

# **Connected and Automated Vehicle education (CAVe)-in-a-box**

## **System Design Document**

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<p>16. Abstract</p> <p>The purpose of this document is to provide an overview for the assembly and configuration of Connected and Automated Vehicle education (CAVe)-in-a-box components and give users a comprehensive system design overview. CAVe-in-a-box is a tool that allows beginners to learn about and test data flows involved with emergency vehicle preemption or the transmission of wireless radio messages. This includes basic safety (BSM), Signal Phase and Timing (SPaT), traveler information (TIM), and personal safety (PSM) in a variety of intelligent transportation system (ITS) environments.</p> <p>Future technicians at community colleges and trade schools, new hires at equipment vendors, bench testers at certification consortiums, and transportation researchers can benefit from CAVe-in-a-box.</p> <p>This system design document, while providing setup and software configuration guides for the onboard and roadside prototype kits, serves as a valuable resource to gain an understanding of ITS systems. The transportation management use cases and overview of future CAVe-in-a-box integrations prepare users to use this tool and understand how it can evolve connected vehicle (CV) research moving forward.</p>			
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## SI\* (MODERN METRIC) CONVERSION FACTORS

### APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
<b>LENGTH</b>				
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
<b>AREA</b>				
in <sup>2</sup>	square inches	645.2	square millimeters	mm <sup>2</sup>
ft <sup>2</sup>	square feet	0.093	square meters	m <sup>2</sup>
yd <sup>2</sup>	square yard	0.836	square meters	m <sup>2</sup>
ac	acres	0.405	hectares	ha
mi <sup>2</sup>	square miles	2.59	square kilometers	km <sup>2</sup>
<b>VOLUME</b>				
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft <sup>3</sup>	cubic feet	0.028	cubic meters	m <sup>3</sup>
yd <sup>3</sup>	cubic yards	0.765	cubic meters	m <sup>3</sup>
NOTE: volumes greater than 1,000 L shall be shown in m <sup>3</sup>				
<b>MASS</b>				
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")
<b>TEMPERATURE (exact degrees)</b>				
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
<b>ILLUMINATION</b>				
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m <sup>2</sup>	cd/m <sup>2</sup>
<b>FORCE and PRESSURE or STRESS</b>				
lbf	poundforce	4.45	newtons	N
lbf/in <sup>2</sup>	poundforce per square inch	6.89	kilopascals	kPa
<b>APPROXIMATE CONVERSIONS FROM SI UNITS</b>				
Symbol	When You Know	Multiply By	To Find	Symbol
<b>LENGTH</b>				
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
<b>AREA</b>				
mm <sup>2</sup>	square millimeters	0.0016	square inches	in <sup>2</sup>
m <sup>2</sup>	square meters	10.764	square feet	ft <sup>2</sup>
m <sup>2</sup>	square meters	1.195	square yards	yd <sup>2</sup>
ha	hectares	2.47	acres	ac
km <sup>2</sup>	square kilometers	0.386	square miles	mi <sup>2</sup>
<b>VOLUME</b>				
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m <sup>3</sup>	cubic meters	35.314	cubic feet	ft <sup>3</sup>
m <sup>3</sup>	cubic meters	1.307	cubic yards	yd <sup>3</sup>
<b>MASS</b>				
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
<b>TEMPERATURE (exact degrees)</b>				
°C	Celsius	1.8C+32	Fahrenheit	°F
<b>ILLUMINATION</b>				
lx	lux	0.0929	foot-candles	fc
cd/m <sup>2</sup>	candela/m <sup>2</sup>	0.2919	foot-Lamberts	fl
<b>FORCE and PRESSURE or STRESS</b>				
N	newtons	2.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in <sup>2</sup>

\*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)

## TABLE OF CONTENTS

<b>CHAPTER 1. INTRODUCTION</b> .....	<b>1</b>
<b>BACKGROUND</b> .....	<b>1</b>
<b>OBJECTIVES</b> .....	<b>2</b>
<b>CHAPTER 2. SYSTEM DESIGN</b> .....	<b>5</b>
<b>INFRASTRUCTURE KIT</b> .....	<b>6</b>
<b>TSC</b> .....	<b>7</b>
<b>RSU</b> .....	<b>9</b>
<b>V2X Hub</b> .....	<b>10</b>
<b>Wired Network Switch</b> .....	<b>12</b>
<b>Wi-Fi Router with Cellular Network</b> .....	<b>13</b>
<b>Power Supply</b> .....	<b>14</b>
<b>Touchscreen Device</b> .....	<b>14</b>
<b>OBU</b> .....	<b>17</b>
<b>CAN Bus</b> .....	<b>18</b>
<b>Power Supply</b> .....	<b>18</b>
<b>Touchscreen</b> .....	<b>19</b>
<b>Wi-Fi Router with Cellular Service (Optional)</b> .....	<b>19</b>
<b>PHYSICAL CONNECTIONS</b> .....	<b>19</b>
<b>INTEGRATED SYSTEM DIAGRAMS</b> .....	<b>21</b>
<b>VENDOR LIST</b> .....	<b>24</b>
<b>CHAPTER 3. SETUP AND CONSTRUCTION</b> .....	<b>27</b>
<b>SOLIDWORKS REPRESENTATIONS: INFRASTRUCTURE KIT</b> .....	<b>27</b>
<b>Current Kit</b> .....	<b>30</b>
<b>Future Design Alterations</b> .....	<b>31</b>
<b>SOLIDWORKS REPRESENTATION: MOBILE KIT</b> .....	<b>31</b>
<b>CHAPTER 4. SOFTWARE CONFIGURATION</b> .....	<b>35</b>
<b>V2X HUB INSTALLATION AND INITIALIZATION</b> .....	<b>35</b>
<b>V2X Hub</b> .....	<b>35</b>
<b>Plugin Configuration</b> .....	<b>36</b>
<b>RSU CONFIGURATION</b> .....	<b>41</b>
<b>IP Address Setup</b> .....	<b>41</b>
<b>RSU Configuration for CAVe-in-a-box</b> .....	<b>42</b>
<b>TRAFFIC SIGNAL CONFIGURATION</b> .....	<b>43</b>
<b>IP Address Configuration</b> .....	<b>43</b>
<b>SPaT Forwarding IP Address</b> .....	<b>43</b>
<b>Enabling SPaT Forward</b> .....	<b>44</b>
<b>WI-FI ROUTER CONFIGURATION</b> .....	<b>44</b>

<b>CHAPTER 5. DATA FLOWS .....</b>	<b>45</b>
<b>CHAPTER 6. USE CASES .....</b>	<b>49</b>
<b>EMERGENCY VEHICLE PREEMPTION.....</b>	<b>49</b>
<b>HARDWARE-IN-THE-LOOP SIMULATION.....</b>	<b>49</b>
<b>PEDESTRIAN SAFETY .....</b>	<b>50</b>
<b>WORK ZONE .....</b>	<b>51</b>
<b>CHAPTER 7. CONCLUSION.....</b>	<b>53</b>
<b>APPENDIX A. CELLULAR VEHICLE-TO-EVERYTHING (C-V2X).....</b>	<b>55</b>
<b>APPENDIX B. CAVE-IN-A-BOX WITH C-V2X RADIO AND CAVERS INTEGRATION</b> <b>.....</b>	<b>57</b>
<b>REFERENCES.....</b>	<b>59</b>

## LIST OF FIGURES

Figure 1. Diagram. System diagram of the CAVe-in-a-box infrastructure kit. ....	6
Figure 2. Photo. A built CAVe-in-a-box infrastructure kit.....	7
Figure 3. Photos. TSC used as a component of the CAVe-in-a-box infrastructure kit.....	9
Figure 4. Photo. RSU used as a component of the CAVe-in-a-box infrastructure kit.....	10
Figure 5. Photo. Embedded computer for V2X Hub software. ....	11
Figure 6. Diagram. V2X Hub operational design diagram. ....	11
Figure 7. Photo. Wired network switch. ....	13
Figure 8. Photo. Wi-Fi router with cellular network access. ....	14
Figure 9. Photo. Touchscreen tablet for GUI.....	15
Figure 10. Diagram. System diagram of the CAVe-in-a-box mobile kit.....	16
Figure 11. Photo. A built CAVe-in-a-box mobile kit showing different components. ....	17
Figure 12. Photos. OBU and the antenna (inset) for DSRC radio. ....	18
Figure 13. Photo. Power strip with multiple sockets. ....	19
Figure 14. Photo. TS 2 connector for signal heads. ....	20
Figure 15. Photo. PoE injector power for RSU. ....	20
Figure 16. Photo. Ethernet switch.....	20
Figure 17. Photo. Power and data connector for the RSU.....	21
Figure 18. Diagram. Infrastructure kit integrated connection diagram. ....	22
Figure 19. Diagram. Mobile kit type 1 integrated connection diagram.....	23
Figure 20. Diagram. Mobile kit type 2 integrated connection diagram.....	23
Figure 21. Diagram. Mobile kit type 3 integrated connection diagram.....	24
Figure 22. Illustrations. TSC shelf.....	27
Figure 23. Illustrations. Components in the shelf design (isometric views).....	28
Figure 24. Illustrations. Completed SolidWorks design of a CAVe-in-a-box infrastructure kit..	29
Figure 25. Illustrations. Rear view of the completed CAVe-in-a-box infrastructure kit.....	30
Figure 26. Illustration. Completed SolidWorks design of a CAVe-in-a-box mobile kit.....	32
Figure 27. Illustrations. CAVe-in-a-box side profile.....	33
Figure 28. Diagram. BSM data flow diagram.....	45
Figure 29. Diagram. SPaT message data flow diagram.....	46
Figure 30. Diagram. TIM data flow diagram.....	47
Figure 31. Diagram. PSM data flow diagram. ....	47
Figure 32. Diagram. Infrastructure kit integrated connection diagram with C-V2X and CAVERS .....	57

## LIST OF TABLES

Table 1. Vendor list for CAVe-in-a-box.....	24
Table 2. Sample manifest file for Immediate Forward plugin.....	34
Table 3. Sample manifest file for MAP plugin.....	35
Table 4. Sample manifest file for SPaT plugin.....	36
Table 5. Sample manifest file for Message Receiver plugin .....	37
Table 6. Sample manifest file for Pedestrian plugin.....	37
Table 7. Sample manifest file for Preemption plugin.....	38
Table 8. Sample manifest file for TIM plugin .....	38



## LIST OF ABBREVIATIONS

AC	alternating current
API	application programming interface
BSM	basic safety message
C-V2X	cellular vehicle-to-everything
CAN	controller area network
CAV	connected and automated vehicle
CAVe	connected and automated vehicle education
CAVERS	Connected and Automated Vehicle Education Research Software
CV	connected vehicle
DC	direct current
DHCP	dynamic host configuration protocol
DMS	dynamic message sign
DSRC	dedicated short-range communications
FHWA	Federal Highway Administration
GPS	Global Positioning System
GUI	graphical user interface
HDMI	high-definition multimedia interface
HIL	hardware-in-the-loop
ITS	intelligent transportation system
ITS JPO	Intelligent Transportation Systems-Joint Program Office
JSON	JavaScript object notation
LiDAR	light detection and ranging

LTE	long-term evolution
NTCIP	National Transportation Communications for ITS Protocol
OBD	onboard diagnostics
OBU	onboard unit
OID	object identifier
PoE	Power over Ethernet
PSID	provider service identifier
PSM	personal safety message
RSU	roadside unit
SAE	Society of Automotive Engineers
SDX	Situation Data Exchange
SNMP	Simple Network Management Protocol
SPaT	Signal Phase and Timing
SRM	signal request message
SSH	secure shell
STOL	Saxton Transportation Operations Laboratory
TFHRC	Turner-Fairbank Highway Research Center
TIM	traveler information message
TMC	traffic management center
TSC	traffic signal controller
UDP	User Datagram Protocol
UPER	Unaligned Packet Encoding Rules
USB	universal serial bus

USDOT	United States Department of Transportation
VAC	volts alternating current
V2I	vehicle-to-infrastructure
V2X	vehicle-to-everything
WAVE	wireless access in vehicular environments
WSA	WAVE service advertisement
WZDx	Work Zone Data Exchange
XML	extensible markup language

## CHAPTER 1. INTRODUCTION

This system design document, while providing setup and software configuration guides for original connected vehicle (CV) test tools, also serves as a valuable resource to gain an understanding of how intelligent transportation systems (ITS) are designed. There has been an emphatic demand to educate the technical workforce for the impending technological revolution in public transportation and mobility caused by the introduction of connected and automated vehicles (CAVs) (FHWA, 2017) in the very near future. Stakeholders and governing bodies like the United States Department of Transportation (USDOT) and Intelligent Transportation Systems Joint Program Office (ITS JPO) have a vested interest in creating programs to address this need (USDOT ITS JPO, 2020). As a continuation of successful efforts to bridge this knowledge gap with a help desk and equipment loan service, ITS JPO and the Federal Highway Administration (FHWA) have tasked the Saxton Transportation Operations Laboratory (STOL) with a project to design education materials for technical workforce development.

One of these education materials, Connected and Automated Vehicle education (CAVe)-in-a-box, is a tool that allows beginners to learn about many of the V2V, V2I, and V2P connected vehicle applications. However, to provide a comprehensive understanding of the technology and the protocols, this document focuses on applications, such as emergency vehicle preemption or the transmission of wireless radio messages like basic safety, Signal Phase and Timing (SPaT), traveler information, and personal safety in a variety of ITS environments. Groups that can benefit from the portability and modularity of CAVe-in-a-box include: future technicians at community colleges and trade schools, new hires at equipment vendors, bench testers at certification consortiums, and transportation researchers.

This system design document serves as a compendium to CAVe-in-a-box. It ensures that users of the onboard and roadside test toolkits are able to understand component setup and configuration, as well as how ITS data flows are used to dictate system designs. Addressing the knowledge gap identified by ITS JPO and FHWA requires that the future workforce not only be able to use test tools, but also understand how and why they work.

### BACKGROUND

As CAV technologies transition from research and pilot applications to large-scale deployments, the current niche skills associated with installation, setup, and maintenance of devices and systems will need to be performed by technicians and engineers on a large scale. The existing workforce does not have the training resources to perform these tasks with consistency in implementation, instead relying on individual knowledge and interpretation of standards and designs to maintain and install devices.

Decades of pedagogical research have shown that a single type of training material is not suitable for deployments with a variety of learning styles and levels. The training used for deploying CAV technologies must be presented with manifold resources to a diverse audience of learners. The CAVe-in-a-box toolkit is a training resource to help the emerging workforce learn different

components of CAV technologies, from the initial learning phase to a complete deployment state.

A wireless communication technology called Dedicated Short Range Communication (DSRC) has traditionally carried out the research, testing, and deployment of CV technologies in the ITS domain. In the past couple of years, another wireless technology, Cellular Vehicle-to-Everything (C-V2X), has moved up in the ranks. The different channelization schemes and timing requirements set C-V2X apart from DSRC. C-V2X is based on a wireless architecture similar to that of cell phones, and, contrary to DSRC, uses multiple carriers in blocks of smaller subframes. This allows for robust resource utilization and scheduling techniques for high-density, high-speed uses cases, featuring roadway safety applications. More research is needed to understand the real-world applications for the widespread usage of C-V2X.

