Connected Vehicle Application Development

Final Report

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DISCLAIMER STATEMENT

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List of Abbreviations

Acronym	**Definition**
API	Application Programming Interface
AV	Automated Vehicle
BSM	Basic Safety Message
CAV	Connected and Automated Vehicle
CI	Connected Intersection
CTSCP	Caltrans Traffic Signal Control Program
CV	Connected Vehicle
C-V2X	Cellular Vehicle-to-Everything
DSRC	Dedicated Short Range Communications
EAD	Eco-Approach and Departure
ECR	El Camino Real
FCC	Federal Communications Commission
FSP	Freight Signal Priority
GPS	Global Positioning System
GTFS	General Transit Feed Specification
HMI	Human Machine Interface
I2N	Infrastructure-to-Network
ITS	Intelligent Transportation System
MMITSS	Multi-Modal Intelligent Traffic Signal System
NTCIP	National Transportation Communications for ITS Protocol
OBU	On-Board Unit
PoE	Power-over-Ethernet
PSM	Personal Safety Message
RSM	Road Safety Message
RSP	Roadside Processor
RSU	Roadside Unit
RTCM	Radio Technical Commission for Maritime Services
SCMS	Security Credential Management System
SNMP	Simple Network Management Protocol
SPaT	Signal Phase and Timing
SRM	Signal Request Message
TMC	Transportation Management Center
TOC	Transit Operations Center
TSP	Transit Signal Priority
V2I	Vehicle-to-Infrastructure
V2N	Vehicle-to-Network
V2P	Vehicle-to-Pedestrian
V2V	Vehicle-to-Vehicle
VSP	Vehicle-Side Processor
VTA	Santa Clara Valley Transportation Authority

Acknowledgements

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1 Introduction

Connected Vehicle (CV) communication technology (i.e., Vehicle-to-Everything, V2X) enables vehicles to "talk" to other vehicles on the road (Vehicle-to-Vehicle, V2V), roadside infrastructure (Vehicle-to-Infrastructure, V2I), vulnerable road users (Vehicle-to-Pedestrian, V2P), and the "cloud" (vehicle-to-network, V2N).

The V2X connectivity will provide more precise knowledge of the traffic situation across the entire road network and vehicle awareness of surroundings, which in turn will help to:

- Reduce accidents by providing drivers with warning about potential danger at intersections and/or aiding automated driving.
- Ease traffic congestion through real-time optimization of traffic flow and platooning; and thereby cut fuel consumption and reduce emissions.

V2X allows a shift of focus from helping people survive crashes to preventing crashes from happening in the first place. According to the National Highway Traffic Safety Administration (NHTSA), up to 80 percent of non-impaired crashes may be prevented by V2X, which, it is hoped, may save a significant number of lives, and may prevent millions of crash-related injuries each year. USDOT estimates V21 applications have the potential to reduce travel time by up to 27 percent on signalized arterial and 42 percent on freeway and yield up to 22 percent of fuel saving and 11 percent reduction in emissions[1].

In the past decade, the USDOT has been sponsoring research to develop more than three dozen CV application concepts, spanned in seven categories including V2I Safety, V2V Safety, Agency Data, Environment, Road Weather, Mobility, and Smart Roadside.

California has been the national leader in the development of connected vehicle, Automated Vehicle (AV), and their combination as Connected and Automated Vehicle (CAV) technologies. In 2005, the California Department of Transportation (Caltrans) partnered with the Metropolitan Transportation Commission (MTC) and the California PATH Program (PATH) to create the nation's first Connected Vehicle Test Bed for facilitating the development and testing of CV applications on public roads. The Test Bed spans 11 consecutive signalized intersections along a two-mile stretch of El Camino Real (ECR, State Route 82) in Palo Alto, California.

Caltrans has been sponsoring research to enhance the capability of the ECR Test Bed and to implement and demonstrate CV applications that can benefit the traveler, the environment, and the economy of California.

Under Task Order 65A0596 – Maintenance, Operations and Enhancement of Dedicated Short-Range Communications (DSRC) Communications Infrastructure, the ECR Test Bed has been upgraded to fully complaint with the national Connected Vehicle Standards, including SAE J2735,

[1] USDOT. Connected Vehicle Benefits. https://www.its.dot.gov/factsheets/pdf/ConnectedVehicleBenefits.pdf.

SAE J2945/1, and IEEE 1609 family of Standard[2]. PATH keeps the Test Bed fully operational and provides technical support to new users.

Under Task Order 65A0601 – One California Deployment Support, PATH has deployed Multi-Modal Intelligent Traffic Signal System (MMITSS) as the core CV-based traffic control applications, and deployed broadcast of Radio Technical Commission for Maritime Services (RTCM) Corrections messages for improving the accuracy and reliability of vehicle positioning.

This project is an extension of Task Order 65A0601. The goals of this project are:

1) To expand the California CV Test Bed to meet the requirements of the National Connected Vehicle Signal and Phase Timing (SPaT) Deployment Challenge (i.e., SPaT broadcasts in approximately 20 signalized intersections in each of the 50 states by January 2020[3]).
2) To develop, implement, and field test a set of connected vehicle applications to establish technological foundations for California CV deployment.
3) To support the deployment of CV in California.

This report contains the work conducted under this project. The rest of this document consists of the following sections and contents:

- Section 2 – Test Bed Expansion.

  Describes the two phases of the ECR test bed expansion – adding five DSRC intersections in phase one expansion and adding fifteen Cellular V2X (C-V2X) intersections in phase two expansion, and installation of NoTraffic[4] sensors at four test bed intersections.
- Section 3 – Development of Connected Vehicle Applications.

  Describes CV applications developed and tested under this project.
- Section 4 – Field Test and Demonstration of CV Applications in the ECR Test Bed.
  Describes conducted field test and demonstration of developed CV applications in the ECR test bed.
- Section 5 – Conclusions and Recommendations

2 Test Bed Expansion

Test bed expansion consists of two phases. In phase one expansion, five (5) DSRC intersections were added to the existing eleven (11) operational DSRC intersections between Stanford Ave @ ECR and W Charleston Rd @ ECR. The sixteen (16) DSRC intersections started operations in November 2019. In phase two expansion, fifteen (15) additional intersections were equipped

[2] Connected Vehicle Standards. https://www.its.dot.gov/factsheets/pdf/ITSJPO Connected Vehicle Standards.pdf.
[3] SPaT Challenge Overview. https://transportationops.org/spatchallenge.
[4] NoTraffic Inc. https://notraffic.tech.

with a C-V2X RSU, completed by December 2021. These 15 C-V2X intersections are not operational yet, pending for Federal Communications Commission (FCC) experimental licenses.

2.1 Phase One Expansion

To meet the requirement of SPaT Challenge[3], USDOT provided Caltrans with six (6) DSRC RSUs for expanding the ECR test bed. Figure 1 illustrates the 6 expansion DSRC intersections (red pins) and 11 existing DSRC intersections (green pins).

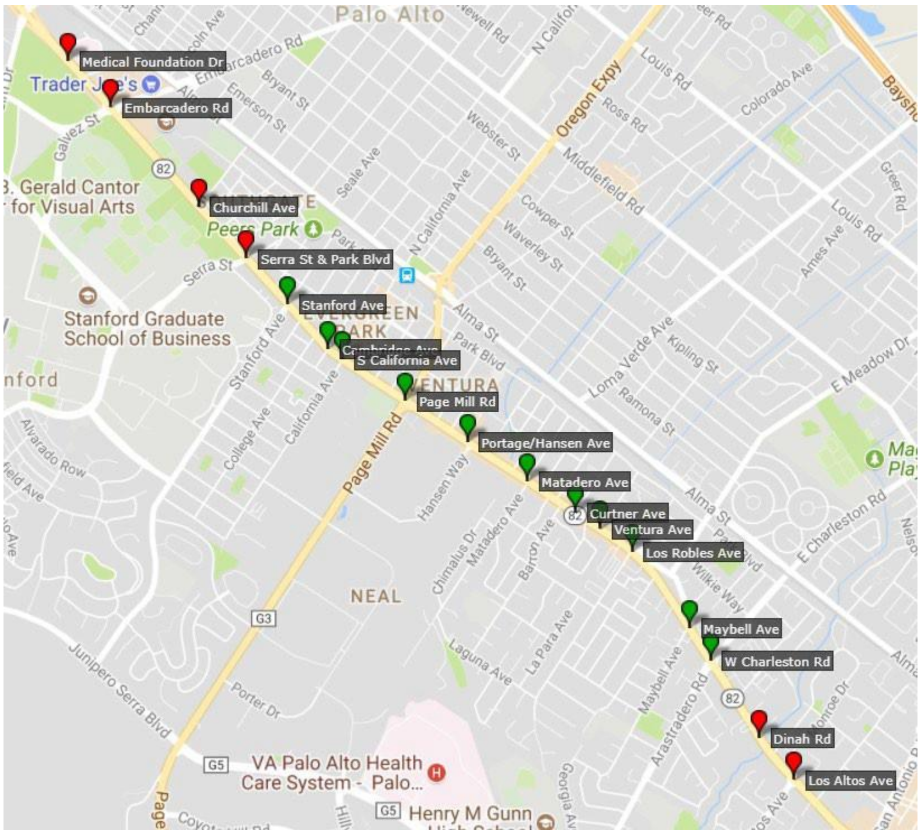

Figure 1 ECR Test Bed Phase One Expansion

The six planned expansion intersections consist of four intersections in the north of the existing DSRC intersections, namely Medical Foundation Dr @ ECR, Embarcadero Rd @ ECR, Churchill Ave @ ECR, and Serra St / Park Blvd @ ECR, and two intersections in the south of the existing DSRC intersections, namely Dinah's Ct @ ECR and Los Altos Ave @ ECR. When conducting site survey before the RSU installation, it was found that the intersection of Los Altos Ave @ ECR has a field master traffic signal controller which could not provide enough serial ports to connect with a roadside processor (RSP) that hosts the MMITSS applications, therefor, the intersection of Los Altos Ave @ ECR was removed from the phase one expansion and included in the phase two expansion.

PATH completed the phase one expansion design document for installing CV equipment at the selected sites in March 2019. The design document is provided in Appendix E of this document. PATH also completed creating MAP messages for the six expansion sites (see Figure 2). The created MAP message payload is provided in Appendix B of this document.

