RBS interfaces with the HRIC for the HRI status input in creating the SAE J2735 messages that are transmitted to the VBS from the RBS radio. The VBS receives SAE J2735 messages and processes them in the RCVW plugin of the VBS CP. The DVI delivers graphical and audible

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[6] IEEE approved amendment to the IEEE 802.11 standard to add wireless access in vehicular environments

[7] IEEE Standard for Wireless Access in Vehicular Environments – Security Services for Applications and Management Messages

[8] SAE Dedicated Short Range Communications (DSRC) Message Set Dictionary

notifications to the vehicle operator. The DVI, which is an external display and speakers, is connected to the VBS via a High-Definition Multimedia Interface (HDMI) connection. The dotted lines indicate the capability of the RBS CP to receive HRI status directly from the HRIC or, alternately, the IEEE 1570 Serial Interface (IEEE Standards Association, 2002). In addition to providing HRI status, the IEEE 1570 interface provides a heartbeat indicating health status of the link between the IEEE 1570 device and the CP. The GNSS module in the RBS subsystem produces RTCM corrections which are broadcasted via DSRC. These RTCM corrections contain real-time data about the GNSS network, as well as perturbations in the ionosphere and troposphere which are used by the VBS GNSS module to correct the position solution of the vehicle.

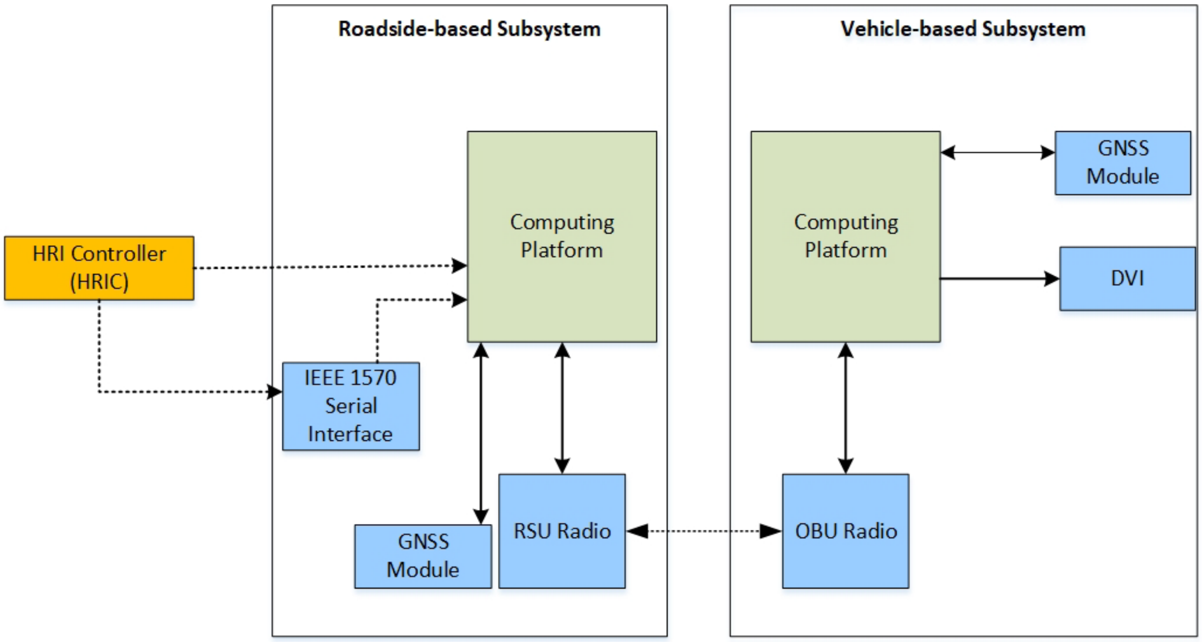

Figure 4. RCVW System Architecture Overview

2.3.2 RCVW System Design Overview

The HRI Hazard Zone, the area between the stop bars on either side of the HRIs, is site-specific and static. It is defined within the RBS CP at the time of deployment and communicated to the VBS CP for determining clear HRI warnings. The geospatial dimensions of the HRI Approach Zone are a function of vehicle approach direction to the HRI and, where applicable, the type of active warning devices implemented at the HRI (e.g., two quadrant versus four-quadrant design). These same factors are used in determining the placement of warning gates and/or stop lines, as specified by the Manual on Uniform Traffic Control Devices (MUTCD) (Federal Highway Administration, 2009) and the American Railway Engineering and Maintenance-of-Way Association (AREMA) Communications & Signal Manual (American Railway Engineering and Maintenance-of-Way Association, n.d). The intention is that the HRI Hazard Zone and end of the HRI Approach Zone closely align with standard rail warning markings and device placements. Polinori et al. (2020) provides more details and definitions of the HRI Hazard Zone and HRI Approach Zone (Polinori, A., Paselsky, B., & Sanchez-Badillo, A., 2020).

HRIs equipped with active warning devices (e.g., flashing lights, gates, etc.) are required by Federal regulation to provide a minimum of 20 seconds warning time to highway vehicles before being occupied by rail traffic. The fail-safe logic of the train detection system triggers a preemption sequence within the HRIC that is used as an input to highway traffic controllers. The RCVW system leverages the state of the preemption signal to determine HRI status. 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 HRIC warning devices, and additional site-specific factors are considered in determining if more than 20 seconds of warning time is required. The RBS CP receives the preemption signal from the HRIC. The RBS HRI Active message sequence is triggered upon receipt of the preemption signal. If a VBS is within the HRI Approach Zone while the HRI Active message is being broadcast, the VBS will issue an alert, and, if necessary, an RCVW warning.[9] It is critical that the VBS receive timely HRI Active messages to issue valid and actionable RCVWs.

2.3.3 System of RCVW Interfaces

Figure 5 depicts the RCVW system composed of two subsystems with interfaces. The RBS provides HRI attributes and HRI status. Using the information provided by the RBS, the VBS determines when to provide informational and fault alerts and RCVWs.

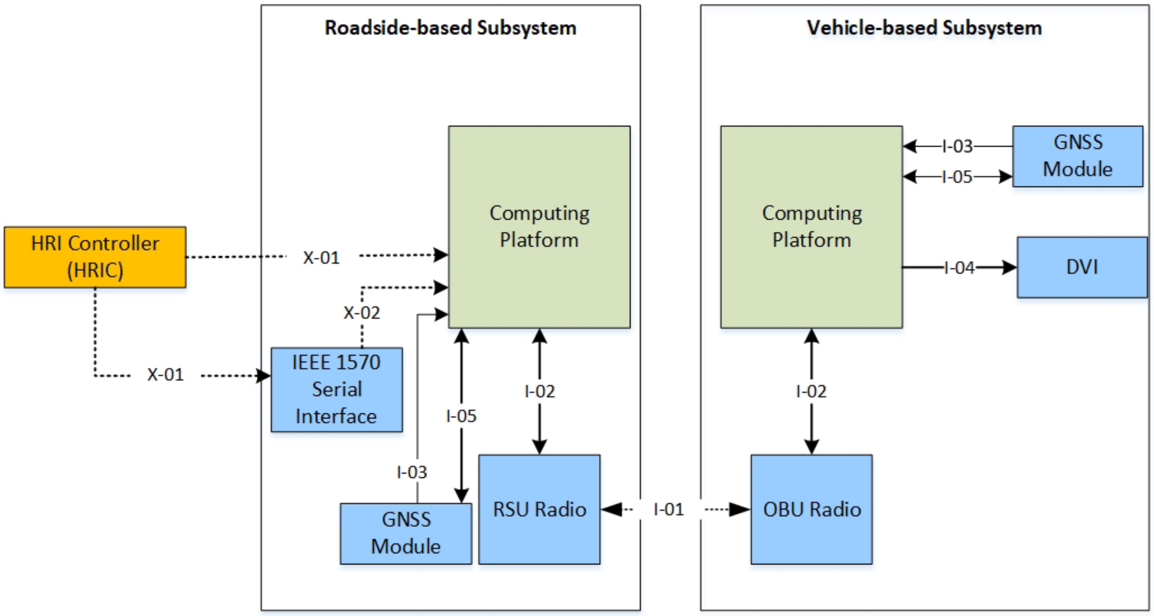

Figure 5. RCVW Overview with Interfaces

Table 3 lists each of the interfaces connecting the subsystems illustrated in Figure 5, as well as the connections made to external systems.

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[9] RCVW warnings within this zone will be determined by an algorithm executed by the VBS that will consider factors including typical reaction time of an operator, assumed worst-case positional inaccuracy, vehicle speed and braking performance.

Table 3. RCVW System Interfaces

Interface Identifier	Interface Type	Exchanged Information
I-01	DSRC	The RBS sends information to the VBS about the geographic layout of the HRI as a MAP message. The RBS also sends HRI status information to the VBS in a SPaT message, and RTCM Correction messages containing the differential GNSS correction. All messages are sent via DSRC.
I-02	TCP Socket	The RBS and VBS have a socket connection to their DSRC radio to send and receive messages.
I-03	TCP Socket	The RBS and VBS have a socket connection to their GNSS module to receive position and time information. This interface uses the Linux GPSD service daemon as a proxy for sending/receiving GNSS data.
I-04	HDMI	The VBS CP transmits warnings and alerts to the DVI.
I-05	USB	The RBS and VBS have a serial connection to the GNSS receiver to send and receive messages.
X-01	Discrete Voltage	The RBS CP or, alternately, the IEEE 1570 device receives the preemption signal from the HRIC.
X-02	IEEE 1570 Data Packet	The IEEE 1570 device sends IEEE 1570 formatted data packets detailing crossing status.

2.3.4 RCVW Inputs and Outputs

There are five data input types to the RCVW system (Polinory, A., Baumgardner, G., Paselsky, B., & Sanchez-Badillo, A., 2020):

- The first input type consists of 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 (e.g., pedestrian, vehicle, etc.), the permitted lane movements (e.g., straight, left turn, right turn, etc.), lane direction (e.g., approach or egress) and lane connection information to 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 to the VBS via DSRC. The MAP for the HRI is generated manually by hand, ideally using the DOT ISD Builder Tool for SAE J2735.[10]

- The second is HRI status. The status, either active or inactive, is provided to the RBS by the HRIC. The HRI status is transmitted by the RBS via the SAE J2735 SPaT message. The SPaT information is used by the VBS RCVW application for determining when an alert or warning should be issued.
- The third input consists of GNSS 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 GNSS must be sufficient to allow placement of the VBS within the lane information provided by the SAE J2735 MAP message. The RCVW system utilizes a high precision multi-band RTK enabled GNSS module that provides a stable sub meter accuracy in optimal conditions.
- The fourth input consists of vehicle speed and acceleration. Vehicle speed used by the VBS HRI algorithm in addition to other parameters when determining if RCVW warnings and alerts should be displayed, and the changes in speed, i.e., the acceleration of the vehicle, is used to determine if user action is sufficient to extinguish an active alert. The speeds can be acquired directly from the CAN network built-in to the vehicle, but alternatively are available from the GNSS receiver.
- The fifth is vehicle type information. The system is prepared to receive three vehicle types:
  - Heavy Truck
  - Light Truck
  - Light Vehicle

This information is provided via a configuration parameter into the VBS RCVW application for use in the RCVW prediction algorithm.

2.3.5 RCVW Vehicle-based Subsystem

The VBS hardware and software is designed for alerting/warning the CV driver of imminent rail crossing violations.

Hardware

The hardware for the VBS consists of a CP, DSRC radio, DVI, and GNSS module.

Computer Platform

The CP serves as the central hub for all RCVW-specific functions on the CV. This device communicates with the other RCVW subsystems as well as the external equipment on the CV.

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[10] Connected Vehicles website.

DSRC Radio

The DSRC radio is the low latency wireless communication method used to transmit/receive the HRI related information that the RCVW algorithm needs to perform its calculations such as HRI geography, HRI status (i.e., active or inactive) and RTCM corrections.

Driver Vehicle Interface

The DVI for displaying and annunciating RCVWs is a commercial-off-the-shelf external Liquid Crystal Display (LCD) display with speakers connected directly to the CP through the HDMI cable. The unit displays warnings and alerts to the driver. For example, an alert is displayed and annunciated if a “known” RBS is not operational. Similarly, a warning is displayed and annunciated if the vehicle is on course to commit an RCVW and/or the roadway vehicle is stopped within the HRI hazard zone

GNSS Module

The GNSS module is used to determine the position of the VBS. The positional accuracy of the GNSS must be sufficient to allow placement of the VBS within the lane information provided by the SAE J2735 MAP message. System requirements (see Appendix C) specify +/-1.5 meters as the GNSS accuracy to achieve lane-level accuracy for the VBS and that the receiver is capable of reaching an RTK solution. The VBS uses a dual phase, dual frequency RTK enabled GNSS module to obtain the needed level of GNSS accuracy. In addition to positional accuracy, the GNSS receiver supplies accurate heading information. The RCVW software algorithm automatically adapts to GNSS lateral positional inaccuracies by “snapping” to a known near lane in the MAP that has been designated for travel in the same direction as the vehicle heading prior to the “snapping.”

Software

The VBS software generates informational and fault alerts and RCVWs to the driver of a CV.

The RCVW application is designed to interface with the V2I Hub software platform. The logic required to perform the needed functions is developed as a set of plugins. Each plugin performs a single discrete function. The diagram in Figure 6 illustrates the plugins, including how they interact with RCVW system components.

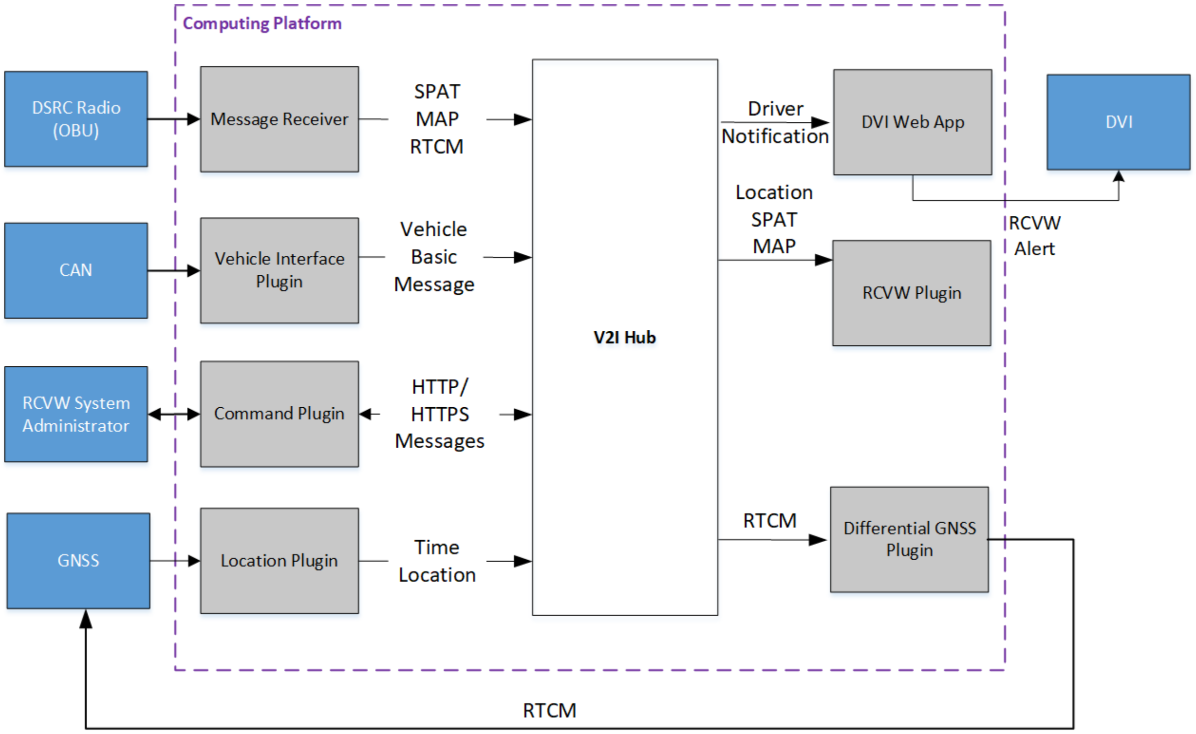

Figure 6. VBS Software Design

Table 4 provides a brief description of each plugin and its associated data exchange.

