Vehicle-to-Everything Hub: Final Report

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FOREWORD

The Turner-Fairbank Highway Research Center performs advanced research for several areas of transportation technology for the Federal Highway Administration. The Office of Operations Research and Development (HRDO) focuses on improving operations-related technology through research, development, and testing.

This report details continuing work sponsored by HRDO to promote the early deployment of connected-vehicle technology. Under this task order, the project team developed and tested four new plugins based on the four use cases for the Vehicle-to-Everything (V2X) Hub. This report describes these plugins, which are essential for implementing the infrastructure requirements for connected-vehicle technology and intelligent traffic systems in general. In addition, this report provides insight into the function of the new V2X Hub plugins and their uses in real-world connected-vehicle deployment. It is the project team's intent that the V2X Hub will continue to enable infrastructure owners and operators by providing a single platform that communicates with pedestrians and other vulnerable road users with mobile devices, connected and automated vehicles (including transit vehicles), or other devices from both the field infrastructure and center-based systems (e.g., traffic/transit-management center).

Brian P. Cronin, P.E.
Director, Office of Operations and Safety
Research and Development

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The United States Department of Transportation is interested in developing individual and consolidated technologies that share safety information between road vehicles, trains, infrastructure, and mobile devices using multiple communications media. The Vehicle-to-Everything (V2X) Hub project was initiated to build a software platform to act as a network intermediary that allows for messages to be sent and received by all users in a connected system, regardless of how widely distributed the systems are or what protocols and standards these systems use to broadcast messages. Feedback and input were solicited from the early adopter community to determine which applications should be prioritized and to develop test cases and procedures. This report provides a high-level description of the V2X Hub system architecture, design, and communication protocols, as well as an overview of the hardware and software required for deployment. This report also summarizes feedback and insight from stakeholders that implemented and used specific plugins for their V2X Hub deployments.</td></tr>
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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1,000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2,000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2,000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	2.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003)

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LIST OF ACRONYMS

API	application programming interface
ARM	advanced reduced instruction set computing machine
BSM	basic safety message
CAV	connected and automated vehicle
COP	community of practice
CSV	comma-separated values
CSW	curve speed warning
CV	connected vehicle
DMS	dynamic message sign
DOT	department of transportation
DSRC	dedicated short-range communication
FHWA	Federal Highway Administration
GNSS	global navigation satellite systems
GPS	Global Positioning System
IP	internet protocol
ITS	intelligent transportation system
IVP	Integrated Vehicle-to-Infrastructure Prototype
JSON	JavaScript Object Notation
NTCIP	National Transportation Communications for Intelligent Transportation System Protocol
NTRIP	networked transport of Radio Technical Commission for Maritime Services via internet protocol
OBU	onboard unit
ODE	Operational Data Environment
OSS	open-source software
PSID	provider service identifier
PSM	personal safety message
ROS	Robotics Operating System
RSU	roadside unit
RTCM	Radio Technical Commission for Maritime Services
SAE	Society of Automotive Engineers
SPaT	signal phase and timing
SRM	signal-request message
TIM	traveler-information message
TMC	traffic-management center
TSC	traffic-signal controller
UDP	user datagram protocol
UPER	unaligned packet encoding rules
USDOT	United States Department of Transportation
V2I	vehicle-to-infrastructure
V2V	vehicle-to-vehicle
V2X	vehicle-to-everything
WAVE	wireless access in vehicular environments

CHAPTER 1. INTRODUCTION

BACKGROUND

The United States Department of Transportation (USDOT) is interested in developing individual and consolidated technologies that share safety information between road vehicles, trains, infrastructure, and mobile devices using multiple communications media. To understand how consolidated technologies contribute to developing and deploying connected infrastructure, it is necessary to first understand how vital connected-vehicle (CV) components will communicate with one another.

A CV is a vehicle equipped with communication equipment that enables it to communicate wirelessly with other CVs, mobile devices, and infrastructure. Vehicle-to-vehicle (V2V) communication involves a wireless data exchange between nearby vehicles through which a CV can determine the location of nearby CVs and inform users of roadside safety. Vehicle-to-infrastructure (V2I) communication takes place between vehicles and deployed roadside infrastructure–connectivity equipment, which capture vehicle-generated data while providing information on safety, mobility, and environmental conditions.

CV technology improves the safety and reliability of automated vehicles and enables the development of connected and automated vehicles (CAVs). CVs communicate via two-way short-to-medium-range wireless communication on the 5.9-GHz spectrum intended for secure high-speed wireless communication. Although CVs currently use dedicated short-range communication (DSRC) as the medium for communication, other communication media can be leveraged to obtain the same functionality. CAVs, for instance, can use 4G/LTE and 5G mobile networks defined by the Third Generation Partnership Project 3GPP.

According to USDOT, fully deployed CV and CAV technologies have the potential to facilitate developing and implementing solutions that transcend the safety aspects of the 5.9-GHz spectrum.[(1)] Technologies like vehicle preemption and priority have the potential to aid emergency vehicles and first responders in navigating roadway congestion, whereas system-performance measures can help traffic-management centers (TMCs) boost the efficiency and efficacy of the entire system.[(1)]

To create a CAV environment, efforts were initially directed toward developing a traffic-signal controller (TSC) capable of relaying phase information to users. In 2006, the Society of Automotive Engineers (SAE) published the J2735 standard, *Dedicated Short Range Communications (DSRC) Message Set Dictionary*, and later released revisions in 2009 for the first CV deployment Safety Pilot in Ann Arbor, MI.[(2)] The standard specifies the message set and data elements related to safety, mobility, and the environment (e.g., a signal phase and timing (SPaT) message broadcast from a TSC to a road user to indicate the current status of signal).