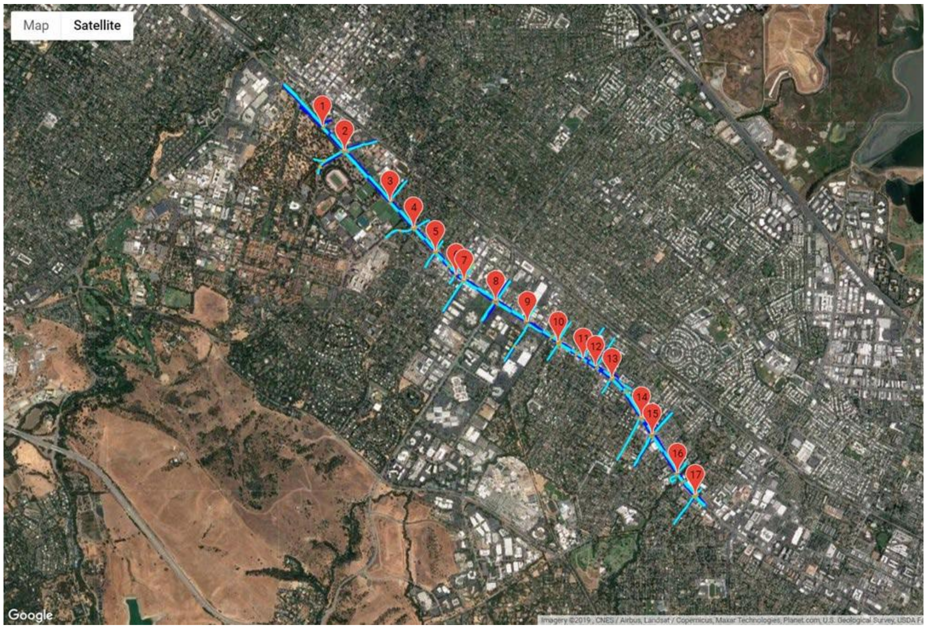

Figure 2 Visualization of California CV Test Bed MAP (Phase One Expansion)

Installing CV equipment at a selected site includes:

- Replacing the existing Type 170E controller with a 2070E controller.
- Updating 2070E's Caltrans Traffic Signal Control Program (CTSCP) firmware with a CV compliant version.
- Installing cabinet CV equipment, including one RSP, one 4G modem/router, one RSU power supply, and one power strip with surge protector in the backpack cabinet.
- Pulling a Power-over-Ethernet (PoE) cable from the traffic cabinet to the signal pole where the RSU is going to be mounted.
- Mounting the RSU on the pole and connecting it with the PoE cable.
- Mounting DSRC radio antennas on the mast arm and connecting with the RSU.
- Configuring the RSU's Application Programming Interfaces (APIs), including
    - The *Store-and-Repeat* API to store the intersection MAP message and broadcast the MAP message on the radio interface at a 100-millisecond interval.
    - The *Immediate Forward* API to broadcast V2X messages received from the RSP (e.g., SPaT message, Signal Status Message – SSM) on the radio interface.
    - The *V2X Message Forward* API to forward V2X messages received on the radio interface (e.g., Basic Safety Message – BSM, Signal Request Message – SRM) to the RSP.

The RSU was mounted on the vertical signal pole rather than directly mounted on the mast arm because the LED lights on RSU's front panel are visible to travelers.

Upon the completion of CV equipment installation, PATH conducted field testing with an DSRC On-Board Unit (OBU) to verify V2I communications are working properly at the expansion intersections and included the real-time operational status of the expansion intersections into the California CV Test Bed website[5]. The expanded ECR test bed with 16 DSRC intersections started operations in November 2019.

2.2 Phase Two Expansion

Test Bed phase two expansion added fifteen C-V2X intersections in the south of the ECR test bed with sixteen operational DSRC intersections. Figure 3 illustrates locations of the expansion C-V2X intersections (blue pins) and the existing operational DSRC intersections (green pins).

Figure 3 ECR Test Bed Phase Two Expansion

2.2.1 Installation Design

PATH conducted site survey and completed the phase two expansion design document for installing CV equipment at the selected sites in Dember 2019. Phase two expansion design document is provided in Appendix C of this document.

[5] California Connected Vehicle Test Bed Website. https://caconnectedvehicletestbed.org.

2.2.2 MAP Creation

PATH completed creating MAP messages for the fifteen expansion sites in December 2019 (see Figure 4). The created MAP message payload is provided in Appendix D of this document.

Figure 4 Visualization of California CV Test Bed MAP (Phase Two Expansion)

2.2.3 Lab Testing

On December 12, 2019, FCC published news release – FCC Seeks to Promote Innovation in the 5.9 GHz Band[6]. Due to uncertainties on the V2X communications technology to be deployed in the ECR test bed, the Caltrans contract manager notified PATH to postpone the purchase and installation of RSU in the fifteen expansion sites until FCC to provide a clear instruction.

On November 20, 2020, FCC released *FCC Modernizes 5.9 GHz Band to Improve Wi-Fi and Automotive Safety*[7], which divides the 5.9 GHz band into two sub-bands – the lower 45 MHz of the 5.9 GHz band for unlicensed operations and the upper 30 MHz for safety-related Intelligent Transportation System (ITS) – and requires DSRC-based operations must transition to C-V2X technology.

With a clear FCC instruction, the Caltrans contract manager and PATH contacted multiple C-V2X RSU vendors requiring them to provide PATH with a sample unit to test in the PATH CAV lab before purchasing. One vendor provided PATH with a sample unit. PATH conducted lab testing

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[6] FCC Seeks to Promote Innovation in the 5.9 GHz Band. https://www.fcc.gov/document/fcc-seeks-promote-innovation-59-ghz-band.

[7] FCC. Use of the 5.850-5.925 GHz Band. https://www.fcc.gov/document/fcc-modernizes-59-ghz-band-improve-wi-fi-and-automotive-safety-0.

to ensure the existing MMITSS software can communicate with the sample unit via the three RSU APIs, namely, the *Store-and-Repeat* API, the *Immediate Forward* API, and the *V2X Message Forward* API. Upon successful lab testing, PATH purchased C-V2X RSUs from this vendor for phase two expansion.

2.2.4 Pre-Installation Training

A pre-installation training session was held in Caltrans District 4 (D4) Maintenance Yard in September 2021. Caltrans contract manager, D4 traffic engineers, and D4 maintenance crew participated in the training session. PATH prepared training materials and demonstrated step-by-step RSU installation procedures. D4 maintenance crew members practiced use of installation tools and materials.

2.2.5 C-V2X RSU Installation

Installation of fifteen C-V2X RSUs were performance in October to December 2021. Five D4 maintenance crew members – Alex Ayala, Antonio Lopez, Daniel Bui, Emanuel Hernandez, and Jared Pulido – participated in the C-V2X RSU installation (see Figure 5 and Figure 6).

Figure 5 District 4 Maintenance Crew Members
(From left to right: Daniel Bu, Alex Ayala, Antonio Lopez, and Jared Pulido)

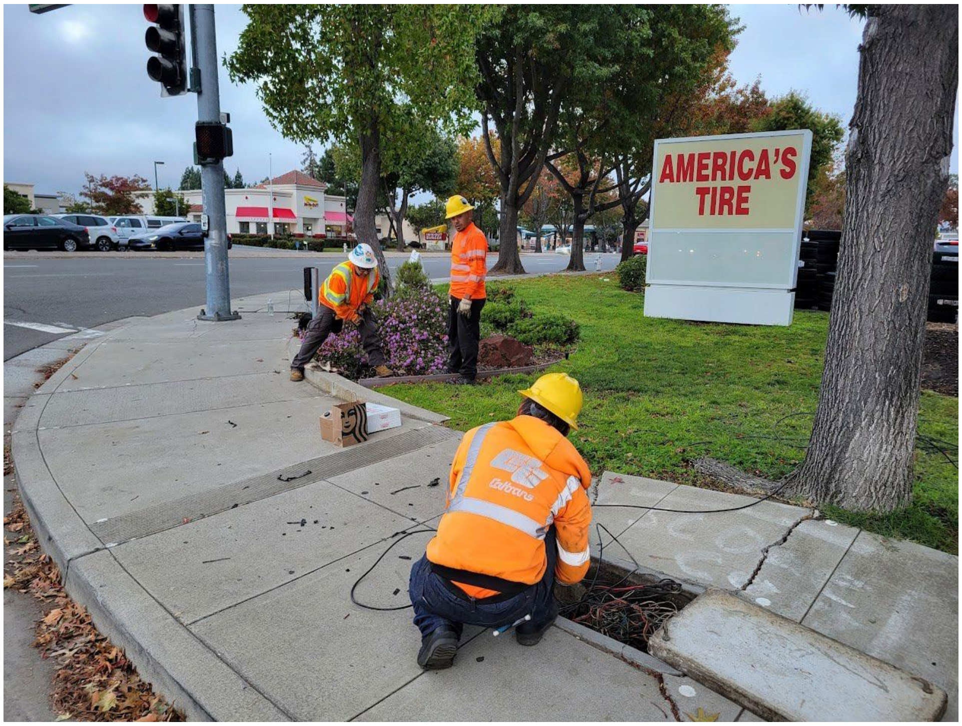

Figure 6 Pulling PoE Cable through the Conduit
(From left to right: Jared Pulido, Emanuel Hernandez, and Daniel Bu)

Figure 7 Mounting the RSU on the Mast Arm
(From left to right: Daniel Bu and Antonio Lopez)

Figure 8 shows the C-V2X RSU installed at the intersection of San Antonio Rd @ ECR.

Figure 8 C-V2X RSU Installed at San Antonio Rd @ ECR

Figure 9 illustrates the CV equipment installed inside the backpack cabinet.

Figure 9 CV Equipment inside the Backpack Cabinet

2.3 Install of NoTraffic Sensor at Four Test Bed Intersections

It was planned to install Smart Microwave Sensors (SMS) at three test bed intersections under this project. SMS is a radar sensor which is not able to provide target classification. NoTraffic sensor[4] integrates radar sensor and image sensor in the sensor unit and can provide Artificial Intelligence (AI) powered detection and classification of multi-modal road users, including vehicle, pedestrian, and cyclist. In July to September 2019, PATH worked with NoTraffic Inc on installing NoTraffic sensors at four test-bed intersections, namely, Medical Foundation Dr @ ECR, Embarcadero Rd @ ECR, Churchill Ave @ ECR, and Serra St / Park Blvd @ ECR.

NoTraffic sensor installation was completed in November 2020. D4 Maintenance crew performed the installation work. NoTraffic and PATH provided technical support for the sensor installation. A total of 16 NoTraffic sensors have been installed at the four test-bed intersection, with one sensor covering one leg of the intersection:

- Medical Foundation Dr @ ECR: T-intersection with three NoTraffic sensors installed.
- Embarcadero Rd @ ECR: Four-leg intersection with four NoTraffic sensors installed.
- Churchill Ave @ ECR: T-intersection with three NoTraffic sensors installed.
- Serra St / Park Blvd @ ECR: four-leg intersection with four NoTraffic sensors installed.

3 Development of Connected Vehicle Applications

3.1 Proposed CV Applications and Reconsiderations

Three CV applications to be developed are included in this contract:

- To add a National Transportation Communications for ITS Protocol (NTCIP) Interface to Model 2070 Controller with a Separate Processor.
- To enable broadcast of a Dynamic Vehicle Location on MAP (DVLoM) V2I Message.
- To develop a CV-Based Transit Eco-Approach and Departure (EAD) Application.

3.1.1 Add an NTCIP Interface to Model 2070 Controller with a Separate Processor

The objective of this application is to implement an NTCIP adapter on a separate processor – either the RSP or an additional processor plugged into the – to improve deployability of California CV applications (see Figure 10).