Table 4. RCVW System VBS V2I Hub Plugins

Plugin	Description	Plugin Input	Plugin Output
Location Plugin	This plugin interfaces with the GNSS hardware and provides the current location and time information to the rest of the system.	Output stream from GNSS receiver	Location Message
Message Receiver Plugin	The DSRC Receive Message plugin relays messages received via the DSRC radio to the rest of the system.	Messages from DSRC Radio	SPaT Message MAP Message RTCM Message
DVI Web App	The Driver Notification web application alerts/warns the vehicle driver via visual and audible cues.	RCVW Warning Clear HRI RCVW System Failure	Suitable audio output annunciated via DVI speakers Events shown on D
Vehicle Interface Plugin	The Vehicle Interface plugin interfaces to the vehicle CAN network to access Vehicle Basic Messages (VBMs)	CAN messages	VBM message

Plugin	Description	Plugin Input	Plugin Output
RCVW Plugin	The RCVW Plugin application processes information from VBS support plugins to determine whether to issue driver warnings and alerts.	SPaT Message MAP Message Location Message	Driver Notification Message
Command Plugin	Interfaces with V2I Hub administration portal for system diagnosis and configuration	Hypertext Transfer Protocol (HTTP)/Hypertext Transfer Protocol Secure (HTTPS) messages	N/A
Differential GNSS Plugin	This plugin receives SAE J2735 RTCM correction messages and passes them on to the GNSS receiver.	RTCM Message	N/A

Figure 7 shows the applications and their data flow inside the RCVW VBS system. To simplify the diagram, the V2I Hub core message router is not shown. Plugins that produce and send messages to the V2I Hub are shown as being directly connected to the consumer of those messages. Figure 7 describes additional details regarding the RCVW application for the VBS.

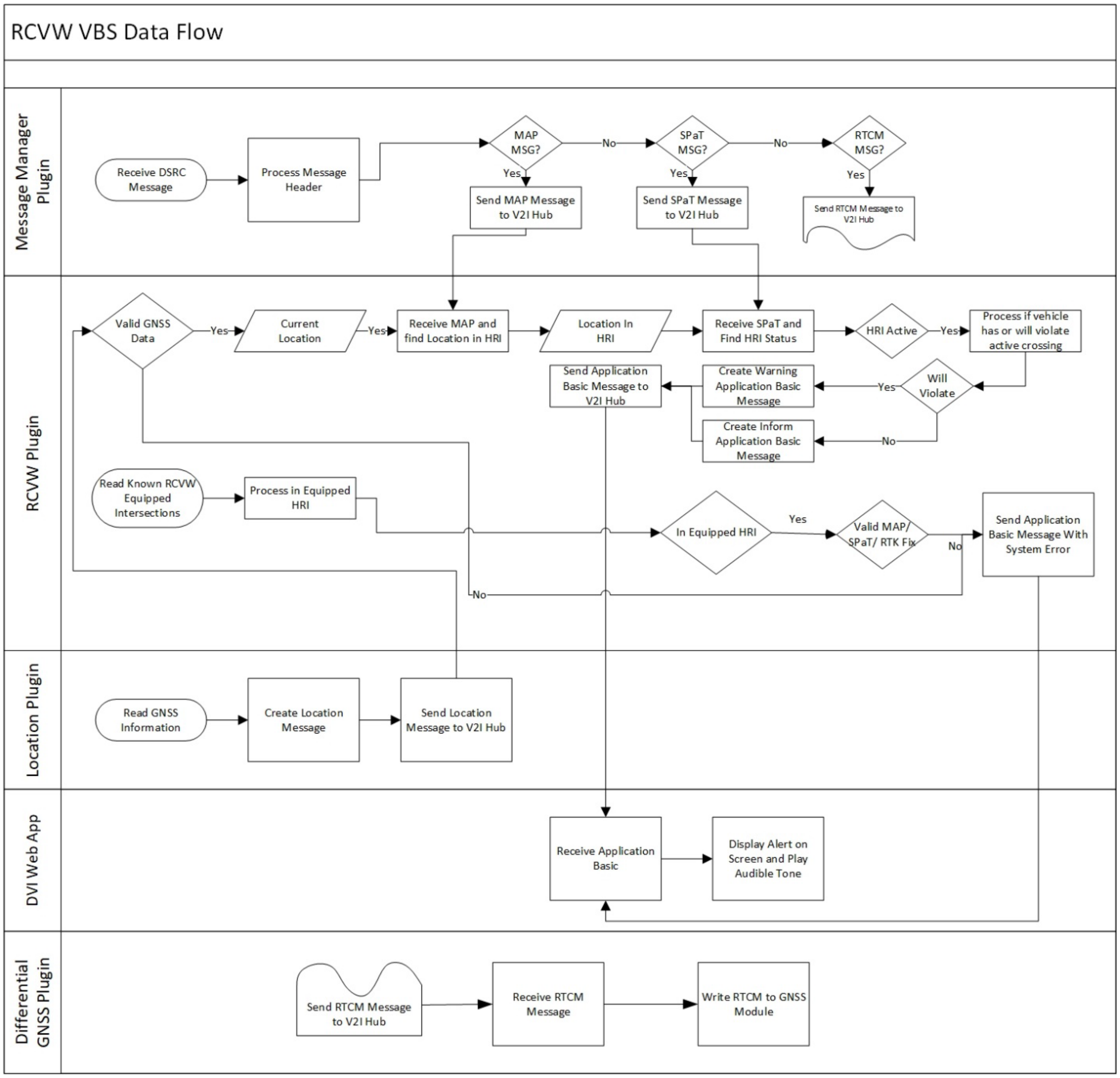

Figure 7. RCVW VBS Applications Flow Chart

VBS Support Plugins

The RCVW application plugin is supported by a suite of plugins designed to interface with the V2I Hub platform. The Message Receiver plugin acts as the interface to the DSRC radio and converts the encoded SAE J2735 messages into a common format used by the V2I Hub platform. The differential GNSS plugin enhances the GNSS position using the correction data from the RTCM SAE J2735 message. The DVI web application supports issuing visual and audible warnings and alerts to the driver and uses notification outputs from the RCVW plugin application to do so. 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 a “known” RBS and the current vehicle location provided by the Location plugin, the RCVW application plugin determines if the vehicle is approaching an HRI, and more importantly, its location relative to the HRI stop bar. The RCVW application plugin processes the HRI geospatial information to determine a site-specific HRI Approach Zone. The RCVW application plugin also 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 determines if an alert/warning is needed to notify the vehicle operator of a potential RCVW.

2.3.6 RCVW Roadside-Based Subsystem

The RBS is responsible for monitoring and reporting the status of the HRI. The RBS wirelessly transmits messages to approaching vehicles consisting of the following: specific details regarding the configuration of the HRI (MAP), HRI status, and RTCM corrections.

Hardware

The hardware for the RBS consists of a CP, a DSRC radio, and a GNSS module.

Computer Platform

The CP communicates with RCVW VBS-equipped CVs as well as the external equipment associated with RCVW prediction at the HRI. It includes interfaces to receive HRI status; broadcast HRI related information via a DSRC radio; and receive, reformat, and broadcast RTCM corrections from a GNSS device.

DSRC Radio

The DSRC radio is the low latency wireless CP used to transmit the HRI related information that the VBS RCVW algorithm needs, such as HRI configuration/geography, HRI status (i.e., active or inactive) and the RTCM corrections (i.e., sent from the GNSS module).

GNSS Module

The GNSS module located at the RBS is configured to function as an RTK base station. The base station generates reference data corrections that are used by the VBS GNSS module to increase its location accuracy. These corrections are sent to the RBS CP and adapted to the SAE-J2735 standard before being forwarded to the DSRC radio.

HRI Status Interface

The train detection system is the source of the HRI status within the RCVW SPaT message. The HRI Active message is initiated by the preemption signal received from the HRIC.

The CP has a DB-15 DIO connector. Pins 1 and 2 are discrete inputs; pins 3 and 9 are grounds. Acceptable input voltages vary between 5–24 VDC for a logic high and for 0-1.5 VDC for logic low. A simulated HRI Active message sequence can be initiated by connecting a positive 24 VDC voltage power supply to pins 1and 9 of the DIO.

The RBS RCVW system is also configurable to convey the preemption signal emanating from the HRIC to the CP via an IEEE 1570 device. The serial communication port of the IEEE 1570 device interfaces to the Communication (COM)-1 port of the CP using TIA/EIA-422 protocol.

Software

The RBS software is designed to provide supporting information to the RCVW plugin operating on the VBS. The RBS provides detailed information about the intersection so that the VBS may determine if an RCVW will be presented to the driver. The key information exchanged includes messages providing detailed roadway geometry for the intersection, HRI status and RTCM corrections.

The RBS software is designed to interface with the V2I Hub software platform as a set of plugins. Each plugin performs a single discrete function. Figure 8 provides a block diagram showing the design of the software.

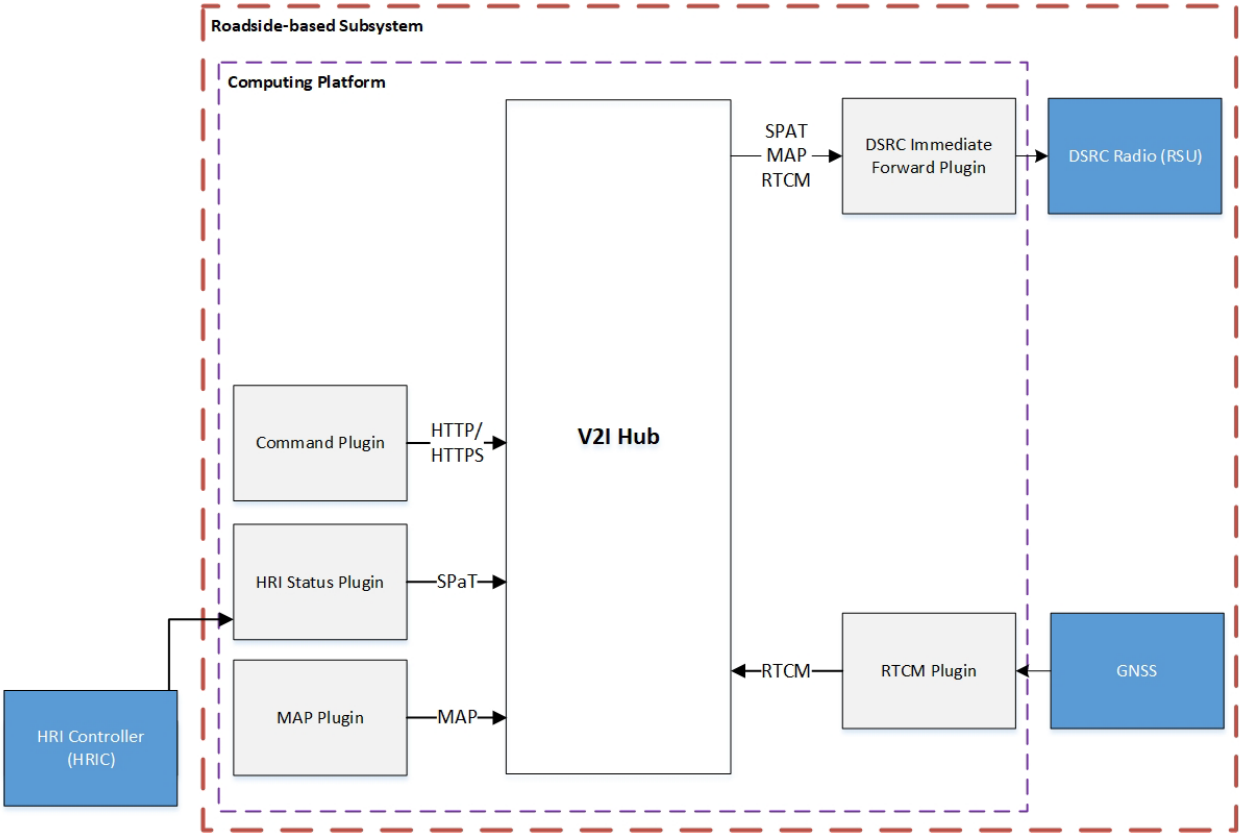

Figure 8. RBS Software Design

The RBS plugins provide situational information for the intersection such as the MAP, HRI status and RTCM messages. Table 5 outlines each plugin used in the RBS with the messages produced and consumed by each plugin.

Table 5. RCVW System RBS V2I Hub Plugins

Plugin	Description	Plugin Input	Plugin Output
MAP Plugin	Generates a site-specific MAP message for the HRI	HRI Geometry Loaded from File System	MAP Message
HRI Status Plugin	Interfaces with the HRIC and generates HRI Status message	Output from HRIC	SPaT Message
DSRC Immediate Forward Plugin	Transmits internal messages via the DSRC radio in UDP format	SPaT Message MAP Message RTCM Message	Input to DSRC
Location Plugin	Interfaces with GNSS receiver to supply the system with location and time information	GNSS National Marine Electronics Association (NMEA) Sentences	Time and Location Information
Command Plugin	Interfaces with V2I Hub administration portal	HTTP/HTTPS messages	N/A
RTCM Plugin	Receives corrections from a base station and creates the SAE J2735 RTCM correction message	RTCM Messages	RTCM Message

The MAP and HRI Status plugins work together 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 HRI Status 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 stop bar. Figure 9 and Figure 10 show the MAP and SPaT message flow in the RCVW RBS system.

The HRI Status message for the HRI contains the HRI Active signal state as “event status.” The HRI Status message contains an HRI ID which will be used to correlate the HRI Status message to its MAP message. The VBS uses both MAP and HRI Status 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, the system uses the event status “stop and remain” as the trigger for HRI Active. Figure 9 shows the flow of the MAP message in the RCVW RBS system. Figure 10 shows the flow of the HRI Status (SPaT) message in the RCVW RBS system.

The RTCM plugin reads the RTCM corrections coming from the RBS GNSS module and creates a J2735 correction message. The message is sent to the V2I Hub where the Message Manager plugin receives it, creates the UDP packet and sends it to the RSU for broadcast. Figure 11 shows the flow of the RTCM message in the RCVW RBS System.