In 2015, the Federal Highway Administration (FHWA) successfully completed the design, development, and testing of a SPaT system that relays interface messages between TSCs and road users.[(3)] The system communicates SPaT information provided by a TSC using an extended version of the National Transportation Communications for Intelligent Transportation System (ITS) Protocol (NTCIP) 1202.[(4)] The information is converted to SAE J2735 message format, which is then broadcasted by a roadside unit (RSU) and received by onboard units (OBUs) in CVs.

Efforts to create a CAV environment were subsequently directed toward developing a prototype that would support V2I technology deployment.(5) In 2013, the V2I Hub was created for the Integrated V2I Prototype (IVP) project.(6) The IVP project aimed to create a roadside prototype system that would supply the needed SAE J2735 message format for CV in-vehicle applications. The V2I Hub, in addition to the TSC, can interface with a greater array of ITS equipment, in addition to the TSC. The V2I Hub simplified integration by translating communication between different standards and protocols into software messages that CV applications could interpret.

The project team developed the latest version of Vehicle-to-Everything (V2X) Hub. This iteration builds upon prior and related efforts and was developed as a single integrated system to support jurisdictions in the deployment of V2I technology by enabling infrastructure owners and operators to utilize a single mechanism to communicate with pedestrians and other vulnerable road users with mobile devices, connected and automated vehicles (including transit vehicles), or other devices from both the field infrastructure and center-based systems (e.g., traffic/transit-management center). Developing the V2X Hub as an open-source software (OSS) application has allowed collaboration between users and experts to enhance the applicability and accelerate the deployment of the platform.

OBJECTIVE

The V2X Hub project was initiated to build a software platform to act as a network intermediary that allows for messages to be sent and received by all users in a connected system, regardless of how widely distributed the systems are or what protocols and standards these systems use to broadcast messages. Feedback and input were solicited from the early adopter community to determine which applications should be prioritized and to develop test cases and procedures.

This report provides a high-level description of the V2X Hub system architecture, design, and communication protocols, as well as an overview of the hardware and software required for deployment. This report also summarizes feedback and insight from stakeholders that implemented and used specific plugins for their V2X Hub deployments.

CHAPTER 2. V2X HUB

V2X HUB SYSTEM

The V2X Hub is a multimodal OSS that enables networked wireless communications among vehicles, infrastructure, and mobile devices. CVs using the SAE J2735 message format share anonymous basic safety messages (BSMs) with connected infrastructure equipment and other CVs. BSMs contain important vehicle information like size, speed, position, heading, acceleration, and brake-system status. The V2X Hub translates these messages and exchanges them in a format that is understood by both CVs and infrastructure and can be used by V2X Hub applications. The platform's OSS design allows it to support a variety of software plugins, which enable efficient device connection, message translation, functionality, and development of software applications that work with V2X Hub.

Advantages of deploying a V2X Hub–based system include the following:

- As an OSS platform with documentation, the V2X Hub avoids the hefty investment and development that often accompany proprietary, custom systems.(7)
- The V2X Hub provides secure remote access to the software to enable monitoring, configuration, and deploying software updates, thereby reducing operations and maintenance efforts.(7)
- The V2X Hub's built-in message-translation and plugin architecture reduces the amount of backend software and integration work needed for jurisdictions to support CVs.(7)
- The V2X Hub offers the ability to efficiently develop custom plugins that meet a jurisdiction's specific operations and equipment.(7)
- The V2X Hub is standard-adherent but manufacturer-neutral, providing operators with the flexibility to incorporate equipment from different vendors and add greater functionality using in-house or third-party resources.(7)
- In addition to supporting communications between subscribing plugins, the V2X Hub architecture facilitates low- and high-latency external communications with a message manager by using external service interfaces and centralized message routing. A system-monitor application in V2X Hub analyzes communication between the various nodes to ensure the health of the system.
- Unlike most ITSs, which focus on a specific user or function (e.g., transit signal priority), the V2X Hub can support virtually any user or scenario. New functionality can be added to the Hub by developing plugins and installing them remotely via a secure connection, removing the need to purchase and install new hardware throughout the infrastructure. For example, transit signal priority can be added to any V2X Hub–equipped intersection to enable transit vehicles to request priority using wireless communications. Emergency-vehicle preemption can be added throughout a network of intersections

running V2X Hub without the need to install and wire new hardware on every intersection approach.(7)

The V2X Hub distributes data and information to CAVs, enabling in-vehicle warnings and collision avoidance upon detecting a dangerous situation. The platform also transmits anonymous vehicle messages to TMCs, providing accurate, real-time information on the locations and speeds of vehicles in the system. Such information is used to identify areas of traffic congestion to help manage the timing of traffic signals and ramp meters.(7)

Intelligent transportation solutions offer opportunities to improve surface transportation safety and boost system efficiency. For the past six years, USDOT has been developing the V2X Hub and similar technologies that share safety information between road vehicles, trains, infrastructure, and mobile devices using multiple communications media. The V2X Hub solves the problem of cross-platform communication between users sending information over an internet protocol (IP), wireless access in vehicular environments (WAVE) protocol, or infrastructure-oriented NTCIP.

Federal CAV research has produced substantial findings and resources that support OSS as a software development strategy that facilitates interoperable systems and provides users access to a variety of different hardware and CAV use scenarios.(1) The V2X Hub as an OSS application also allows for a community of practice (COP) composed of users and experts who can support each other by contributing code to address common needs and providing experienced insight.

V2X HUB SOFTWARE

The V2X Hub software is a robust and deployment-ready solution for implementing CAV applications in roadside infrastructure. The software was tested on Ubuntu™ 18.04 LTS, but it can run on most operating systems that can support Docker® containers. Currently, the software is compiled for 64-bit advanced reduced instruction set computing machine (ARM) and 64-bit processors. The software architecture allows the V2X Hub to be configured to run a suite of different software applications and plugins, and each plugin is created to perform a specific function (e.g., communicate with a TSC and produce SPaT messages). The V2X Hub software contains information regarding the communication routing, configuration for the plugins, and start/stop/monitoring processes for the plugins.