## **OBJECTIVES**

The objectives of this document are as follows:

1. Introduce CAVe-in-a-box as a technical tool for educational purposes.
2. Provide detailed documentation of all aspects related to CAVe-in-a-box, from required electrical and mechanical components to physical connections.
3. Provide information on software requirements for the kit, including testing and debugging.
4. Provide hands-on use cases and examples related to CAVe-in-a-box.

While ITSs encompass a variety of applications and technologies, CAV technology is primarily concerned with how vehicles can leverage wireless communication to interact with infrastructure, surrounding vehicles, pedestrians, and/or other roadway users. Thus, the future workforce in the CAV space should be familiar with the required components, communication protocols, and embedded systems concepts. CAVe-in-a-box makes these key components accessible, enabling the teaching, development, testing, and eventual deployment of CV applications. CAVe-in-a-box can allow students and educators to test many applications, such as:

- Pedestrian safety applications, to understand how pedestrian messages can be used to provide safe roadway access to pedestrians
- SPaT applications, to understand the process of intersection signal controller operation
- Basic Safety Message (BSM) application, to study how vehicles transmit their vehicle data

When scaled down, a CAV system can be represented as two interacting entities: the vehicle and its environment. As such, CAVe-in-a-box contains two major components: the mobile kit, representing the vehicle, and the infrastructure kit, representing the environment. The two kits

interact with each other through encoded broadcasts from a variety of possible data flows. For example, one function of the mobile kit is to collect vehicle data, such as location, and broadcast this data to its surrounding environment. The infrastructure kit will decode and log any received messages. In the reverse direction, the infrastructure kit may receive information from another environmental entity, such as a pedestrian or traffic management center, and broadcast this message to the mobile kit. There are a variety of possible data flows from various entities in a CAV system. The CAVe-in-a-box toolkit will replicate these two environments, showing the exchange of data between them.

Details of the components of each CAVe-in-a-box toolkit, the relevant standards and protocols, and the potential data flows can be found in the following chapters:

- Chapter 2 describes the system design of the toolkit.
- Chapter 3 focuses on the data flows in different components.
- Chapter 4 shows the setup and construction of the toolkit.
- Chapter 5 describes software configurations required to set up different components.
- Chapter 6 highlights a few use cases for CAVe-in-a-box.
- Chapter 7 concludes and provides an overall summary of the toolkit.



## CHAPTER 2. SYSTEM DESIGN

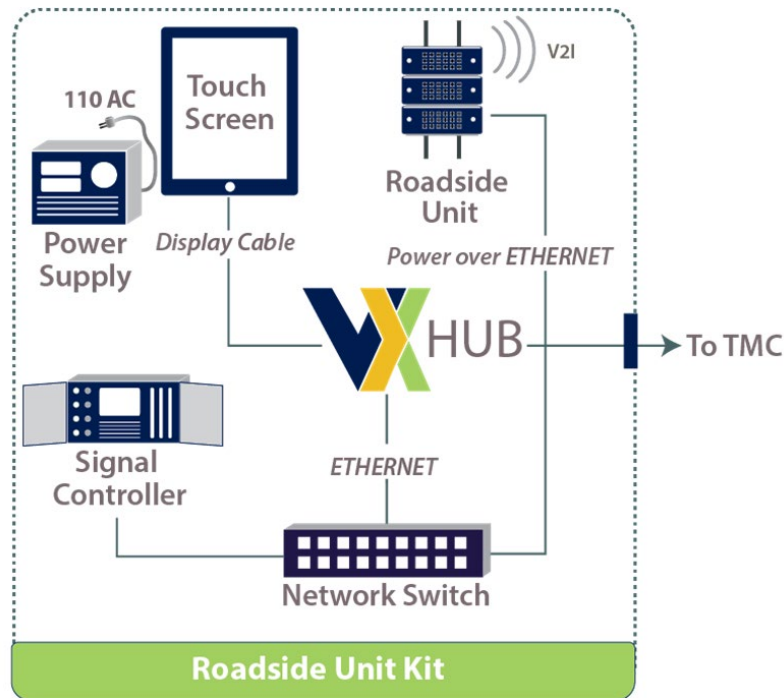
CAVe-in-a-box is an interconnected set of ITS components designed to co-operate to enable the teaching, development, testing, and deployment of CV applications. The kit is designed with a focus on portability, reliability, and usability, so that it can function anywhere, as needed, by anyone, with minimum technical expertise. The purpose of the kit is to allow the technical workforce studying advanced transportation systems to explore and adapt themselves to the new and upcoming technologies that are inevitably going to saturate the market in the coming years. USDOT's vision of preparing the workforce for the rapidly evolving ITS has played a major role in the outcome of this system.

Some of the features of CAVe-in-a-box include, but are not limited to, the following:

- A hands-on module with different ITS components.
- A design with laboratory use in mind, so that the system can be easily built for classroom and lab work while promoting a real-world infrastructure.
- A portable setup in a box consisting of the most vital technical components that make up the infrastructure and vehicular sides of an ITS.
- A simple plug-and-play module that can be installed virtually anywhere and tested for CAV applications.
- A two-part design:
  - Infrastructure unit with a roadside unit (RSU) (*infrastructure kit*).
  - Mobile unit with an onboard unit (OBU) (*mobile kit*).
- Available updates and extension capabilities.
- Example use cases include lab/classroom education purpose, real-world application development, testing purpose, and field deployment, to name a few.

The design of the infrastructure kit is shown in figure 1. The kit was designed so that the components can be readily available and easily found from many transportation system vendors.





Source: FHWA.

TMC = traffic management center; V2I = vehicle-to-infrastructure.

**Figure 1. Diagram. System diagram of the CAVe-in-a-box infrastructure kit.**

The components for the CAVe-in-a-box infrastructure kit are listed below in their generic nomenclature:

- Traffic signal controller (TSC).
- RSU.
- Vehicle-to-Everything (V2X) Hub computer.
- Wired network switch.
- Wi-Fi router with cellular network.
- Power supply.
- Touchscreen personal computer or tablet computer.

## INFRASTRUCTURE KIT

The purpose of the CAVe-in-a-box infrastructure kit is to support the non-vehicular side of the ITS supporting communication and messaging between applications. The design and components of an assembled infrastructure kit are shown in figure 1. The infrastructure kit is

stationary and located preferably at a site that mimics an active intersection. The kit comes with all the equipment needed to construct a CAV system environment, except the signal head lights. Instead, the real-time status of traffic lights is displayed using the kit's emulation software. The emulation software is designed to display real-time CAV messages and has a graphical user interface (GUI) representing an intersection like the site where the kit would be deployed. Figure 2 shows the initial version of the infrastructure kit developed as part of the project.



Source: FHWA.

**Figure 2. Photo. A built CAVe-in-a-box infrastructure kit.**

The integral components of the infrastructure kit are described below.

## **TSC**

The first component required for building a CAVe-in-a-box infrastructure kit is a National Transportation Communications for ITS Protocol (NTCIP) v1202 V3 (USDOT ITS Standards Program, 2009) compliant TSC that has a front panel for necessary configuration and an Ethernet connector port for Simple Network Management Protocol (SNMPv3) messaging (IETF, 1990) between this component and others, at the minimum. The TSC component, shown in figure 3, will be the actuator for SPaT messages and is connected to an RSU via a V2X Hub computer. The TSC also has an Ethernet connection to the V2X Hub computer inside the kit. The actual physical connection between these devices is shown in later chapters. This component also preferably includes hookups for cabinet wiring that can be exposed outside of the kit, so that an external signal head can be connected to the kit, if needed. The TSC is configured in fixed-timed

mode, by default; however, the front panel can be used for reconfiguring the modes, as needed, for any application being tested or demonstrated.



Source: FHWA.  
A. TSC front view



Source: FHWA.  
B. TSC different connectors in view



Source: FHWA.

C. TSC connectors on the front panel

**Figure 3. Photos. TSC used as a component of the CAVE-in-a-box infrastructure kit.**

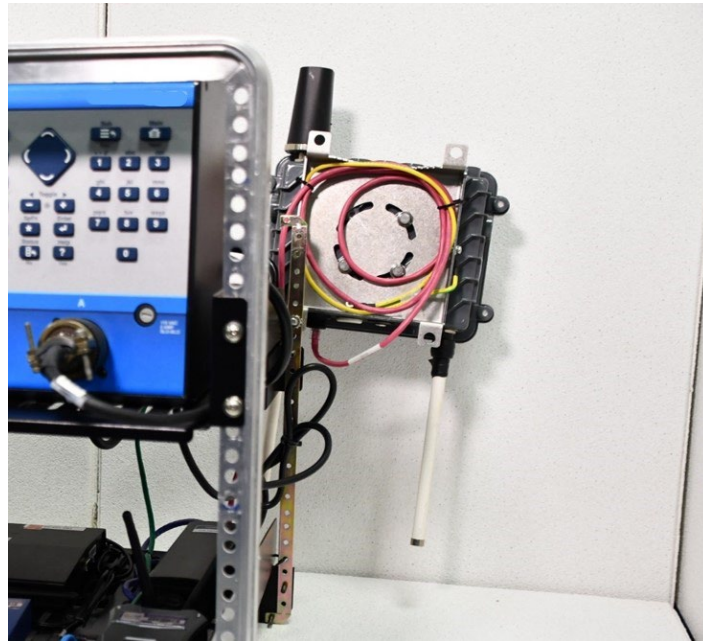
## RSU

The RSU is a wireless gateway that allows bidirectional message forwarding between wired and wireless networks. The RSU complies with the USDOT RSU 4.1 specification, and comes with features that are associated with that standard. This includes the immediate forwarding of Wireless Access in Vehicular Environment (WAVE) (J.B. Kenney, 2011) messages to and from a User Datagram Protocol (UDP) application. This feature allows for configuration so that the messages coming from dedicated short-range communications (DSRC) (J.B. Kenney, 2011) or Cellular-Vehicle to Everything (C-V2X) wireless interfaces are forwarded to applications, such as the V2X Hub middleware application running in the V2X Hub computer and vice versa.

Figure 4 shows one of the RSUs used in the CAVE-in-a-box infrastructure toolkit. The RSU adheres to the US DOT RSU 4.1 specification, which enables immediate forward independent of the radio technology. In this iteration, the RSU supports DSRC protocol and is capable of communicating with the 802.11p protocol in the 5.9 GHz band. The 75 MHz available channel width is divided into seven channels. One of these channels is a control channel mostly used for association and detection purposes, while the remaining six channels are dedicated to different ITS applications, including safety, mobility, and management.

The most common vehicular message, broadcasted from vehicles at the rate of 10 messages per second, is the BSM. BSMs use one of the seven channels, particularly channel number 172, so the RSU is configured to listen for BSMs in that channel. The RSU also broadcasts SPaT and MAP messages on the same channel, 172. The WAVE Service Advertisement (WSA) is another type of system message broadcasted by RSUs for advertisement purposes of different services running as an application. The WSA uses channel 178. Therefore, the RSUs usually come with two sets of radio front ends and antennas so that they can transmit or receive at two different frequencies at the same time. However, the DSRC protocol does not allow for transmitting or

receiving using the same interface at the same time. A C-V2X RSU may enable sending and receiving messages within the 20-megahertz (MHz) bandwidth.



Source: FHWA.

**Figure 4. Photo. RSU used as a component of the CAVe-in-a-box infrastructure kit.**

## **V2X Hub**

V2X Hub is a dedicated computer module running the middleware software of the same name. V2X Hub imitates a software stack that is a messaging service and an encoder/decoder for Society of Automotive Engineers (SAE) J2735 standard messages (SAE, 2016). It can be installed in a small, embedded computer, like the one shown in figure 5.

The DSRC or C-V2X wireless network used by vehicles and infrastructure use encoded J2735 messages for communication purposes, but these messages are not in human-readable form. V2X Hub works as a translator, translating the encoded J2735 messages into human-readable forms, such as JavaScript Object Notation (JSON) or Extensible Markup Language (XML), which also allows for their use in traditional TMC applications.

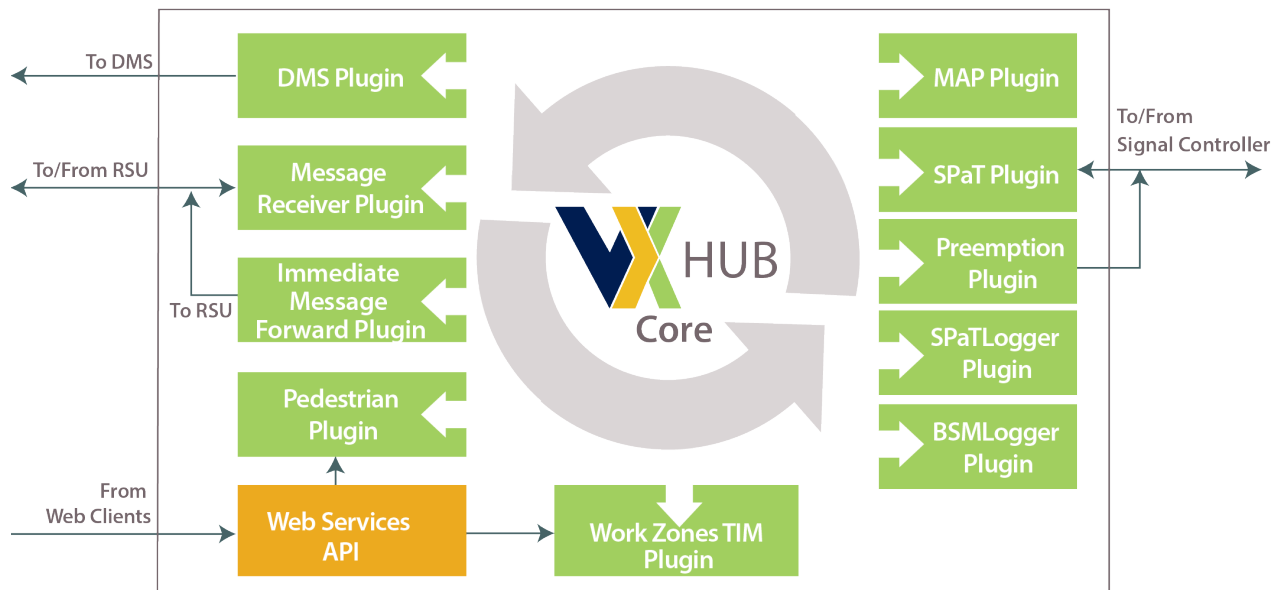
For example, a BSM coming in from a nearby vehicle would be decoded using the V2X Hub asn1 decoder and published internally in human-readable form for any subscribing application to receive. This allows for an independent component that can communicate with ITS field units, like OBUs and RSUs, as well as pass messages between these components, human user interfaces, and ITS applications. The V2X Hub computer will have an Ethernet connection with the RSU through a network switch.



Source: FHWA.

**Figure 5. Photo. Embedded computer for V2X Hub software.**

A plugin for V2X Hub is an independent sub-component application that uses V2X Hub for its messaging and coding service while supporting an ITS application, such as SPaT messages, traveler information messages (TIMs), MAP messages, personal safety messages (PSMs), and traffic performance analysis, to name a few. Figure 6 shows the set of plugins developed for V2X Hub that are already available for deployment.