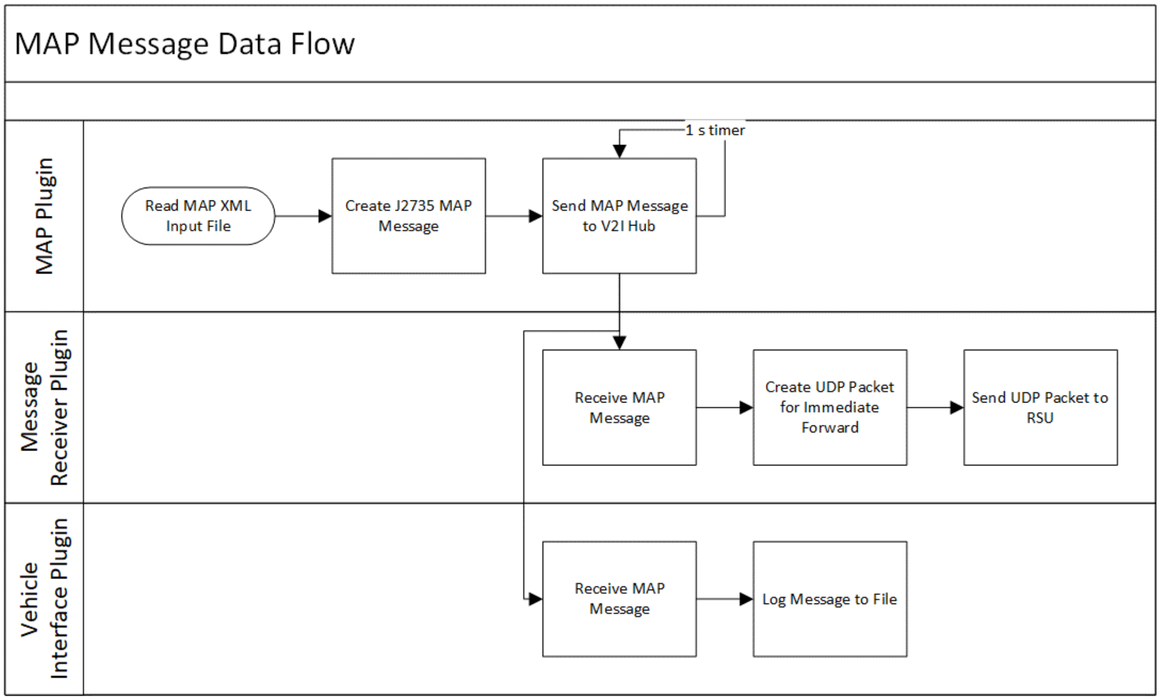

Figure 9. MAP Message Data Flow

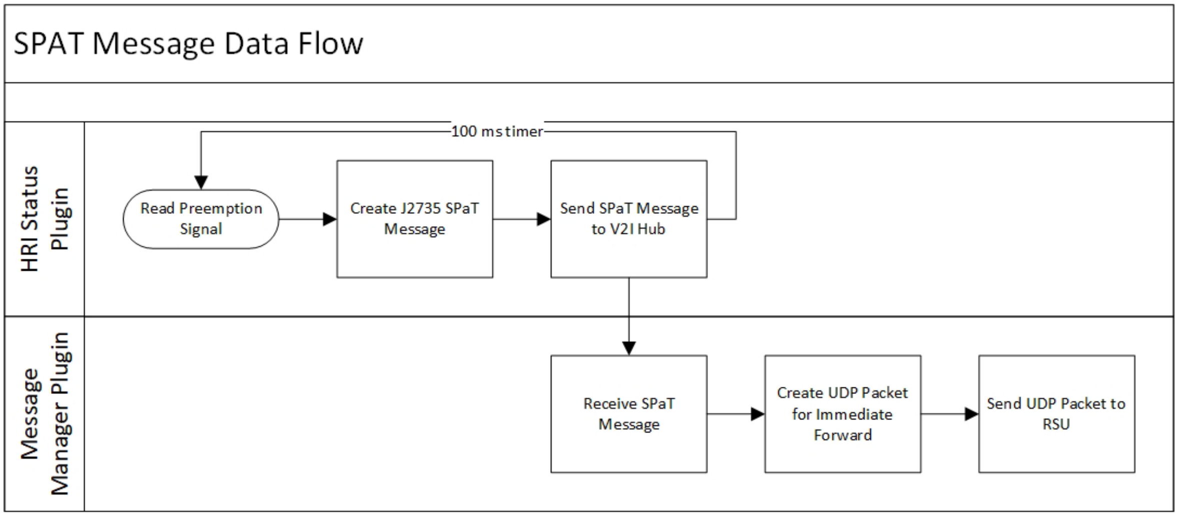

Figure 10. SPaT Message Data Flow

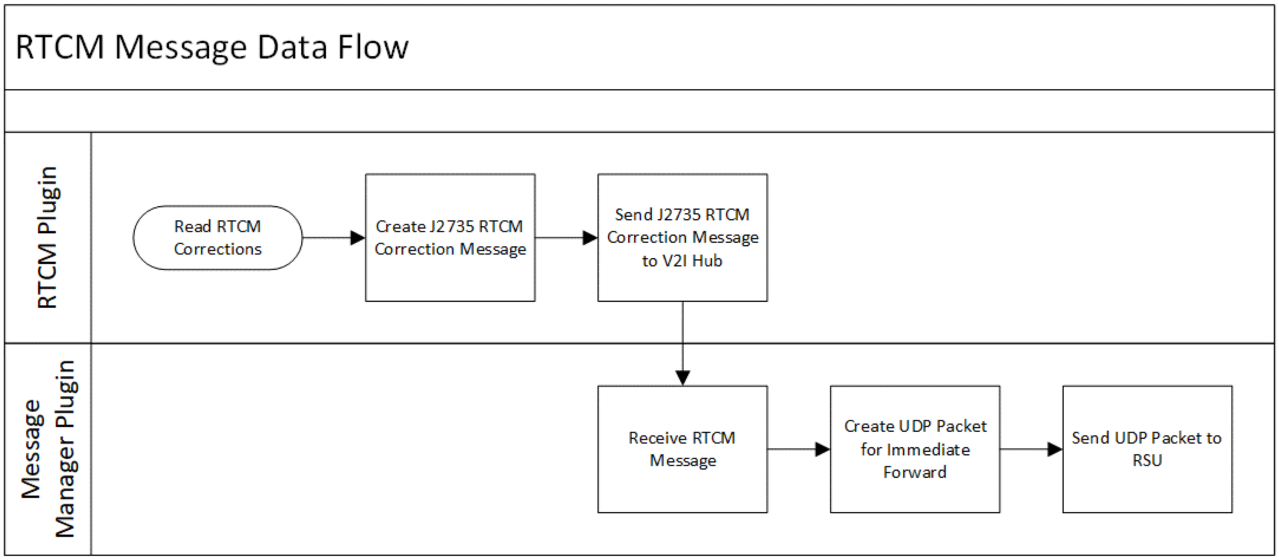

Figure 11. RTCM Message Data Flow

2.4 Updated Visual and Audio Alerts

RCVW Phase I activity identified two violation conditions that required a message to be issued to the vehicle driver: (1) RCVW warning and (2) clear HRI warning. These messages had both a visual and auditory component. In RCVW II, researchers tasked human factors/interface experts to design a DVI approach suitable for field testing and model deployment activities. The approach included engineered graphics and audibles that would support both rapid driver comprehension of the message and a safe and timely response.

The human factors research group used a scenario-driven task analysis to identify conditions where the RCVW system needed to issue in-vehicle alerts. This analysis allowed the identification of information that was needed by the driver to support safe driving decisions and actions. Using project specifications, HRI crash statistics, and discussions with FRA aided in to identifying specific scenarios. A subset of these scenarios was then compiled based on permutations of probable driver states, situational factors and constraints of a given situation (e.g., *Driver State*: Driver is distracted and *Vehicle State*: Vehicle is inside of the warning distance) and probable driver state, decision, and action sets (e.g., *Driver State*: Attentive, *Decision*: Compliant, *Action*: Stop) (Baumgardner, G. M., Hoekstra-Atwood, L., & Prendez, D. M., 2020). Using this list aided in generating RCVW specific design requirements which served as the design basis for the creation of the visual and auditory messages.

This section presents the messages developed for the RCVW II application along with the three primary aspects of the DVI message design characteristics: 1) general, 2) visual message, and 3) auditory message; along with the design guidance from reference sources, and design decisions for each message.

2.4.1 Developed RCVW II Messages

The following are the RCVW II messages that were created as a result of the research performed by the human factors research group.

Inform Message for RCVW Active

The Inform Message for RCVW Active (Figure 12) is presented to the driver when approaching an active HRI and no violations have been detected.

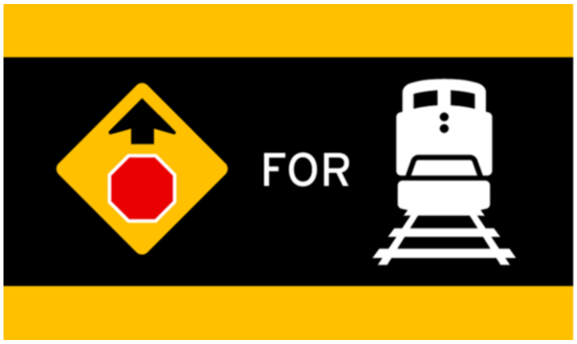

Figure 12. Inform Graphic Message

Warning Message for RCVW Warning

The Warning Message for RCVW Warning (Figure 13) is presented to the driver when the vehicle is approaching an active HRI and the system is predicting an imminent violation.

Figure 13. Warning Graphic Message

Note: The message contains a dynamic element involving the red bars on top and bottom to move back and forth.

Clear HRI Messages

Initially, the Inform and Warning messages for Clear HRI were designed to be issued when a highway vehicle is fouling the crossing when the HRI was inactive (see Figure 14) and when the HRI was active (see Figure 15). However, the current SAE J2735 messaging does not allow for the RCVW system to distinguish whether the HRI is active and inactive when a vehicle is fouling the tracks. As a result, a message was created that provides a warning to the driver when the vehicle is fouling the crossing regardless of HRI activity (see Figure 16).

Inform Message for Clear HRI (Currently Not Used)

The Inform Message for Clear HRI was created to be issued to a driver of a vehicle that is fouling the crossing, and the HRI is inactive.

Figure 14. Inform Clear HRI Message

Warn Message for Clear HRI (Currently Not Used)

The Warning Message for Clear HRI (see Figure 15) was created to be issued to a driver of a vehicle that is fouling the crossing, and the HRI is active.

Figure 15. Warning Clear HRI Active Message

Clear HRI Message

The Clear HRI message (see Figure 16) was created to be issued to a driver of a vehicle that is fouling the crossing regardless of HRI status.

Figure 16. Clear HRI Warning Message

2.4.2 General Characteristics

Warning Stages

Multi-stage warnings include one or more stages of a message that differ in criticality. The stages typically increase in urgency with each progressive stage, indicating the increasing criticality of the situation before presenting an imminent crash situation. Table 6 presents the design guidance followed.

Table 6. Warning Stages Design Guidance

ID	Guidance	Reference
1.1.1	Two-stage alerts are recommended when hard braking is to be avoided or when there is sufficient time and accuracy to estimate that the driver is on a collision path.	(Campbell, J. L., Brown, J. L., Graving, J. S., Richard, C., Lichty, M. G., Sanquist, T., Bacon, P. L., Woods, R., Li, H., Williams, D. N., & Morgan, J. F., 2016)
1.1.2	Warning messages, whether in one - or two-stage systems, should only be used in critical situations when a collision is imminent if no action is taken.	(Campbell, J. L., Brown, J. L., Graving, J. S., Richard, C., Lichty, M. G., Sanquist, T., Bacon, P. L., Woods, R., Li, H., Williams, D. N., & Morgan, J. F., 2016)
1.1.3	The urgency communicated by the message at each stage should map to the urgency of the situation.	(Campbell, J. L., Brown, J. L., Graving, J. S., Richard, C., Lichty, M. G., Sanquist, T., Bacon, P. L., Woods, R., Li, H., Williams, D. N., & Morgan, J. F., 2016)
1.1.4	When the primary goal of the system is to provide continuous information, use multi-stage graded warnings.	(Campbell, J. L., Brown, J. L., Graving, J. S., Richard, C., Lichty, M. G., Sanquist, T., Bacon, P. L., Woods, R., Li, H., Williams, D. N., & Morgan, J. F., 2016)

Design Decisions

During RCVW II, a two-stage scheme of Inform and Warning messages was developed. The following recommendations informed the design of the two messages:

- Inform: An unobtrusive message that occurs well in advance of the HRI to prepare the driver to stop. This message supplements the HRI protective devices and serves three primary objectives:
    1. Provides an advanced message to distracted or fatigued drivers who, once alerted, may require a relatively long response time

    2. Provides the status of the HRI under low-visibility conditions
    3. For drivers that intend to comply, the message may prompt an earlier deceleration response. This may preclude the need for stage-two messages.
- Warning: Obtrusive, attention-getting message that occurs if drivers are predicted to not stop before the HRI stop bar (i.e., based on the RCVW prediction algorithm) or are stopped in the HRI Hazard Zone. This message provides unique HRI violation information and serves two primary objectives:
    1. Provides a 'last-second' warning to stop for drivers who remain unaware of the active HRI ahead because of distraction or fatigue, or other impairment
    2. Provides a last-chance prompt to influence drivers who are considering proceeding across the HRI even though it is active
- Clear HRI Warning: Consists of an urgent warning for drivers that are stopped within the HRI Hazard Zone to exit by any means regardless of HRI status.

Design Basis

The following Design Basis was created from the guidelines in Table 6:

- The Inform stage should minimize hard braking for drowsy or distracted drivers or drivers who do not see the rail crossing ahead or the train approaching (1.1.1).
- The RCVW system is assumed to have enough time and kinematic information to reliably estimate that a vehicle is on a collision path with a train (1.1.1).
- The situation is safety critical since the vehicle will collide with the train and/or drive through the gates unless the driver stops before the rail crossing and outside of the HRI Hazard Zone (1.1.2).
- The first stage, the Inform message, provides a cautionary warning while the driver is still far enough away from the rail crossing such that immediate action is not necessary. The second stage, the Warning message, provides an urgent warning because the driver must start braking at the warning onset to avoid a collision with a train and/or drive through the gates (1.1.3).

In general, adding an Inform stage would prompt some drivers to begin slowing sooner, which would reduce the likelihood that a warning-level message will be needed.

Multimodal Stages

Multi-stage warnings include one or more stages of a message that differ in criticality. The stages typically increase in urgency with each progressive stage, before presenting an imminent crash situation. Table 7 presents the design guidance followed.

Table 7. Multimodal Stages Design Guidance

ID	Guidance	Reference
1.2.1	Multiple, simultaneously activated signals are used to provide redundancy, maximizing the likelihood a driver will receive the alert	(Campbell, J. L., Brown, J. L., Graving, J. S., Richard, C., Lichty, M. G., Sanquist, T., Bacon, P. L., Woods, R., Li, H., Williams, D. N., & Morgan, J. F., 2016)
1.2.2	Less imminent warning stages use less invasive signals, like visual icons, while auditory alerts can be used for more imminent warning stages	(Campbell, J. L., Brown, J. L., Graving, J. S., Richard, C., Lichty, M. G., Sanquist, T., Bacon, P. L., Woods, R., Li, H., Williams, D. N., & Morgan, J. F., 2016)

Design Decisions

For the RCVW Warning application, the current system design uses visual and auditory message modalities in both warning stages.

- Visual: The static Inform visual is displayed when a vehicle is within the range of a known RBS (defined by the Distance to HRI parameter [see Appendix A]) and the HRI is active, regardless of speed and acceleration level, and does not turn off until the HRI is inactive or the Warning message initiates. The dynamic, flashing Warning visual only appears if the onset conditions are met and stays visible until the vehicle decelerates enough to stop before the HRI (see Section 2.2.1).
- Auditory: The Inform message plays a brief sequence of chimes from when a vehicle is within the range of a known RBS (defined by the Distance to HRI parameter [see Appendix A]) and the HRI is active to draw attention to the display. If the onset conditions are met for a warning, the Warning message plays an obtrusive alert until the vehicle decelerates enough to stop before the HRI stop bar (see Section 2.2.1).