The V2X Hub–software architecture can be broken down into two main layers: the V2X Hub Core and V2X Hub plugins. The V2X Hub Core is the heart of the V2X Hub software. The Core performs all message routing between plugins and displays the current configuration status via a web browser. V2X Hub plugins are the interface for two-way communication between the Core and external subsystem components. The specific applications running on the V2X Hub determine the plugins and external subsystem components required to run the application. The plugins can also use a webservice application programing interface (API) layer, allowing connections to transportation management systems and mobile devices.

Plugin modules are the application-specific pieces of code in the V2X Hub. Plugin modules are responsible for processing data extracted from external peripheral components and generating statuses or other information that is then published to the V2X Hub router. Plugins can also control or communicate with external subsystem components based on processing resulting from messages received from other application plugins installed on the V2X Hub. Using plugins reduces the work required to add functionality or connectivity to new devices and lessens the work of backend software and integration often required for operators to support CAVs.

EXISTING V2X HUB PLUGINS

V2X Hub plugins share and exchange information between external subsystem components and the V2X Hub Core. This section describes the 10 existing V2X Hub plugins.

Immediate Forward

The Immediate Forward plugin forwards messages in the SAE J2735 format from the V2X Hub to a DSRC 5.9-GHz RSU compliant with the latest RSU 4.1 specification for immediate broadcast.[8] The plugin also immediately forwards messages in the SAE J2735 format received by an RSU to the V2X Hub for logging or use by other plugins.

Within the V2X Hub system, the Immediate Forward plugin monitors all messages in the Hub and packages those flagged for transmission. The message sent by the Immediate Forward plugin to the RSU is transmitted using the protocol described in appendix A, which sends a message to the RSU over a user datagram protocol (UDP) network connection. Data are subsequently packaged and signed by the RSU and transmitted for use by other CV DSRC radios.

The Immediate Forward plugin can be configured to send messages to four different destinations. A destination is defined by an IP address and port pair. The Immediate Forward plugin, for example, can send messages to four different RSUs. Some RSUs allow only a single Provider Service Identifier (PSID) per immediate forwarded application. RSUs that require multiple immediate forward applications to transmit messages (i.e., an application for PSID 0x8002 and a separate application for PSID 0x003) require configuring multiple destinations to which to send all requested messages. Refer to the *V2X Hub Plugin Programming Guide* for configuration variables, default values, and descriptions of the Immediate Forward plugin.[9]

MAP

The MAP plugin creates SAE J2735 MAP messages in SAE J2735 2016 format. Inputs for the plugin can be created using USDOT's MAP Message Creator. The MAP Message Creator is a tool that enables creating MAP messages that include intersection geometry and is available in the USDOT Connected Vehicle Tools Library.[10] The online tool aids in creating SAE J2735 2016 MAP messages, which can be used as inputs for the V2X Hub MAP plugin. The input required by the MAP plugin can be created by using the export tool, setting the Message Type dropdown to MAP, and copying the JavaScript Object Notation (JSON) from the MAP Data text block into a file with a .json extension. The JSON format is a lightweight data-exchange format that is human-readable and easy for machines to serialize and deserialize.

SPaT

The SPaT plugin receives SPaT information about an intersection from a TSC. Upon receiving a UDP bit-encoded stream from the TSC, the SPaT plugin combines objects with preconfigured MAP messages and creates and broadcasts the standard SAE J2735 SPaT messages for road users via an RSU. The SPaT plugin and TSC use the NTCIP 1202v3 standard for communication. The SPaT plugin sends only the necessary message to the TSC to enable and disable sending the UDP bit-encoded stream.

The SPaT plugin can be configured to communicate and receive SPaT information from a single TSC. Refer to the *V2X Hub Plugin Programming Guide* for SPaT configuration values.[9]

BSM Logger

The BSM Logger receives BSMs forwarded from an RSU through the user's IP address and port configured in the message-receiver plugin and logs each message to a comma-separated values (CSV) file. The BSM Logger decodes each received data packet containing the BSM and extracts the values for the relevant fields. It then appends those values to a log file as CSV under specific columns identified by the ASN.1 field names defined in SAE J2735. The location of the CSV files is user-configurable through the plugin. A new CSV file is created every 5 min to enable timely access to logs.

SPaT Logger

The SPaT Logger receives and logs unaligned packet encoding rules (UPER)-encoded SPaT messages generated by the SPaT plugin in the V2X Hub. It logs the UPER-encoded SPaT messages, along with a system-generated timestamp for each message, to a CSV file. The SPaT logger appends subsequent SPaT messages to the log file for as long as the plugin is enabled. The location of CSV files is user-configurable through the plugin.

Radio Technical Commission for Maritime Services

The Radio Technical Commission for Maritime Services (RTCM) is an international standards organization that created RTCM 10402.3, *Recommended Standards for Differential GNSS (Global Navigation Satellite Systems) Service* Version 2.3, and RTCM 10403.3, *Differential GNSS (Global Navigation Satellite Systems) Service* Version 3.[11,12] The RTCM plugin uses the networked transport of RTCM via IP (NTRIP) to receive RTCM real-time correction information, create a corresponding RTCM SAE J2735 2016 message, and transmit the message to the V2X Hub. Currently, the RTCM plugin supports RTCM Version 2.3.