Source: FHWA

API = application programming interface; BSM = basic safety message; DMS = dynamic message sign; MAP = Map data; RSU = roadside unit; TIM = traveler information message; SPaT = Signal Phase and Timing.

**Figure 6. Diagram. V2X Hub operational design diagram.**

The following are brief descriptions of the V2X Hub plugins:

- **Dynamic Message Sign (DMS) Plugin.** This plugin sends information to display messages about road conditions and hazards ahead. The display could be an app or an actual DMS.
- **Message Receiver Plugin.** This is the receiver plugin that handles incoming J2735 BSMs and Signal Request Messages (SRMs). The plugin decodes/parses the BSMs and SRMs and broadcasts them using message handlers for other subscriber plugins.
- **Immediate Message Forward Plugin.** This plugin is used to broadcast J2735 messages through an RSU. The plugin interfaces with the RSU 4.1 specification forwarding feature.
- **Pedestrian Plugin.** This plugin is designed to handle pedestrian calls. A pedestrian near an intersection would be able to send a personal safety message (PSM) to the V2X Hub, which can alert any nearby drivers of the pedestrian's presence.
- **Work Zones TIM Plugin.** This plugin allows remote client, such as a Transportation Management Center, to issue TIM message information to V2X Hub for Immediate Message Forward Plugin to broadcast.
- **MAP Plugin.** This plugin reads MAP files and broadcasts them through the RSU in MAP messages format. The Immediate Message Forward Plugin handles the broadcasting of the MAP message.
- **Preemption Plugin.** This plugin receives and checks for preemption at the signalized intersection for emergency vehicles. If the preemption is associated with an emergency vehicle with sirens and lights, the plugin issues preemption movement in phases to the attached TSC.
- **SPaT Plugin.** This plugin connects with a TSC, reads NTCIP 1202 messages, converts them into J2735 messages, and forwards them to an RSU for immediate broadcast.
- **SPaTLogger Plugin.** This plugin logs SPaT messages in human-readable form.
- **BSMLogger Plugin.** This plugin logs any valid BSM received at the V2X Hub in a human-readable form.

## Wired Network Switch

The wired network switch is required for the network connection inside the CAVe-in-a-box infrastructure kit. If the components inside the box are set up on the same subnet, it becomes suitable to swap or add any components in the future and wire them through the switch (Cisco, 2020). All communications that occur inside the box through the wires are unicast. A standard 48 Volt direct current (DC) Power over Ethernet (PoE) switch is recommended, as some RSU vendors require PoE as the power source. Figure 7 shows the networked switch with multiple wired connections.



Source: FHWA.

**Figure 7. Photo. Wired network switch.**

### **Wi-Fi Router with Cellular Network**

Figure 8 shows a Long-Term Evolution (LTE) cellular network-enabled wireless router. Cellular network support in the CAVe-in-a-box infrastructure kit allows remote access and monitoring of the devices. This can inherently change the deployment strategies for CAVe-in-a-box at actual intersections without prior connectivity, as well as testbeds where network connectivity is not present. Using cellular networks for wireless access with a Wi-Fi router allows for connection to all devices in the kit from a monitoring center or indoor lab. By allowing port forwarding in the wireless router, any device can be tagged to a specific port for secure access and control (S. Corrigan, 2016). The infrastructure kit comes with an optional Wi-Fi router with cellular network access, if needed by a test site.





Source: FHWA.

**Figure 8. Photo. Wi-Fi router with cellular network access.**

### **Power Supply**

The standard 110 volts alternating current (VAC) power supply is the compliant power supply for the CAVe-in-a-box infrastructure kit. Most of the kit components run through AC power, so there is no need for an alternating current (AC) to DC converter. The power supply for the infrastructure kit has an AC wall socket extension that can be connected to a wall socket or a power outlet along an intersection for outdoor testing.

### **Touchscreen Device**

The touchscreen is the only available human interface unit in the CAVe-in-a-box infrastructure kit; however, a laptop with an Ethernet connection to the network switch may be required if there is a need to reconfigure components. The kit and many of the required software applications can be easily accessed using the touchscreen device. The touchscreen is a Windows tablet with Secure Shell (SSH) capability with Ethernet and Wi-Fi support. The touchscreen is connected to the V2X Hub through a High-Definition Multimedia Interface (HDMI) connector (if applicable), Ethernet wired connector, or Wi-Fi access. The touchscreen is used to access the V2X Hub computer using an SSH application, log in to the admin portal, and bring up a terminal emulator so that the packet sniffing applications can be used.

In the future, a set of applications will be deployed on the V2X Hub and the touchscreen tablet for debugging purposes as well as for testing different features of the kit. Figure 9 shows an example touchscreen tablet PC.



Source: FHWA.

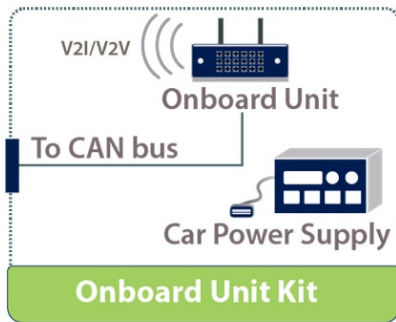
**Figure 9. Photo. Touchscreen tablet for GUI.**

### **Mobile Kit**

The CAVE-in-a-box mobile kit is installed in the CAVs for testing and educational purposes. With the necessary connections, the mobile kit allows vehicles to communicate with infrastructure and networks. The main purpose of this kit is to broadcast BSMs from a vehicle under study and receive SPaT and MAP messages from intersections. Figure 10 shows a block diagram of the mobile kit in two separate versions (with and without the tablet PC). This is just an outline of the system and certain changes can be made to the design, such as a wireless router installed in the mobile kit. Figure 11 shows the existing build of a mobile kit. It is built as a single box design with necessary components mounted on the inner side. The box opens with the tablet PC facing the user.

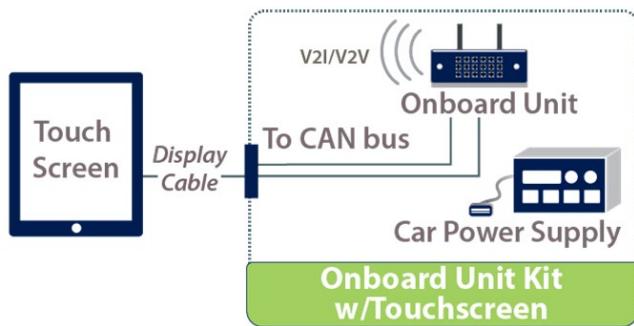
The components for the CAVE-in-a-box mobile kit are listed below, in their generic nomenclature:

- OBU.
- Controller Area Network (CAN) bus.
- Power supply.
- Touchscreen PC or tablet computer.
- Wi-Fi router with cellular service (optional).



Source: FHWA.

A. Mobile Kit without touch screen.



Source: FHWA.

B. Mobile kit with touch screen.

**Figure 10. Diagram. System diagram of the CAVe-in-a-box mobile kit.**

The integral components of the mobile kit are described below.



Source: FHWA.

**Figure 11. Photo. A built CAVe-in-a-box mobile kit showing different components.**

## OBU

The OBU is the vehicle counterpart to the RSU. The OBU is installed inside a vehicle, with the OBU antenna mounted on the roof, as close to the center as possible, for the best wireless performance. OBUs are configured to receive SPaT and MAP messages sent from an RSU and log them; however, the log files grow quickly because of the size and frequency of these messages. Therefore, it is advised to frequently delete logs, or relocate the logs if they are important. The OBUs also broadcast BSMs, which are created using the Global Positioning System (GPS) location of the vehicle, as well as data from the CAN bus.



Source: FHWA.  
A. An OBU.



Source: FHWA.

B. DSRC antenna for an OBU.

**Figure 12. Photos. OBU and the antenna (inset) for DSRC radio.**

## **CAN Bus**

The CAN bus is a standard used by many process manufacturing systems, as well as vehicles, for communicating the control and status information of different subsystem components. The CAN bus is an interface endpoint for the CAN system to allow status messages to be passed outside of the vehicle network. The CAN bus is connected from the vehicle's Onboard Diagnostics (OBD) II port<sup>1</sup> to the CAN input in an OBU. The CAN bus is used to share vehicle safety status messages, such as brake status and steering wheel angle, with the OBU. These messages become an important part of the BSM when transmitted. The CAN input may have to be converted from manufacturer specific descriptions to the generic messages developed by CAMP for the OBUs to work with different vehicles. A translator device configured for a specific vehicle may have to be used to send the vehicle data to the OBU using the generic message IDs that are in the 600-700 range. Please note that while BSMs can contain information obtained from the CAN bus, they can still be created and sent without a CAN connection.

## **Power Supply**

The power supply for the CAVe-in-a-box mobile kit is very similar to that of the infrastructure kit, with only one difference. Because the kit is installed within the vehicle, the outlet resembles a car lighter power socket. Therefore, the components in the vehicle work with DC power.

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<sup>1</sup> Please consult your vehicle manufacturer for details.

## Touchscreen

The purpose of the touchscreen in the CAVe-in-a-box mobile kit is like its use in the infrastructure kit: it is the human interface for a user to interact with different components of the kit. The touchscreen is connected to the OBU.

## Wi-Fi Router with Cellular Service (Optional)

The Wi-Fi router with cellular service allows the user to access the OBU wirelessly using a tablet or laptop with a compatible Wi-Fi interface. If the Wi-Fi router supports cellular networks, such as 3G/4G/LTE, then the components in the mobile kit can be accessed remotely. This enables remote configuration of the mobile kit in test vehicles. There are three options for mobile kit design: (a) with a Wi-Fi cellular component, (b) with a Wi-Fi-only component, or (c) without a Wi-Fi or cellular component. The version of the mobile kit that lacks Wi-Fi and cellular components will have a Universal Serial Bus (USB) wired connector for tablet or laptop PC.

## PHYSICAL CONNECTIONS

This section details the connection and ports available in the CAVe-in a-box, as well as the different interconnections among the individual components. The objective of this section is to identify varieties of interconnections in the system and identify external ports for future enhancements. Below are the different types of connections required for the kit to function.

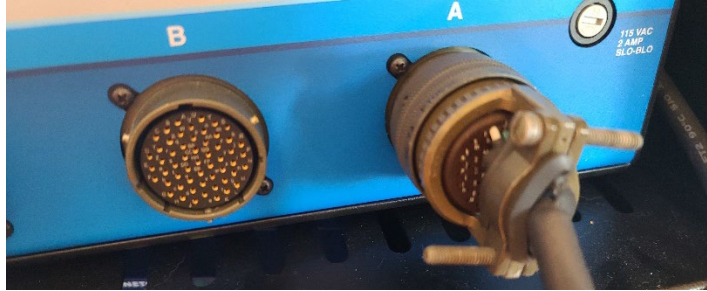
The following types of connectors are required:

- **Power.** Every component in the kit requires a DC or an AC power supply. As shown in figure 13 and figure 14, the power supply unit in the infrastructure kit can provide up to 120 V/15 A surge-protected and distribute it to each component using a power strip connector that will support it. The RSU needs PoE for powering requirements. The PoE switch is powered by AC power and provides the 48 VDC/30 W power needed by the RSU. Each component of the kit comes with its power adapter(s); therefore, the power strip is enough to support the power needs.



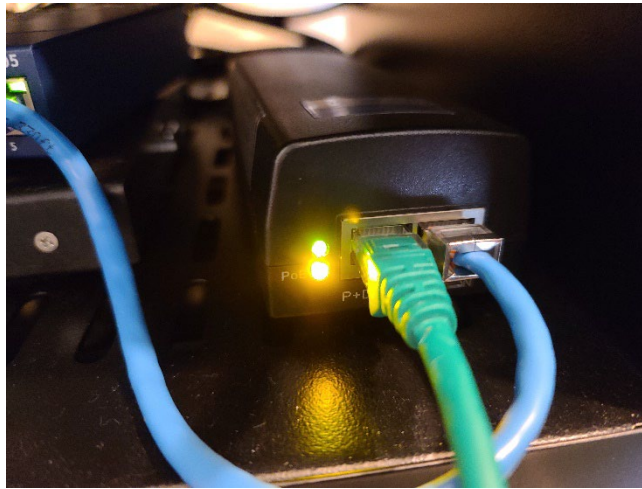
Source: FHWA.

**Figure 13. Photo. Power strip with multiple sockets.**



Source: FHWA.

**Figure 14. Photo. TS 2 connector for signal heads.**



Source: FHWA.

**Figure 15. Photo. PoE injector power for RSU.**

- **Ethernet Connection.** The data connection among components is made using Gigabit Ethernet. The higher-end data throughput available with the Ethernet is sufficient to enable current and future updates to the system. The Ethernet connector RJ-45 connects the V2X Hub computer, RSU, and TSC to the unmanaged network switch, which is also connected to a Wi-Fi router that acts as the gateway.



Source: FHWA.

**Figure 16. Photo. Ethernet switch.**



Source: FHWA.

**Figure 17. Photo. Power and data connector for the RSU.**

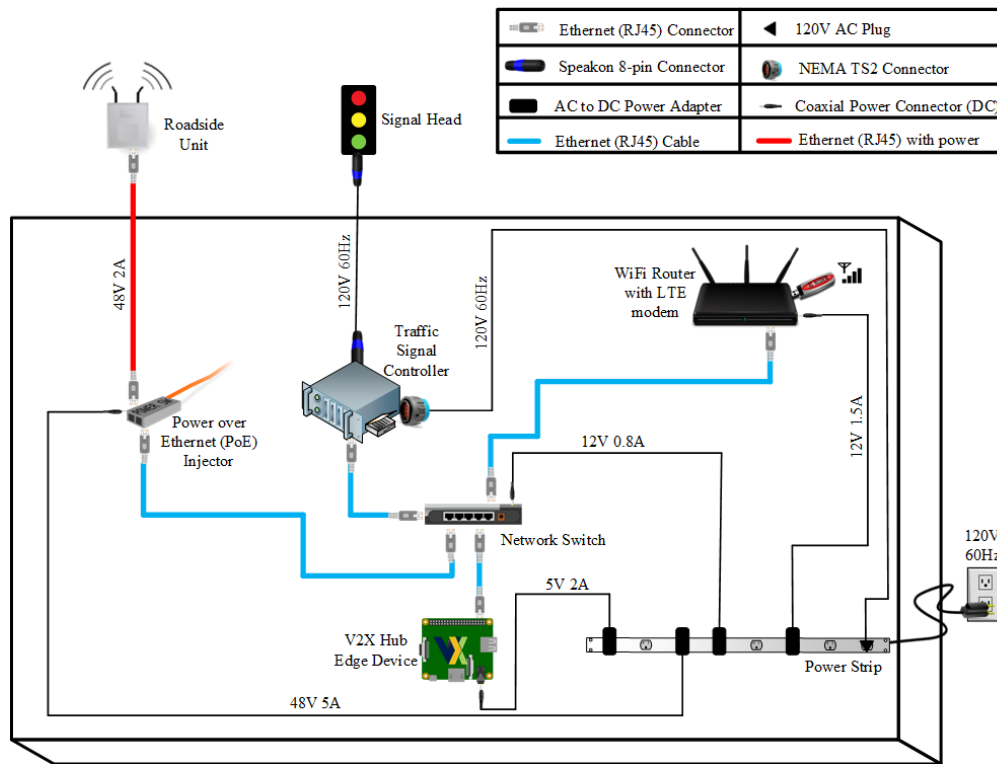
- **Display and Input Interfaces.** The touchscreen available as part of the kit connects with the V2X Hub computer using an HDMI port for display. It uses a USB port for the keyboard and mouse connections. Bluetooth options are also available.
- **Wireless Router.** A wireless switch is connected with the wired switch that allows external devices to connect with the kit. The wireless link is expected to have a password and encryption enabled for securing access to the test kit. The router has Dynamic Host Configuration Protocol (DHCP) enabled for Wi-Fi clients to reduce connection and configuration time. The wireless and wired interfaces are on the same subnet to enable efficient communication.