For the Clear HRI messages when the vehicle is stopped within the HRI Hazard Zone, the Clear HRI Warning message is displayed simultaneously with the same auditory sound level as the RCVW Warning message. These messages extinguish once the vehicle is moving within or has exited the HRI Hazard Zone.

Design Basis

The following Design Basis was created from the guidelines in Table 7:

- Auditory displays are not typically recommended for Inform messages (Campbell, J. L., Brown, J. L., Graving, J. S., Richard, C., Lichty, M. G., Sanquist, T., Bacon, P. L., Woods, R., Li, H., Williams, D. N., & Morgan, J. F., 2016), but are used in this application in the approach scenario at onset to ensure that drowsy or distracted drivers can receive some notice since they may not see the visual message (1.2.1).

- If the driver reaches the Inform trigger distance and the HRI is active, the Inform auditory alert accompanies the Inform visual display to alert distracted/drowsy drivers (1.2.2).
    - Note: The trigger location and design of the Inform message needs to be studied using human drivers to ensure that the timing of the trigger is optimized and that the nature of the messaging is not annoying to drivers.
- The visual Inform message is displayed when the HRI is active even though the vehicle is not traveling fast enough to trigger the Warning criteria further downstream. This approach confirms proper system operation and helps maintain driver trust in the system. Note that in this case, the auditory Inform message is not annunciated when the display state changes from Warning to Inform and it does not loop or repeat any time following initial onset to avoid annoying the driver (1.2.2).
- At the Warning message stage, the simultaneous visual and auditory message are more urgent and invasive than the Inform message, indicating to the driver that the situation has become more critical (1.2.2).

Message Complexity

Message complexity refers to the number of information elements in a message or image. It is important to consider because messages that are too complex may take longer to comprehend and acted upon by the driver. Table 8 presents the design guidance.

Table 8. Message Complexity Design Guidance

ID	Guidance	Reference
1.3.1	Visual messages consist of simple icons and fonts with only necessary detail included	(Campbell, J. L., Brown, J. L., Graving, J. S., Richard, C., Lichty, M. G., Sanquist, T., Bacon, P. L., Woods, R., Li, H., Williams, D. N., & Morgan, J. F., 2016)
1.3.2	Auditory messages are simple for situations where an immediate response is required	(Campbell, J. L., Brown, J. L., Graving, J. S., Richard, C., Lichty, M. G., Sanquist, T., Bacon, P. L., Woods, R., Li, H., Williams, D. N., & Morgan, J. F., 2016)

Design Decisions

Since the RCVW application requires a time-sensitive response from drivers to avoid an imminent conflict, the message design minimizes complexity to provide the driver with information that can be quickly understood in a safety critical situation.

- Visual: The *Inform* and *Warning* contain three information units: 1) the traffic sign followed by 2) the word “FOR” and 3) a train icon.

- Auditory: Messages consist of simple tones that accompany and bring attention to the in-vehicle display, designed for distracted or drowsy drivers.

In the Clear HRI situation, vehicle occupants will likely have substantially more time to respond to the message than in an imminent conflict situation (i.e., >10 sec vs. 1–2 sec); however, the potential consequences of not responding are severe. Therefore, the design of the Clear HRI messages prioritized the clarity and directness of the message over simplicity. The message includes text instruction about how to respond and why, in addition to visual depictions of response options (i.e., driving forward or backwards).

Design Basis

The following Design Basis was created from the guidelines in Table 8:

- Both the Inform and Warning visual messages for the RCVW message have simple and easily recognized icons (i.e., the stop ahead sign and train icon) because they are from the MUTCD (1.3.1).
- The auditory messages are simple tones for the Inform and Warning messages because of the critical safety situation (1.3.2).

Less complex messages reduce driver perception and reaction times and decrease cognitive demand, giving drivers a longer distance to come to a stop before the HRI.

2.4.3 Visual Messaging

Icon

An icon is a pictorial representation of a message or concept. The use of icons has several benefits over text-only messages. Icons allow quick and accurate recognition of messages, display visual or spatial concepts, uses a more efficient amount of space on the display, and can have a generally accepted meaning based on prior associations. Table 7 presents the design guidance followed.

Table 9. Icon Design Guidance

ID	Guidance	Reference
2.1.1	No more than half of the background is covered with objects	(Campbell, J. L., Richman, J., Carney, C., & Lee, J., 2004)
2.1.2	Use solid shapes over thin or dotted line edges	(Campbell, J. L., Richman, J., Carney, C., & Lee, J., 2004)
2.1.3	Use closed figures without discontinuous lines or outlines	(Campbell, J. L., Richman, J., Carney, C., & Lee, J., 2004)
2.1.4	Icons should be simple with only necessary detail included	(Campbell, J. L., Richman, J., Carney, C., & Lee, J., 2004)

ID	Guidance	Reference
2.1.5	Commonly accepted or standardized elements should be used when possible	(Campbell, J. L., Richman, J., Carney, C., & Lee, J., 2004)

Design Decisions

- RCVW Inform symbols: Uses an easily recognizable, standard stop ahead sign to tell the driver that they will have to begin braking and stop soon. A train icon is used for context so that the driver knows that they must stop because a train is approaching or occupying the HRI ahead, see Figure 17.

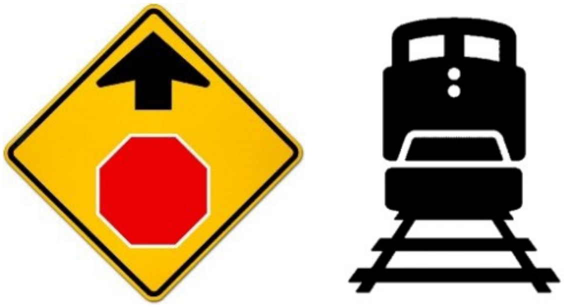

Figure 17. RCVW Inform Symbol

- RCVW Warning symbols: In this scenario an easily recognizable, standard stop sign is employed to notify the driver to begin braking and stop. A train icon is used for context so that the driver knows that they must stop because a train is approaching or occupying the HRI ahead, see Figure 18.

Figure 18. RCVW Warning Symbol

- Clear HRI symbols: These symbols are based on the HRI depiction found in the MUTCD. The vehicle icon is simple and familiar with cues showing the direction that the vehicle is facing, see Figure 19.

Figure 19. Clear HRI Symbol

Design Basis

The following Design Basis was created from the guidelines in Table 9:

- Neither the Inform nor Warning visual icons take up more than half of the background (2.1.1).
- All icons have solid outlines or edges (2.1.2).
- There are no discontinuous edges on the icons (2.1.3).
- All icons are simple; there is a train icon and either a stop ahead or stop sign (2.1.4).
- The icons used are in the MUTCD or based on icons/symbols in the MUTCD, which makes them easier to recognize (2.1.5).

Other factors were considered as well:

- Signs related to stopping were used to convey to the driver of the need to slow down.
- The generic-looking train icon is sufficient to communicate the nature of the risk at the HRI because the surrounding environment (active HRI) provides context about the type of hazard.
- The visual elements in the Clear HRI messages fill a large portion of the background. This is necessary to communicate the required response.
- The visual point of view (POV) in the Clear HRI messages (e.g., driver's eye view) results in a more complex visual message than typical POVs (e.g., plan view or side view). However, this POV was specifically selected because it more directly represents what a driver sees and better communicates that the driver is the person that must act in this situation.
- Shadows depicted with the vehicle icon in the Clear HRI message are embellishments that are typically not recommended in safety-critical messages. However, in this case, the shadows facilitate figure-ground separation and help distinguish the arrows from the vehicle without the need to introduce additional colors for the arrows.

Dynamic Elements

Dynamic elements use flashing or blinking to simulate motion, drawing attention to particular areas or objects in the visual display. Table 10 presents the design guidance followed.

Table 10. Dynamic Elements Design Guidance

ID	Guidance	Reference
2.2.1	Higher flash rates are used for more urgent situations (3–4 Hz is optimal)	(Campbell, J. L., Brown, J. L., Graving, J. S., Richard, C., Lichty, M. G., Sanquist, T., Bacon, P. L., Woods, R., Li, H., Williams, D. N., & Morgan, J. F., 2016)
2.2.2	Warnings are presented in appropriate temporal proximity to the dangerous situation	(Campbell, J. L., Brown, J. L., Graving, J. S., Richard, C., Lichty, M. G., Sanquist, T., Bacon, P. L., Woods, R., Li, H., Williams, D. N., & Morgan, J. F., 2016)
2.2.3	Flashing is only used for important situations because they have the potential to distract the driver	(Campbell, J. L., Brown, J. L., Graving, J. S., Richard, C., Lichty, M. G., Sanquist, T., Bacon, P. L., Woods, R., Li, H., Williams, D. N., & Morgan, J. F., 2016)
2.2.4	Sequential illumination is used to convey motion and/or direction, but text should remain stationary	(Campbell, J. L., Brown, J. L., Graving, J. S., Richard, C., Lichty, M. G., Sanquist, T., Bacon, P. L., Woods, R., Li, H., Williams, D. N., & Morgan, J. F., 2016)

Design Decisions

- RCVW Warning Application: The Warning stage message uses 4-Hz flashing motion to draw attention to the visual display and indicate urgency to the driver. The location that flashes is the border of the message which represents the gate arms of an HRI.
- Clear HRI Application: The arrows blink on and off at 4 Hz, and the rear gate is coordinated with the arrows so that it alternates between “normal” (no arrow) and “broken” (with arrows).

Design Basis

The following Design Basis was created from the guidelines in Table 10:

- The Inform message does not contain dynamic elements because it is not an immediate safety-critical message (2.2.3).
- The Warning message uses a high flash rate on the red border elements to indicate a safety critical situation and draw attention to the gate arms (2.2.1). Key information elements remain stationary (2.2.4).

- The dynamic elements flash with the Warning message onset, which represents the critical point where the driver must take action to avoid a collision with the train (2.2.2).
- The arrows and rail crossing gate arms are dynamic elements in the Clear HRI messages to highlight that the driver should move forward or reverse out of the HRI (2.2.2, 2.2.3).

Color

Color is a useful component in visual displays because it can convey the meaning or urgency of alerts and warnings on its own. The advantage over uncolored text and symbols is that color adds an immediacy of recognition and inherent meaning of a color through prior association (e.g., a red octagon is associated with stopping). Table 11 presents the design guidance followed.

Table 11. Color Design Guidance

ID	Guidance	Reference
2.3.1	Red is associated with danger or critical situations Yellow is associated with caution Green is associated with normal, safe conditions	(Campbell, J. L., Brown, J. L., Graving, J. S., Richard, C., Lichty, M. G., Sanquist, T., Bacon, P. L., Woods, R., Li, H., Williams, D. N., & Morgan, J. F., 2016)
2.3.2	Colors used are compatible with symbols based on prior association	(Campbell, J. L., Brown, J. L., Graving, J. S., Richard, C., Lichty, M. G., Sanquist, T., Bacon, P. L., Woods, R., Li, H., Williams, D. N., & Morgan, J. F., 2016)
2.3.3	Number of colors used is minimized and does not exceed four	(Campbell, J. L., Brown, J. L., Graving, J. S., Richard, C., Lichty, M. G., Sanquist, T., Bacon, P. L., Woods, R., Li, H., Williams, D. N., & Morgan, J. F., 2016)

Design Decisions

- For the Inform message (see Figure 20):
  - A conventionally colored Stop Ahead sign is used
  - The primary color of the border is yellow to imply caution

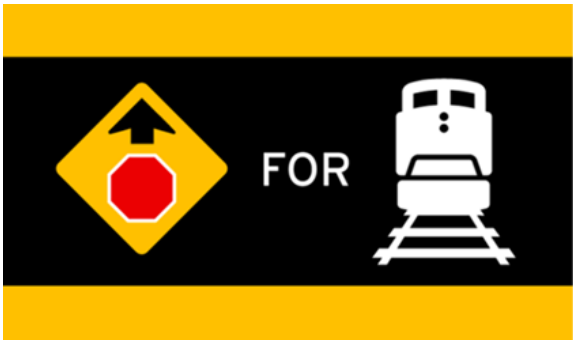

Figure 20. Inform Message

- For the Warning message. (See Figure 21):
  - A conventionally colored Stop sign is used
  - Red-striped borders representing the HRI gate arms are used to imply danger

Figure 21. Warning Message

Design Basis

The following Design Basis was created from the guidelines in Table 11:

Inform:

- A yellow-colored border is used to convey a cautionary warning to drivers (2.3.1).
- The Stop Ahead sign icon uses the same standard colors as a Stop Ahead sign which drivers should have familiarity with from past experience (2.3.2).
- The quantity of colors does not exceed four (e.g., red, yellow, black, and white) (2.3.3).

Warning:

- A red and white striped border is used to convey an urgent and critical warning to drivers and represents the rail crossing gate arm that is closing on the HRI ahead (2.3.1).
- The Stop sign icon uses the same standard colors as a Stop sign which drivers have seen before from experience (2.3.2).
- The quantity of colors is less than four (e.g., red, black, and white) (2.3.3).

Other factors were considered as well (Clear HRI):

- Employing more than four colors to create a recognizable HRI road scene.

- The car has shadows (color gradients) for emphasis and to create better figural distinctiveness

Text

Text enhances visual displays by clearly defining or clarifying the meaning of messages or symbols. When used with icons, the message becomes more effective through increased comprehension. Table 12 presents the design guidance followed.

Table 12. Text Design Guidance

ID	Guidance	Reference
2.4.1	Text labels should be brief with no more than 2–3 words	(Campbell, J. L., Richman, J., Carney, C., & Lee, J., 2004)
2.4.2	Use a clear and simple sans serif typeface	(Campbell, J. L., Richman, J., Carney, C., & Lee, J., 2004)
2.4.3	Avoid using boldface, italics, underlining, or multiple color fonts	(Campbell, J. L., Richman, J., Carney, C., & Lee, J., 2004)
2.4.4	Use both uppercase and lowercase as opposed to one or the other, unless using uppercase to denote hazard level or abbreviations	(Campbell, J. L., Richman, J., Carney, C., & Lee, J., 2004)
2.4.5	Font used should have open space inside, ample space between the letter forms to prevent blurring, and proportional spacing	(Campbell, J. L., Brown, J. L., Graving, J. S., Richard, C., Lichty, M. G., Sanquist, T., Bacon, P. L., Woods, R., Li, H., Williams, D. N., & Morgan, J. F., 2016)
2.4.6	Text characters should have a width-to-height ratio of 0.6 to 0.85	(Campbell, J. L., Brown, J. L., Graving, J. S., Richard, C., Lichty, M. G., Sanquist, T., Bacon, P. L., Woods, R., Li, H., Williams, D. N., & Morgan, J. F., 2016)
2.4.7	A stroke width-to-height ratio of 0.08 to 0.2 is acceptable, with 0.167 to 0.2 preferred for critical information.	(Campbell, J. L., Brown, J. L., Graving, J. S., Richard, C., Lichty, M. G., Sanquist, T., Bacon, P. L., Woods, R., Li, H., Williams, D. N., & Morgan, J. F., 2016)

Design Decisions

- Interstate sans-serif font type selected

Design Basis

The following Design Basis was created from the guidelines in Table 12:

- Both the Inform and Warning messages use one text unit, "for" (2.4.1)
- The same Interstate sans-serif font is used for all warning messages (2.4.2).
- No boldface, italics, underlining, or multiple colors are used for text (2.4.3)
- Only uppercase is used to stick out and provide greater urgency to drivers (2.4.4)
- The Interstate sans-serif font was chosen because it conforms to all guidelines on spacing (2.4.5), width-to-height ratio (2.4.6), and stroke width-to-height ratio (2.4.7).