Dynamic Message Sign

The Dynamic Message Sign (DMS) plugin communicates with a DMS using NTCIP 1203 Version 3.[13] The plugin receives requests for messages to be displayed from other plugins in the V2X Hub and sends the appropriate message string configured in the plugin to the DMS for display. The plugin may send up to four messages to the DMS, and these messages are identified by the computational unit attached to the DMS using their index values, thereby reducing the delay in displaying the message. When the messages are updated, they are sent to the DMS to be displayed.

Curve-Speed Warning

The Curve-Speed Warning (CSW) plugin transmits information pertaining to an approaching sharp curve, monitors BSMs, and requests display of messages on a DMS when the vehicle's current speed is above the recommended speed for the curve. Using zones, the CSW plugin monitors and transmits geometry leading up to the entrance of the curve. The zones are numbered from 1 to 4, with 1 being the zone closest to the entrance of the curve. Each zone is configured with the recommended speed that is communicated to the CV using an SAE J2735 traveler-information message (TIM) in SAE J2735 2016 format.

A vehicle driving toward a curve will enter zone 4 first, then 3, and so on, until the vehicle enters the curve. The zones are directional, meaning that a vehicle traveling toward the curve will interact with the zones and a vehicle traveling away from the curve will not. To allow CSW alerts in both directions, zones must be created for each direction of travel. An in-vehicle application will use the four zones to give the driver different alerts or warnings depending on the zone and their speed. For example, when the CSW plugin detects that a decoded vehicle-speed value from the BSM is exceeding the recommended speed in zones 3 through 1, the CSW plugin will send a request to the DMS to display a "Slow Down" message.

BSM Receiver

Most RSUs have an application that forwards certain messages from the radio to a configured device. The data received from an RSU are sent to the V2X Hub computer in the SAE J2735 2016 format, and the most common data type sent is the BSM. The BSM Receiver plugin obtains the forwarded BSMs from RSUs and sends them to the V2X Hub for other applications, such as the CSW plugin, to use. The BSM Receiver works with any device, including simulation software that forwards BSMs in SAE J2735 2016 format over UDP.

V2X HUB HARDWARE

The hardware and software required for the V2X Hub are largely dependent on the desired applications to be deployed. The V2X Hub software can be run on any platform running a Linux operating system, but the following minimum hardware specifications were used in testing and deploying the V2X Hub under this project:

- ARM, x64, or x86 computer architecture.
- Between 2 and 4 GB of RAM meeting or exceeding specifications for DDR3.
- Minimum of 16 GB of SSD storage capacity.

SUPPORTED COMMUNICATION STANDARDS

As part of USDOT's goal of making roadways safer, and because USDOT has encouraged State and local authorities to deploy CAV technology, standardized CAV communication protocols were developed by the various standards organizations. USDOT enabled the development of the V2X Hub software following applicable industry standards to provide a scalable and interoperable solution for widespread CAV deployments. The V2X Hub software is compliant with the following standards:

- **IEEE 1609, Family of Standards for WAVE.** WAVE standards define an architecture and standardized set of services and interfaces for V2V and V2I wireless communication.[14]
- **NMEA 0183, Version 4.10.** The NMEA 0183 standard defines electrical-signal requirements and data-transmission protocol for serial data buses.[15]
- **NTCIP 1202, Object Definitions for Actuated TSC Units.** The NTCIP 1202 standard provides the information necessary for traffic-management personnel to manage actuated TSC units and contains object definitions to support transportation applications.[4]
- **NTCIP 1203, Object Definitions for DMS.** The NTCIP 1203 standard provides the vocabulary (i.e., commands, responses, and information) necessary for traffic-management and -operations personnel to advise and inform vehicle operators of current highway conditions using DMSs.[13]
- **DSRC RSU Specifications, Version 4.1.** The DSRC RSU Specifications standard sets the minimum requirements for DSRC RSUs.[8]
- **RTCM 10402.3, Recommended Standards for Differential GNSS Service, Version 2.3.** The RTCM worldwide standard is used by differential satellite navigation systems.[11]
- **SAE J2735, DSRC Message Set Dictionary.** The DSRC Message Set Dictionary supports interoperability among DSRC applications.[2]
- **SAE J2945/1, On-Board Minimum Performance Requirements for V2V Safety Communications.** The SAE J2945/1 standard sets the minimum performance requirements for V2V safety system interoperability.[16]

CHAPTER 3. OVERVIEW OF V2X HUB DEPLOYMENT

The V2X Hub is designed to work as part of a larger CAV system. Therefore, an understanding of how a connected system might be deployed is integral to understanding the V2X Hub deployment process.

DEPLOYMENT CONSIDERATIONS

Deploying the V2X Hub or any other infrastructure-connectivity equipment requires careful consideration of factors like the following throughout the deployment process:

- **Site selection.** Physical and technical limitations of a site should be considered when selecting a deployment site.
- **Stakeholder identification and coordination.** Stakeholders will vary from location to location and should be identified and engaged during the deployment process. Examples of stakeholders include municipalities, regional and State departments of transportation (DOTs), utility owners (e.g., of power and telephone poles), electrical contractors, TMCs, and internet providers.
- **Licensing and permitting.** Deployment may require applying for necessary licenses and permits per requirements by the Federal Communications Commission.
- **Hardware procurement.** The party responsible for purchasing the required hardware should be identified.
- **Installation.** The electrical contractor or other agency responsible for installing and maintaining the deployed system should be identified.
- **Configuration.** The party responsible for configuring the V2X Hub hardware and software after the system installation should be identified.