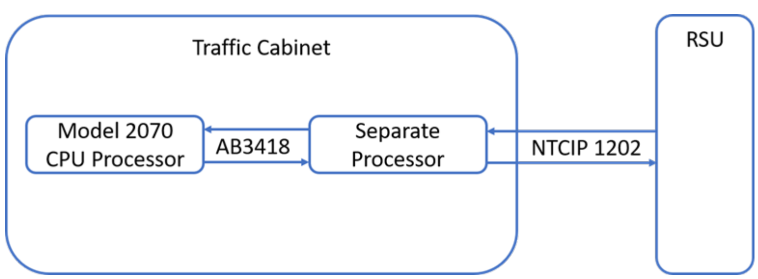

Figure 10 Message Flow with Added NTCIP Interface to Modal 2070 Controller

NTCIP 1202 v03A was published in May 2019. Due to the following considerations, the development of an NTCIP adapter is on hold, waiting for further NTCIP standards development:

- NTCIP 1202 v03A is not a replacement of the existing RSU APIs (i.e., the *Store-and-Repeat*, *Immediate Forward*, and *V2X Message Forward* APIs).
- NTCIP 1202 v03A defines SPaT and MAP data objects and communication protocols to transmit SPaT data and MAP data to an RSU. Other broadcast V2X messages, such as SSM and RTCM, still need to use the *Immediate Forward* API.
- NTCIP 1202 v03A does not specify how to forward BSM, Personal Safety Message (PSM), and SRM messages received from connected vehicles to an NTCIP-compliant controller and how the controller utilizes these forward messages.
- NTCIP 1202 v03A does not specify a SSM data object which is required to support the applications of Transit Signal Priority (TSP) and Freight Signal Priority (FSP). NTCIP 1211 v2 defines data objects and communications protocols to exchange data between an NTCIP-compliant controller and an RSU for signal prioritization. However, NTCIP 1211 v2 was published in September 2014, a relative older standard compared to the SAE J2735 standard[8] which is published in November 2022 in supporting TSP and FSP.
- Potential SPaT communication latency issues. NTCIP 1202 v03A uses the Simple Network Management Protocol (SNMP) version 3 for data exchange. SNMP is a widely used protocol in network monitoring and it is not designed for real-time operations which will likely increase SPaT communication latency. It is expected the SNMPv3 will be updated in the future in response to the real-time need for transmitting the SPaT messages.

3.1.2 Enable broadcast of a Dynamic Vehicle Location on MAP V2I Message

The objective of this application is to utilize infrastructure-based traffic detection and classification data to improve connected vehicles' awareness of surroundings. The proposed Dynamic Vehicle Location on MAP (DVLoM) V2I message consists of data elements of timestamp, vehicle ID, vehicle classification, intersection ID, approach ID, lane ID, distance to the stop-line, speed, and heading. Due to the considerations of potential broader use of infrastructure-based data on the vehicle side, development of this application switched to broadcast BSM (for vehicle) and PSM (for pedestrian and cyclist) messages that are generated from the infrastructure-based traffic detection and classification data.

3.1.3 Develop a CV-based Transit Eco-Approach and Departure Application

The objective of this application is to integrate Transit Eco-Approach and Departure (EAD) with TSP so that EAD speed advisories are consistent with obtained TSP treatments. After discussions with the Santa Clara Valley Transportation Authority (VTA), development of this application switched to develop a cloud-based TSP application due to the following considerations:

[8] SAE International. V2X Communications Message Set Dictionary J2735_202211.

- Bus drivers constantly multitask as they drive passengers to their destination. Adding additional EAD speed advisory information for bus drivers to process in real-time could lead to safety concerns.
- Applications that aim to improve transit efficiency and reliability, such as TSP, should run in the background, without direct interactions with bus drivers.
- Using an OBU for CV-based TSP requires connecting the OBU with transit vehicles on-board computer systems to obtain operational status data, such as schedule adherence, headway adherence, and passenger counts. This integration is a challenge for continuing operations and maintenance.
- VTA already equipped the entire bus fleet with mobile backhaul to transmit second-by-second bus operational status data to VTA Transit Operations Center (TOC). A cloud-based TSP system that utilizes the data already available in the TOC is much easier and more cost-effective for large-scale deployment.

3.2 Developed CV Applications

3.2.1 Host MMITSS Applications on a 2070-1C CPU Processor

PATH obtained the toolchain for programming software running on the 2070-1C CPU card from Caltrans Headquarters Traffic Operations in May 2020. PATH successfully compiled MMITSS applications using the toolchain and conducted lab testing to verify the communications between the MMITSS 2070-1C processor, the CTSCP 2070-1E processor, the RSU, and the OBU.

Figure 11 Testing of CV Applications running on a 2070-1C Processor

Settings of the lab testing is illustrated in Figure 11. CV equipment used in this lab testing includes:

- A 2070E controller with a 2070-1E CPU processor which runs the CTSCP software
- A 2070LX controller with a 2070-1C CPU processor which hosts MMITSS applications (the same applications running on the RSP in the ECR CV Test Bed)
- A DSRC RSU
- A C-V2X RSU
- A DSRC OBU

CV applications that have been successfully tested in the lab testing include:

- SPaT broadcasts:
  - The MMITSS processor receives SPaT data from the CTSCP processor, encodes SAE J2735 SPaT message, and sends the message to the RSU via the *Immediate Forward* API.
  - The RSU transmits the received SPaT messages on its radio interface.
  - Confirming the OBU receives the SPaT messages on its radio interface.

- MAP broadcast:
    - The RSU broadcasts MAP messages on its radio interface, via the *Store-and-Repeat* settings.
    - Confirming the OBU receives the MAP messages on its radio interface.
- CV-based actuation:
    - The MMITSS processor sends actuation commands to the CTSCP processor to place a service call on a vehicular phase, a pedestrian phase, or a bike phase.
    - Confirming the CTSCP processor grants the service calls.
    - The MMITSS processor sends actuation commands to the CTSCP processor to hold the active vehicular/bike phase in green (i.e., green extension).
    - Confirming the CTSCP processor extends the green.
    - In the future, triggers for the MMITSS processor to generate actuation commands will be based on BSM and PSM messages received from connected traveler.
- CV-based TSP:
    - The OBU broadcast SRM messages to request signal priority.
    - The RSU forwards the received SRMs to the MMITSS processor.
    - The MMITSS processor sends a priority call to the CTSCP processor, generates SSM message and sends SSM to the RSU.
    - RSU broadcasts SSM on its radio interface.
    - Confirming the CTSCP processor grants the signal priority.
    - Confirming the OBU receives SSMs on its radio interface.

Figure 12 illustrates communications links between a 2070LX+ controller with dual processors, an RSU, and Caltrans Transportation Management Center (TMC). One of the dual processors runs CTSCP and the other hosts MMITSS. In this scenario, there is no need for a standalone RSP.

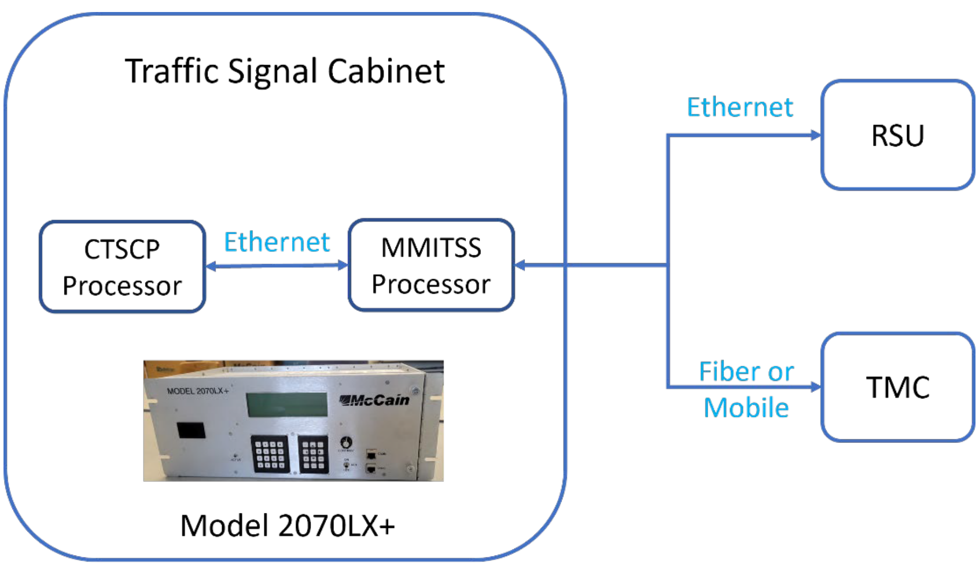

Figure 12 2070LX+ Controller with Dual Processors

3.2.2 Broadcasts BSM and PSM messages generated from NoTraffic Sensor Data

As illustrated in Figure 13, the NoTraffic cabinet processor outputs BSMs for detected vehicles and PSMs for detected pedestrians or cyclists to the RSP. In this application, the RSP forwards the received BSM and PSM messages to the RSU via the *Immediate Forward* API and the RSU transmits the messages on its radio interface to OBUs.

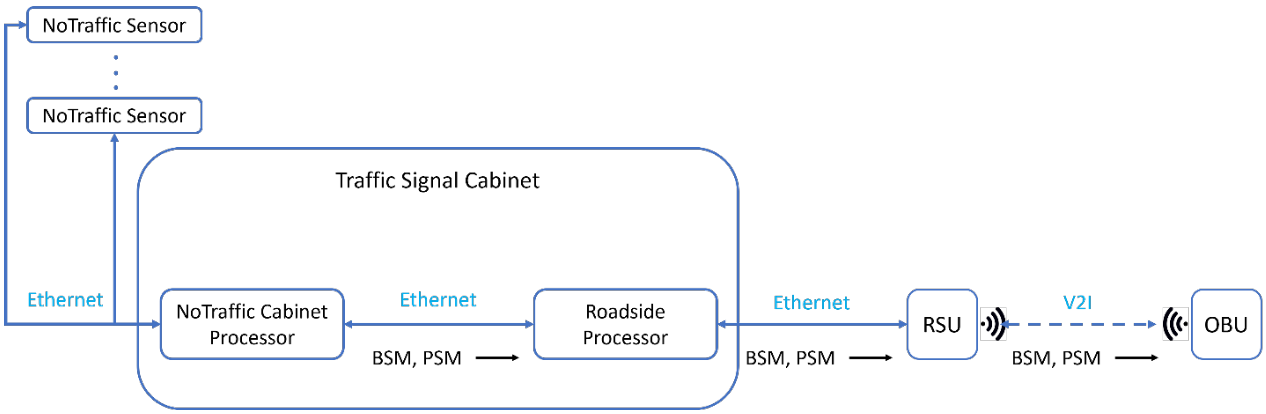

Figure 13 Broadcast BSM and PSM Generated from NoTraffic Sensor Data

PATH tested this application at the intersection of Embarcadero Rd @ ECR, using an OBU to verify receiving BSM and PSM messages on its radio interface. This application was turned off after field testing since the detection accuracy and classification reliability of NoTraffic data need to be evaluated against ground truth before turning the application on.

3.2.3 A Cloud-based V2X Communications System

To support cloud-based CV applications, PATH developed a cloud-based V2X communications system (see Figure 14).