The Clear HRI messages use four to five text units each to better convey the complex HRI clearing situation. The message communicates the action and reason for action.

2.4.4 Auditory Messaging

Display Type

Choosing appropriate auditory signal types can provide effective warnings and augment necessary visual information. In general, there are four different display types to choose from:

- Simple Tones: Single or grouped frequencies presented simultaneously
- Earcons: Abstract musical tones used in structured combinations
- Auditory Icons: Environmental sounds that convey information about the object they represent
- Speech Messages: Voice messages that add information beyond pure sound

Table 13 presents the design guidance followed.

Table 13. Display Type Design Guidance

ID	Guidance	Reference
3.1.1	Select an auditory signal type that facilitates drivers' understanding of the hazard and supports appropriate and timely responses	(Campbell, J. L., Brown, J. L., Graving, J. S., Richard, C., Lichty, M. G., Sanquist, T., Bacon, P. L., Woods, R., Li, H., Williams, D. N., & Morgan, J. F., 2016)
3.1.2	Simple tones should be used for highly time-critical messages, such as imminent collision warnings or situations that require immediate action	(Campbell, J. L., Brown, J. L., Graving, J. S., Richard, C., Lichty, M. G., Sanquist, T., Bacon, P. L., Woods, R., Li,

ID	Guidance	Reference
		H., Williams, D. N., & Morgan, J. F., 2016)
3.1.3	Earcons should be used for cautionary warnings or drawing attention to visual status information	(Campbell, J. L., Brown, J. L., Graving, J. S., Richard, C., Lichty, M. G., Sanquist, T., Bacon, P. L., Woods, R., Li, H., Williams, D. N., & Morgan, J. F., 2016)
3.1.4	Auditory icons should be used for imminent collision warnings or infrequent alerts	(Campbell, J. L., Brown, J. L., Graving, J. S., Richard, C., Lichty, M. G., Sanquist, T., Bacon, P. L., Woods, R., Li, H., Williams, D. N., & Morgan, J. F., 2016)
3.1.5	Speech messages should be used for less time-critical messages, conveying complex information, or situations that require more detailed information	(Campbell, J. L., Brown, J. L., Graving, J. S., Richard, C., Lichty, M. G., Sanquist, T., Bacon, P. L., Woods, R., Li, H., Williams, D. N., & Morgan, J. F., 2016)
3.1.6	The amplitude envelope of the initial pulse should include a 20 millisecond (ms) onset to reduce startle effects.	(Campbell, J. L., Richman, J., Carney, C., & Lee, J., 2004)

Design Decisions

- Inform: The auditory signal type should consist of Earcons.
- Warning: The auditory signal type should consist of obtrusive, urgent-sounding simple tones.

Design Basis

The following Design Basis was created from the guidelines in Table 13:

- Auditory signals are chosen to help drivers understand the situation and make timely responses for each warning stage (3.1.1).
- Earcons are used for the Inform message as a cautionary warning and draws attention to the visual display (3.1.3).
- Simple tones are used for the Warning message to present a highly time-critical message for a situation that requires immediate action (3.1.2).
- The onset includes a 20 ms attack time to reduce startle effects (3.1.6).

Perceived Urgency

Auditory warning messages must convey a level of urgency that matches the urgency of the hazard situation to elicit an appropriate response from the driver. Table 14 presents the design guidance followed.

Table 14. Perceived Urgency Design Guidance

ID	Guidance	Reference
3.2.1	Use faster auditory signals (e.g., 6 pulse/sec)	(Campbell, J. L., Brown, J. L., Graving, J. S., Richard, C., Lichty, M. G., Sanquist, T., Bacon, P. L., Woods, R., Li, H., Williams, D. N., & Morgan, J. F., 2016)
3.2.2	Use regular rhythms (i.e., all pulses equally spaced)	(Campbell, J. L., Brown, J. L., Graving, J. S., Richard, C., Lichty, M. G., Sanquist, T., Bacon, P. L., Woods, R., Li, H., Williams, D. N., & Morgan, J. F., 2016)
3.2.3	Use a greater number of pulse burst units (e.g., 4 units)	(Campbell, J. L., Brown, J. L., Graving, J. S., Richard, C., Lichty, M. G., Sanquist, T., Bacon, P. L., Woods, R., Li, H., Williams, D. N., & Morgan, J. F., 2016)
3.2.4	Use auditory signals that speed up	(Campbell, J. L., Brown, J. L., Graving, J. S., Richard, C., Lichty, M. G., Sanquist, T., Bacon, P. L., Woods, R., Li, H., Williams, D. N., & Morgan, J. F., 2016)
3.2.5	Use high fundamental frequencies (e.g., 800 Hz)	(Campbell, J. L., Brown, J. L., Graving, J. S., Richard, C., Lichty, M. G., Sanquist, T., Bacon, P. L., Woods, R., Li, H., Williams, D. N., & Morgan, J. F., 2016)
3.2.6	Use a large pitch range (e.g., 9 semitones)	(Campbell, J. L., Richman, J., Carney, C., & Lee, J., 2004)
3.2.7	Use a random pitch contour	(Campbell, J. L., Brown, J. L., Graving, J. S., Richard, C., Lichty, M. G., Sanquist, T.,

ID	Guidance	Reference
		Bacon, P. L., Woods, R., Li, H., Williams, D. N., & Morgan, J. F., 2016)
3.2.8	Use an atonal musical structure (e.g., random sequence of pulses)	(Campbell, J. L., Brown, J. L., Graving, J. S., Richard, C., Lichty, M. G., Sanquist, T., Bacon, P. L., Woods, R., Li, H., Williams, D. N., & Morgan, J. F., 2016)
3.2.9	Use a fast onset ramp	(Campbell, J. L., Brown, J. L., Graving, J. S., Richard, C., Lichty, M. G., Sanquist, T., Bacon, P. L., Woods, R., Li, H., Williams, D. N., & Morgan, J. F., 2016)
-	Attributes that decrease perceived urgency:	(Campbell, J. L., Brown, J. L., Graving, J. S., Richard, C., Lichty, M. G., Sanquist, T., Bacon, P. L., Woods, R., Li, H., Williams, D. N., & Morgan, J. F., 2016)
3.2.10	Use slower auditory signals (e.g., 1.5 pulse/sec)	(Campbell, J. L., Brown, J. L., Graving, J. S., Richard, C., Lichty, M. G., Sanquist, T., Bacon, P. L., Woods, R., Li, H., Williams, D. N., & Morgan, J. F., 2016)
3.2.11	Use irregular rhythms (i.e., pulses not equally spaced)	(Campbell, J. L., Brown, J. L., Graving, J. S., Richard, C., Lichty, M. G., Sanquist, T., Bacon, P. L., Woods, R., Li, H., Williams, D. N., & Morgan, J. F., 2016)
3.2.12	Use a fewer number of pulse burst units	(Campbell, J. L., Brown, J. L., Graving, J. S., Richard, C., Lichty, M. G., Sanquist, T., Bacon, P. L., Woods, R., Li, H., Williams, D. N., & Morgan, J. F., 2016)
3.2.13	Use auditory signals that slow down	(Campbell, J. L., Brown, J. L., Graving, J. S., Richard, C., Lichty, M. G., Sanquist, T.,

ID	Guidance	Reference
		Bacon, P. L., Woods, R., Li, H., Williams, D. N., & Morgan, J. F., 2016)
3.2.14	Use low fundamental frequencies (e.g., 200 Hz)	(Campbell, J. L., Brown, J. L., Graving, J. S., Richard, C., Lichty, M. G., Sanquist, T., Bacon, P. L., Woods, R., Li, H., Williams, D. N., & Morgan, J. F., 2016)
3.2.15	Use a regular harmonic series	(Campbell, J. L., Brown, J. L., Graving, J. S., Richard, C., Lichty, M. G., Sanquist, T., Bacon, P. L., Woods, R., Li, H., Williams, D. N., & Morgan, J. F., 2016)
3.2.16	Use a small pitch range (e.g., 3 semitones)	(Campbell, J. L., Brown, J. L., Graving, J. S., Richard, C., Lichty, M. G., Sanquist, T., Bacon, P. L., Woods, R., Li, H., Williams, D. N., & Morgan, J. F., 2016)
3.2.17	Use a down or up pitch contour	(Campbell, J. L., Brown, J. L., Graving, J. S., Richard, C., Lichty, M. G., Sanquist, T., Bacon, P. L., Woods, R., Li, H., Williams, D. N., & Morgan, J. F., 2016)
3.2.18	Use a resolved musical structure (i.e., from natural scales)	(Campbell, J. L., Brown, J. L., Graving, J. S., Richard, C., Lichty, M. G., Sanquist, T., Bacon, P. L., Woods, R., Li, H., Williams, D. N., & Morgan, J. F., 2016)
3.2.19	Use a slow onset ramp	(Campbell, J. L., Brown, J. L., Graving, J. S., Richard, C., Lichty, M. G., Sanquist, T., Bacon, P. L., Woods, R., Li, H., Williams, D. N., & Morgan, J. F., 2016)

Design Decisions

- Inform: Should have a lower perceived urgency to match the less time-critical situation

- Warning: Should have a higher perceived urgency to match the highly time-critical situation

Design Basis

The following Design Basis was created from the guidelines shown in Table 14:

Inform:

- Uses slower auditory signals (3.2.10)
- Uses irregular rhythms (3.2.11)
- Uses fewer pulse burst units (3.2.12)
- Uses a regular harmonic series (3.2.15)
- Uses a small pitch range (3.2.16)
- Uses a down or up pitch contour (3.2.17)
- Uses a resolved musical structure (3.2.18)

Warning:

- Uses faster auditory signals (3.2.1)
- Uses regular rhythms (3.2.2)
- Uses more pulse burst units (3.2.3)
- Uses auditory signals that speed up (3.2.4)
- Uses high fundamental frequencies (3.2.5)
- Uses a large pitch range (3.2.6)
- Uses a random pitch contour (3.2.7)

Other factors were considered as well:

- The Inform does not use low fundamental frequencies (3.2.14) to avoid potential masking issues and does not use auditory signals that slow down (3.2.13).
- The Warning does not use an atonal musical structure (3.2.8).
- The design guidelines included nearly all attributes than can increase/decrease urgency, so for the auditory alerts, only a subset of those attributes was selected to balance the alerting and distracting nature of the sounds.

Perceived Annoyance

Auditory warnings should be designed to minimally annoy drivers yet still convey the appropriate level of urgency. Careful selection of auditory warnings can reduce perceived annoyance while maintaining the driver's attention in critical driving situations. Table 15 presents the design guidance followed.

Table 15. Perceived Annoyance Design Guidance

ID	Guidance	Reference
3.3.1	The perceived urgency of a sound is matched with the urgency of its referent. Drivers who perceive the benefits of an obtrusive signal will be less likely to be annoyed by it.	(Campbell, J. L., Brown, J. L., Graving, J. S., Richard, C., Lichty, M. G., Sanquist, T., Bacon, P. L., Woods, R., Li, H., Williams, D. N., & Morgan, J. F., 2016)

Design Decisions

The Warning stage auditory signal shall be more obtrusive and attention-grabbing than the Inform auditory signal, matching the different levels of urgency to the driver.

Design Basis

The following Design Basis was created from the guidelines in Table 15:

- The more urgent Warning auditory signal is presented in a more obtrusive manner than the less urgent Inform auditory signal (3.3.1).

Loudness

To present clearly perceivable auditory warnings, they must be loud enough to overcome masking sounds from the sounds from road noise, cab environment, and other equipment. Table 16 presents the design guidance followed.

Table 16. Loudness Design Guidance

ID	Guidance	Reference
3.4.1	The amplitude of auditory signals is in the range of 10–30 dB above the masking threshold[11] (MT), with a recommended minimum level of 15 dB above the MT.	(Campbell, J. L., Brown, J. L., Graving, J. S., Richard, C., Lichty, M. G., Sanquist, T., Bacon, P. L., Woods, R., Li, H., Williams, D. N., & Morgan, J. F., 2016)
3.4.2	The signal does not exceed a maximum intensity of 90 dBA.	(Campbell, J. L., Brown, J. L., Graving, J. S., Richard, C., Lichty, M. G., Sanquist, T., Bacon, P. L., Woods, R., Li, H., Williams, D. N., & Morgan, J. F., 2016)

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[11] The masking threshold is the quietest level of the signal perceived when combined with a specific masking noise (Gelfand, S. A., 2004).

Design Decisions

The Inform and Warning message auditory signals shall be played between 15–30 dB above the MT. The signal intensities shall not exceed 90 dBA.

Design Basis

The following Design Basis was created from the guidelines in Table 16:

- Auditory signals are between 10–30 dB, with a recommended 15 dB minimum (3.4.1)
- Auditory signals shall not be played at more than 90 dBA (3.4.2)

Distinctiveness

Auditory warning messages must be designed to be distinguishable from other auditory signals inside the vehicle to be recognized, understood, and acted upon in a timely manner by the driver. Table 17 presents the design guidance followed.

Table 17. Distinctiveness Design Guidance

ID	Guidance	Reference
3.5.1	Auditory cautionary warning signals are distinctive from imminent warnings	(Campbell, J. L., Brown, J. L., Graving, J. S., Richard, C., Lichty, M. G., Sanquist, T., Bacon, P. L., Woods, R., Li, H., Williams, D. N., & Morgan, J. F., 2016)
3.5.2	Auditory warnings use distinctive sounds that are easily distinguished from other sounds in the cab	(Campbell, J. L., Brown, J. L., Graving, J. S., Richard, C., Lichty, M. G., Sanquist, T., Bacon, P. L., Woods, R., Li, H., Williams, D. N., & Morgan, J. F., 2016)

Design Decisions

The Warning auditory signal should be designed completely different from the Inform auditory signal to distinguish between the two signals. Not only are the auditory signal types different, but so are the perceived urgency and physical characteristics such as fundamental frequency and pulse rate. The auditory signals are also designed so that they are easily distinguished and differentiated from any other sounds in the cab.

Design Basis

The following Design Basis was created from the guidelines in Table 17:

- The Inform and Warning message auditory signals are distinctive from one another (3.5.1).
- The Inform and Warning message auditory signals are distinctive from other auditory signals inside the cab (3.5.2).

2.5 Positional Solution Comparative Analysis

As part of the project, researchers performed Baumgardner's (2020) Positional Solution Comparative Analysis between two GNSS units considered as candidates to be implemented in RCVW II. The analysis compared two readily available devices which use localized corrections sent by augmentation systems to correct positional errors. The first system uses additional satellite transmissions to correct positional errors, known as Satellite Based Augmentation System (SBAS) while the other transmits the corrections using other terrestrial communications means, known as Real-Time Kinematics (RTK). The data from both units was then compared to data collected concurrently by a high performance, survey grade RTK system. The research team performed testing by installing all units in a vehicle and collecting data as the vehicle was in movement. The testing tracks selected for this analysis were the tracks selected for use in the subsequent Field Test and Evaluation (FT&E) task of the project (e.g., a flat course and a graded course). See Section 2.6 for more information regarding the testing tracks.