## INTEGRATED SYSTEM DIAGRAMS

With the components and connections described previously, the various versions of the infrastructure and mobile kits for CAVe-in-a-box can be built, as shown in figure 18 to figure 21. The interconnection diagram in figure 18 shows the connection and bridging of different components to build the infrastructure kit. If a wireless connection to the components of the kits is needed, then a wireless router can be configured to allow a Wi-Fi network with users outside the kit. The wireless router is also available with cellular network support, which allows remote connection with CAVe-in-a-box. The wireless router will also have DHCP that assigns IP addresses to each of the connected components. The address assignment can be fixed based on the type of device (hardware address-based). The wireless router can also provide Network Address Translation for isolating the subnetwork inside the CAVe-in-a-box and allow a single interface for secure internet access. The connections needed for the infrastructure kit are shown in figure 18, such as power connection between each of the devices, including the PoE required for RSU, wired connections required among RSUs, TSC and V2X Hub computer through a single wired network switch. The connectors required for different components are also shown in figure 18. This setup is vendor-specific; certain connectors and interfaces may be different for



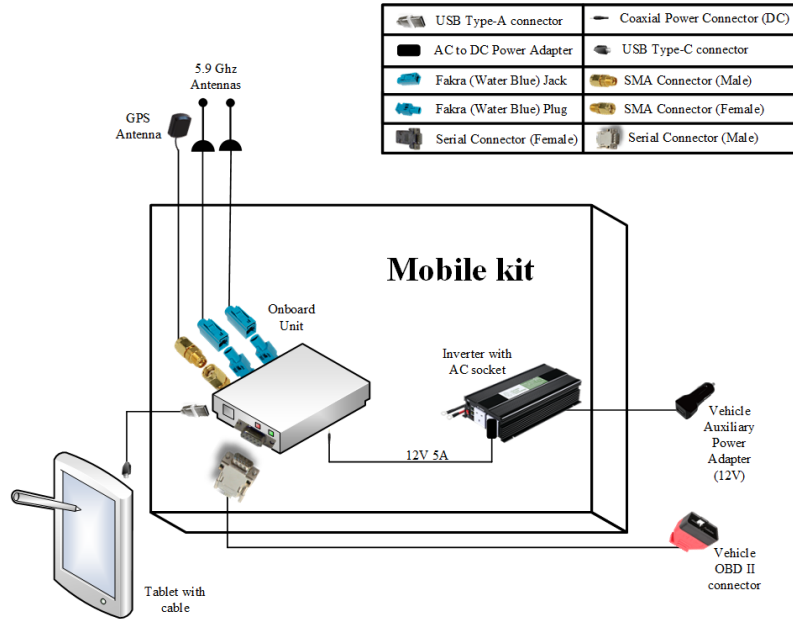
different vendors, so it is highly recommended to reference the vendor-specific manuals. An additional diagram of CAVe-in-a-Box with C-V2X radio and Connected and Automated Vehicle Education Research Software (CAVERS) integration can be found in appendix B.



Source: FHWA.

**Figure 18. Diagram. Infrastructure kit integrated connection diagram.**

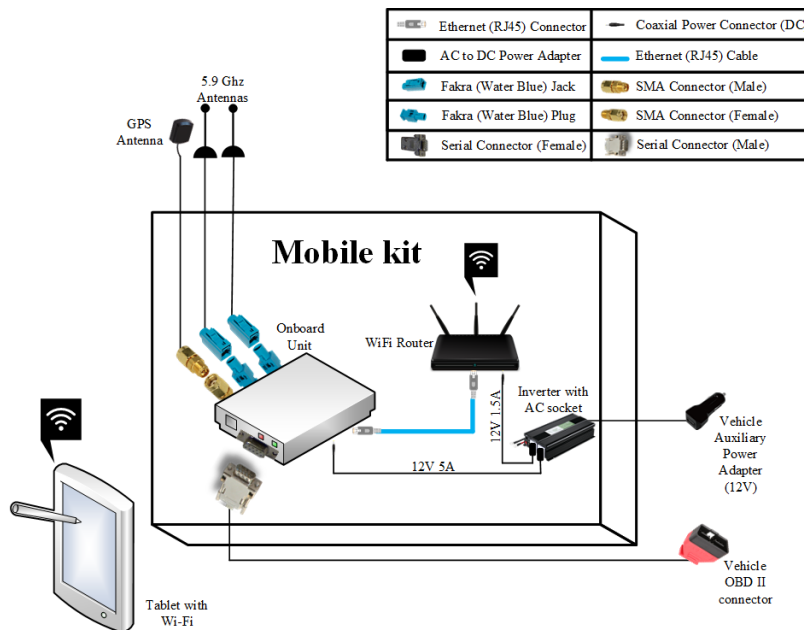
The interconnection diagrams for the mobile kit are shown in figures 15-17. The mobile kit is envisioned to have three potential versions that may have varying amounts of equipment. The OBU with a wireless radio is common among all three versions and has the primary task of communicating with the connected environment. Figure 19 shows the version without any wireless networking support, called mobile kit type 1. This version of the mobile kit allows users to interface with the kit using a USB to Ethernet connection with a tablet PC or laptop. The OBU is powered using an inverter through the car DC power supply. This type of mobile kit does not have internet or remote access support. The antennae shown in figure 19 are mounted on top of the vehicle where this kit is installed. Therefore, the wires need to be routed inconspicuously along the frames of the vehicle.



Source: FHWA.

**Figure 19. Diagram. Mobile kit type 1 integrated connection diagram.**

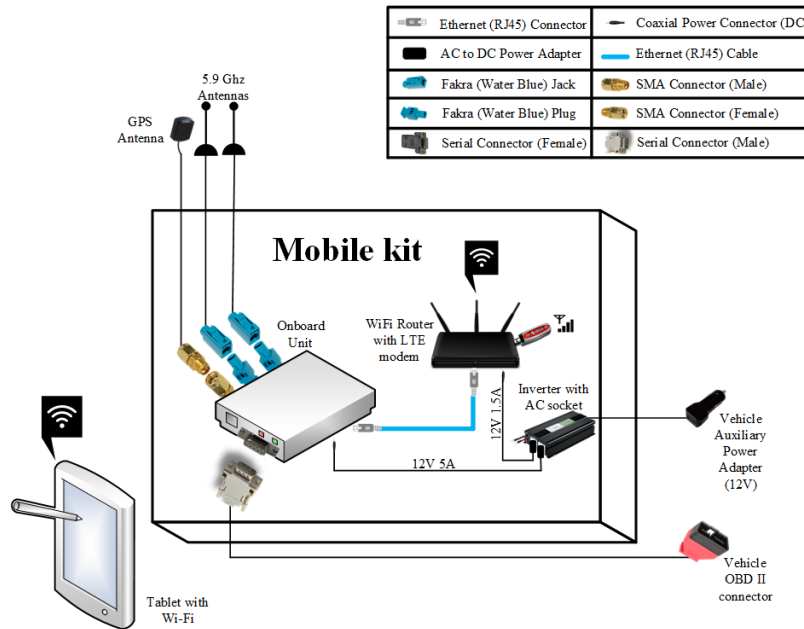
The second type of mobile kit (type 2) is shown in figure 20. This version of the mobile kit has an internal wireless router that allows wireless connection with users but lacks cellular service. Therefore, this version also lacks remote access support for the mobile kit.



Source: FHWA.

**Figure 20. Diagram. Mobile kit type 2 integrated connection diagram.**

The third type of the mobile kit (type 3) is shown in figure 21. This version of the mobile kit has a wireless router with cellular service (like the infrastructure kit), allowing remote access to the mobile kit, if needed.



Source: FHWA.

**Figure 21. Diagram. Mobile kit type 3 integrated connection diagram.**

## VENDOR LIST

There are many vendors available for supporting the construction of a test kit like CAVE-in-a-box. The kit has been designed with generic interfaces and requirements so that many vendors are able to provide support. Table 1 provides a list of some of the commonly available components with their respective vendors.

**Table 1. Vendor list for CAVE-in-a-box.**

Component	Used in this Document	Vendor
TSC	Econolite	Econolite Cobalt Rackmount, McCain 2070 EN1, ASC/3 Rack mount Econolite, Commander Trafficware, Peel, Intellight
RSU	Cohda	Cohda, Lear, Savari, Kapsch, Siemens
OBU	Cohda, Savari	Cohda, Lear, Savari, Kapsch

V2X Hub computer	nanoPi	Raspberry Pi, NanoPi, Intel NUC, Asus Tinkerboard
Touchscreen	Asus, Windows tablet	Windows/Android tablet

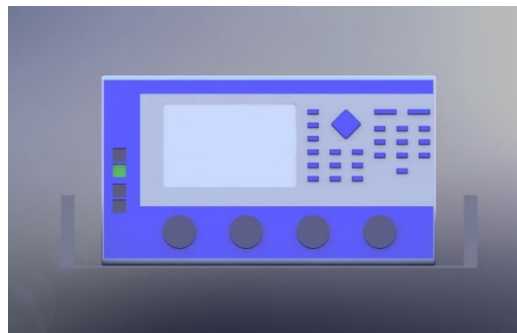


## CHAPTER 3. SETUP AND CONSTRUCTION

CAVe-in-a-box is a toolkit that is used out in the field and in academic settings to test devices and act as an aid to educate future transportation engineers. The toolkit consists of a box housing multiple devices that allow for V2X communication. This section provides information on building the CAVe-in-a-box, with a focus on the infrastructure kit due to the need for rugged outdoor use cases.

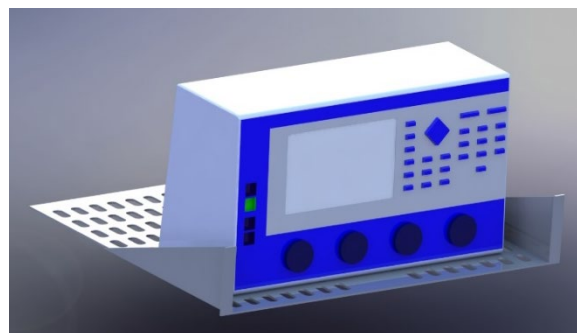
### SOLIDWORKS REPRESENTATIONS: INFRASTRUCTURE KIT

This section will provide a visual representation of the infrastructure kit with all of its components inside using the SolidWorks software (D. Systèmes, 2020). Figure 22 displays the TSC shelf. Due to the size of the TSC, it has its own dedicated shelf in the infrastructure kit. The TSC is mechanically fastened to the shelf with the use of screws.



Source: FHWA.

A. Front view of TSC shelf.

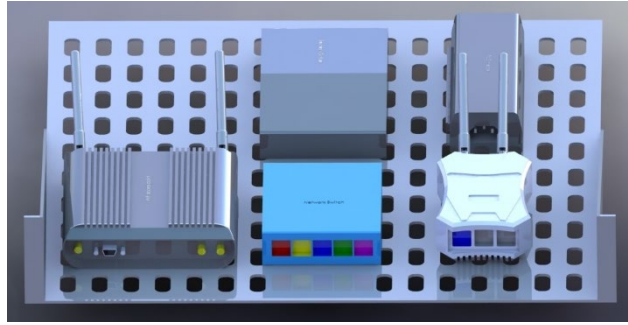


Source: FHWA.

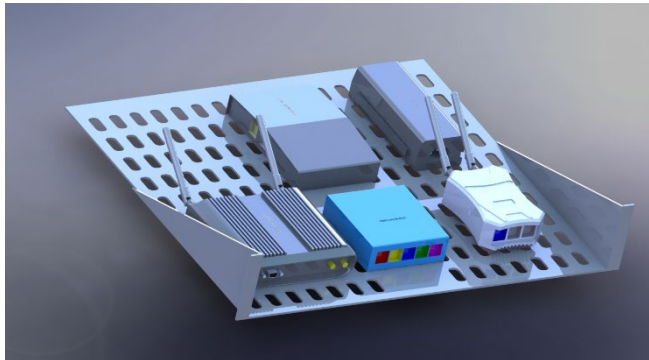
B. Orthogonal side view of TSC shelf.

**Figure 22. Illustrations. TSC shelf.**

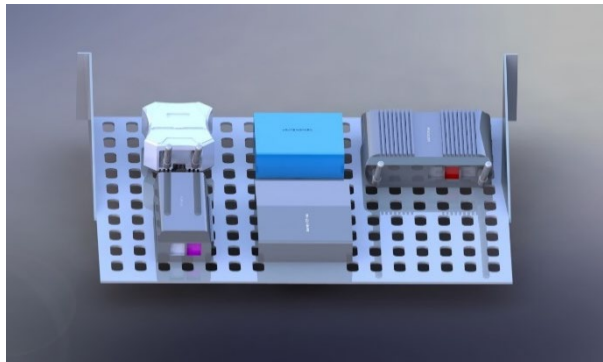
Figure 23 displays the component shelf. The devices included on this shelf are the network switch, PoE, boundary V2X, V2X Hub, and the network Wi-Fi router. To represent the Ethernet connections, the Ethernet ports on the devices have been color-coded. Because the initial CAVe-in-a-box is a prototype, these devices are affixed to the shelf via hook-and-loop fasteners. This allows for rapid replacement of devices. Further iterations will require brackets to be made for some of the devices to properly fasten them down.



Source: FHWA.  
A. Top view of component shelf.



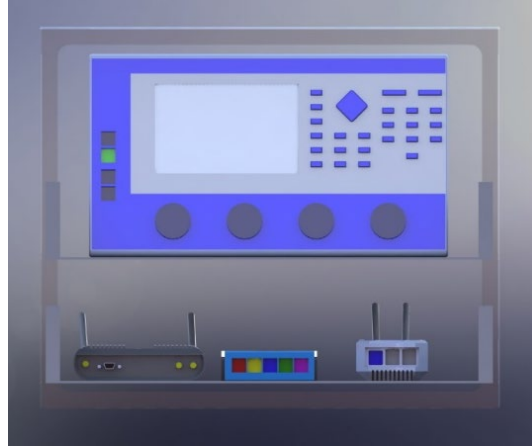
Source: FHWA.  
B. Side view of component shelf.



Source: FHWA.  
C. Rear view of component shelf.