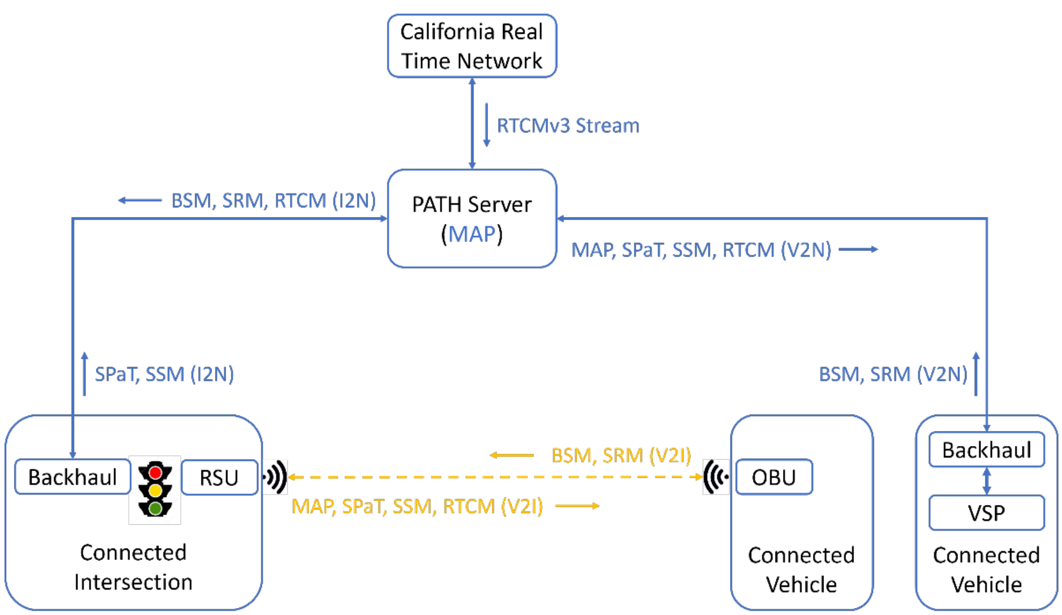

Figure 14 Direct V2I and Cloud-based V2X Communications System

Each test bed intersection is equipped with an RSU for direct communications with OBUs and a 4G modem/router for backhaul. Each intersection sends SPaT and SSM messages that are broadcasted by the RSU to a server located at PATH Headquarters in Richmond Field Station (RFS), using the backhaul (i.e., I2N). The PATH server stores the MAP of all connected intersections. For a connected vehicle equipped with backhaul, a vehicle-side processor (VSP) generates BSM and SRM messages and sends the messages to the PATH server via the backhaul (i.e., V2N). The PATH server processes BSM and SRM messages received from the vehicle, determines the relevant intersections to the vehicle – based on vehicle location and MAPs, forwards MAP, SPaT and SSM messages of the relevant intersections to the vehicle, and forwards BSM and SRM messages to the relevant intersections. Figure 14 also includes a communications link between the PATH server and the California Real-time Network (CRTN) for obtaining differential correction data streams. Interested readers are referred to the project final report for Contract No 65A0775[9].

Under Contract No 65A0704, PATH compared SPaT communication latency between DSRC and 4G long-term evolution (LTE). Although as expected, SPaT communication latency over 4G LTE is higher than that over DSRC, SPaT communication latency over 4G LTE is within 100 milliseconds for more than 95 percent of the time, which is adequate to support a wide range of cloud-based CV applications. Interested readers are referred to the project final report for Contract No 65A0704[10].

3.2.4 A Virtual Platform for the Development of Cloud-based CV Applications

To best utilize the PATH CAV lab equipment, PATH developed a virtual platform for the development and test of cloud-based CV applications. In this virtual platform, a VSP located in the PATH CAV lab reads Global Positioning System (GPS) trace files that were logged by driving around in the ECR test bed, generates BSM and SRM messages, and sends the messages to the PATH server via backhaul. The PATH server will perform the same processes as if the vehicle is traveling in the ECR test bed. Further, a Human Machine Interface (HMI) – a web-based dashboard that is connected to the VSP – displays information received from the PATH server (e.g., SPaT countdown, lane of travel, allowed maneuvers at the stop-line) and provides visual and auditory warning / alert about upcoming traffic hazards (e.g., lane close ahead, reduced speed ahead).

Figure 15 shows a screenshot of the in-vehicle HMI dashboard, with explanation of displayed information. This virtual platform significantly increases productivity in the development and test of cloud-based CV applications. When conducting testing using this virtual platform, test bed intersections are turned off granting signal priority requested from network (i.e., cloud) to avoid potential impacts to traffic.

[9] California PATH Program. Support Deployment of RTCM Broadcasts. Final Report. December 2022.
[10] California PATH Program. Red-Light Violation Warning over Cellular Network. Final Report. October 2022.

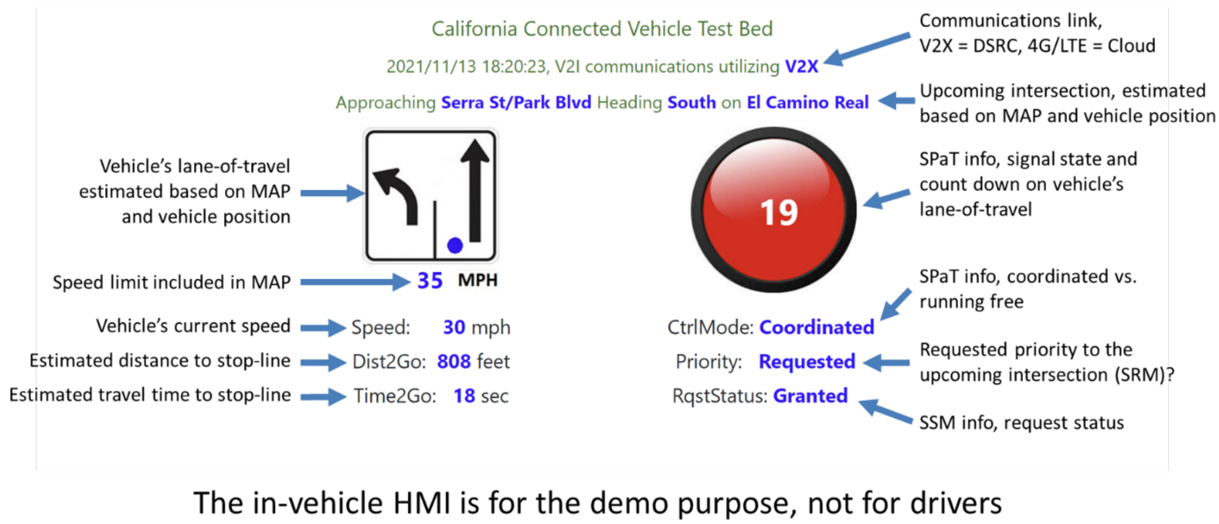

Figure 15 In-Vehicle HMI Dashboard

3.2.5 Cloud-based TSP Application

PATH proposed a cloud-based TSP system architecture to VTA as illustrated in Figure 16. This system utilizes the existing communications links between a VTA bus and the VTA POC and between a ECR test bed intersection and the PATH server, and the existing VTA public general transit (GTFS) and GTFS real-time data feeds to determine the needs for signal priority and to transmits the needs (as SRM messages) to ECR test bed intersections for granting the priority.

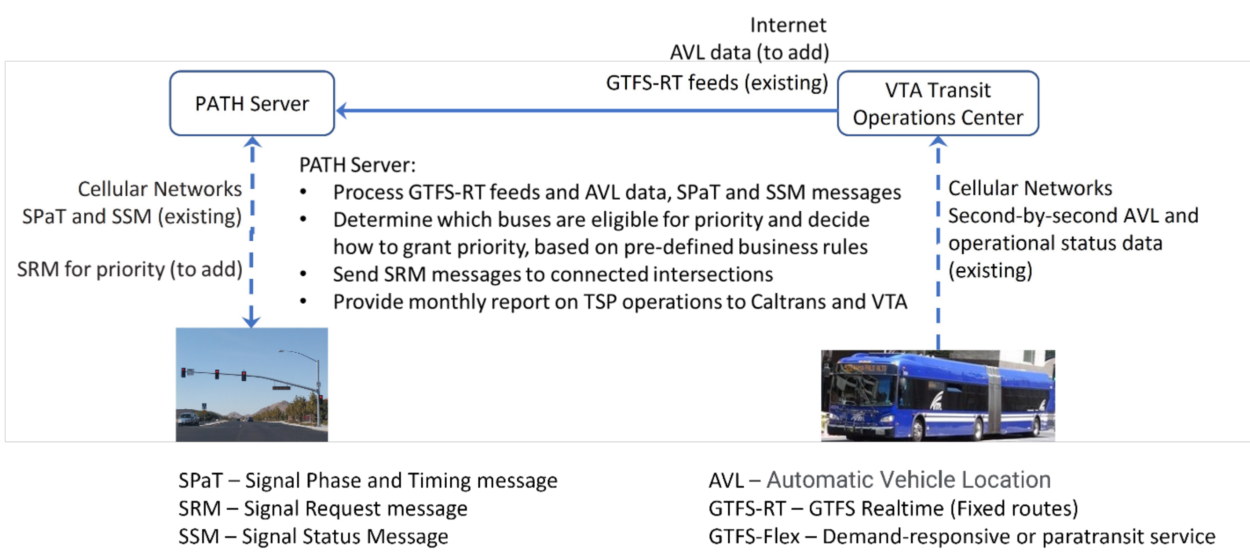

Figure 16 Cloud-based TSP System Architecture

VTA concurred the proposed cloud-based TSP system architecture and expressed their concerns on supporting the field testing and potential wide-range deployment:

- The ECR test bed with 31 intersections accounts for about one-fourth of VTA routes 522 and 22, which are the two major VTA bus routes that travel along ECR. It will be a challenge for VTA buses to continue obtain priority treatments using two approaches: the cloud-based TSP along the ECR test bed and the traditional TSP along the rest of 522 and 22 bus routes.

- Rules to grant TSP should be conditional on transit schedule adherence or headway adherence. Unconditional TSP treatments that VTA buses are obtained along the ECR worse the bus bunching problems, where two or more buses that were scheduled at regular intervals along a common route arrive at the same bus stop simultaneously.

Realizing that adding backhaul to another 34 Caltrans owned ECR intersections and implementing rules for granting TSP based on transit schedule adherence or headway adherence are out of the scope of this project (we do hope these could be done under a separate project or an extension of this project), PATH developed a cloud-based TSP application using the system architecture as illustrated in Figure 14 and focusing on generating SRM messages on the PATH server and sending the SRMs to local controller for priority granting.

3.2.6 A Standalone SPaT Application

For connected intersections that just need to enable SPaT broadcasts and without sending commands to the traffic signal controller, PATH developed a standalone SPaT application in communications with the traffic signal controller and the RSU. User guide of the standalone SPaT application is provided in Appendix E of this document.

3.2.7 Test of RSU Enrollment Tool for Security Certificates

The C-V2X vendor provided an RSU enrollment tool to use experimental security certificates with the vendor partnered Security Credential Management System (SCMS) service provider. RSU enrollment procedures and certificates downloading procedures are the same as that for enrolling with production SCMS service. PATH conducted lab testing of RSU enrolling experimental SCMS service and certificate downloading in March 2021. The lab testing was successful – all RSU transmitted messages, including *store-and-repeat* messages and *immediate forward* messages, were properly signed with security certificates. There was no noticeable message latency by enabling message signing. All signed messages received by the RSU were properly processed and forwarded to the RSP.

Currently, there are very few SCMS service providers. When RSUs and OBUs become widely deployed, there will be coexist of multiple SCMS service providers. Sharing information between SCMS service providers so that a vehicle enrolled with SCMS service provider A can communicate with an RSU enrolled with SCMS service provider B is critical for the interoperability of security certificates.

4 Field Test and Demonstration of CV Applications in the ECR Test Bed

4.1 Demonstration of CV-based TSP to VTA

In the contract, it is proposed to install OBU on five (5) VTA buses to conduct a field operational test of CV-based TSP. VTA has 29 buses for route 522. VTA expressed concern that if conducting a field operational test with five equipped buses, the majority 522 buses will be able to obtain TSP treatments which will impact transit service. The plan is then switched to install OBU on one VTA bus and use that bus to provide a demonstration of CV-based TSP to VTA.

In July 2020, PATH staff and Caltrans contract manager worked with VTA maintenance staff at the VTA North Yard in Mountain View to install an OBU on one VTA 60-foot BRT bus. A successful field demonstration of CV-based TSP using the instrumented VTA BRT bus was conducted on August 5, 2020. CV-based TSP worked well at all the sixteen operational ECR intersections. The CV-based TSP system obtained positive feedback from VTA maintenance staff and the bus driver who participated in the field demonstration.

4.2 Field tests of Developed CV Applications

Field tests of developed CV applications in the ECR test bed were conducted by using a PATH test vehicle. As illustrated in Figure 17, the PATH test vehicle is equipped with an OBU for direct V2I communications, a 4G modem/router for cloud-based communications, a VSP for hosting vehicle-side CV applications, and an HMI device – Android tablet – for displaying V2I communications information and warnings/alerts generated to the driver.