The SBAS system was developed for civil aviation use across wide areas. The most common United States based SBAS system is the Wide Area Augmentation System (WAAS) run by the Federal Aviation Administration (FAA). The primary benefit is the significantly larger coverage area. Some GNSS receivers use the WAAS correction because it is freely available, and the signals are similar to those emitted by the positioning satellites. The WAAS Performance Analysis report presents a maximum horizontal positional accuracy of 2.797 meters and a minimum of 0.872 meters. This accuracy was maintained for 95 percent of the time within the continental United States (Williams J. Hughes Technical Center Federal Aviation Administration, 2020).

RTK is a Differential GNSS (DGNSS) system that searches for errors in the carrier wave signal, which is a high frequency modulated signal, and can produce high precision position solutions once ambiguities in the wave are resolved. DGNSS systems are those that utilize two physically separated receivers in conjunction with one another; a base station, and a rover. The base station is fixed to a known location, and the rover is the mobile receiver. Assuming the two are in relatively close proximity (i.e., typically under 20 km apart), both the base station and the rover are essentially receiving the same GNSS signal, including the same errors and clock skew. However, because the base station is located at a known point, it is relatively easy to determine the errors and generate a set of corrections for each visible satellite. These corrections are then sent to the rover. The rover algorithm relies on the application of received fixed integers until the position solution presents itself. When this occurs, the system enters what is known as fixed mode. Prior to this, the RTK receiver initially applies floating point numbers to obtain a solution, which is known as float mode. Although both modes are capable of providing sub-meter horizontal accuracies, the fixed mode is typically in the centimeter range while float mode is more in the decimeter range (European Space Agency, n.d.).

Section 2.5.1 provides an overview of the analysis performed.

2.5.1 GNSS Devices

The SBAS and the RTK GNSS systems used in the comparison are both manufactured by the Swiss semiconductor company uBlox. Data collection for these devices was performed using a laptop with the uBlox uCenter software. The software recorded the complete set of iterations and exported them into separate Keyhole Markup Language (KML) files for later replay.

SBAS GNSS System

The SBASS GNSS system used is the uBlox EVK-M8U module with SBAS augmentation and untethered Dead Reckoning (DR). The manufacturer's data sheet specifies a 50 percent Circular Error Probable (CEP) horizontal accuracy of 2.5 meters using a GPS and GNSS. The data sheet specifies that the accuracy improves to 1.5 meters when augmented with SBAS (Ublox, n.d.).

RTK GNSS System

The RTK GNSS system used is the ZED-F9P module which is a low-cost RTK solution that can function either as a rover unit or a base station. This module was contained within the Ublox C099-F9P breakout board. Horizontal accuracy is stated to be 1.5 m for 50 percent CEP without achieving a fixed RTK solution and 0.01 m with a fixed RTK solution.

Ground Truth System

The OxTS RT3000 v3. is a high performance, survey grade RTK system that was used for ground truth measurements. It has a stated accuracy of 0.01 m and a maximum data rate of 250 Hz. The ground truth system is intentionally set for a more frequent update rate of position, velocity, and time (PVT) than that of the uBlox unit.

2.5.2 Results

Whereas much positional accuracy testing is based on stationary testing, this study focused on the specific RCVW application, which requires a moving vehicle.

SBAS GNSS System Results

According to the logs, SBAS corrections were effectively applied over the entirety of the flat course runs. The horizontal accuracy of the unit under these conditions showed a median (50%) measure of 0.52 m, and a 95 percent measure of 1.46 m. The results confirm the manufacturer documented an accuracy claim of 1.5 m CEP (50%) with SBAS. The nominal performance on the graded course shows a very large drop off from the accuracy seen in the flat course. With over 78 percent of the time failing to meet the 1.5 m tolerance, the median (50%) CEP is 1.81 m while the 95 percent CEP is 2.76 m.

RTK GNSS System Results

RTK corrections were available for 100 percent of the runs on both courses. In the flat course, the RTK solution met the RCVW requirements with a median accuracy of 0.99 m, and a 95 percent accuracy measure of 1.01 m. The nominal accuracy of the RTK system on the graded course was under 1 m. The median accuracy value was 0.25 m and a 95 percent CEP of 0.97 m was measured. Only a couple dozen data points in the runs exceeded the 1.5 m tolerance.

A possible explanation on why the graded course accuracy is superior to that of the flat course is due to the use of two different RTK base stations at the flat course. During the flat course tests, the ground truth system received corrections from a local base station, while the RTK GNSS test device received corrections from the Ohio Department of Transportation's (ODOT) Virtual Reference Station (VRS) network. During the graded course tests, both devices received corrections from the ODOT VRS network as the local base station was not available.

Despite reasonably satisfactory performance by the SBAS device, the overall reliability of the unit was insufficient as shown in the graded course results. The RTK system exhibited highly reliable performance across the board with consistent 1-meter accuracy on the flat course and sub-meter accuracy on the graded course.

Based on the results of this analysis, the decision was made to modify the RCVW II system to incorporate an RTK enabled unit. However, the following needs to be considered:

- The SBAS device incorporates an integrated inertial measurement unit (IMU) to perform DR calculations during brief periods of GNSS outage. The use of an RTK device able to perform DR calculations would be ideal.
- RTK systems are highly dependent on the base station used. Therefore, it is recommended that the RTK solution utilize a base station within the RBS equipment with the capability to generate its own correction values based on the known position and broadcast them locally through the existing DSRC radio in lieu of adding additional communication equipment. The VBS must then relay the corrections into the RTK unit to apply them.
- The time needed to apply the received corrections and subsequently obtain a fixed integer solution is a potential source of concern and needs to be further investigated. The Ublox RTK-enabled GNSS units used in the RCVW testing require up to 10 seconds to converge to a fixed integer solution. In the case of RCVW, this needs to occur prior to the vehicle being in the Approach Zone. This was not an issue during the testing phases of the project as the VBS was in communication with the system at all times.

2.6 RCVW System Field Test & Evaluation Summary

2.6.1 Background

The primary focus of the FT&E summary was to assess the performance of the system and verify that it meets its functional and performance requirements described in the project's system requirements specification document (Polinori, A., Paselsky, B., & Sanchez-Badillo, A., 2020). Three days of testing took place on the system with different road conditions, such as wet/dry pavement, different road grades, obstructed GNSS satellite view, and different vehicle speeds. A heavy truck and a light vehicle were instrumented to observe the performance of the RCVW algorithm when applied to different vehicle types. A braking and throttle robot controlled vehicle speed and deceleration. The results presented throughout the remainder of this section are a summary of the details found in the FT&E report. (See Appendix B).

Approach to Field testing

All field-testing activities took place at the TRC Smart Center Test Track or at the TRC graded course. On October 27, 2020, RBS integration at a mock railroad crossing along with vehicle configuration took place. A series of trial runs were performed to:

1. Understand vehicle and system performance
2. Understand driver and braking robot performance
3. Practice overall duties for all team members

These trial runs afforded the team the opportunity to calibrate the TRC testing equipment and for the professional driver to understand the different alerts and warnings the system would issue. Scenario-based testing started on October 28, 2020, at 11:00 AM and ended on October 30, 2020, at 4:20 PM.

A total of 28 test cases were performed. These tests were performed in a closed test track solely dedicated for the testing of the RCVW application with the RCVW system integrated into surrogate infrastructure. All scenario-based tests used a real vehicle driven towards a mock equipped HRI.

The following parameters applied across all scenario-based test cases:

- Two types of vehicles were used. Type A represents a light passenger vehicle and Type C represents a Heavy Truck.
- The Type A CV was an Acura MDX 2017, SH-AWD with an Anti-lock Braking System (ABS), while the Type C CV was a Volvo Truck 2017 VHD with an air brake system.
- The approach lane length for both courses (i.e., flat and graded) was set at 1,525 feet. This distance was calculated based on the Decision Sight Distance (DSD) of 535 feet for a speed limit of 55 mph plus the distance from the DSD point to the placement of the Advance Warning sign. For example, for a 55-mph rural road with a DSD of 535 feet and an Advance Warning sign placement of 990 feet (per the MUTCD Table 2C-4) to the HRI, an approach lane for the vehicle should begin at 535 + 990 = 1,525 feet from the stop bar.[12]
- The initial CV approach speed achieved near the start (1,525 feet from HRI stop bar) of the Approach Zone and maintained throughout the approach to the point when the RCVW alert varied depending on the type of vehicle and test case.
- All scenario-based test cases involved driving the vehicle straight along the approach except the following:
  - Two test cases involved the vehicle driving straight along the approach and swerving one lane width to the right or left (depending on the case) after receiving an RCVW. The purpose of these tests was to verify the “snap to lane” functionality which enables the system to position the vehicle in the approach lane in case of a GNSS multipath error.
- All scenario-based test cases began with the HRI in the active state, except the following:
  - The HRI was specified to become active with the vehicle on approach with less than the full approach lane distance remaining such as 3/4 warning point, the warning midpoint, or the 1/4 warning point. See Figure 22.

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[12] This value was selected specifically for the RCVW II field test stages and was based on the configurable parameter Distance to HRI (see Appendix A). This value will vary depending on the specific HRI approach geometry and characteristics and it reflects the distance where the system can reliably receive DSRC messages from the RSU. The value should be greater than the DSD value calculated for the speed limit of the HRI approach to allow for issue of inform messages prior to receiving warning messages

- One test case began with the HRI in the active state and as the vehicle reached the midpoint, the HRI became inactive.
- Two deceleration rates were programed into the braking robot depending on the vehicle types:
    - 3.92 m/s^2 (0.4 g) for light vehicle (Type A)
    - 2.67 m/s^2 (0.27 g) for heavy truck (Type C)

Note: Details on the calculation of the deceleration rates can be found in the FT&E report. (See Appendix B)

- Five traffic cones were used along the Approach Zone (i.e., for visual reference only) while conducting tests.
    - Cone #1: Approach Zone entry
    - Cone #2 and # 3: Expected point of RCVW Activation for CV type A and CV type C travelling at 50 mph (respectively)
    - Cone #4 and #5: Expected vehicle stopping for CV type A and CV type C travelling at 50 mph (respectively

Figure 22. 3/4 Mark, Midpoint and 1/4 Mark locations

- Two test track locations were used during field test activities; see Figure 23 and Figure 24.

- A flat course located at:
    - Latitude: 40.313618
    - Longitude: -83.555281
- A graded course (-10% grade) located at
    - Latitude: 40.322333
    - Longitude: -83.619414

Note: The RCVW Activation and Expected Vehicle Stopping Icons in Figure 23 and Figure 24 are for illustration purposes and do not reflect the actual locations where these situations occurred.

Figure 23. Flat Course

Figure 24. Graded Course

- All tests were performed using an IEEE 1570-compliant serial interface which was used to receive and relay HRI status (i.e., the preemption signal) from the HRIC to the RBS.
- Voltage based grade HRI status reception was not performed as this functionality had been successfully tested during Phase I of the project.
- The American Association of State and Highway Transportation Officials (2018) Green Book recommends the use of 2.5 seconds for perception reaction time. This value reflects observed behavior for the 90th percentile driver.
- Different road conditions (e.g., wet/dry) were tested during RCVW II FT&E.
- Two MAP files were created and used for field testing; one for the Smart Center course (0% grade) and one for the Graded Course (-10% grade).

2.6.2 Summary of RCVW Performance

A detailed account of all FT&E activities as well as a summary of performance by requirement can be found in the FT&E report (see Appendix B). In summary all requirements were confirmed to have been met with one exception:

- Requirement RBS-4: The RBS shall broadcast the HRI Active message 10 times per second when an associated HRIC activates a preemption signal—was not confirmed (see Appendix B for more information).

The scenarios focused on assessing violation detections with the CV on approach. The RCVW system was found to reliably warn the driver when the vehicle was approaching the active crossing at a speed calculated to be too fast to be able to stop safely within distance between the vehicle and the HRI stop bar. Following the actions of the programed braking robot, the vehicle was able to safely decelerate and stop both vehicle types before reaching the stop bar—except in some cases when the braking robot failed to decelerate at the programmed rate and in the specific test case where the HRI Active signal was issued after the vehicle reached the 3/4 length of the approach.

CAN Bus Data

CAN bus based speed was used for the light vehicle calculations and GNSS-based speed was used for the heavy truck. Analysis of logs showed that using a RTK enhanced GNSS system to derive vehicle speed yielded readings within 0.1 mph of the CAN bus readings (i.e., for vehicles travelling at 35 mph). In contrast, data from tests prior to FT&E activities show that CAN bus-based acceleration data is suboptimal for determining vehicle deceleration, when comparted to the measured change in speed. The analysis shows an acceleration error of 0.85 m/s^2 when compared to the ground truth calculated deceleration data. The analysis also showed fluctuation between negative and positive acceleration values as the vehicle was decelerating. This resulted in the RCVW system issuing a string of incorrect Warning and Alert messages to the driver. For these reasons it was decided to not use CAN bus-based deceleration data.

Positional Accuracy

The accuracy of the positional subsystem varied based on the vehicle and velocity. The accuracy can be broken into two different categories, processing-latency based error and positional based error. Processing-latency based error is a result of the movement of the vehicle over the duration of time it takes to receive and process the measured position from the GNSS receiver and it manifests itself as a proportional error based on the velocity of the vehicle (e.g., including the heading of the vehicle). The positional error is a result of the GNSS Module's inherent limitation in accuracy when compared to a ground truth system—RT3003 High Accuracy Multi-Axis GNSS aided Inertial Navigation System used for comparison. This error value is constant across speeds. The total positional error, consisting of both the processing latency based and positional-based component is divided in this section with respect to longitudinal and lateral errors to help understand potential causation.

The analysis conducted prior to the field test activities (see Section 2.5) showed an accuracy of 1.01 m at 35 mph at the flat course and 0.25 m at the graded course. The analysis of the data showed that the RCVW RTK device did not provide the level of accuracy advertised by the manufacturer (1 cm 50% CEP), however, performed better in the more challenging environment of the graded course. The likely reason for the discrepancy in accuracy between the two test tracks is the use of different base stations. For tests conducted at the flat course, the high-performance device (ground truth) received corrections from a local base station, whereas the RCVW RTK device used a remote virtual base station. For tests conducted in the graded course, both devices used the same remote virtual base station.

Given, an expected better than 1.01 m GNSS accuracy due to implementation of an RTK base station at the RBS, the analysis of the data from the field tests suggests that a large component of the longitudinal error is the result of processing latencies. The difference in longitudinal error between Type A and Type C vehicles was approximately 3 meters. The error is not of a great concern as long as it is in the longitudinal axis because the equation for the stop bar allows for

3.12 m error (i.e., V2 GPS Error parameter [see Appendix A]). However, given the sub-meter advertised accuracy of the RTK unit, seems to indicate there are other factors affecting the accuracy on the vehicle type C. One possibility could be the large overhang from the dump truck causing degraded performance and possibly causing the error to be consistently in the same direction. Lateral error ranged from 0.02 to 0.64 m for the Type A vehicle and 0.62 to 0.84 m for the Type C vehicle.

Alert Performance

The distance equation used by the RCVW system factors in communication latency, GPS error, and processing latency to calculate the issuance of alerts and warnings. These configurable parameters are used to account for the effects of the time-based error and GPS error (i.e., as explained in the Positional Accuracy section) when performing calculations. The analysis showed that this error is within the allowed error of the equation (i.e., V2 GPS Error parameter [see Appendix A]).