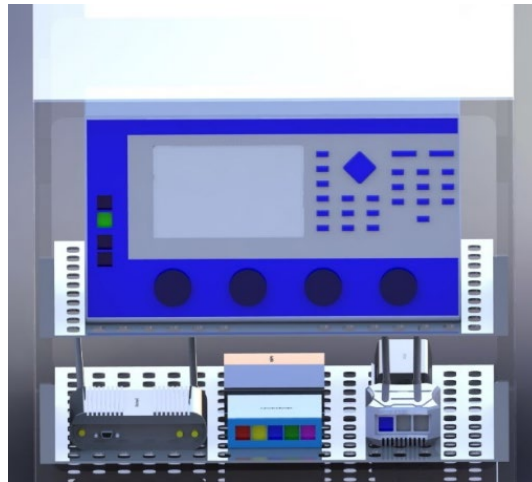
**Figure 23. Illustrations. Components in the shelf design (isometric views).**

Figure 24 displays front views of the infrastructure kit as an assembled box. For this iteration, the TSC shelf is mounted above the component shelf. From this angle, two of the color-coded Ethernet connections are visible.



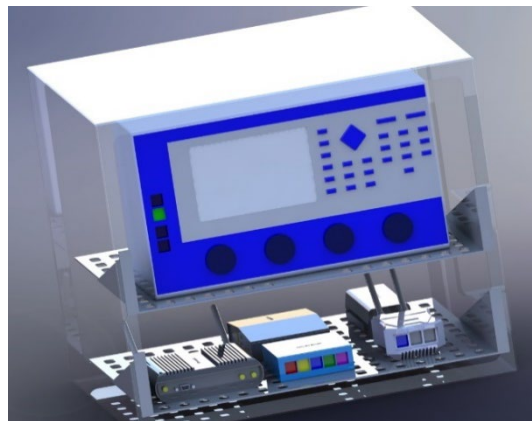
Source: FHWA.

A. Front view of the CAVe-in-a-box design.



Source: FHWA.

B. Tilted front view of the CAVe-in-a-box design.



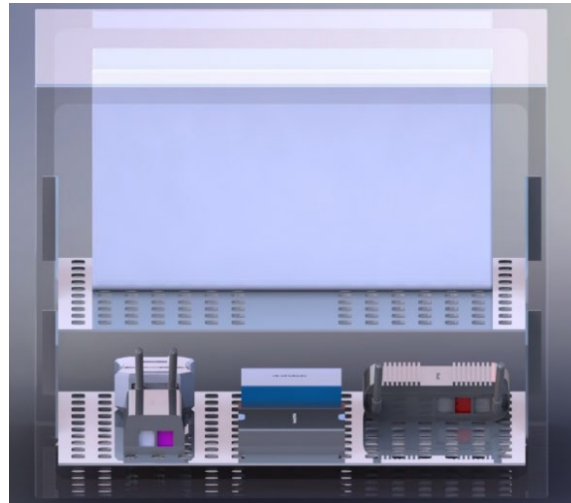
Source: FHWA.

C. Side view of the CAVe-in-a-box design .

**Figure 24. Illustrations. Completed SolidWorks design of a CAVe-in-a-box infrastructure kit.**

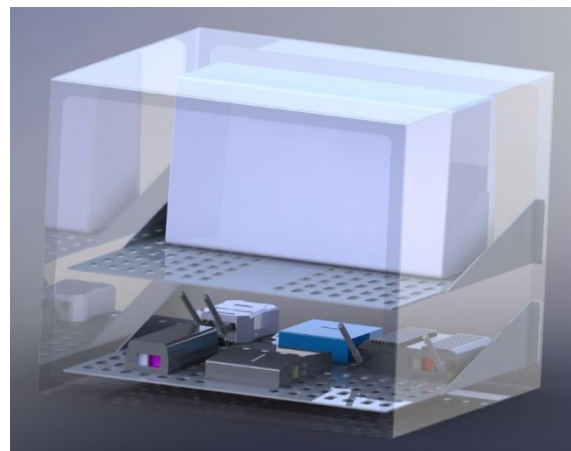


Figure 25 displays rear views of the roadside kit. Here, the remaining color-coded Ethernet connections are visible. In the actual device, cabling is routed neatly between the devices to provide DC power and Ethernet connectivity.



Source: FHWA.

A. Rear view of the CAVe-in-a-box.



Source: FHWA.

B. Rear side view of the CAVe-in-a-box.

**Figure 25. Illustrations. Rear view of the completed CAVe-in-a-box infrastructure kit.**

## Current Kit

The current infrastructure kit design is a proof-of-concept that serves as a base for further product development while enabling a real-time view of working components. For this kit, the goal was to develop a case that could highlight the devices and technology being used. With this goal in mind, a simple rack mount case with two shelves was used. Except for the TSC, the kit components are held in place with a hook-and-loop fastener for two reasons: the components do not have built-in mounting locations, and this setup preserves the modularity of the design.

## **Future Design Alterations**

Because the proof-of-concept version of the infrastructure kit has been established, the next step is to consider future design alterations that improve the function of the kit. First, for this kit to be used in the field, a weather-proof case is needed to protect all the components inside. Sliding shelves in lieu of rigid mount shelves would allow for the exchange and access of components. Second, installation of red, yellow, and green signal light LEDs would make it easier to quickly determine the phase that the TSC is in without requiring the kit to be directly plugged into a signal head. Further design modifications that would allow this kit to be more robust include adding cooling fans, shock mounting the components, or mechanically fastening all devices to the shelves. This would be done by fabricating bracketry that can then be either drilled and tapped or through-bolted to securely mount devices. Lastly, a more secure RSU mounting location on the kit will need to be determined without inhibiting the durability of the case.

CAVe-in-a-box is durable and weather-proof. For this iteration, the Pelican Mac-Rack MR1917 has been chosen. It utilizes a 9U rack that can be dismounted from the box for installation and removal of equipment. This box also utilizes all stainless-steel hardware and sliding shelves. Both lids are mated to the box with weather tight seals to prevent any water intrusion into the box.

The box has been modified for this project's specific purposes to include weather tight grommets to allow for wires to pass through the box while the lids are attached. An outdoor electronics' cooling fan has also been added to monitor interior temperature. Red, green, and yellow lights have been flush mounted to the box to serve as indicators of the traffic signal phase. A specialized bracket has been constructed to mount to the box as well to allow for the installation of an RSU.

Within the box, the top shelf is outfitted with a Cobalt (model) TSC. This controller has been mechanically fastened to the shelf via machine screws to ensure that the controller stays in place and cannot come loose. Power is fed to the controller via a 120V power supply mounted on the interior backside of the box.

The second shelf within the box contains the other necessary hardware that enables the toolkit to serve its desired function. These devices include the V2X Hub, network switch, network router, a PoE, and the necessary Ethernet cables to connect the devices.

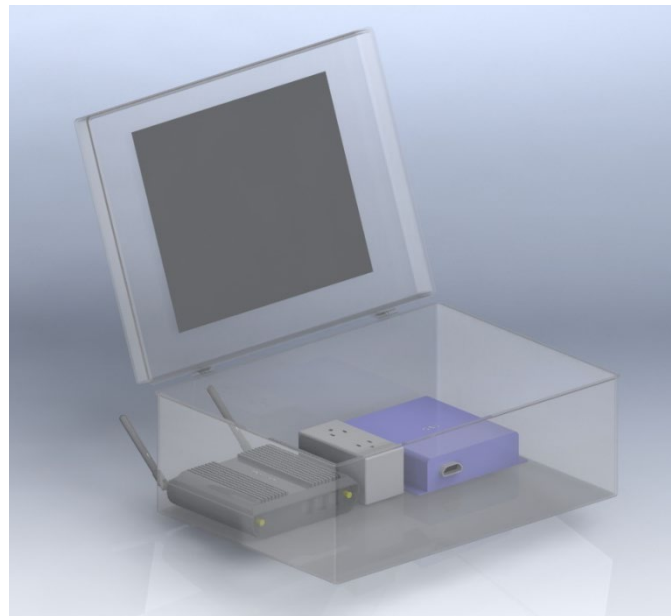
Once constructed, the shelves are mounted to the rack within the box with machine screws. The rack is then re-installed into the box and attached to the shock mounts within the box.

## **SOLIDWORKS REPRESENTATION: MOBILE KIT**

The purpose behind the design of the CAVe-in-a-box mobile kit is to create a device that can be placed into a vehicle, connect to the vehicle's OBD2 port, and serve its function as a mobile onboard communications device.

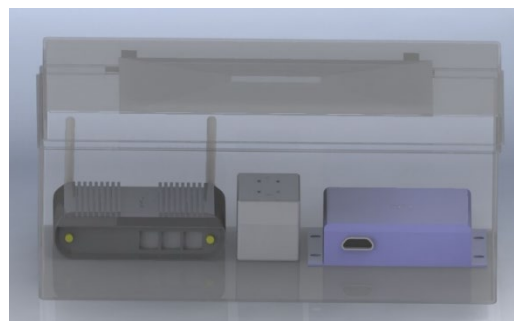
Items included in the mobile kit are the OBU, a wireless network router, and a tablet screen PC to display information. The tablet PC is mounted on the lid to give the user the ability to view the screen within the mobile kit. This keeps the design of the kit integrated. The wireless network router and the OBU are mounted within the kit in a way that allows for access to the antenna connections and CAN connectors. As shown in figure 26 and figure 27, a 120V power strip is included to provide power to the devices via an existing inverter installed inside of the anticipated test vehicle. Future design alterations will allow for a 12V inverter or power supply to be mounted within the mobile kit.

The compact, mobile, and integrated design of the CAVe-in-a-box mobile kit allows for testing, as a single kit may be used for multiple vehicles.



Source: FHWA.

**Figure 26. Illustration. Completed SolidWorks design of a CAVe-in-a-box mobile kit.**



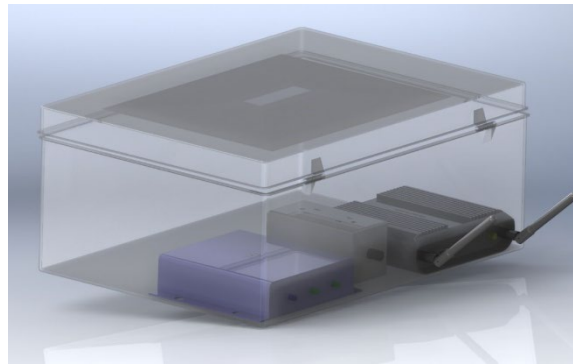
Source: FHWA.

**A. Front view of CAVe-in-a-box mobile kit side profile.**



Source: FHWA.

B. Rear view of CAVe-in-a-box mobile kit side profile.



Source: FHWA.

C. Isometric view of CAVe-in-a-box mobile kit side profile.

**Figure 27. Illustrations. CAVe-in-a-box side profile.**



## CHAPTER 4. SOFTWARE CONFIGURATION

This chapter provides details on the software configurations required to set up different components in CAVe-in-a-box for operation. Due to the technical nature of this chapter, the readers are assumed to be familiar with networking and terminal shell in a Linux environment.

### V2X HUB INSTALLATION AND INITIALIZATION

#### V2X Hub

The V2X Hub is available as a Docker image that may be run in a containerized environment (FHWA, 2020). The primary requirement for running V2X Hub is a local computer that can support Docker. Having root access to the device is preferred. For the development of this documentation, a Nano-pi M4 board installed with a variant of Ubuntu 18.04 (Canonical, 2020) was used.

The container is configured to use the host network for communications, so being able to control the IP address for the interface connected to the CAVe-in-a-box network on the computer running V2X Hub is required for a successful implementation. It is recommended to configure the computer to use *192.168.0.3* as the static IP address to be able to mimic the configurations stated within this document.

The initialization scripts for AMD or ARM 64-bit architecture processors are available through the V2X Hub GitHub repository. Once the V2X Hub source code has been downloaded, navigate to *V2X-Hub/configuration/amd64* or *V2X-Hub/configuration/arm64* depending on the system and run the following commands:

```
$ chmod +x initialization.sh
$ sudo ./initialization.sh
```

This script will execute the following:

1. Ask you to set up a custom username and password to access the V2X Hub GUI. The password must be within the required constraints.
2. Remove any older unsupported versions of Docker.
3. Run a system update and upgrade.
4. Install the latest versions of Docker along with all the prerequisites.
5. Install python3-pip and subsequently install docker-compose through pip3.
6. Execute the docker-compose.yml file to download and run V2X Hub through the following three images available from Docker Hub:

- a. Database (mysql)–mysql:5.7.
- b. Web server (apache-php)–php:7.2.2-apache.
- c. V2X Hub–usdotfhwaops/v2xhubamd:latest.

Upon successful execution of the initialization script, V2X Hub will be accessible using the local static IP address configured for the V2X Hub computer. Using an internet browser on the computer running V2X Hub or any other computer on the same network, navigate to `https://192.168.0.3:19760`. A webpage asking you to “add an exception to the security certificate requirements” will open up in the browser. This is to add the self-signed certificate generated by the V2X Hub container to your browser. You will be prompted to accept a security warning. Click to continue. This is a necessary security feature to ensure controlled and secure access to the system in a real-world deployment.

Following successful addition of the certificate, open a new browser tab and navigate to `https://192.168.0.3`. This will open up the landing screen for V2X Hub. There will be an IP address field at the top left. Re-enter `192.168.0.3` in this space and click the *Enter* key on the keyboard. This will bring up the login screen. Use the username and password created at the beginning of the initialization script to gain access to the V2X Hub configuration page.

This document will address basic configuration for the V2X Hub applications. For further reading, please visit the [V2X Hub GitHub repository](#).

## **Plugin Configuration**

For successful CAVe-in-a-box implementation, please configure the plugins with the following values.

### ***Immediate Forward Plugin***

The RSU will be configured to the IP address shown in table 2. The port number provided in this document is for a Cohda RSU; please refer to the manufacturer’s instructions to configure the Immediate Forward port on any other RSU. The Provider Service Identifier (PSID) configuration is necessary to enable complete utilization of CAVe-in-a-box features. User configuration for the plugin occurs through an inbuilt manifest file in JSON. Table 2 shows a sample manifest file for the Immediate Forward plugin.

**Table 2. Sample manifest file for the Immediate Forward plugin.**

Key	Default Value	Description
Messages_Destination_1	{ "Messages": [ { "TmxType": "SPAT-P", "SendType": "SPAT", "PSID": "0x8002" }, { "TmxType": "MAP-P", "SendType": "MAP", "PSID": "0x8002" }, { "TmxType": "PSM", "SendType": "PSM", "PSID": "0x8002" }, { "TmxType": "TIM", "SendType": "TIM", "PSID": "0x8003" } ] }	JSON data defining the message types and PSIDs for messages forwarded to the DSRC radio at destination 1.
Messages_Destination_2	{ "Messages": [ ] }	JSON data defining the message types and PSIDs for messages forwarded to the DSRC radio at destination 2.
Messages_Destination_3	{ "Messages": [ ] }	JSON data defining the message types and PSIDs for messages forwarded to the DSRC radio at destination 3.
Messages_Destination_4	{ "Messages": [ ] }	JSON data defining the message types and PSIDs for messages forwarded to the DSRC radio at destination 4.
Destination_1	192.168.0.4:1516	The destination UDP server(s) and port number(s) on the DSRC radio for all messages specified by Messages_Destination_1.
Destination_2	0	The destination UDP server(s) and port number(s) on the DSRC radio for all messages specified by Messages_Destination_2.
Destination_3	0	The destination UDP server(s) and port number(s) on the DSRC radio for all messages specified by Messages_Destination_3.
Destination_4	0	The destination UDP server(s) and port number(s) on the DSRC radio for all messages specified by Messages_Destination_4.
Signature	False	True or False value indicating whether the RSU should sign the messages being transmitted.