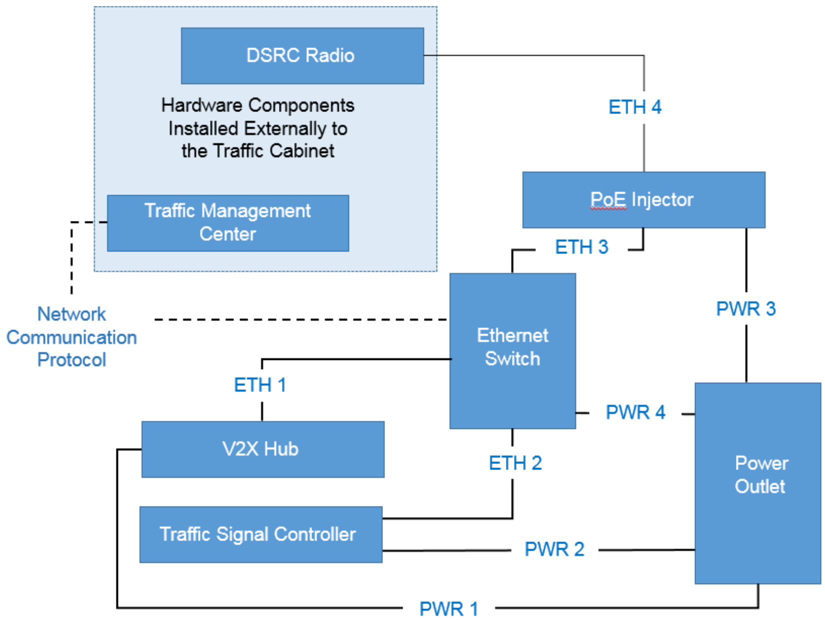
Refer to the *V2X Field Deployment Guide* for additional guidance on deployment.(17)

SAMPLE V2X HUB DEPLOYMENT

For this project, the sample roadside V2X Hub deployment consisted of the following subsystems for the roadside infrastructure: a V2X Hub computer, a TSC, and an RSU. The project team connected the V2X Hub to the TSC to obtain SPaT data and the RSU to transmit messages in SAE J2735 format over DSRC. The V2X Hub was connected to a TMC to send and receive data and configuration instructions.

DESIGN OVERVIEW

The V2X Hub is intended for infrastructure or roadside deployments. The basic design of the V2X Hub roadside deployment consists of a V2X Hub computer, external hardware, an RSU, and a network. Figure 1 is a block diagram of a typical V2X Hub system roadside deployment at a signalized intersection and identifies the required hardware and interconnections.



Source: FHWA.
ETH = Ethernet cable; PWR = power outlet.

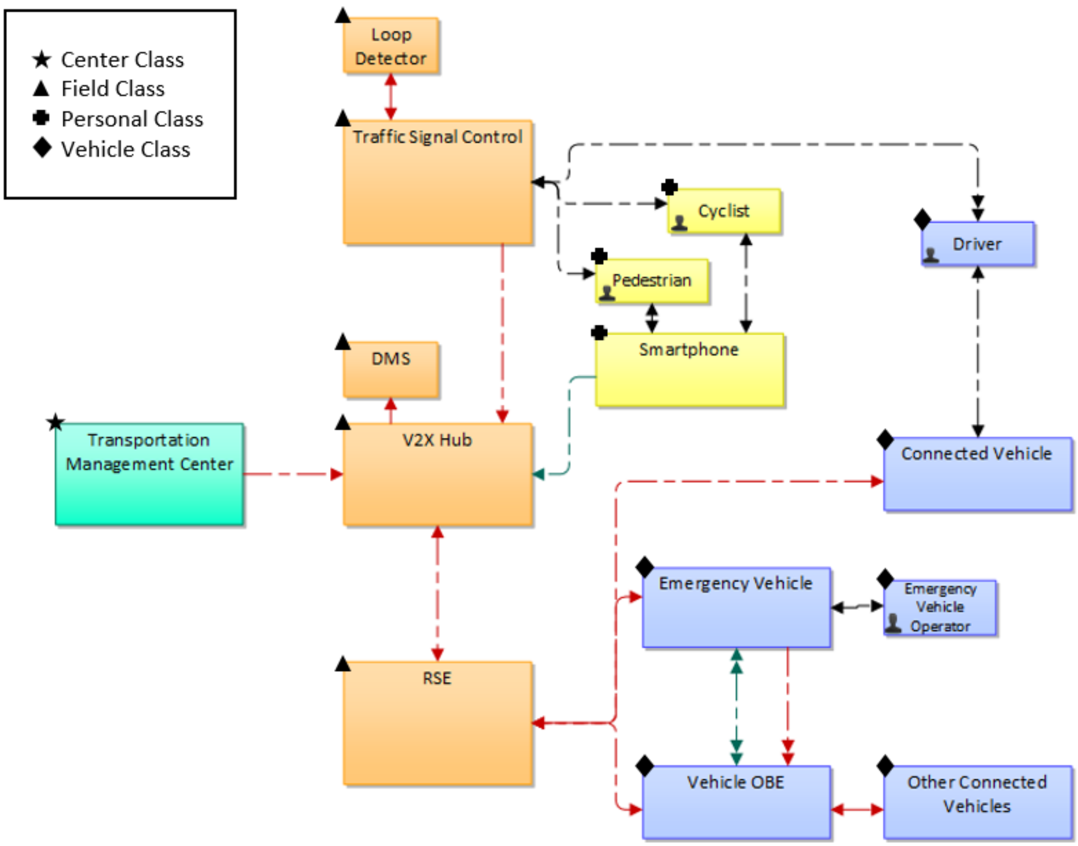
Figure 1. Diagram. High-level overview of V2X Hub system hardware and interconnections for roadside deployment at a signalized intersection.

The specific hardware required for a complete V2X Hub deployment includes the following:

- The **industrial computer (V2X Hub)** hosts the V2X Hub software.
- The **TMC** allows remote connectivity for monitoring, managing, and configuring the V2X Hub.
- The **RSU**, using a DSRC radio, transmits and receives CAV messages.
- The **GPS antenna** transmits GPS location information.
- **Two DSRC radio antennas** transmit and receive CAV messages.
- The **TSC** provides SPaT information about the intersection.
- **Ethernet cable 1** connects the externally mounted RSU to the surge protector.