System Warnings and Alerts

Several test cases were performed where the HRI Active message was received after the CV had entered the Approach Zone. The objective was to validate if the Type A and Type C vehicles would have enough distance to reach a full stop prior to the stop bar when a train was detected later than usual. The vehicle speed during these tests was 50 mph. When the HRI Active message was received at the 3/4 and 1/2 points to the stop bar, both vehicles had ample time to travel down the approach lane, receive the warning and safely decelerate and come to a complete stop before reaching the stop bar. In the case of the HRI Active message being received at the 1/4 mark from the stop bar both stopped beyond the stop bar, as expected.

A third scenario tested the light vehicle travelling at 70 mph and the HRI Active indication being issued at the Approach Zone midpoint. The system issued a warning message at the expected location and provided ample time for a safe deceleration and came to a complete stop before reaching the stop bar.

One test case involved removing the HRI Active indication being rescinded at the midpoint after the vehicle had entered the Approach Zone. An inform alert was issued as the vehicle entered the Approach Zone as expected. The HRI Active was then rescinded before a warning message was deemed necessary, resulting in the removal of the inform alert and permission for the vehicle to travel across the HRI with no nuisance alerts.

A set of test cases were designed to test the performance of the system under high speeds. The tests were designed for both vehicles travelling within the approach at 70 mph with the HRI Active. Due to limited run up distance to the approach zone (i.e., ingress MAP lane), the Heavy Truck was not able to reach 70 mph. As a result, it was decided to reduce the vehicle speed to 60 mph. Under the lower speed regimen, the RCVW system was able to generate a warning at the proper distance and provide ample time for both vehicles to safely decelerate and come to a complete stop prior to reaching the stop bar.

A test case was designed to verify the proper issue of a special warning when a vehicle, after traversing the Approach Zone, stopped in the HRI Hazard Zone. On all iterations of the test, the vehicle received the proper “Clear HRI” warning when remaining at a stop in the HRI Hazard Zone. The message cleared as soon as the vehicle started moving.

Test cases were performed to verify the “Snap to Lane” functionality. This feature snaps a vehicle to the approach lane in case its location deviates laterally as a result of GNSS multipath effects or any other GNSS accuracy condition. To simulate this effect, the tests required the vehicle to travel down the approach with the HRI Active. Once the VBS system issued an RCVW warning, the driver swerved the vehicle one lane width to the right or the left, depending on the case. Three iterations of each test case were performed. During all the iterations, the RCVW system continually issued the approach warning while the vehicle swerved away from the lane. The lane change detection and “snapping” the vehicle location to the correct lane was confirmed during post-analysis of the RCVW system data log.

Pavement Condition

Several tests were designed where the pavement conditions would change from dry to wet to compare system performance and validate the use of the Green Book formula. It was observed during these tests that wet pavement conditions did not have negative impact on system performance. Both vehicles were able to safely decelerate after receiving the warning message and come to a complete stop before reaching the stop bar on all iterations.

Graded Course

A specific test case was designed to have the system evaluated on a course with a grade different than 0 percent. A -10 percent graded course located at TRC’s facilities was used for this test. The location is surrounded by heavy tree foliage which had the potential to result in a degradation of the GNSS signal. The roadside unit was positioned next to the stop bar at the bottom of the course, resulting in the vehicle not having a direct line-of-sight for DSRC radio communications throughout the course. Seven iterations of this test case were performed. Despite the location challenges, the system was able to maintain an RTK GNSS solution (e.g., fixed/float) throughout each of these iterations. Several System fault alerts were issued when the vehicle was out of direct line-of-sight to the RBS (i.e., MAP Data not Received, SPaT Data not Received) as expected, but recovered immediately as the line-of-sight was re-established. Once the VBS system regained full functionality, the system generated the proper alerts and warnings and the vehicle was able to safely decelerate and come to a complete stop before reaching the stop bar on all iterations.

System Stability when Near/In/Beyond the HRI

Tests were conducted to confirm that a driver that stops along the boundary of the HRI Hazard Zone does not receive nuisance/intermittent warnings/lack of warnings (i.e., the GPS accuracy is sufficient for the VBS to reliably know where the vehicle is located relative to the HRI Hazard Zone boundaries, and this fix does not drift over a significant period). The test was performed for 10 minutes at each of the locations shown below:

a) Vehicle is located on the edge of the Approach Zone and the stop bar

b) Front of Vehicle is inside the HRI Hazard Zone

c) Entire Vehicle is beyond the HRI Hazard Zone

No inappropriate warnings appeared during each of the 10-minute periods. Similarly, the ‘Clear HRI’ warning did not cease to display over a 10-minute period with the vehicle positioned as specified in test iteration (b).

System Fault Verification

Researchers designed and performed specific test cases to verify and validate the different system faults the RCVW system is designed to recognize and inform the vehicle driver.

1. Loss of DSRC after the CV has received an RCVW
2. Loss of DSRC prior to the CV entering the MAP
3. Loss of RTK Fix/Degraded GNSS Solution
4. Loss of MAP
5. Loss of IEEE 1570 Heartbeat

All test cases performed as expected. The system issued a System fault alert for all the conditions being tested. In addition to the RTK fix loss System fault alert, the system is designed to issue a System Fault alert when the GPS position update rate falls below the configured threshold. This was validated across all test cases by reviewing the log files for each test case iteration.

DSRC Messaging and Data Processing Latency Requirement Verification

The following requirements are associated with the RCVW system latency. The system met all requirements listed below pertaining to messaging and latency with the exception of RBS 4. See Appendix B for more information.

- RBS 4: The RBS shall broadcast the HRI Active message 10 times per second when an associated HRIC activates a preemption signal.
- RBS 7: The RBS shall broadcast the HRI Configuration Data File[13] (HCDF) once per second
- RBS 21: The RBS shall be capable of receiving HRI message packets across the IEEE 1570 serial interface in less than 250 ms, conforming to the IEEE 1570 standard.
- VBS 22: The vehicle-based subsystem shall be capable of receiving messages sent by the RBS within 50 ms.
- VBS 23: The vehicle-based subsystem shall be capable of processing received data within 85 ms.

2.6.3 Summary of Detected Issues

The following is a summary of relevant detected issues and anomalies. For more information see Appendix B.

Heavy Truck Position Accuracy

Results from the position accuracy analysis of the Heavy Truck show an average longitudinal positional error of 4.13 m at 35 mph, 4.54 m at 50 mph, and 4.46 m at 60 mph. When compared with the errors from the Light Vehicle, the discrepancy is around 3 m, generally fixed in the

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[13] The HRI Configuration Data File includes the MAP.

longitudinal direction. One hypothesis for the cause of such a large offset relates to the location of the GNSS antenna on the Heavy Truck, which was situated nearby a large metal overhang.

Lane Shift

During the analysis of the RCVW logged test data, it was discovered that six runs showed the vehicles had a large positional error (>2 m) in the lateral direction. This issue occurred on both the heavy truck and the light vehicle. While data from the log files show the system receiving GPS data at the correct rate and holding an RTK solution, the vehicle was not being positioned in an accurate location. The "Snap to Lane" function identified the vehicle as having shifted lanes and repositioned its location on the correct travel lane. This avoided the issuance of a System Fault alert.

CAN Communications

Log file analysis showed that the VBM data (CAN) of the light vehicle often reported a non-zero speed even when the vehicle was at a complete stop. During several tests which required the vehicle to be at a complete stop, the VBM reported a speed of about 0.5 m/sec. (See GNSS Signal Bounce When Vehicle Reaches a Stop section for additional information).

DSRC Signal Communications Gap

Throughout the 3 days of testing, it was observed that the Heavy Truck system experienced a 0.5 to 1.0 second loss of DSRC radio signal at the same location. The truck entered the approach followed by the VBS issuance of the Inform Alert. The truck then arrived at the aforementioned location followed by issuance of the System Fault alert. A 0.5 to 1.0 second later, the Inform Alert was re-issued by the VBS. An analysis of the log files indicated that the roadside system was effectively sending the required messages. However, it was observed that data packets were not being received at the aforementioned locations, resulting in the issue of the System Fault alerts.

Periodic DSRC Signal Latency Increase

Throughout testing, DSRC signal latency was, on average, 4 ms. However, analysis of the log data showed that a periodic DSRC message latency increase of 20 ms occurred every 4 to 5 seconds. The issue was observed in field testing of the Heavy Truck and Light Vehicle RCVW systems.

GNSS Signal Bounce When Vehicle Reaches a Stop

When the vehicle reaches a full stop, the RCVW system locks GPS speed to zero and filters out vehicle oscillations that occur as a result of the inertial forces applied to the vehicle shock absorbers. When the vehicle re-initiates movement, the RCVW system filters out the first seven location points to ensure that vehicle is in fact moving, updates vehicle heading from received GPS data, and continues to perform its functions.

During field tests, as the vehicle reached a full stop, it would perform the procedure described above (i.e., filter out signal bounces and lock GPS speed to zero). When the vehicle was at a complete stop, speed information received via the CAN interface indicated an incorrect vehicle speed of about 0.5 m/s. The RCVW system detected this vehicle speed and continued to perform calculations assuming the vehicle was moving. Since the GNSS module does not update the vehicle heading (i.e., the vehicle is not moving), the module reads the last data received, which, in some cases is not correct, as a result of the oscillations described. This results in the RCVW performing dynamic calculations with incorrect information, resulting in erroneous DVI messages.

Processor Lag

After a few hours of continuous usage, the RCWV plugin experienced a delay in processing the Location Messages, resulting in a low data frequency fault. During field test activities, and between tests, the RCVW plugin needed to be restarted every 3 hours to reset the processor memory. After the reset, the system resumed normal operations and all processing delays cleared. A revision of the code which corrected several software bugs and solved this issue, was performed following completion of the FT&E.

Dilemma Zone

The dilemma zone, which is defined as the distance to the stop bar where drivers approaching a HRI must either decide to stop or proceed, is not addressed by the RCVW algorithm. That is, the algorithm considers the dilemma zone as simply part of the approach zone and issues alerts and warnings accordingly. Several test cases triggered the HRI activation as the vehicle reached the 1/4 distance of the Approach Zone to the stop bar. This resulted in the vehicle not being able to stop prior to reaching the stop bar due to inadequate stopping distance. Further analysis is required to determine the threshold distance from the stop bar at which no RCVW should be issued. The factors to determine the threshold include vehicle position, vehicle speed, HRI design, grade, and vehicle type.

3. Conclusion

The performance of the RCVW II system shows that a reliable application for enhancing safety at active HRIs can be built using currently available technology.

Current GNSS solutions offer the accuracy required for precise positioning of moving vehicles critical to safety related applications. However, an RTK based approach may require additional infrastructure to be procured and installed.

It was observed that a longitudinal error increases linearly as a function of speed—a potentially "fixable" error. This indicates a system processing latency effect on the perceived accuracy. However, system performance regarding warnings, alerts, and vehicle stoppings were not impacted due to the Warning Distance equation constraints which account for measured processing latency and GNSS module accuracy.

Although DSRC was used to communicate data between vehicles and the RBS, any short-range, low latency, wireless communication platform capable of covering the distance between an approach zone and a HRI could be used for this purpose.

Tests results showed that the warning distances calculated by the RCVW II algorithm allowed the vehicles to stop safely prior to the HRI stop bar. This ensured a minimal amount of nuisance warnings for approaching vehicles.

Data from this phase of testing showed that using an RTK enhanced GNSS system to derive vehicle speed yielded readings within 0.1 mph of the CAN bus readings, with the vehicle traveling at 35 mph. However, when the vehicle remained stationary, CAN based data speed showed a vehicle movement of 0.5 m/sec. CAN based deceleration data was not used since the analysis showed the need of further data processing along with a discrepancy of 0.85 m/s^2 when compared to the ground truth calculated deceleration. Therefore, CAN bus data may not be required in this application. This may remove the need for custom integration with each vehicle manufacturer and enable implementation of a more generic solution usable with any vehicle.

The key successes achieved by the prototype RCVW system include:

- Successful integration of an IEEE 1570 device for conveying the preemption signal from the HRIC to the RBS CP using serial communications
- Implementation of a System Fault check informing the user when the system is disabled as a result of the lack of essential data
- Use of RTCM corrections broadcasted over DSRC to achieve an RTK solution
- Ability to successfully integrate the RCVW system to distinct types of vehicles
- Development of a human factors-based set of RCVW messages

4. Future Work

4.1 Field Testing

The field test activities identified several issues that need further analysis. An extended period of field testing where system and performance data is gathered and required to better understand the issues, refine, and harden the overall RCVW system.

Updated graphic and audio messages were not evaluated due to the nature of the field test performed. A deployment where the system is installed in vehicles of volunteering participants would allow for an evaluation and potential refinement of these messages.

4.2 Pilot Deployment Projects

Outreach should be conducted to the different stakeholders such as vehicle manufacturers, local and State agencies and railway companies to demonstrate the RCWV system. With their support, model deployments and pilot installations across the United States can be performed to evaluate the efficacy of the system in real life scenarios.

4.3 Integration with Novel Technologies and Standards

Adaptation of the RCVW system to novel and emerging communication protocols such as C-V2X should be researched and implemented to increase system compatibility and functionality.

4.4 Additional Functionality

Research into additional functionality of the system such as implementation at crossings with multiple train tracks, track fouling alerts, and extending the functionality to pedestrian violations should be explored.

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Appendix A.
RCVW System Parameters

Table A-1 shows the configurable parameters of the system. All parameters prefixed with the word “V2” are set specific to the RCVW II implementation. All others are common (Phase I and Phase II).

Table A-1. Test1

Key	Default	Description
Message Expiration	2000	The parameter used to enter the amount of time in milliseconds to wait before issuing a warning indicating that current message data is stale.
Output Interface	0	The parameter used to input the value that corresponds to the type of interface that the application needs to display its messages on. 0=Digital Visual Interface (DVI), 1=Ford SYNC, 2=Android Auto.
Distance to HRI	480	The parameter that indicates the maximum distance (in meters) away from an equipped HRI that a system fault may be issued due to communication failure. When the VBS is within this distance of the HRI, the system checks for MAP and SPAT expiration timeout, if the GNSS system achieved an RTK fix and if location messages are being received at the configured rate.
HRI Locations	":"{ \"HRIs\": [\n {\"Latitude\":0, \"Longitude\": 0, \"HRIName\":\"TBD\"}\n] }",	This parameter shows the JavaScript Object Notation (JSON) data defining a list of equipped HRI locations loaded into the system.
Extended Intersection	0.1	The percentage to add to the radius of the intersection divided by 100. i.e., in this case the percentage to be added is 10%. So, the value to enter is 10/100 = 0.1
HRI Warning Threshold Speed	1.0	The maximum vehicle speed in meters per second for which the HRI warning will be active if the vehicle is in the HRI and moving. If the vehicle’s speed falls below this threshold, a warning will be issued to the driver.
Use Calculated Deceleration	false	Use calculated deceleration to determine if the vehicle will stop before HRI in addition to velocity-based warning calculation.
Log Level	DEBUG	The logging level of the RCVW system.