### **MAP Plugin**

After the MAP file (ex. map\_file.txt) is copied to the MAP folder created in the *V2X-Hub/configuration/amd64* or *V2X-Hub/configuration/arm64* folder on the V2X Hub computer, replace *map\_file.txt* in the following configuration with the name of the MAP file. Table 3 shows a sample manifest file for the MAP plugin.



**Table 3. Sample manifest file for the MAP plugin.**

Key	Default Value	Description
Frequency	1000	The frequency to send the MAP message in milliseconds.
MAP_Files	<code>{"MapFiles":[{"Action":0, "FilePath":"/var/www/plugins/MAP/map_file.txt"}]}</code>	JSON data defining a list of map files. One map file for each action set specified by the TSC.

***SPaT Plugin***

The Signal Group to Phase mapping is configured by matching the correct Signal Groups in the MAP file to the right phases configured in the TSC. Change the *intersection ID* and *intersection name* to match with the MAP file as per constraints set by the transportation authority. The document assumes that the TSC SNMP port number is *501*. Table 4 shows a sample manifest file for the SPaT plugin.

**Table 4. Sample manifest file for the SPaT plugin.**

Key	Default Value	Description
Intersection_Id	1	The intersection ID for SPAT generated by this plugin.
Intersection_Name	Intersection	The intersection name for SPAT generated by this plugin.
SignalGroupMapping	<code>{"SignalGroups":[{"SignalGroupId":1, "Phase":1, "Type":"vehicle"}, {"SignalGroupId":2, "Phase":2, "Type":"vehicle"}, {"SignalGroupId":3, "Phase":3, "Type":"vehicle"}, {"SignalGroupId":4, "Phase":4, "Type":"vehicle"}, {"SignalGroupId":5, "Phase":5, "Type":"vehicle"}, {"SignalGroupId":6, "Phase":6, "Type":"vehicle"}, {"SignalGroupId":7, "Phase":7, "Type":"vehicle"}, {"SignalGroupId":8, "Phase":8, "Type":"vehicle"}, {"SignalGroupId":22, "Phase":2, "Type":"pedestrian"}]}</code>	JSON data defining a list of active SignalGroups and phases.
Local_IP	192.168.0.3	The IPv4 address of the local computer for receiving TSC Broadcast Messages.
Local_UDP_Port	6053	The local UDP port for reception of TSC Broadcast Messages
TSC_IP	192.168.0.5	The IPv4 address of the destination TSC.
TSC_Remote_SNMP_Port	501	The destination port on the TSC for SNMP NTCIP 1202 v2 communication.

### *Message Receiver Plugin*

The Message Receiver plugin only requires pointing to the IP address of the V2X Hub computer. The port number needs to be configured to 26789 to ensure successful functionality. Table 5 shows a sample manifest file for the Message Receiver plugin.

**Table 5. Sample manifest file for the Message Receiver plugin.**

Key	Default Value	Description
IP	192.168.0.3	IP address for the incoming message network connection.
Port	26789	Port for the incoming message network connection.
RouteDSRC	False	Set the flag to route a received J2735 message over DSRC.
EnableSimulatedBSM	False	Accept and route incoming BSMs from a V2XHub simulator.
EnableSimulatedSRM	False	Accept and route incoming SRMs from a V2X Hub simulator.
EnableSimulatedLocation	False	Accept and route incoming GPS location messages from a V2X Hub simulator.

### *Pedestrian Plugin*

The port number for the WebServicePort may be changed if the specific port mentioned in the following configuration is being used by a different application. Table 6 shows a sample manifest file for the Pedestrian plugin.

**Table 6. Sample manifest file for the Pedestrian plugin.**

Key	Default Value	Description
Frequency	1000	The frequency to send the PSM in milliseconds.
Instance	0	The instance of the Pedestrian plugin.
WebServiceIP	192.168.0.3	The IP address associated with interface where the webservice is listening for requests. This should be set up such that anyone can send valid requests to the webservice; hence, it should be the outside-facing IP address on the V2X Hub machine.
WebServicePort	9000	The port to which webservice is bound. The incoming requests must be associated with this port; otherwise, they won't be serviced.

### ***Preemption Plugin***

After the geofence file (ex. geofence.json) is copied to the MAP folder created in the *V2X-Hub/configuration/amd64* or *V2X-Hub/configuration/arm64* folder on the V2X Hub computer, replace *geofence.json* in the following configuration with the name of the geofence file. The preemption call is requested in an Econolite Cobalt ATC TSC using SNMP to configure the value for the corresponding Object Identifier in the MIB database defined by the NTCIP 1202 v3 protocol. Please refer to the manufacturer’s instructions to configure the correct object identifier (OID) for other TSCs following the NTCIP 1202v3 protocol. Table 7 shows a sample manifest file for the Preemption plugin.

**Table 7. Sample manifest file for the Preemption plugin.**

<b>Key</b>	<b>Default Value</b>	<b>Description</b>
BasePreemptionOid	.1.3.6.1.4.1.1206.4.2.1.6.3.1.2.	The BasePreemptionOid of Preemption Plugin
Instance	0	The instance of the Preemption Plugin
ipwithport	192.168.0.5:6053	The IP address with port number where the TSC is listening on for any request coming from Preemption Plugin
map_path	./geofence.json	Location of the map file that contains geo location for geo fence
snmp_community	public	Snmp_community for Preemption Plugin

### ***TIM Plugin***

The broadcast time for the TIM plugin may be configured manually, or through the webservice. For manual configuration, after the TIM file (e.g., *tim\_file.xml*) has been copied to the MAP folder created in the *V2X-Hub/configuration/amd64* or *V2X-Hub/configuration/arm64* folder on the V2X Hub computer, replace *tim\_file.xml* in the following configuration with the name of the TIM file.

The same information may also be sent to V2X Hub with the information with the broadcast date. This XML input will override any manually inserted information. The port number for the WebServicePort change if the specific port mentioned in the following configuration is being used by a different application. Table 8 shows a sample manifest file for the TIM plugin.

**Table 8. Sample manifest file for the TIM plugin.**

Key	Default Value	Description
Frequency	1000	The frequency to send the TIM in milliseconds.
MapFile	“tim_file.xml ”	Location of a pre-existing TIM file (xml).
Start_Broadcast_Date	01-01-2019	The Start Broadcast Date for the TIM in the <i>MM-DD-YYYY</i> format.
Stop_Broadcast_Date	12-31-2020	The Stop Broadcast Date for the TIM in the <i>MM-DD-YYYY</i> format.
Start_Broadcast_Time	06:00:00	The Start Broadcast Time for the TIM in the <i>HH:MM:SS</i> format.
Stop_Broadcast_Time	21:00:00	The Start Broadcast Time for the TIM in the <i>HH:MM:SS</i> format.
WebServiceIP	192.168.0.3	IP address at which the webservice exists.
WebServicePort	9999	Port at which the webservice exists.

## RSU CONFIGURATION

This section details the configuration for a Cohda RSU. Please refer to manufacturer instructions to perform similar configurations for other RSUs.

### IP Address Setup

The default IP address for the Cohda RSU may be determined by converting the last four digits of the device serial number. The first two octets for the IP address by default are *169.254*. The third octet may be obtained by converting the first two of the last four digits of the serial number from hexadecimal to decimal. The fourth octet may be obtained by converting the last two digits of the serial number from hexadecimal to decimal.

For example, suppose that the last four digits of the serial number for a Cohda RSU are *3728*. The decimal value for “37” is “55” and the decimal value for “28” is “40.” The IP address to access this particular Cohda device would then be *169.254.55.40*.

The RSU may be accessed using a SSH client like putty, or a terminal application that allows SSH connections.

On the SSH client, use the IP address identified for the RSU along with the port number 22, which is the standard SSH port. Please refer to the user manual for initial login credentials. If using a terminal application, the syntax will be:

```
$ ssh username@169.254.55.40
```

```
Password: “password”
```

## RSU Configuration for CAVe-in-a-box

Once the password has been entered and access has been granted, the next step is to create a custom username and password. Certain steps need to be executed to ensure successful configuration of the RSU within CAVe-in-a-box. Please refer to manufacturer instructions for any specific actions that need to be performed during the configuration.

### *Configuring the Static IP Address*

Please refer to the manufacturer's instructions to change the IP address of the RSU to the following values:

```
$ fw_setenv static_ip_addr "192.168.0.4"
$ fw_setenv static_ip_mask "255.255.255.0"
$ fw_setenv static_ip_bcast "192.168.0.255"
$ fw_setenv static_ip_gw "192.168.0.1"
$ fw_setenv static_ip_ns "8.8.8.8"
```

### *Creating an SNMP User (Generally After Halting RSU Functioning)*

Change "Admin," which is the username, and "password" in the following command to the desired values:

```
$ net-snmp-config --create-snmpv3-user -A password -X password -a SHA -x AES Admin
```

### *BSM Forwarding Rules*

Replace */this/location/should/be/mib-directory* with the location of the MIB directory on the RSU. Also, change "Admin," which is the username, and "password" in the following commands to the values created in the previous command:

```
$ snmpset -v3 -lauthPriv -uAdmin -Apassword -Xpassword -aSHA -xAES -mRSU-MIB -
M/this/location/should/be/mib-directory -O T 127.0.0.1 iso.0.15628.4.1.99.0 i 2

$ snmpset -v3 -lauthPriv -uAdmin -Apassword -Xpassword -aSHA -xAES -mRSU-MIB -
M/this/location/should/be/mib-directory -O T 127.0.0.1 \
iso.0.15628.4.1.7.1.11.1 i 4 \
iso.0.15628.4.1.7.1.2.1 x 0x20 \
iso.0.15628.4.1.7.1.3.1 x 0x000000000000000000000000c0a80003 \
iso.0.15628.4.1.7.1.4.1 i 26789 \
```

```
iso.0.15628.4.1.7.1.5.1 i 2 \  
iso.0.15628.4.1.7.1.10.1 i 1  
$ snmpset -v3 -lauthPriv -uAdmin -Apassword -Xpassword -aSHA -xAES -mRSU-MIB -  
M/this/location/should/be/mib-directory -O T 127.0.0.1 \  
iso.0.15628.4.1.7.1.11.2 i 4 \  
iso.0.15628.4.1.7.1.2.2 x 0xBFEE \  
iso.0.15628.4.1.7.1.3.2 x 0x000000000000000000000000c0a80003 \  
iso.0.15628.4.1.7.1.4.2 i 26789 \  
iso.0.15628.4.1.7.1.5.2 i 2 \  
iso.0.15628.4.1.7.1.10.2 i 1 \  
iso.0.15628.4.1.99.0 i 4
```

## **TRAFFIC SIGNAL CONFIGURATION**

Most TSCs provide manual configuration using keys available on the device. Please refer to the TSC manufacturer’s instructions for more details:

### **IP Address Configuration**

Configure the TSC to the following IP address:

```
IP Address: 192.168.0.5  
Subnet Mask: 255.255.255.0  
Default Gateway: 192.168.0.1  
DNS Server: 8.8.8.8
```

### **SPaT Forwarding IP Address**

This IP address may sometimes be termed as “Ping Server” or “SPaT Server.”

```
IP Address: 192.168.0.3
```

## Enabling SPaT Forward

Certain TSCs may require an extra step to enable forwarding of SPaT objects to the application. In this case, the user will enable the forwarding of the SPaT objects to the computer running V2X Hub. Any external SNMP application may be used to pass the following command to the TSC to start forwarding SPaT objects. Please refer to the manufacturer's instructions for the correct OID.

```
$ snmpset -v3 -c public 192.168.0.5:501 1.3.6.1.4.1.1206.3.5.2.9.44.1.0 i 2
```

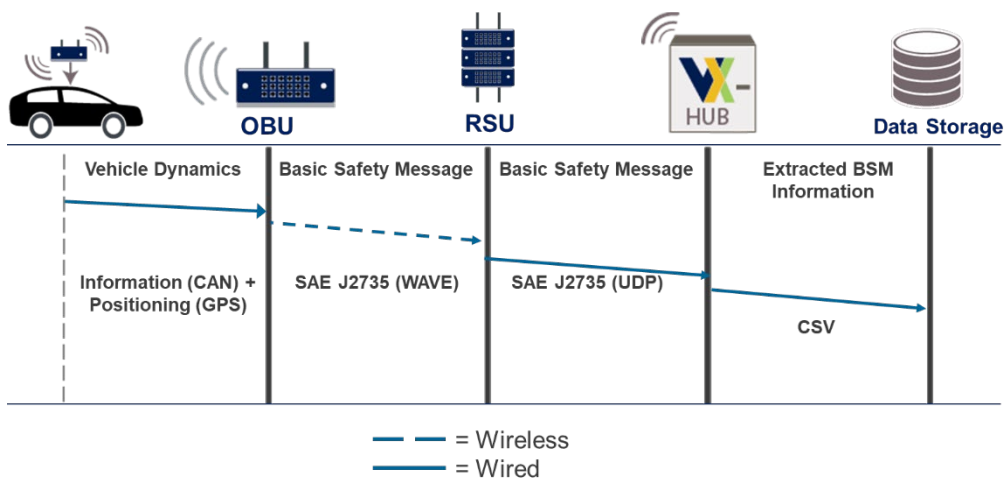
## WI-FI ROUTER CONFIGURATION

A Wi-Fi router may be used for access and configuration to CAVe-in-a-box. The router must be configured with the IP address of *192.168.0.1* and client list using the same subnet. It is preferable to enable DHCP for the wireless interface and static IP configuration for the Ethernet interface. A 4G LTE modem may be used to provide internet access to CAVe-in-a-box for remote configuration.

## CHAPTER 5. DATA FLOWS

This chapter discusses the different types of data, including their source and destination, and how they are managed by different applications within the scope of CAV. This chapter tries to bring an extended ITS scenario into the scope of CAVE-in-a-box so that readers can understand how CAVE-in-a-box acknowledges the real CAV environment. The communication networks available in the CAVE-in-a-box toolkit include a wireless vehicular network using DSRC or C-V2X and a wired network. The messages between the RSU and the OBU are exchanged via a wireless DSRC network, and the messages between the V2X Hub computer, TSC, and RSU are exchanged on a wired Ethernet network. Every application supported by the CAVE-in-a-box has its own set of messages that are exchanged between the interlinked components. The messages sent by V2X Hub for broadcast follow the SAE J2735 standard and are used to convey ITS-relevant information between infrastructure and mobile components. In the case of this setup, the messages are exchanged primarily between the mobile kit and the infrastructure kit. V2X Hub is the managing component in the kit that handles every message that is received by the kit as well as messages that are to be broadcasted from the kit. V2X Hub generally acts as a middleware, handling messages and data from different protocols and standards and cross-translating them for efficient functionality of the overall system.

Figure 28 shows the component data flow diagram for the BSM application responsible for broadcasting vehicle status and positioning information to surrounding vehicles and nearby infrastructure. An OBU gathers information about vehicle status, such as the brake status and the steering wheel position, from the CAN bus connector and appends it with GPS localization information such as latitude, longitude, and altitude to create a unique BSM. The BSM is then broadcasted using WAVE over the wireless interface. WAVE is a hierarchical upper-layer protocol that manages messaging and networking by using the broadcast capability of the wireless interface. The BSM is forwarded to V2X Hub by the RSU after receiving it through the wireless interface. The BSMLogger plugin in V2X Hub is capable of decoding and logging the BSM received from different vehicles.