- **Ethernet cable 2** connects the surge protector to the power over Ethernet (i.e., PoE) injector.
- **Ethernet cable 3** connects the PoE injector and the Ethernet switch.
- **Ethernet cable 4** connects the V2X Hub to the Ethernet switch.
- **Ethernet cable 5** connects the TSC to the Ethernet switch.
- The **surge protector** prevents electrical damage from lightning strikes.
- The **Ethernet switch** allows multiple Ethernet connections to be made on a single device on the same network.
- **Four power outlets** provide power for the hardware installed in the traffic cabinet.

All hardware components should be installed inside the traffic cabinet, except for the DSRC radio, the GPS and DSRC antennas attached to the DSRC radio, and a portion of Ethernet cable 5, which is routed from inside the traffic cabinet to outside the traffic cabinet where the RSU is installed. Figure 2 shows the placement of V2X Hub in the connected infrastructure environment.



Source: FHWA.
OBE = onboard equipment; RSE = roadside equipment.

Figure 2. Diagram. High-level overview of V2X Hub external subsystem components.

The following are the external subsystem components for the V2X Hub:

- The **DSRC radio** communicates with the Immediate Forward plugin and is the primary means for achieving V2I communications for the V2X Hub platform. The DSRC radio is a component of equipment positioned along highways, at traffic intersections, and at other locations that support wireless communication between CVs and infrastructure.
- The **GPS** receiver obtains location information and is a precise time source for the V2X Hub.
- The **NTRIP** caster is a data source from a network of base stations providing RTCM differential corrections for location and time position; these data allow a user to calculate a more accurate GPS position than that of an unassisted user.
- Installed at signalized intersections, the **TSC** communicates with the SPaT plugin to generate SPaT information, which is displayed via traffic lights, controlling vehicular traffic flow.

- The **DMS** is an electronic traffic sign positioned alongside roadways that displays special event information—such as traffic congestion, accidents, roadwork zones, or speed limits—to travelers.

- **ODE** is a cloud-based data repository created by USDOT for storing CAV data obtained from deployments.

- The **SSH (also known as "secure shell") protocol** is a method for creating a secure and encrypted remote connection between a client and server.(18)

- The **web browser** uses internet connectivity to facilitate access to the V2X Hub for remote configuration and maintenance.

- The **webservice API** allows socket connections from nomadic devices and TMCs.

CHAPTER 4. USER-COMMUNITY OUTREACH

One of the primary goals of the continued development of the V2X Hub project was to identify and implement four use cases that would support deployment of CV infrastructure.

To ensure the use cases would provide the greatest benefit to the CAV community, a COP of V2X Hub early adopters was created. The goal of the COP was to conduct regular meetings to assess implementation statuses, identify needs, receive feedback on upcoming updates to the V2X Hub, and provide opportunities for users to interact with one another and solve common problems.

Information gathered from stakeholders generated valuable insights that shaped this project. The results of this outreach effort are presented in this chapter, including recommendations for V2X Hub use cases (implemented as software plugins) that should be developed under this project.

OUTREACH

To identify areas of interest to the V2X Hub COP, the project team conducted several virtual information sessions between April and June 2019. The sessions served to share individual project developments and solicit recommendations and feedback from the COP to direct project efforts. Over three sessions, the project team conversed with more than 26 stakeholders from State DOTs, universities, consulting firms, and Government agencies.

SUMMARY OF FINDINGS

Feedback gathered from the COP helped identify the following areas for development of the V2X Hub as use cases and plugins:

1. Preemption.
2. Pedestrian.
3. Work Zones.
4. System Performance Measures.

The Preemption plugin emerged from discussions between multiple stakeholders who expressed a desire to provide traffic priority for snow plows on the roadways. Ultimately, it was decided that if an emergency-vehicle Preemption plugin was developed, it would provide the necessary functionality, such as allowing preemptive right of way for emergency vehicles while also assisting first responders. Any OBU capable of sending signal-request messages (SRMs) and BSMs with fixed vehicle IDs and extended information would be considered for whitelisting by the Preemption plugin. Emergency, transit, and freight vehicles were identified and monitored with SRM-capable OBUs transmitting vehicle-location and -speed information as they passed through intersections. OBUs with SRM capability needed to be identified so that the plugin could be tested. Alternatively, fixed vehicle IDs could be utilized, instead of randomly varying vehicle IDs in BSMs, with plugins recognizing specific vehicle IDs. COP members discussed collaborating and sharing data from their deployments with live feeds of collected messages. The Preemption plugin was a high-priority use case for the COP as reducing emergency response times was critical to COP members.

The Pedestrian plugin was created after the COP expressed interest in enhancing the existing pedestrian functionality to enable RSUs to broadcast personal safety messages (PSMs) over available wireless communication technology. The existing functionality was entirely web-based and allowed pedestrians using a web-based app on their mobile devices to send alert messages to drivers through cloud services, thereby reducing the chance of accidents. The COP identified the Pedestrian plugin as a high-priority use case because RSU reporting of imminent crash situations to vulnerable drivers has positive implications for transportation safety.

The COP discussed the Work Zones plugin in the context of broadcasting work-zone maps and roadside safety messages. Although the ability to adjust MAP messages onsite to reflect changing conditions was the goal of the plugin, messages required scheduling in real time, which eventually required validation to reflect actual events. Both the project team and stakeholders collaborated to ensure alignment between the project and stakeholders' work-zone data-exchange efforts.