Key	Default	Description
V2 Antenna Placement X	0.5	Antenna placement X with respect to front left corner of vehicle in meters
V2 Antenna Placement Y	2.5	Antenna placement Y with respect to front left corner of vehicle in meters
V2 Antenna Placement Height	1.5	Antenna height with respect to the road surface in meters
V2 GPS Error	3.12	GPS longitudinal error in meters. The system uses this value directly in the RCVW calculation formula to calculate the issuing of alerts and warnings. This value represents the longitudinal error of the GNSS system. It is a configurable parameter and as such it can be modified according to the system and vehicle performance. The default value of 3.12 was selected as a result of preliminary testing to show good system performance.
V2 Reaction Time	2.5	Perception-Reaction time in seconds. AASHTO uses the term "Perception-reaction" time and it represents the time it takes for a road user to 1) realize that action is needed due to a road condition, 2) decide what action to take and 3) start the action.
V2 Communication Latency	0.3	Communication latency in seconds. The system uses this value directly in the RCVW calculation formula to calculate the issuing of alerts and warnings. This parameter accounts for DSRC radio signal communication latencies and IEEE 1570 data package reception latencies (if used). The default value of 0.3 is based upon RCVW system requirements VBS-22 and RBS-21 (see Appendix C) for allowable communication latency.
V2 Application Latency	0.085	Application latency in seconds. The system uses this value directly in the RCVW calculation formula to calculate the issuing of alerts and warnings. It considers the latency of the whole RCVW application for processing data and issuing warnings and alerts. The default value of 0.085 is based upon RCVW system requirement VBS-23 (see Appendix A) for allowable application latency.
V2 Deceleration Car	3.4	Minimum expected controlled deceleration for a car in $\frac{m}{s^2}$
V2 Deceleration Light Truck	2.148	Minimum expected controlled deceleration for a light truck in in $\frac{m}{s^2}$

Key	Default	Description
V2 Deceleration Heavy Truck	2.322	Minimum expected controlled deceleration for a heavy truck in in $\frac{m}{s^2}$
V2 Vehicle Type	1	Vehicle type, 1 = Car, 2 = Light Truck, 3 = Heavy Truck
V2 Vehicle Length	4.8	The length of the vehicle in meters
V2 Use Vehicle Based Measurement (VBM) Deceleration	false	Use VBM deceleration to determine if the vehicle will stop before HRI in addition to velocity-based warning calculation.
V2 Log SPaT	500	Log SPaT messages at DEBUG level
V2 Critical Message Expiration	false	The amount of time in milliseconds to wait before issuing a warning that the current critical message data is stale.
V2 Use Config Grade	0	If False, the system will use the grade directly from the receiving MAP. If True, the system will use the V2 Grade configurable variable for grade calculations.
V2 Grade	true	If Parameter V2 Use Config Grade is set to True, this grade value will be used in warning distance calculations. The value is defined as change in height over change in distance.
V2 Check RTK	true	If enabled check location message for RTK fix while in range of HRI. If enabled and the location message does not show an RTK fix, a system fault is issued.
V2 Check Location Frequency	true	If set to true, the system will check the location message reception rate. If the rate of location messages falls below the value of the parameter shown in V2 Minimum Location Frequency, a System Fault message is issued.
V2 Location Frequency Sample Size	30	This parameter is used if V2 Check Location Frequency is set to true. It is the number of location messages to sample to determine frequency.
V2 Minimum Location Frequency	8	This is the minimum allowed average location message frequency in messages per second.
V2 Max Heading Change	45	The maximum allowed heading change in degrees before ignoring the new position.
V2 Max Ignored Positions	7	The maximum number of consecutively ignored positions due to heading change.

Appendix B.
Field Test and Evaluation Report

Sanchez-Badillo, A., Baumgarder, G., Paselsky, B., Seitz, T. (2022). "Appendix B. Vehicle-to-Infrastructure Rail Crossing Violation Warning – Phase II: Field Test & Evaluation Report." Report No. DOT/FRA/ORD-22/07. Washington, DC: U.S. Department of Transportation, Federal Railroad Administration.

Appendix C.
RCVW System Requirements

This appendix provides the system requirements in Table C-1 for the RCVW.

Table C-1. RCVW System Requirements

RCVW Requirement No	System /Subsystem	Requirement
RCVW-1	RCVW System	The system shall include a vehicle-based subsystem component and a RBS component.
RCVW-3	RCVW System	The system shall be modular and sufficiently extensible to address all design objectives defined in this SRS.
RCVW-5	RCVW System	The only point(s) of connection between the RCVW system and the train detection system shall be the preemption signal available through a track-circuit or IEEE 1570-compliant serial interface.
RCVW-7	RCVW System	The vehicle-based subsystem OBU and RBS RSU shall communicate in compliance with SAE J2735-2016, IEEE 1609, SAE J2739, and SAE J2450 (ITIS) Standards.
RCVW-8	RCVW System	All "over-the-road" licensed vehicles (i.e., vehicles of all vehicle classes) are included.
RCVW-11	RCVW System	The system shall be compliant with Connected Vehicle Personally Identifiable Information (PII) standards and guidelines.
VBS-1	Vehicle-Based Subsystem (VBS)	The vehicle-based subsystem DVI shall have the capability to produce alerts suitable for all licensed drivers.
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, and neither by the driver.

RCVW Requirement No	System /Subsystem	Requirement
VBS-3a	Vehicle-Based Subsystem (VBS)	The vehicle-based subsystem will present alerts that conform to In-Vehicle Display Icons and Other Information Elements, Volume 1: Guidelines and Human Factors Design Guidance for Driver-Vehicle Interfaces.
VBS-3b	Vehicle-Based Subsystem (VBS)	The system shall provide two-stage alert messaging consisting of an informational, and, if applicable, a warning alert. Note: An Approach Inform Alert is non-obtrusive and serves to inform the driver of an active HRI ahead. This alert primes the vehicle operator for the potential need to stop at the HRI. A warn alert is obtrusive and occurs if it is predicted that the vehicle will not stop prior to the HRI using non-emergency braking. This alert serves to notify the vehicle operator that remains unaware of the active HRI ahead or who has decided to exercise poor judgement.
VBS-3c	Vehicle-Based Subsystem (VBS)	The inform and warn alerts shall be multimodal in nature. Note: Multimodal alerts may be visual, auditory, or haptic.
VBS-4	Vehicle-Based Subsystem (VBS)	The vehicle-based subsystem 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.
VBS-5	Vehicle-Based Subsystem (VBS)	The vehicle-based subsystem shall receive and process RTK corrections using the RTCM messaging protocol broadcasted from the RBS to achieve a R95 probability of horizontal position accuracy of less than or equal to 1.5 meters.
VBS-6	Vehicle-Based Subsystem (VBS)	The vehicle-based subsystem shall process HRI configuration (GID) data that describes the geographic composition of the intersection
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.
VBS-8	Vehicle-Based Subsystem (VBS)	The system shall provide a driver-vehicle interface (DVI) and, alternately, support display to OEM displays through standardized physical and electrical outputs.

RCVW Requirement No	System /Subsystem	Requirement
VBS-9a	Vehicle-Based Subsystem (VBS)	The vehicle-based subsystem shall not interfere with any of the onboard safety systems, especially automotive industry automated safety systems.
VBS-9b	Vehicle-Based Subsystem (VBS)	The vehicle-based subsystem shall not interfere with any existing infrastructure subsystems (i.e., traffic control and HRI warning systems).
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.
VBS-11a	Vehicle-Based Subsystem (VBS)	The vehicle-based subsystem shall issue a unique warn alert that directs users to take evasive action to clear the HRI by any means when the vehicle is stopped within the HRI Hazard Zone. Note: In the future, when SAE J2735 has been modified to better support rail applications and the intersection zone (HRI Hazard Zone) or when an alternative approach is found to be viable, it is anticipated that the RCVW tool will be capable of distinguishing whether the crossing is active when the vehicle is within the HRI Hazard Zone. At that time, it is desired that this requirement will be transformed into two requirements—one for when the crossing is active where a warn alert such as the one described here is issued, and one when the crossing is not active where a new Approach Inform Alert will instead be presented.
VBS-11b	Vehicle-Based Subsystem (VBS)	The vehicle-based subsystem shall issue warnings while the HRI is active when the vehicle is in the HRI Approach Zone if the vehicle is not decelerating sufficiently to stop safely before the HRI using non-emergency braking.
VBS-11c	Vehicle-Based Subsystem (VBS)	The warning alert shall use a dynamic visual icon(s) and invasive auditory alert(s) in accordance with Campbell et al. (2016).
VBS-12	Vehicle-Based Subsystem (VBS)	The vehicle-based subsystem shall issue an Approach Inform Alert to the vehicle operator when the crossing ahead is active and rail crossing signage for an active crossing is within visual range according to the Guidelines for Advance Placement of Warning Signs in Table 2C-4 of the 2009 Manual on Uniform Traffic Control Devices (MUTCD), Revision 2, June 13, 2012. Note: These guidelines identify where to place a warning sign (i.e., stop sign) in advance of a location with a potential stop condition according to the speed of the vehicle. The presentation

RCVW Requirement No	System /Subsystem	Requirement
		of an Approach Inform Alert is limited to approaches toward active rail grade crossings to avoid nuisance alerting.
VBS-13	Vehicle-Based Subsystem (VBS)	The Approach Inform Alert shall use static visual icons and non-invasive audible alert(s) in accordance with Campbell et al. (2016).
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, acceleration, and other vehicle parameters to determine if an RCVW should be issued.
VBS-15	Vehicle-Based Subsystem (VBS)	An RCVW warning shall be presented to the vehicle operator based on: 85th percentile driver response time, vehicle characteristics (i.e., vehicle class), and vehicle telematics (i.e., velocity, acceleration).
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.
VBS-17	Vehicle-Based Subsystem (VBS)	Once issued, the graphical component of an Approach Inform Alert will persist while the vehicle is within the approach zone, except when superseded by a warning or fault alert, or when the crossing becomes inactive.
VBS-18	Vehicle-Based Subsystem (VBS)	The vehicle-based subsystem shall issue a fault alert to the vehicle operator when the RCVW system is not functioning in "normal" operations mode. A fault alert will be triggered when the VBS does not receive critical information, including: 1) Position information a) GNSS information being received at a rate lower than 10 Hz b) GNSS solution not reaching and RTK fix, either floating or fixed integer 2) MAP 3) SPaT (which includes loss of the IEEE 1570 interface communication heartbeat from the HRI warning system, when this interface is used), or 4) DSRC communications (MAP and SPaT) when expected and needed

RCVW Requirement No	System /Subsystem	Requirement
VBS-19	Vehicle-Based Subsystem (VBS)	Fault alerts shall supersede all other annunciations.
VBS-20	Vehicle-Based Subsystem (VBS)	Warn alerts shall supersede Approach Inform Alerts.
VBS-22	Vehicle-Based Subsystem (VBS)	The vehicle-based subsystem shall be capable of receiving messages sent by the RBS within 50 ms.
VBS-23	Vehicle-Based Subsystem (VBS)	The vehicle-based subsystem shall be capable of processing received data within 85 ms.
VBS-24	Vehicle-Based Subsystem (VBS)	The vehicle-based subsystem shall know the position of the GNSS antenna relative to the front of the vehicle and the rear of the vehicle.
RBS-1	Roadside-Based Subsystem (RBS)	The RBS shall interoperate with current infrastructure safety systems (e.g., traffic control and Train Approaching warning devices) in accordance with NEMA TS 2-2016 v03.07.
RBS-2	Roadside-Based Subsystem (RBS)	The RBS shall operate using 60 Hz 115VAC power as the primary power source.
RBS-2b	Roadside-Based Subsystem (RBS)	The RBS shall determine HRI crossing status using preemption signal information from a IEEE 1570-compliant serial interface or from a voltage-based interconnection circuit.
RBS-3	Roadside-Based Subsystem (RBS)	The infrastructure-based communication equipment shall be compliant with the V2I Hub Reference Implementation platform.
RBS-4	Roadside-Based Subsystem (RBS)	The RBS shall broadcast the HRI Active message 10 times per second when an associated HRIC activates a preemption signal.

RCVW Requirement No	System /Subsystem	Requirement
RBS-5	Roadside-Based Subsystem (RBS)	The RBS shall stop broadcasting the HRI Active message when the HRIC deactivates the preemption signal(s).
RBS-7	Roadside-Based Subsystem (RBS)	The RBS shall broadcast the HRI Configuration Data Format (HCDF) once per second.
RBS-10	Roadside-Based Subsystem (RBS)	The RBS 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.
RBS-11	Roadside-Based Subsystem (RBS)	The RBS shall employ methods to prevent unauthorized physical and cyber access.
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 DOT for V2I communications will be exercised.
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.
RBS-16	Roadside-Based Subsystem (RBS)	The RBS shall identify and log system failures to the extent that it is practicable.
RBS-18	Roadside-Based Subsystem (RBS)	The RBS shall incorporate self-recovering routines to recover from a major system failure associated with firmware/software systems.
RBS-20	Roadside-Based Subsystem (RBS)	The RBS shall not interfere with any HRI infrastructure subsystems.

RCVW Requirement No	System /Subsystem	Requirement
RBS-21	Roadside-Based Subsystem (RBS)	The RBS shall be capable of receiving HRI message packets across the IEEE 1570 serial interface in less than 250 ms conforming to the IEEE 1570 standard.
RBS-22	Roadside-Based Subsystem (RBS)	The RBS shall be capable of generate and broadcast RTK corrections using the RTCM messaging protocol.

Abbreviations and Acronyms

ACRONYMS	EXPLANATION
APTA	American Public Transportation Association
AREMA	American Railway Engineering Maintenance-of-Way Association
ASME	American Society of Mechanical Engineers
ABS	Anti-lock Braking System
AAR	Association of American Railroads
AASHTO	Association of State and Highway Transportation Officials
AV	Automated Vehicle
CEP	Circular Error Probable
COM	Communication
CP	Computer Platform
CAN	Controller Area Network
CV	Connected Vehicle
CARMA	Cooperative Research Mobility Applications
DR	Dead Reckoning
DSD	Decision Sight Distance
DSRC	Dedicated Short-Range Communications
DGNSS	Differential Global Navigation Satellite System
DIO	Digital Input/Output
DVI	Driver-Vehicle Interface
FAA	Federal Aviation Administration
FMVSS	Federal Motor Vehicle Safety Standards
FRA	Federal Railroad Administration
FT&E	Field Test and Evaluation
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GVWR	Gross Vehicle Weight Rating
HDMI	High-Definition Multimedia Interface
HRI	Highway-Rail Intersection
HCDF	Highway-Rail Intersection Configuration Data File

ACRONYMS	EXPLANATION
HRIC	Highway-Rail Intersection Controller
HTTP	Hypertext Transfer Protocol
HTTPS	Hypertext Transfer Protocol Secure
IMU	Inertial Measurement Unit
IEEE	Institute of Electrical and Electronics Engineers
JSON	JavaScript Object Notation
KML	Keyhole Markup Language
LCD	Liquid Crystal Display
MUTCD	Manual on Uniform Traffic Control Devices
MAP	Map Data
MT	Masking Threshold
m/s	Meters per Second
ms	Millisecond
NMEA	National Marine Electronics Association
NOCoE	National Operations Center of Excellence
ODOT	Ohio Department of Transportation
OBU	On-Board Unit
OS	Operating System
POV	Point of View
PVT	Position, Velocity, and Time
RTCM	Radio Technical Commission for Maritime Services
RCVW	Rail Crossing Violation Warning
RTK	Real-Time Kinematics
RBS	Roadside-Based Subsystem
RSU	Roadside Unit
SBAS	Satellite Based Augmentation System
SPaT	Signal Phase and Timing
SAE	Society of Automotive Engineers
TRC	Transportation Research Center
V2I	Vehicle and Infrastructure
VBM	Vehicle Basic Message

ACRONYMS	EXPLANATION
VBS	Vehicle Based Subsystem
V2V	Vehicle to Vehicle
V2X	Vehicle to Everything
VRS	Virtual Reference Station
DOT	U.S. Department of Transportation
USB	Universal Serial Bus
UDP	User Datagram Protocol
WAAS	Wide Area Augmentation System