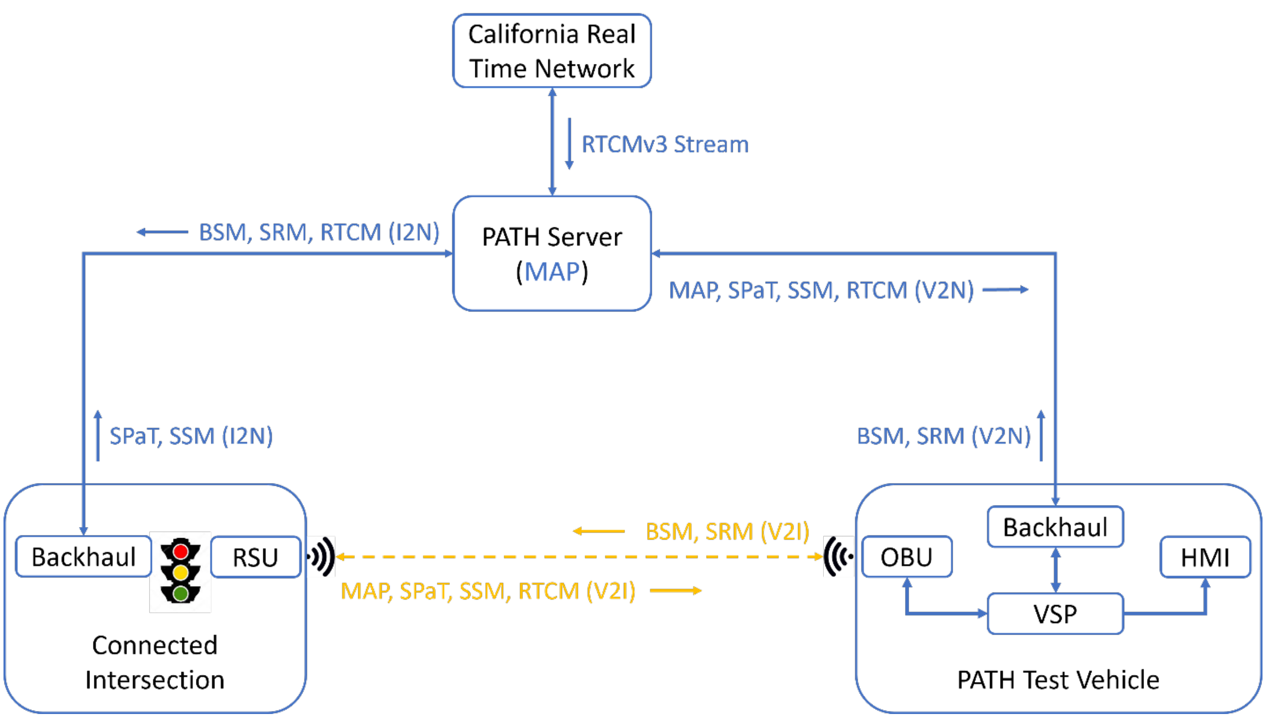

Figure 17 Field Test Setup

The VSP runs two instances of vehicle-side CV applications, with one instance communicating with test bed intersections using direct communications (i.e., DSRC) and the other using cloud-based communications (i.e., 4G LTE). Figure 18 shows a screenshot of side-to-side dashboard displays using the two communications approaches.

Figure 18 Side-to-Side HMI Dashboard with DSRC and 4G LTE

4.2.1 Mid-Block Pedestrian Crosswalk Ahead Warning

Figure 19 shows a screenshot of mid-block pedestrian crosswalk ahead warning.

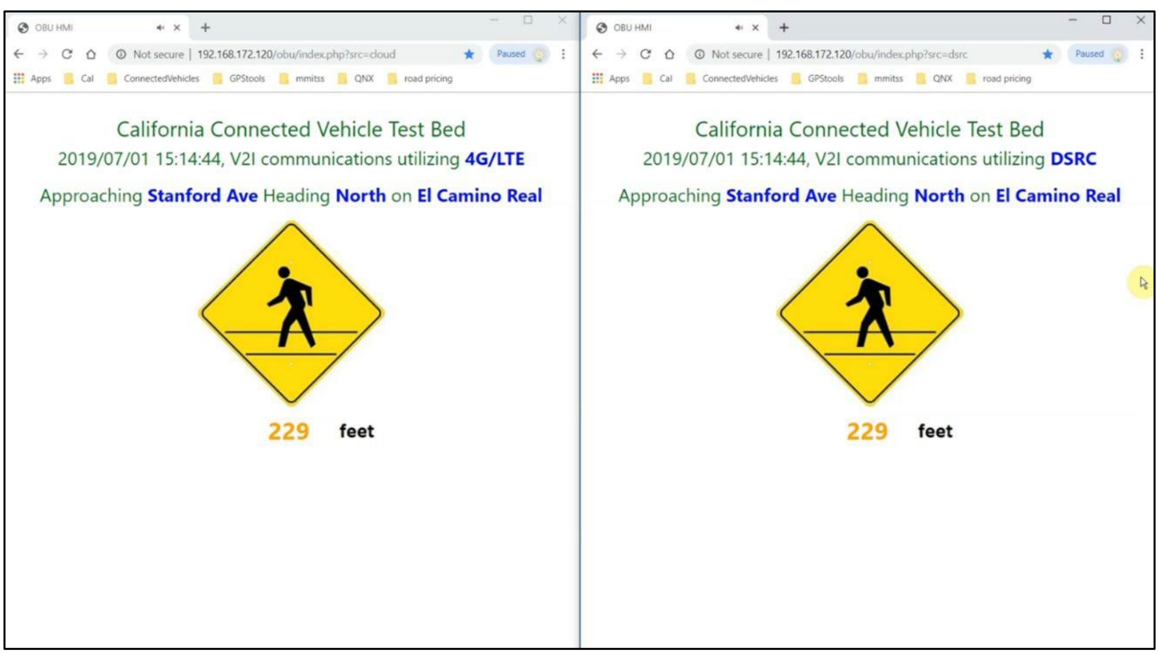

Figure 19 Mid-Block Pedestrian Crosswalk Ahead Warning

This application aims to warn a driver about unsignalized mid-block pedestrian crosswalk ahead. The warning is generated based on distance and estimated travel time to the crosswalk. Both visual and auditory warnings are provided to the driver. In the future when pedestrian presence and/or movement data are available via PSM, this application can generate active warnings to only warn the driver when a pedestrian is walking on the crosswalk.

4.2.2 Lane Closed Ahead Warning

Figure 20 shows a screenshot of lane closed ahead warning. This application aims to warn a driver about lane-closed ahead due to work zone so that the driver is aware that a lane-changing is required. Both visual and auditory warnings are provided to the driver. The application utilizes Road Safety Message (RSM) broadcasted by the RSU to know work-zone configurations (e.g., lane closures and reduced speed zones).

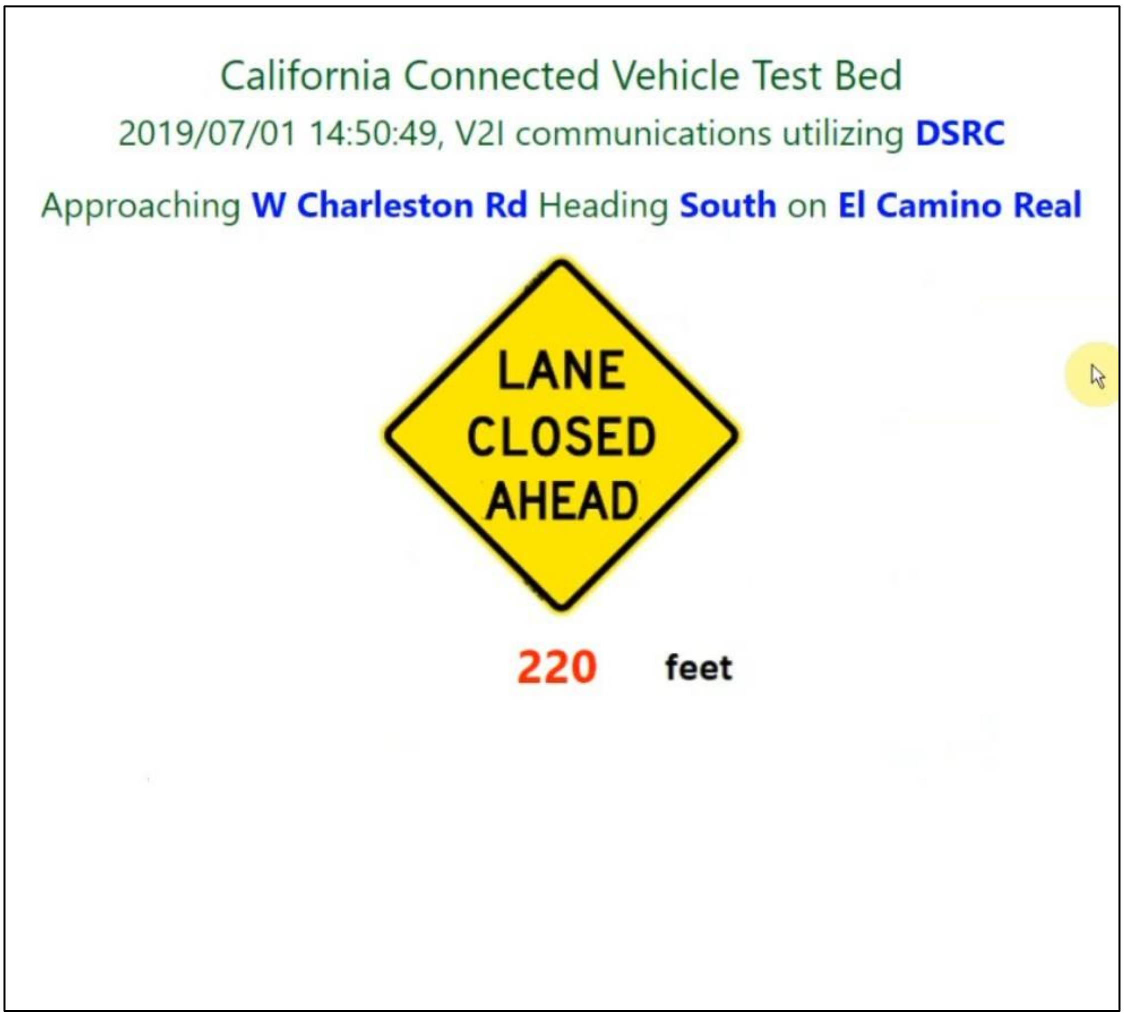

Figure 20 Lane Closed Ahead Warning

4.2.3 Reduced Speed Ahead Warning

Figure 21 shows a screenshot of reduced speed ahead warning. This application aims to warn a driver about reduced speed ahead due to work zone. The application utilizes RSM broadcasted by the RSU to know work-zone configurations (e.g., lane closures and reduced speed zones). Both visual and auditory warnings are provided to the driver.