The System Performance Measures plugin was created because the COP wanted a way to evaluate the performance of traffic operations at the field level using full BSM and SPaT decoding. Each performance measure would be developed and released in phases over the span of several months. Stakeholders expressed interest in including performance measures based on PSMs. Because PSMs are similar to BSMs, comparable methods can be used to quantify both. Among various traffic metrics, the project team selected queue length and average control delay as pilot performance measures.

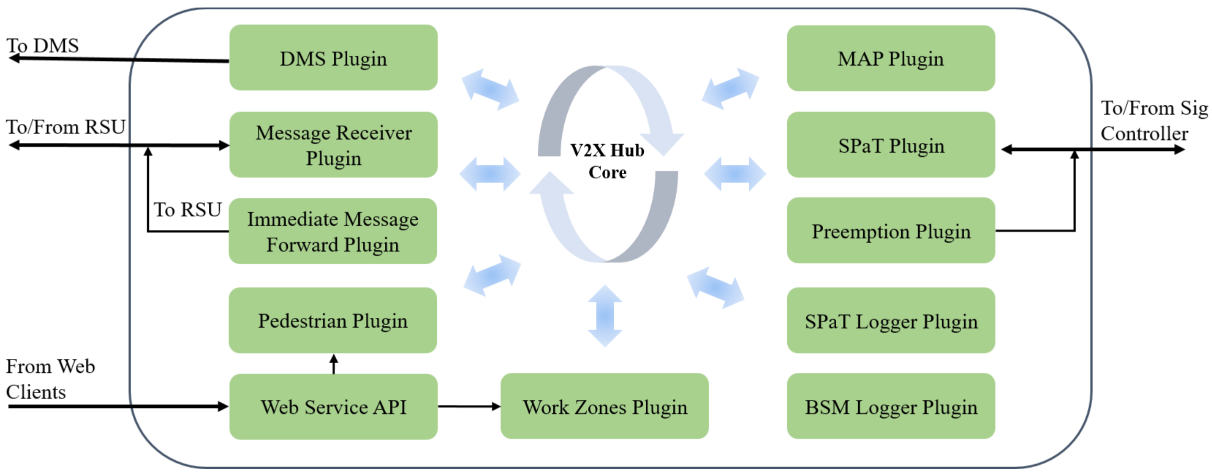
RECOMMENDATIONS

Based on feedback from the COP, the project team targeted V2X Hub development efforts to four plugins: Preemption, Pedestrian, Work Zones, and System Performance Measures. Collaboration among COP members helped identify areas of greatest potential benefit to the CAV community. To optimize V2X Hub development, deployment, and integration, the project team focused on understanding and meeting the COP's expressed needs.

CHAPTER 5. DEVELOPED V2X HUB PLUGINS

The configuration of various V2X Hub plugins can help transportation agencies deploy and customize the V2X Hub. This chapter describes the newly developed V2X Hub plugins (i.e., Preemption, Pedestrian, Work Zones, and System Performance Measures), including basic core functionality and plugin architecture, as well as information regarding the configuration values and any external configuration files necessary to execute the plugins.

Figure 3 shows the high-level layout of all critical V2X Hub plugins and the hardware systems with which they interact. The Preemption, Pedestrian, and Work Zones plugins are shown in the diagram, but the System Performance Measures plugin is excluded because it is an external analytics tool that leverages offline BSM and SPaT logger data.



Source: FHWA.

Figure 3. Diagram. High-level overview of existing and developed plugins of the V2X Hub.

PEDESTRIAN

The Pedestrian plugin integrates pedestrians without V2X radios into the CAV environment by providing an interface to connect a pedestrian's status with ITS infrastructure. For example, a pedestrian on a sidewalk about to cross a roadway uses a mobile device to initially send information about their location to a webservice available on the computer running the V2X Hub. The Pedestrian plugin encodes the pedestrian call into SAE J2735 standard PSM format and routes it to the V2X Hub through an open-networked webservice API. The V2X Hub subsequently reroutes the PSM to an RSU for broadcasting to nearby vehicles equipped with OBUs.

The Pedestrian plugin uses the Immediate Forward plugin to broadcast through the RSU. PSMs that originate from pedestrian traffic near intersections or RSUs allow OBUs to push pedestrian warnings to drivers and deliver a safe crossing signal for pedestrians.

The Pedestrian plugin is dependent on successful integration with a webservice. The webservice currently available on the V2X Hub is Qt engine–based and was developed using openAPI architecture.[19,20] The plugin requires active webservice to deliver requests. To ensure incoming messages are properly routed and serviced, the port number and IP address of the web server must be defined before initiating the webservice. Refer to the V2X Hub Plugins document for configuration parameters for the Pedestrian plugin.[9]

PREEMPTION

The Preemption plugin supports the V2X Hub in preempting the traffic-signal timing plan for first responders (i.e., police, fire, and emergency medical services). The Preemption plugin detects emergency vehicles using BSMs and changes traffic lights using signal preemption, holding traffic until the emergency vehicle passes through the intersection. Within the V2X Hub, the Preemption plugin is designed to seek extended BSMs and, in particular, detect emergency vehicles that have sirens and lights activated. The state of sirens and lights is embedded into the special-vehicle extension of the SAE J2735 message set.[2] Once the Preemption plugin receives a BSM about an emergency vehicle with enabled sirens and lights, it verifies whether the vehicle is whitelisted. If the emergency vehicle is whitelisted, the plugin inspects whether the vehicle is within a geofence defined as an active boundary for triggering preemption. If the emergency vehicle is positioned outside the geofence boundary, then a preemption request is not issued to the TSC. If the emergency vehicle is positioned within the geofence boundary and no previous preemption request has been successfully issued for the vehicle, the plugin requests preemption on the exact phase of the traffic-signal set where the geofence was triggered. Once the emergency vehicle leaves the geofence in the egress direction, a preemption cancel request is issued, and the TSC returns to normal operation.