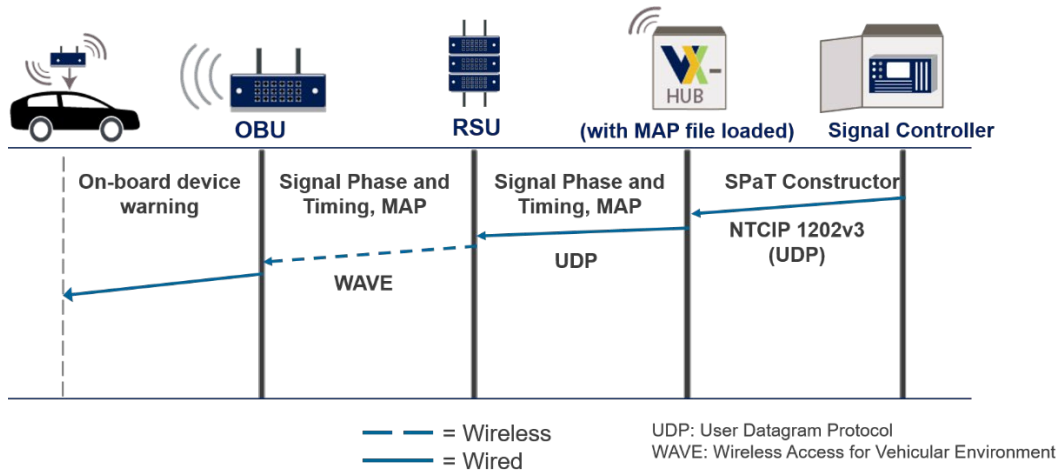


Source: FHWA.

**Figure 28. Diagram. BSM data flow diagram.**



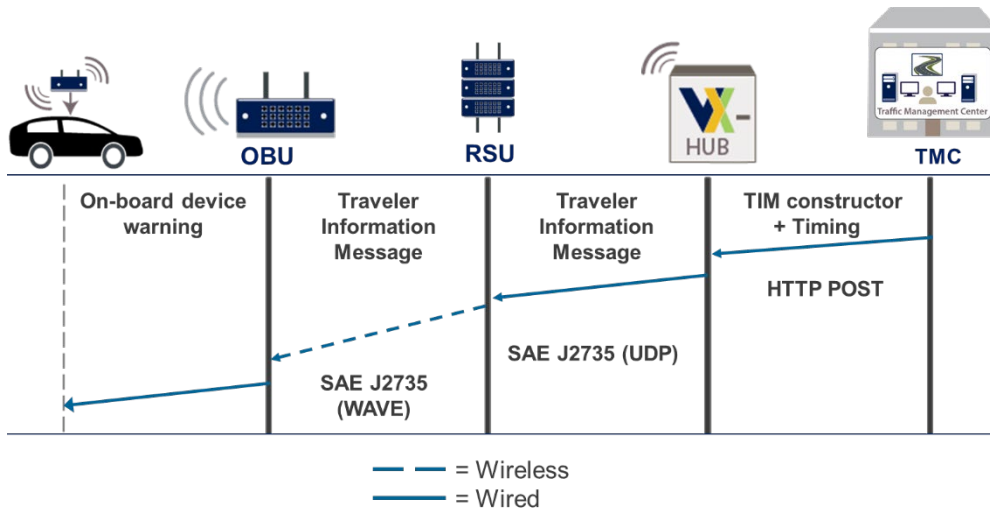
Figure 29 shows the data flow diagram for the SPaT application. The SPaT application runs with the plugin of the same name in V2X Hub. The TSC initially sends the SPaT message to the V2X Hub in NTCIP 1202 V3 format, updating the signal, phase, and timing information for the intersection. The SPaT plugin in V2X Hub creates an SAE J2735 standard SPaT message using the information sent by the TSC, which is then forwarded to the RSU for broadcast. A vehicle within the range of the RSU receives the SPaT message through the wireless interface. In this case, the message flows from the infrastructure kit to the mobile kit.



Source: FHWA.

**Figure 29. Diagram. SPaT message data flow diagram.**

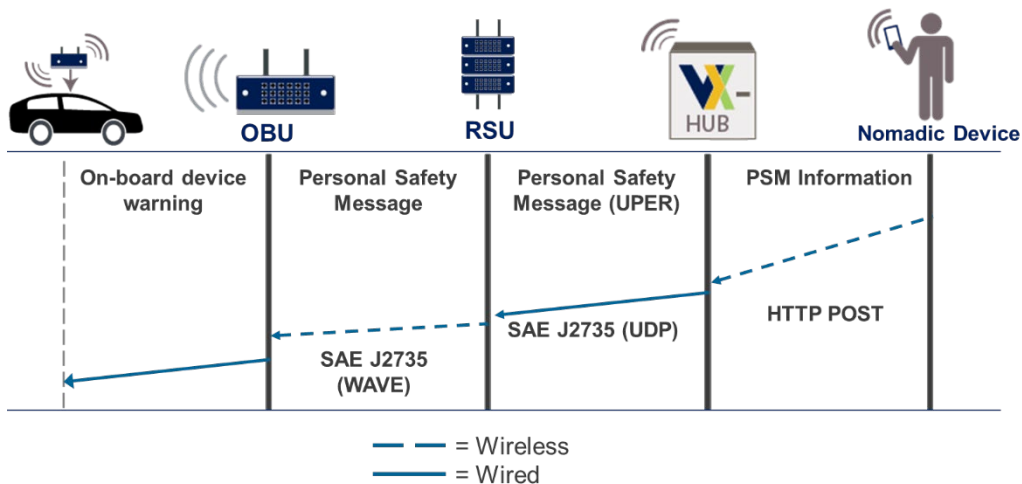
The TIM allows vehicles and drivers to receive updates about lane closures related to work zones and incidents on the roadway. A TIM originates at a higher layer managerial entity, like the traffic management center (TMC), and is pushed down to the vehicles through the RSU. V2X Hub maintains a web server end point that allows the TMC to send the TIM message constructor information, which is then used by V2X Hub's TIM plugin to create a TIM that is forwarded to the RSU for broadcast. In addition to the TIM, the higher layer entity will also send out a timing schedule specifying when to start and stop the TIM broadcast for each RSU. Figure 30 shows the data flow for the TIM application.



Source: FHWA.

**Figure 30. Diagram. TIM data flow diagram.**

PSMs are used by the infrastructure to warn nearby vehicles of the intention of a pedestrian or cyclist to cross the roadway. PSMs are very important for intersections and mid-block crossings that are not equipped with feed-forward inputs for pedestrians and cyclists to indicate their intentions to cross the roadway. A nomadic device, such as a cell phone, equipped with applications to send the PSM constructor call to the V2X Hub, through Wi-Fi or cellular networks, by utilizing the webserver is needed for this application to function. The PSM constructor call to V2X Hub is used to create a PSM, which is then broadcasted using the RSU to all nearby vehicles for warning purposes. Figure 31 shows the data flow diagram for the PSM application.



Source: FHWA.

**Figure 31. Diagram. PSM data flow diagram.**



## CHAPTER 6. USE CASES

This section highlights a few CAVe-in-a-box uses cases. CAVe-in-a-box supports many CAV applications, some of which are presented here for reference. Applications supported by CAVe-in-a-box include, but are not limited to, emergency vehicle preemption, PSM, and work zone TIMs. CAVe-in-a-box also supports hardware-in-the-loop (HIL) scenarios. Supported applications are described below with the CAVe-in-a-box perspective of how they can be tested.

### EMERGENCY VEHICLE PREEMPTION

This use case allows the testing and teaching of emergency vehicle preemption application in the field. The requirements for this application to function properly include the following:

- A CAVe-in-a-box infrastructure kit installed on a roadway or test track. If the test track has no access to an intersection, then CAVe-in-a-box can be mounted on the side of the road and implemented as a virtual intersection for testing purposes.
- A CAVe-in-a-box mobile kit installed on a test vehicle. The preemption application requires sirens and lights to be enabled and associated with the BSM. Therefore, the mobile kit needs to be configured for this purpose. Some OBU vendors have made sirens and lights available through minimum configurations, so it is recommended that the user refer to the manuals when required.
- The TSC in CAVe-in-a-box must be configured to enable preemption and have preset plans for preemption with which to act.
- A signal head to see the traffic light status.

The use case progresses as follows: A vehicle equipped with a mobile kit broadcasting BSMs with extended fields encapsulating sirens and light status drives towards the infrastructure kit mounted on a test track. The vehicle is approaching the infrastructure kit in phases 2 and 4, where the initial setting of the signal heads has RED lights on phase 2. This testing demonstrates that, as the vehicle approaches within the DSRC or C-V2X range of the RSU installed in the infrastructure kit, the presence of sirens and lights on the BSM triggers a preemptive phase change in the TSC. The extended BSM containing sirens and light status is processed by V2X Hub, and the preemption signal is passed onto the TSC. The TSC, upon receiving the preemption call, uses the preset tables and changes the phases in 2 to be GREEN while pushing RED on all other phases—thereby allowing the emergency vehicle with sirens and lights to move through the intersection with minimum delay.

### HARDWARE-IN-THE-LOOP SIMULATION

One of the interesting scenarios for CAVe-in-a-box is the HIL test case (Ma et al., 2018). This use case is appropriate for classroom or lab instruction, where the availability and logistics for a test track and outside testing may not always be feasible. In this test case, CAVe-in-a-box is used

as a real interface for a simulation. Many traffic simulation software have interfaces that allow information to be exchanged with the outside world. A traffic simulation of an intersection can be made more interesting if the SPaT messages from the simulated intersections can be broadcasted from a real TSC, or a real TSC's SPaT messages could be broadcasted to the virtual vehicles in a simulated environment. In addition, the BSMs from virtual vehicles can be broadcasted through the RSU so other mobile kits can receive them for educational purposes. CAVe-in-a-box can be the most important component in an educational toolkit that teaches students about ITS in a classroom setting.

## **PEDESTRIAN SAFETY**

Pedestrian safety is a critical part of the ITS (USDOT, 2020). There have been various attempts at improving pedestrian safety using technology, including pedestrian detection cameras, Light Detection and Ranging (LiDAR), and PSM broadcast, among others. The need to enhance safety for pedestrians and other vulnerable road users led to the development of the Pedestrian application on V2X Hub.

CAVe-in-a-box can support pedestrian safety applications, such as by generating a PSM through the Pedestrian application available on V2X Hub. The PSM is created using data received from a nomadic device in the pedestrian's possession, such as a cell phone. An application on the nomadic device is used to generate the data that will be used to create an SAE J2735 PSM using V2X Hub on CAVe-in-a-box. The data generated on the nomadic device will include the position, speed, and heading of the pedestrian, among other information. The data will be encoded in the XML format and sent to a public-facing web server created by V2X Hub using the available network connection, like cellular or Wi-Fi. The data may be generated at a frequency of 100 Hz to 1Hz, depending on the configuration.

The data received on V2X Hub will then be parsed and converted into an unaligned packet encoding rules (UPER)-encoded SAE J2735 PSM through the Pedestrian application. This message will subsequently be relayed to the designated port on the RSU for immediate forward. The RSU will add the necessary security headers and forward the message over the available radio interface.

PSMs for each individual will have a unique identification number, and vehicles approaching the intersection equipped with CAVe-in-box will receive these messages through the wireless interfaces. The OBUs on these vehicles can subsequently warn the driver if there are any potential safety concerns by comparing the relative trajectory of pedestrian movement to that of the vehicle. The development of such an application for the OBU will be done at the discretion of the OBU manufacturers.

Additional enhancements to the pedestrian safety use case include adding a network backhaul to the CAVe-in-a-box installation in the event of multiple connected intersections and adding a message distribution system developed at the discretion of the agency responsible for the infrastructure. This distribution system hosts a master web server for receiving PSM data within the jurisdiction. It will then be responsible for sending the PSM data received from the nomadic

device to the web server for a particular CAVe-in-a-box system that is most relevant to the position of the pedestrian.

## **WORK ZONE**

Work zone safety (USDOT, Work Zone Data Exchange [WZDx], 2020) is very important when it comes to freeway applications for CAVe-in-a-box. There is a need for improved safety at active work zones. Vehicles traveling at generally higher speeds on freeways are at a risk of causing critical accidents. An FHWA study concluded that there are around 773 deaths in work zone crashes every year (USDOT Work Zone Management Project, 2020). Various efforts to improve work zone safety are underway. One such effort led to the development of the SAE J2735 TIM. TIMs provide the opportunity to inform drivers about existing work zones using available radio communications. To enable this feature, this project developed the work zone safety application in V2X Hub.

A TIM includes the geometry of the applicable work zone and could also provide information regarding speed regulations or other road warnings using a combination of a Manual on Uniform Traffic Control Devices code and an International Traveler Information System code. This provides the opportunity to create a message that could inform the driver about the location of the work zone, the diversion to be used, and the speed regulations while driving through the diversion. This will also enhance the ability of CAVs to safely navigate around a work zone.

The TIM may be created using the USDOT TIM message creator tool, which is available as an open-source resource. This tool will allow the user to draw the TIM over a geographical map by adding surveyed points, thus allowing for an accurate geometry. The message may then be converted into an XML structure for the work zone safety application in V2X Hub. A sample XML structure is available on the V2X Hub GitHub page. In addition to the elements of the TIM, the XML structure also requires start and stop broadcast times to ensure that the message is sent out only within a designated time period. Once the complete XML structure is ready, it may be sent to a web server available on V2X Hub specifically for the work zone application. Alternatively, a TIM XML may also be copied to the persistent memory of the V2X Hub computer in CAVe-in-a box and the start and stop broadcast times may be manually configured. Once a TIM XML is received by the work zone application, V2X Hub will encode the message into the SAE J2735 UPER and send it to the RSU for broadcast. The TIM will then be received by the OBU on the vehicle and may provide warnings to the driver depending on the applications available on the OBU.

The ability to send the TIM to a remote web server makes it possible for the message to be modified or updated through the TMC. Such a centralized system also helps with the integration of work zone data through other USDOT initiatives, including the use of a Situation Data Exchange (SDX) and the Work Zone Data Exchange (WZDx) programs. However, care must be taken to ensure that any modifications to the work zone elements have undergone rigorous verifications to ensure consistency with the ground truth. There are certain limitations to the TIM that would not allow for a particular work zone to be marked as active during a certain time of day, or switch between multiple lanes within the same geometry to be marked as being under construction and assigned diversions. To mitigate this problem, an update to the standard is

currently under development by adding a roadside safety message. This message aims to address any such shortfalls and enhance overall work zone safety. Future updates to V2X Hub and CAVe-in-a-box may attempt to incorporate any improvements through the open-source effort.

## CHAPTER 7. CONCLUSION

The future ITS workforce has an established need for scaled-down test tools and training materials that can prepare technicians to configure and maintain devices that are available now and make informed procurement decisions for the future. This system design document for the CAVe-in-a-box prototype addresses this knowledge gap by providing the ITS community with a scaled-down test tool for examining data flows as well as a comprehensive assembly and configuration guide.