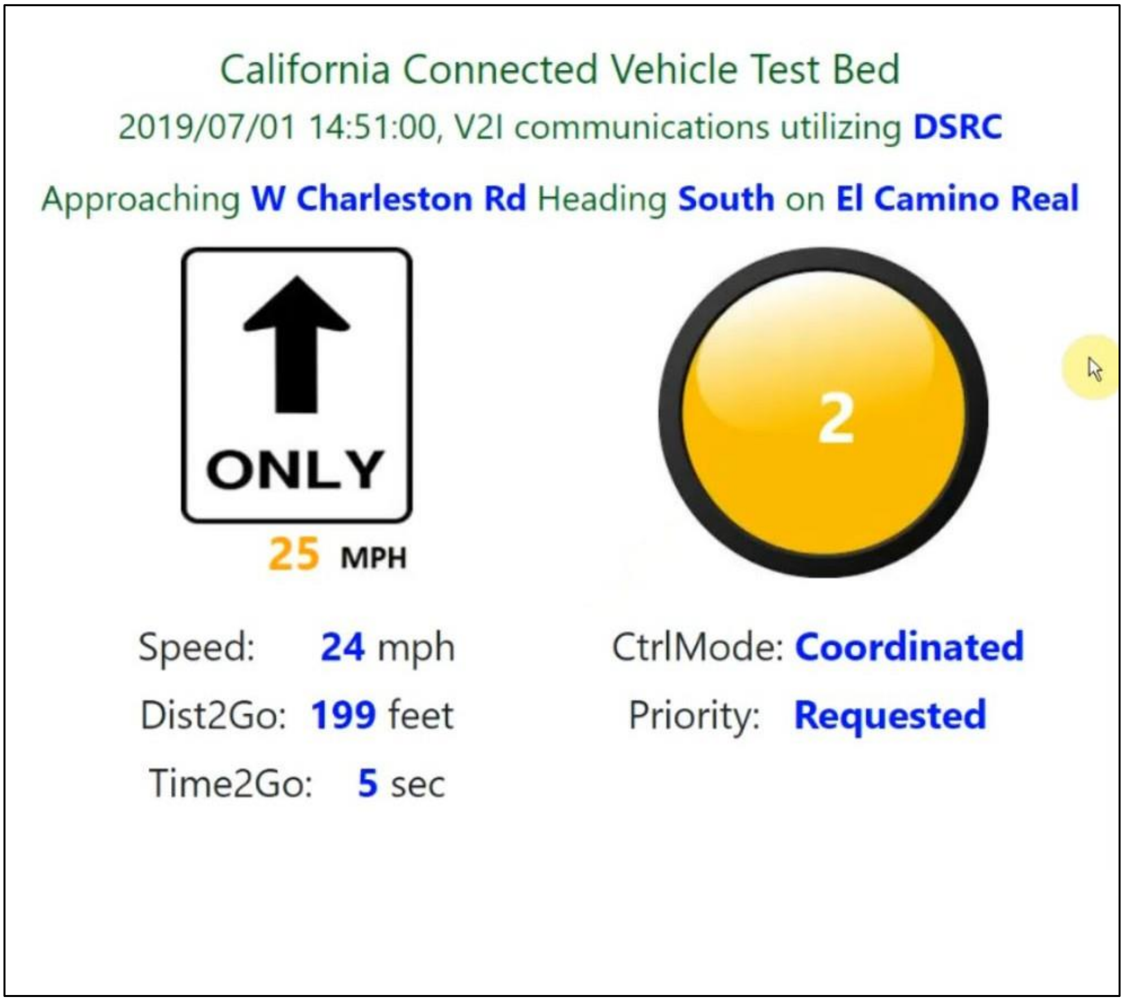

Figure 21 Reduced Speed Ahead Warning

4.2.4 Merge Ahead Warning

Figure 22 shows a screenshot of merge ahead warning. This application aims to warn a driver about lane merging ahead so that the driver can pay attention to the merging maneuver. The warning is generated based on distance and estimated travel time to the merging point (see Figure 23). Both visual and auditory warnings are provided to the driver.

In the future when vehicles are equipped with connectivity – either via OBU or via mobile network – and share movement data via BSM, this application can generate active warnings to only warn the driver when a potential merging hazard is detected.

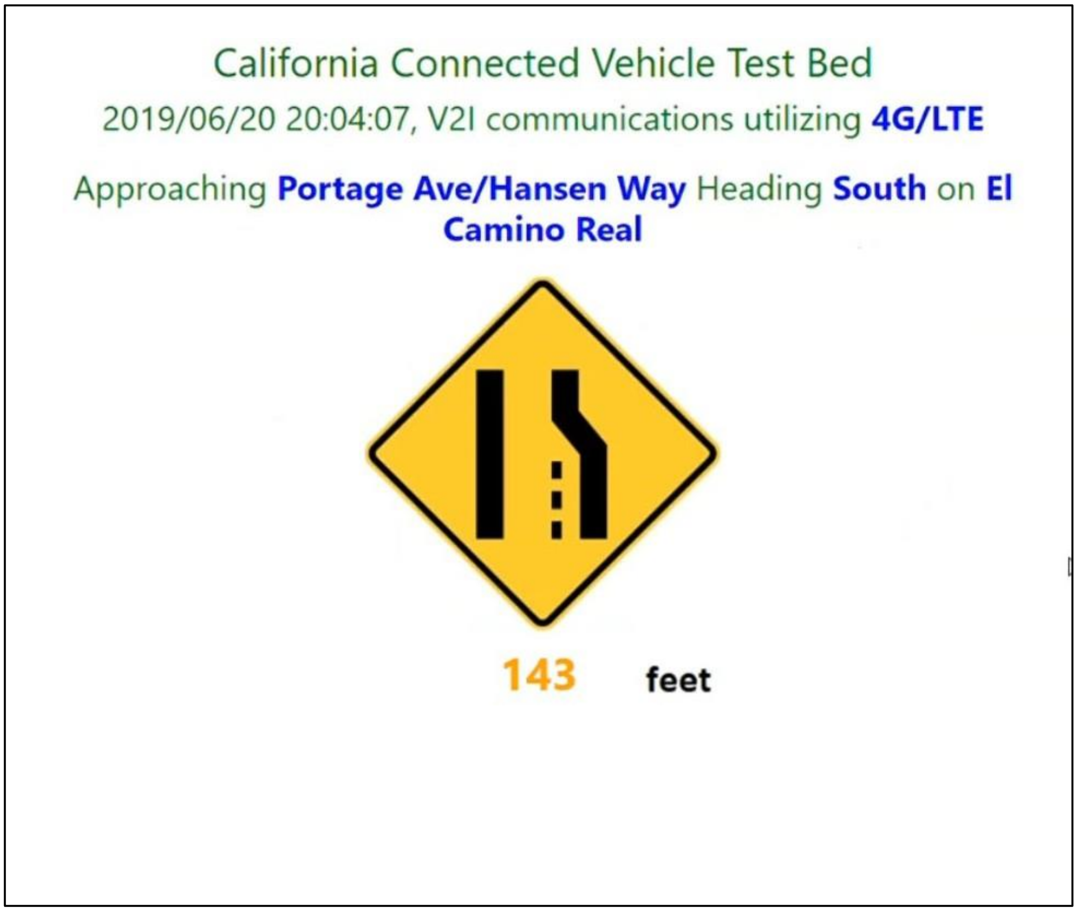

Figure 22 Merge Ahead Warning

Figure 23 Lane-Merging Information Contained in SAE J2735 MAP

4.2.5 Mid-block Left-Turn yield to Opposite Traffic Warning

The application aims to warn a driver to watch out for opposite traffic when making a left-turn movement at an unsignalized intersection or a mid-block left-turn pocket. The warning is generated based on distance and estimated travel time to the turning point (see Figure 24). Only auditory warning is provided to the driver to avoid potential distraction. In the future when vehicles are equipped with connectivity – either via OBU or via mobile network – and share movement data via BSM, this application can generate active warnings to only warn the driver when a potential turning hazard is detected.

Figure 24 Left-Turn vs. Opposite Traffic Conflict

5 Conclusions and Recommendations

5.1 Conclusions

Under this contract, five (5) DSRC intersections have been added to the ECR test bed to form a total of sixteen DSRC intersections in a 3-mile stretch on the ECR. These sixteen DSRC intersections started operations in November 2019 and stopped operations in November 2022 due to FCC's ruling on the use of the 5.9 GHz band[7]. Under Contract No 65A0917, these 16 DSRC RSUs will be replaced with C-V2X RSUs by the end of 2023.

In phase two expansion, fifteen (15) C-V2X RSUs have been added to the ECR test bed to form a total of thirty-one intersections in a 7-mile stretch on the ECR. These C-V2X intersections will be put into operation once FCC experimental licenses are obtained.

A successful field demonstration of CV-based TSP has been provided to VTA in August 2020, using a VTA bus that is instrumented with a DSRC OBU. Further, a set of CV applications, including lane closed ahead warning, reduced speed ahead warning, pedestrian crosswalk ahead warning, lane merge ahead warning, and watching out for opposite traffic warning, have been developed and tested in the ECR test bed, using both direct V2X communications and cloud-based (network) communications. These developments establish technological foundations for California CV deployment.

5.2 Recommendations

5.2.1 Best Use of the ECR Test Bed Facility

The ECR test bed facility supports simultaneous direct V2I communications – between RSU and OBU – and cloud-based (network) V2I communications. This unique setup makes the ECR test bed an idea facility for comparing the performance of CV applications using different V2I communications links, establishing an application map in terms of which V2I communications link supports better which CV applications, and developing guidelines for California CV deployment.

5.2.2 Best Use of the PATH CAV Laboratory Facility

The PATH CAV lab not only has CV equipment such as various traffic signal controllers, RSUs, OBUs, and RSPs but also a virtual platform for the development and testing of CV applications. This unique setup makes the PATH CAV lab an idea facility for testing V2X devices and CV applications from various vendors and developing application specifications to support CV deployment in California.

5.2.3 CV Applications that can be Rapidly Deployed to Improve Safety and Mobility

The following two CV applications are ready to be rapidly deployed:

- Cloud-based Conditional TSP

  Many transit agencies already have mobile backhaul installed on bus fleets to provide high-resolution bus operational status data to transit TOC and made GTFS and GTFS real-time data feeds available to the public as well as Google Transit. The cloud-based TSP application developed and tested under this contract has laid out foundations for the deployment of cloud-based conditional TSP, where requests for priority are granted based on transit needs – to improve schedule adherence or headway adherence. To facilitate this deployment, we recommend having an extension of this contract to:

  - Establish center-to-center communications between the PATH server or D4 TMC and VTA TOC for receiving GTFS real-time feeds, and
  - Develop strategy, business rules, and parameters for conditional priority.

- Cloud-based Bike Signal Priority

  Cloud-based bike signal priority – where when approach a signalized intersection, a cyclist will obtain appropriate bike timing automatically and when traveling inside the intersection conflict area, the intersection will extend the green to allow the cyclist to clear the conflict area safely – and cloud-based TSP have very similar system architecture. To improve the safety of vulnerable road users, we recommend having an extension of this contract to develop a smartphone application as a tool to collect cyclist's movement data to be used as input to the cloud-based bike signal priority.