WORK ZONES

The Work Zones plugin is primarily used for sending roadway-incident information, such as messages regarding active work zones, lane closures, and speed-limit changes, to surrounding vehicles. Road management is informed of work zones ahead of projects and plans accordingly by alerting the local area broadcast unit, such as an RSU linked to a TMC via a dedicated connection, and dispersing TIMs to nearby vehicles. The Work Zones plugin identifies work-zone information, along with the interface between the TMC and V2X Hub, to support HTTP requests for posting updated TIMs to the V2X Hub, allowing active work zones with frequent changes in lane status to be updated as frequently as possible. The HTTP interface on the V2X Hub connects HTTP clients running in a TMC to send timed TIM updates. The V2X Hub then broadcasts the TIM updates based on the timed information associated with the message. Appendix B contains a sample XML TIM update message.

The Work Zones plugin has a manifest file setting that can be used when there is no connection to a TMC. The initial setting on the manifest file includes start/stop date and time. Based on these dates, the Work Zones plugin will allow or block the broadcast of a TIM preset as an XML document in a predefined location. The updates through the webservice overwrite the existing settings, allowing the broadcasting operation to be managed by remote TMC server.

SYSTEM PERFORMANCE MEASURES

The proliferation of CVs provides a new opportunity for traffic engineers to collect performance data on transportation-system elements, particularly intersections. Historically, data collection at intersections has focused on short intervals of a few hours targeted to a single measure, such as queue volume at regular intervals or spot speed. Trajectory information from CVs allows precision data about multiple measures (such as signal state and vehicle location) over extended periods of time. However, the market-penetration rate for CVs remains low, and agencies may wish to wait to adopt such performance-measure calculations until proliferation supports reporting within acceptable error.

The System Performance Measures plugin pulls information offline from the BSM and SPaT Logger plugins for a specific intersection. The System Performance Measures plugin runs as a Python™ script and takes the following inputs:

1. The location of the BSM and SPaT Logger plugin outputs.
2. The location of the System Performance Measures plugin outputs.
3. The option to use BSM, SPaT, and MAP postprocessed data.
4. The type(s) of performance measures.
5. The timestamp of the moment in question.
6. Parameters including the default values for shockwave speeds where none can be calculated, stopping speeds, and jam spacing.

CHAPTER 6. FUTURE WORK

The most integral part of any data-communication system is the messaging framework—the middleware that can handle ingress and egress messages. For vehicular ad hoc networks composed of DSRC networks, the V2X Hub is qualified to be that middleware, even if standards use newer and possibly better communication technologies.

The following V2X Hub functionalities make the platform well suited to support continued CAV deployment as technologies evolve:

- The V2X Hub can siphon messages for CAVs irrespective of underlying technologies.
- The V2X Hub can moderate as a network-agnostic entity, addressing the needs of various CAV applications.
- The V2X Hub is a free OSS that reduces the need for proprietary systems, drastically reducing development costs and accelerating deployment.

Many industry sectors have already requested to use the V2X Hub for their products. Research communities can leverage the existing framework of the V2X Hub and continue its extension for their specific purposes. For tests and demonstration purposes, the integration of the V2X Hub into deployments and testbeds is easier than any other messaging middleware that exists for vehicular networks. Projects at the FHWA Saxton Transportation Operations Laboratory—such as CARMA℠, CARMA Cloud℠, HIL, and OSS4ITS—already use or plan to use the V2X Hub as a frontend for messaging.(21) The V2X Hub improves the scalability and adoption of transit operations, such as the Multimodal Intelligent Traffic Signal System.

The future of the V2X Hub lies in how it will be embedded into existing and future ITS environments. The V2X Hub can serve as the test-suite component for transportation operators, enabling operators to check the validity, performance, and dependability of the system with minimal effort. The platform can attract and engage the user community to develop newer applications and test cases for ITS. The V2X Hub can support test devices and probes that function to validate deployment, operation, performance, and up time, among others. In addition, the V2X Hub can incorporate security credentials for existing ITS components and act as a proxy for checking, verifying, and validating credentials. Thus far, the V2X Hub has been discussed within the scope of an infrastructure feature; however, a future vehicular version of the V2X Hub with the ability to leverage OBUs and local sensors may be devised to support CAV applications in vehicles, using a Robotics Operating System (ROS)–based plugin or upgrading the internal messaging framework to use the ROS as the middleware.

APPENDIX A. PSM XML SAMPLE

The following text is a sample XML PSM.


```
<?xml version="1.0" encoding="UTF-8"?>
<PersonalSafetyMessage>
<basicType>
<aPEDESTRIAN/>
</basicType>
<secMark>0</secMark>
<msgCnt>0</msgCnt>
<id>87654321</id>
<position>
<lat>406680509</lat>
<long>-738318466</long>
<elevation>40</elevation>
</position>
<accuracy>
<semiMajor>255</semiMajor>
<semiMinor>255</semiMinor>
<orientation>65535</orientation>
</accuracy>
<speed>75</speed>
<heading>3672</heading>
<crossState>
<true/>
</crossState>
<clusterSize>
<medium/>
</clusterSize>
<clusterRadius>6</clusterRadius>
</PersonalSafetyMessage>
```

APPENDIX B. TIM XML SAMPLE

The following text is a sample XML TIM.


```xml
<?xml version="1.0" encoding="utf-8"?>
<timdata>
<starttime> 12:00:00 </starttime>
<stoptime> 19:00:00 </stoptime>
<startdate> 01-01-2019 </startdate>
<stopdate> 12-31-2020 </stopdate>
<timupdate>
<![CDATA[<Curve xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance"
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    <SpeedLimit>25</SpeedLimit>
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</Approaches>
</Curve>]]></timupdate>
</timdata>

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