Through a step-by-step explanation of the process by which CAVe-in-a-box was designed using computer-aided design and assembled into a working prototype, future technicians can understand how to configure and manage their own CAVe-in-a-box as well as the types of considerations that go into any ITS procurement and deployment. By including in-depth explanations of both the hardware and software considerations in ITS design, this document also ensures that a user's understanding of the CAVe-in-a-box prototype goes beyond the hardware components and encompasses software and device interconnection as well. The toolkit presented in this document can help instructors and researchers in bringing a large-scale CAV environment inside their classrooms and laboratories. This enables a hands-on, cost effective, and flexible teaching and testing tool for anyone interested in CAV.

The initial CAVe-in-a-box design was envisioned for use in laboratories and classrooms where instructors can work with students to advance hands-on and practical training for ITS- and CAV-oriented education. However, the transitional domain of CAVe-in-a-box can leverage technical support to encompass an additional scope in research labs and industry needs. The future of CAVe-in-a-box would allow more streamlined design, supported by the flexible generic design pattern used in the earliest version of the toolkit, which can focus on specific aspects of CAV and ITS research and implementation. While the current design of CAVe-in-a-box continues supporting the needs of an educator to provide real world use cases for different ITS applications, message types, and implementations, the future of CAVe-in-a-box can be tailor-made for specific research needs. Some of the foreseeable research needs are as follows:

- **CAVe-in-a-box as an onboarding tool for new hires/interns in an ITS industry.** This allows CAVe-in-a-box to house necessary components that make it appropriate for new hires to gain tabletop knowledge of industry-level vehicle messaging and traffic applications.
- **CAVe-in-a-box as a sandbox for newer application and technology integration.** Newer applications and technologies such as 802.11 bd (Wi-Fi), C-V2X, and 5G new radio (G. Naik, 2019) need to be integrated into the ITS and this toolkit can rise as the generic suite for building newer applications, embedding advanced wireless technologies, and undergoing controlled testing for real world investment. One of the implications of this is enabling multiple wireless network technologies to leverage a heterogeneous network.
- **CAVe-in-a-box for industry level validation and certification suite.** This discipline allows CAVe-in-a-box to be built with one objective: to suite up for industry level



validation and testing so that newer technologies/vendors/markets can be tested rigorously against the existing standards. This allows mandatory standard and protocol adherent requirements to be tested in real time.

Interested parties should refer to their respective vendor manuals for the proper instruction on using chosen equipment. However, the following list provides links to websites where information for V2X Hub documentation can be referenced:

- **V2X Hub GitHub:** <https://github.com/usdot-fhwa-OPS/V2X-Hub>.
- **V2X Hub documentation:** <https://usdot-carma.atlassian.net/wiki/spaces/CH/pages/174620673/V2X+Hub+Project+Documentation>.

A limited number of CAVe-in-a-box prototypes are available for lease through an equipment loan program hosted at STOL in Turner-Fairbank Highway Research Center (TFHRC). For more information on the program, please email [CAVSupportServices@dot.gov](mailto:CAVSupportServices@dot.gov).

For feedback/comments, please email [CAVSupportServices@dot.gov](mailto:CAVSupportServices@dot.gov).

## APPENDIX A. CELLULAR VEHICLE-TO-EVERYTHING (C-V2X)

In the past few decades, DSRC, a wireless communication technology, has traditionally carried the research, testing, and deployment of CV technologies in the ITS domain. Even though the technological advancement of DSRC reached its peak in the early 2010s, comparative adoption of CV technologies being deployed within the United States has been limited to testing and demonstration phases only. A list of deployments featuring DSRC-based CV technologies is given in the USDOT ITS JPO Connected Vehicle testbed website.

In the last couple of years, another wireless technology, called C-V2X, has moved up in the ranks to compete with DSRC. C-V2X technology is based on cellular network technology and is capable of using two transmission modes. C-V2X with mode 3 uses existing cellular infrastructure and mode 4 uses PC5 for direct V2V communication.

The wireless protocol used for C-V2X is significantly different from DSRC, due to different channelization schemes and timing requirements. The wireless front end design of the two technologies entails a significant variation in operation and deployment strategies. In terms of operation, the two wireless communication systems use the same frequency range—the 5.9 GHz, identified by the Federal Communication Commission (FCC) as a core wireless band for vehicular safety application.

In the case of DSRC, the 5.9 GHz is divided into seven independent 10 MHz channels using the total bandwidth of 75 MHz. However, the most recent NPRM (and subsequent ruling) released by the FCC identified devoting the first 45 MHz to unlicensed wireless operation, such as Wi-Fi, and allowing the remaining 30 MHz to be used for vehicle safety applications. With these recent policies, it is becoming more and more evident that DSRC could be phased out to make room for the newer and more advanced, yet superficially understood, technology in C-V2X. It is still an open research topic whether C-V2X will fulfill the promises that DSRC started with but failed to showcase.

C-V2X is similarly based on the wireless architecture of cell phones. This technology is enabled by a new interface, called PC5, for vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication using the side link in LTE. The vehicular application messages are broken into multiple radio layer frames, which are multiplexed into channel symbols transmitted in blocks of subcarriers within a fixed amount of consecutive timeslots, called subframes. In C-V2X, the smallest subframe is 1 millisecond, and the subcarrier is 15 KHz. Messages are collated into a group of transmission blocks, called resource blocks, which are 12 subcarriers that span  $\frac{1}{2}$  of a subframe (0.5 ms) in size. Contrary to DSRC, which uses a single carrier for transmission within the 10 MHz bandwidth in 5.9 GHz frequency, C-V2X uses multiple carriers, also known as subcarriers, in blocks of smaller sub-frames. This allows for robust resource utilization and scheduling techniques for high-density, high-speed use cases, featuring roadway safety applications.

In mode 4, a C-V2X transmitter is able to listen for usage in the subcarriers and determine how many resources they would require based on the application message that needs to be supported.

This process happens autonomously, with no assistance from the infrastructure. Semi-persistent scheduling is a resource allocation and acquisition technique used by the C-V2X transmitters in mode 4 that allows the radios to independently identify the quantity of resources needed. This is in contrast to DSRC, which is based on the IEEE 802.11p protocol and is based on carrier sense multiple access. DSRC transmissions can happen virtually, as soon as needed, if the channel is open, compared to C-V2X, where the transmitter has to wait for the scheduled time slot and subframes to fill the resource blocks with data to be transmitted.

However, studies have shown that C-V2X responds better in terms of highly congested scenarios (i.e., high-density vehicular traffic) compared to DSRC. Studies have also found that C-V2X is capable of supporting the requirements placed upon it by safety applications, which affect network performance metrics such as latency, data rate, and packet loss. Such studies have been focused mostly on a simulated environment; more research is needed to understand real world implications for widespread usage of C-V2X.

Further study references:

1. List of existing CV pilot testbeds in the US:  
[https://www.its.dot.gov/research\\_archives/connected\\_vehicle/dot\\_cvbrochure.htm](https://www.its.dot.gov/research_archives/connected_vehicle/dot_cvbrochure.htm).
2. FCC NPRM and ruling on 5.9 GHz channel allocation strategy:  
<https://docs.fcc.gov/public/attachments/FCC-20-164A3.pdf>.

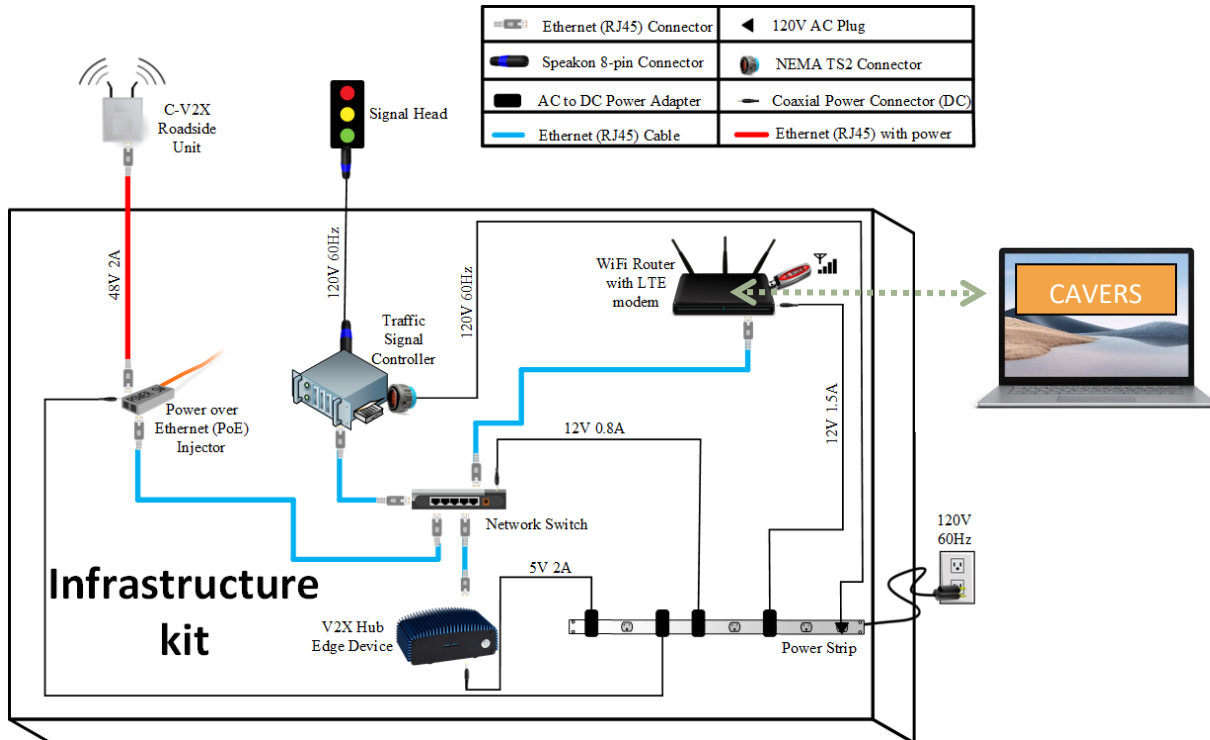
Overview on C-V2X technology:

1. F. Eckermann, M. Kahlert, and C. Wietfeld. (2019). "Performance analysis of C-V2X mode 4 communication introducing an open-source C-V2X simulator." *2019 IEEE 90th Vehicular Technology Conference (VTC2019-Fall)*, pp 1–5.
2. R. Weber, J. Misener and V. Park, (2019). "C-V2X - A Communication Technology for Cooperative, Connected and Automated Mobility," *Mobile Communication - Technologies and Applications; 24. ITG-Symposium*, pp. 1-6, Osnabrueck, Germany.

## APPENDIX B. CAVE-IN-A-BOX WITH C-V2X RADIO AND CAVERS INTEGRATION

This appendix highlights integration plans and specifics in developing a CAVE-in-a-box with C-V2X wireless standard. CAVE-in-a-box was initially designed with DSRC wireless systems, however with changing requirements where C-V2X is being considered, this appendix is added to help with the transition.

### SYSTEM DESIGN



Source: FHWA.

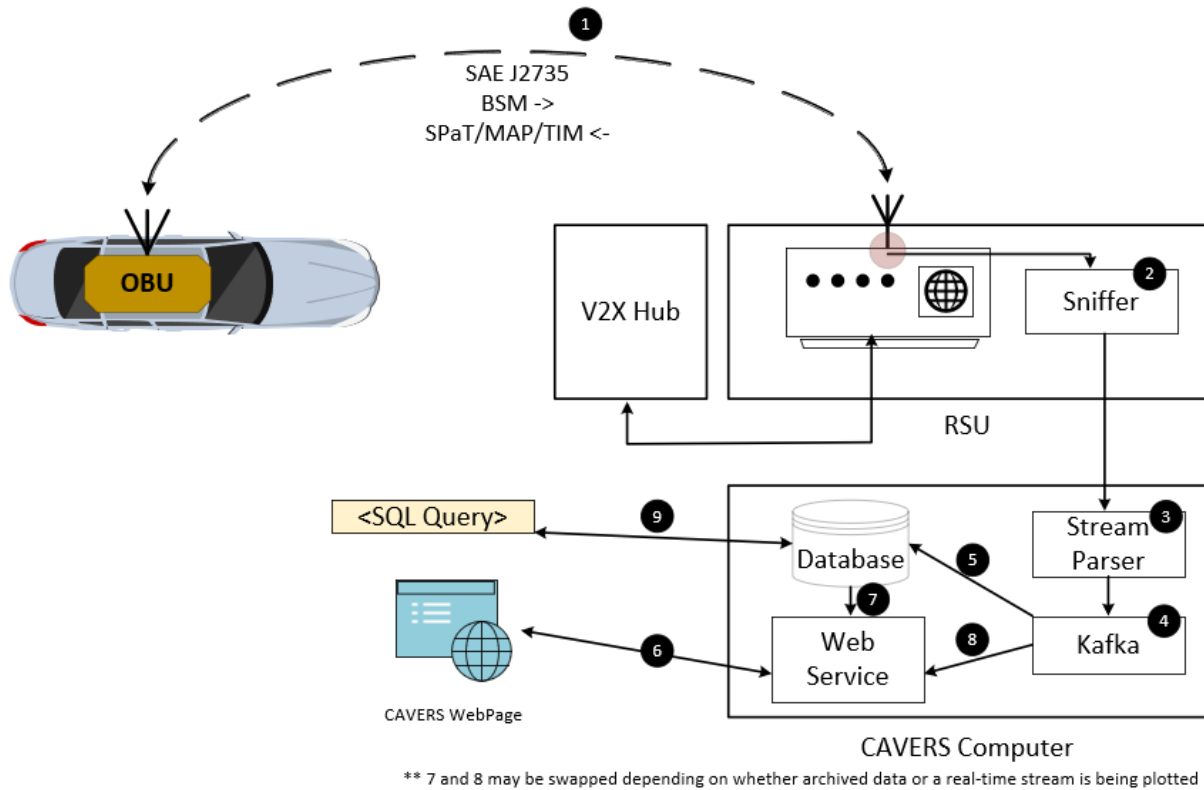
**Figure 322. Diagram. Infrastructure kit integrated connection diagram with C-V2X and CAVERS.**

As seen in figure 32, one of the two changes that occurs is the swapping of the existing DSRC RSU with a C-V2X RSU. Once the RSUs are swapped, the previous RSU IP address must be assigned to the replacement. With this configuration, the system functions as it did previously, but with a different radio component. The second change is the addition of a computer running CAVERS.

### CAVERS

CAVERS is a visualization tool that supports SAE J2735 messages and allows for live monitoring with minimal delay over a network. Messages can be incorporated at any time and can be archived for further analysis and research. This software and V2X Hub may be installed

on the same small-form factor computer meeting the required minimum specifications on its GitHub page: <https://github.com/usdot-fhwa-stol/cav-education/tree/develop>.



Source: FHWA.

**Figure 33. Diagram. CAVERS data flow diagram.**

This CAVERS diagram shows the data flow and interaction between components. The messages are being exchanged between a vehicle and infrastructure. A message sniffer that is part of CAVERS runs at the wireless network interface and captures live messages. These messages are then processed by the stream parser and fed to the CAVERS core software that handles further steps. The stream parser then publishes the messages to the Kafka message broker, which re-publishes the messages to the web server and database. The end-user application, which is a web page for interaction with CAVERS, can access the messages live or through the database.

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