Appendix A Test Bed Phase One Expansion – Design Document

Design Guidance for Installation of CV Infrastructure Equipment

Six Expansion Intersections at Palo Alto Testbed

California PATH

Version 2.0

March 2019

Appendix B Test Bed Phase One Expansion – MAP Messages

payload ecr-medical-foundation
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Appendix C Test Bed Phase Two Expansion – Design Document

Design Guidance for Installation of CV Infrastructure Equipment

Fifteen Expansion Intersections at El Camino Real Testbed

December 2019

Appendix D Test Bed Phase Two Expansion – MAP Messages

payload ecr-medical-foundation


```
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payload ecr-embarcadero


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payload ecr-churchill


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payload ecr-serra-park


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```

Appendix E SPaT Application User Guide

Connected Vehicle Application Development (CVAD)

Task 3 Development of CV Applications: User Guide for SPaT Application

California PATH Program

12/27/2021

Design Guidance for Installation of CV Infrastructure Equipment

Six Expansion Intersections at Palo Alto Testbed

California PATH

Version 2.0

March 2019

Design Guidelines for Installation of Connected Vehicle Equipment at 6 Signalized Intersections along El Camino Real in Palo Alto

Background

The California Partners for Advanced Transportation Technology (PATH) program of the University of California, Berkeley is assisting Caltrans with the installation of electrical equipment at six (6) signalized intersections along El Camino Real (SR 82) in the City of Palo Alto, California. This work is part of a national effort to build a number of test beds for a Connected Vehicle (CV) environment. Caltrans currently operates CV equipment at eleven (11) signalized intersections along El Camino Real in Palo Alto. With these six additional intersections, the test bed size will be increased to 17 intersections.

Figure 1 shows the locations of existing eleven (11) DSRC-equipped intersections (Green pin) and six (6) expanding intersections (red pin).

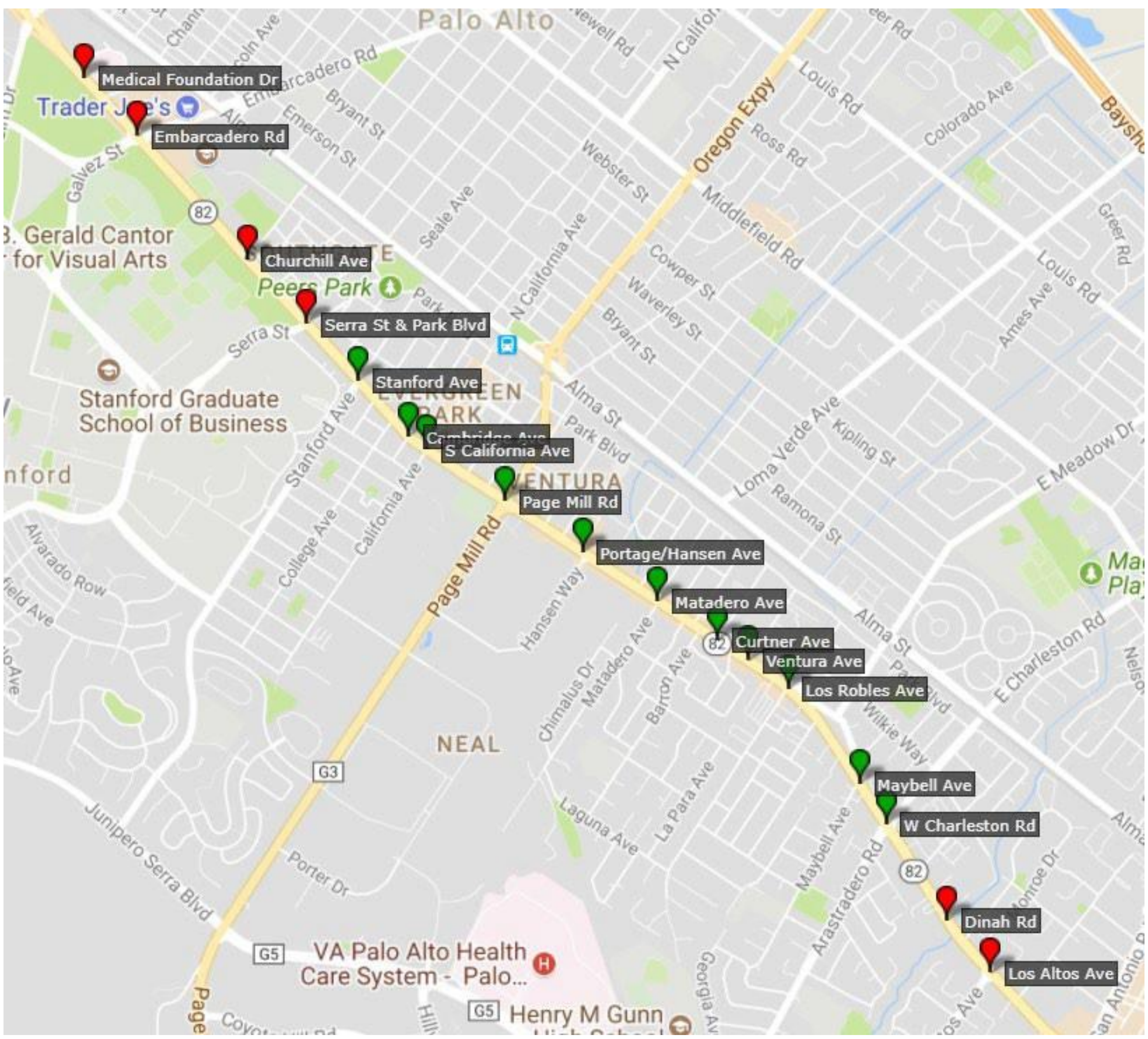


Figure 1 Palo Alto CV Test Bed Intersections (Green – Existing, Red – Expanding)

Scope of work

Figure 2 shows a generic schematic for a typical installation. Each installation is unique since each intersection is unique in terms of number and location of underground conduits, availability of space in the conduits, geometry, and signal equipment such as the number and types of poles and mast arms. Table 1 includes a list of intersections where the equipment is to be installed.

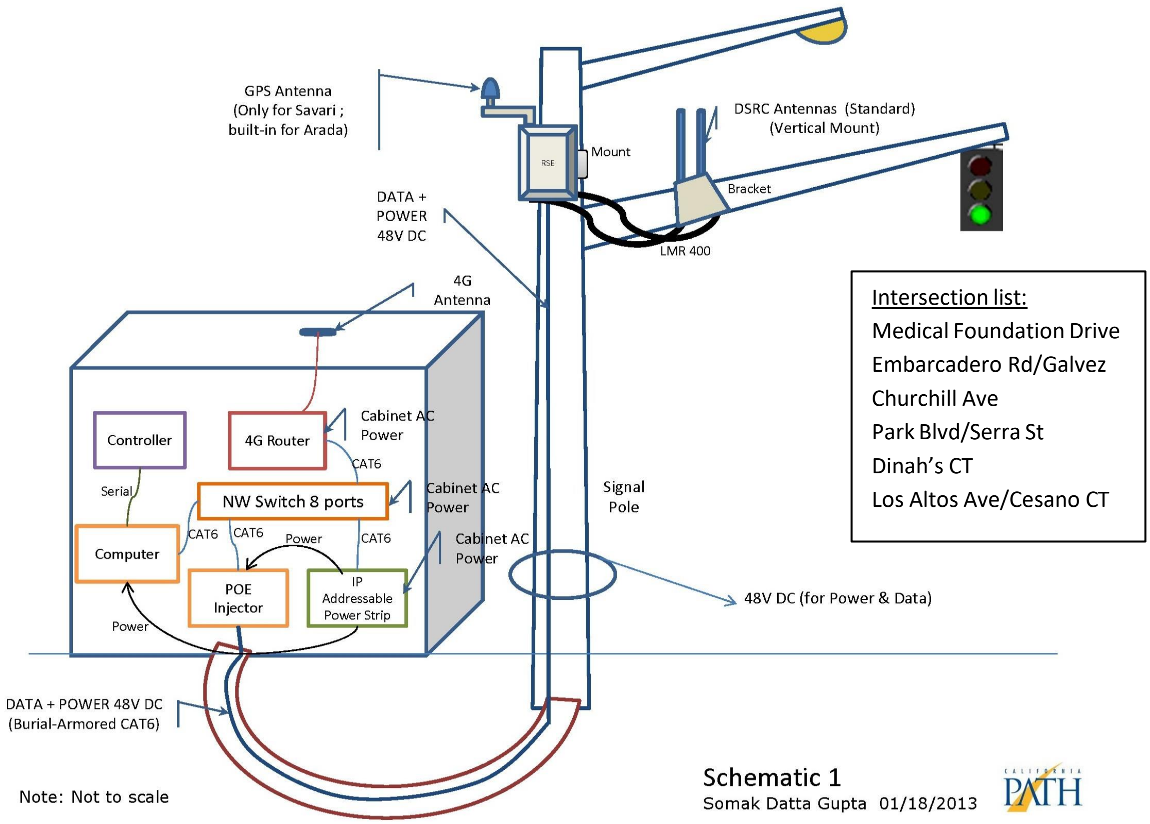


Figure 2 Installation schematic

The following provides a general description of the work required at each installation:

- procure specified CV and ancillary equipment (see Table 1 and Table 2);
- produce brackets to hold antennas (see Appendix A for details);
- attach a 2-inch flexible conduit from an opening on the host pole near the signal head to the Roadside Unit (RSU);
- attach RSU to the host pole (see Appendix B for pictures and dimensions and Appendix C for RSU mount accessories),
- attach antenna bracket to the mast arm,
- run low-loss, braided coax cables between the RSU and antenna,
- place antenna on the bracket attached to the mast arm,
- run a PoE cable from the traffic control cabinet to the RSU through Caltrans signal conduits and the host pole and the 2-inch flexible conduit,
- Install a new auxiliary cabinet alongside the existing traffic signal controller cabinet if one does not exist and if controller cabinet has insufficient space for CV equipment

- Install CV equipment (see Table 1 and Table 2) in auxiliary cabinet or controller cabinet, if space allows
- install a 4G antenna atop of the cabinet and connect it to a 4G router inside the auxiliary cabinet,
- connect all the cables including those inside the cabinet and plug in all the devices
- weather proof all the connections,
- Support an end-to-end acceptance test at each site.

The antenna mount in the diagram is a placeholder. Details for this mast arm type of installation are available in Appendix A.2 and A.3.

List of signalized intersections and CV equipment

Table 1 shows the intersections and major CV equipment components to be installed at each site. All of the intersections are in the city of Palo Alto, California, along El Camino Real.

Table 1 CV Equipment needed for each installation

Site #	Intersection Name	Savari RSU w/ GPS antenna	DSRC antenna pair w/ bracket	Field hardened PC	4G modem/router w/ static IP address	2070 controller w/ TSCP 2.21 firmware
1	ECR @ Medical Foundation Drive	1	1	1	1	1
2	ECR @ Embarcadero Rd/Galvez	1	1	1	1	1
3	ECR @ Churchill Ave	1	1	1	1	1
4	ECR @ Park Blvd/Serra St	1	1	1	1	1
5	ECR @ Dinah CT	1	1	1	1	1
6	ECR @ Los Altos Ave	1	1	1	1	1
	Total	**6**	**6**	**6**	**6**	**6**

Note: All of RSUs, GPS antennas, DSRC antennas and 4G antennas, 4G routers and computers will be furnished by California PATH and installed by Caltrans with assistance from PATH. The six new 2070 controllers will be furnished and installed by Caltrans. Each of the new 2070 controllers will need to have TSCP 2.2.1 firmware and will need a 7B serial card.

List of Additional Equipment

With the exception of the auxiliary cabinet to be installed at El Camino Real and Park/Serra, all of the following equipment and supplies with stated specification, lengths, and quantities will be provided by PATH for each installation. Caltrans will furnish and install the auxiliary cabinet. Caltrans will install all other equipment with PATH assistance.

Table 2 Additional Equipment needed for each installation

Description of Equipment	Total Quantities
Pre-fab LMR 400 cable with N-Type Male and N-Type Female connectors	2-20ft, 4-30ft, 6-40ft lengths*
Burial armored cat-6 cable and its connectors (Superior Essex – Part Number: 04-001-64)	Variable length*
Cat-6 cable (2-ft long)	30
Bracket for mounting DSRC antenna on the mast arm or light pole	6
Strapping metal bands to attach RSU to the host pole	As needed
Band strapping saddle brackets for antenna mounts	As needed
Serial cable and its connectors (8-ft long), 2 serial cables per intersection	12
Network switch with 8 ports Black Box LBH600A-P- Long-term operating: -40 to +167° F (-40 to +75° C)	6
IP addressable power switch Synaccess Networks, Inc. : NP-02 2 Switchable Outlets	6
Surge Protected power strip (6 outlets)	6
MobileMark LTM-502 antenna	6
Auxiliary cabinet at SR82@Park/Serra	1

* see the aerial photograph of each site for specific cable lengths

Installation details for RSUs and antennas at each intersection

This section contains layout information for installation of RSUs and antennas along El Camino Real (ECR) in Palo Alto, California. The following Google Earth aerial pictures provide a visual for the location of each major component of installation at selected intersections. Construction notes are included with each aerial.

NOTES:

- The following abbreviations are used in the document:

  C = Cabinet, R = Road Side Equipment (RSU) and A = Antenna

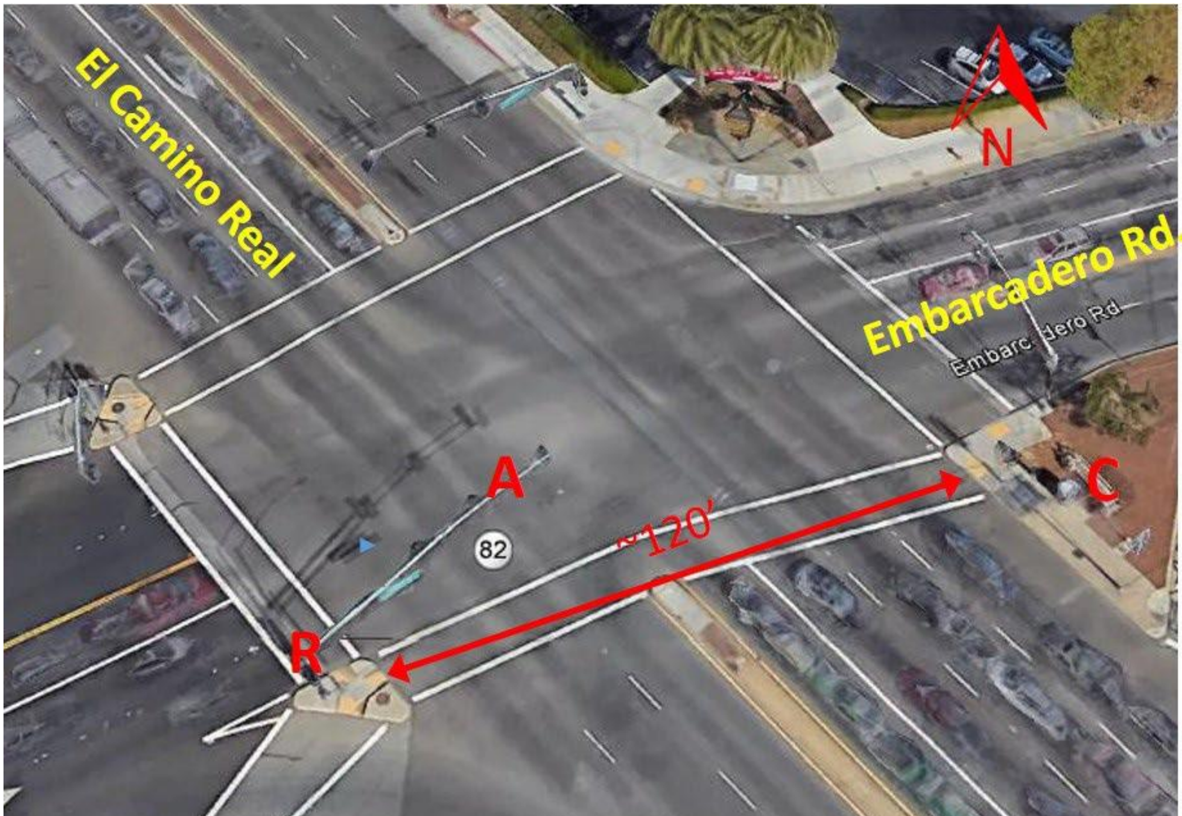
- Wherever field conditions allow, the location denoted by "1st Choice for RSU" should be used.

- Further, the relative positioning of the RSU with respect to the pole it is being attached to, should always be on the side of the pole opposite the street.

Site #1: El Camino Real and Medical Foundation Dr.

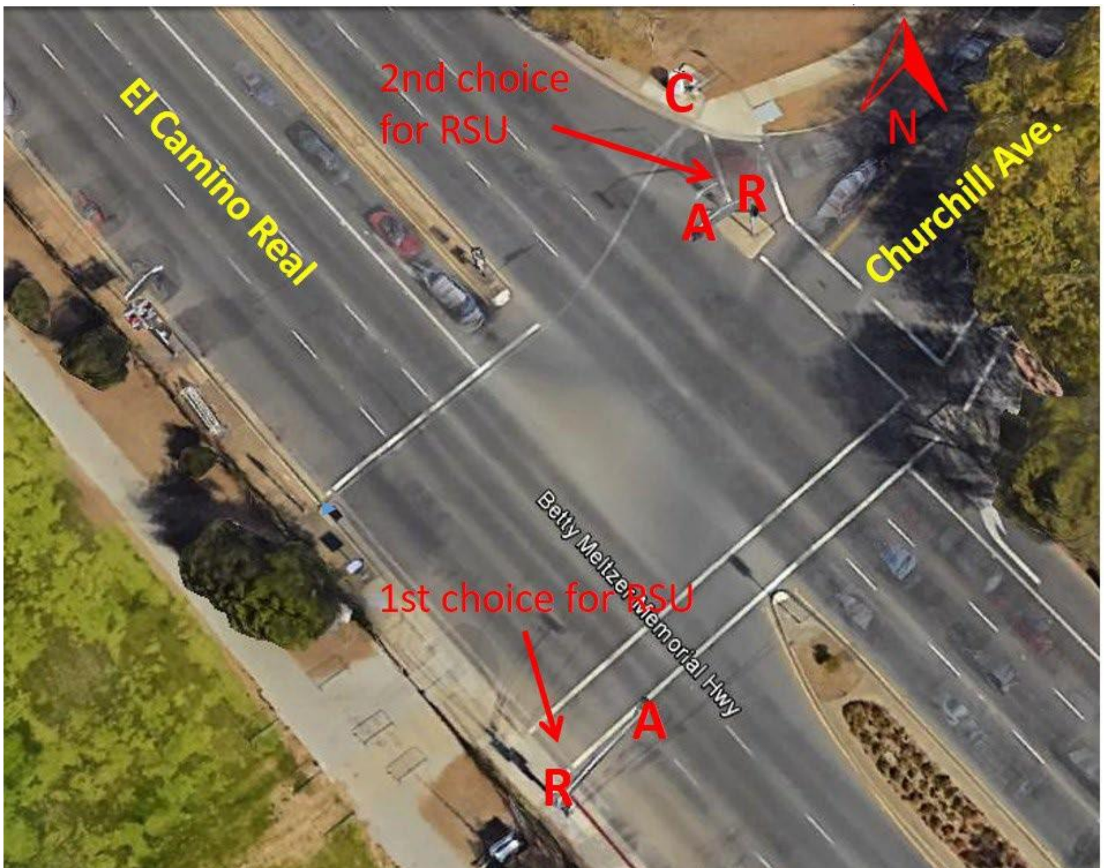
1. Install antenna (A) on mast arm with bracket.
2. Install RSU (R) on upright above mast arm.
3. Connect RSU to antenna with 30' coax cables.
4. Connect RSU to cabinet (C) through pole and pull boxes with PoE cable.
5. Install new 2070 controller in existing controller cabinet.
6. Install CV equipment in existing cabinet and connect to new 2070 controller and other equipment per cabinet diagram.

Site #2: El Camino Real and Embarcadero Rd/Galvez St.



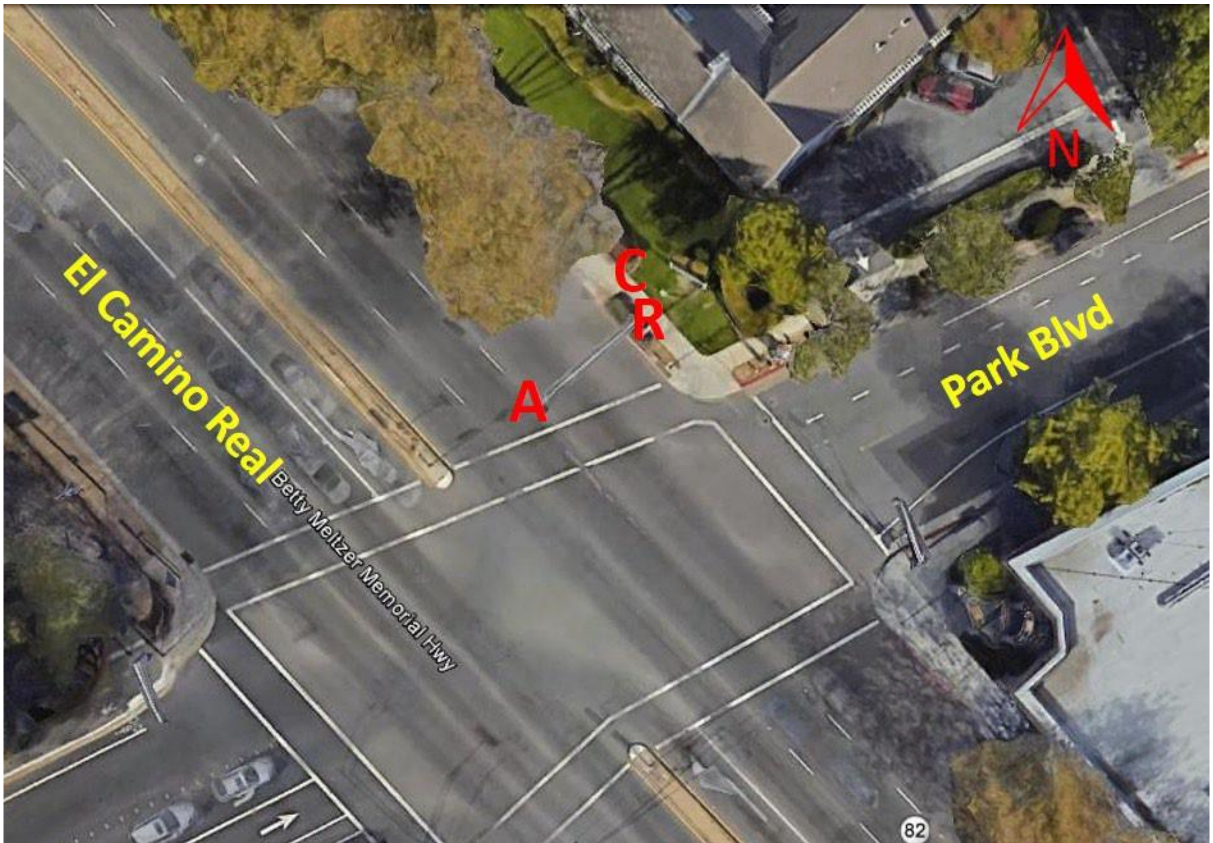
1. Install antenna (A) on mast arm with bracket.
2. Install RSU (R) on upright above mast arm.
3. Connect RSU to antenna with 40' coax cables.
4. Connect RSU to cabinet (C) through pole and pull boxes with PoE cable.
5. Install new 2070 controller in existing controller cabinet.
6. Install CV equipment in existing auxiliary cabinet and connect to new 2070 controller and other equipment per cabinet diagram.

Site #3: El Camino Real and Churchill Ave.



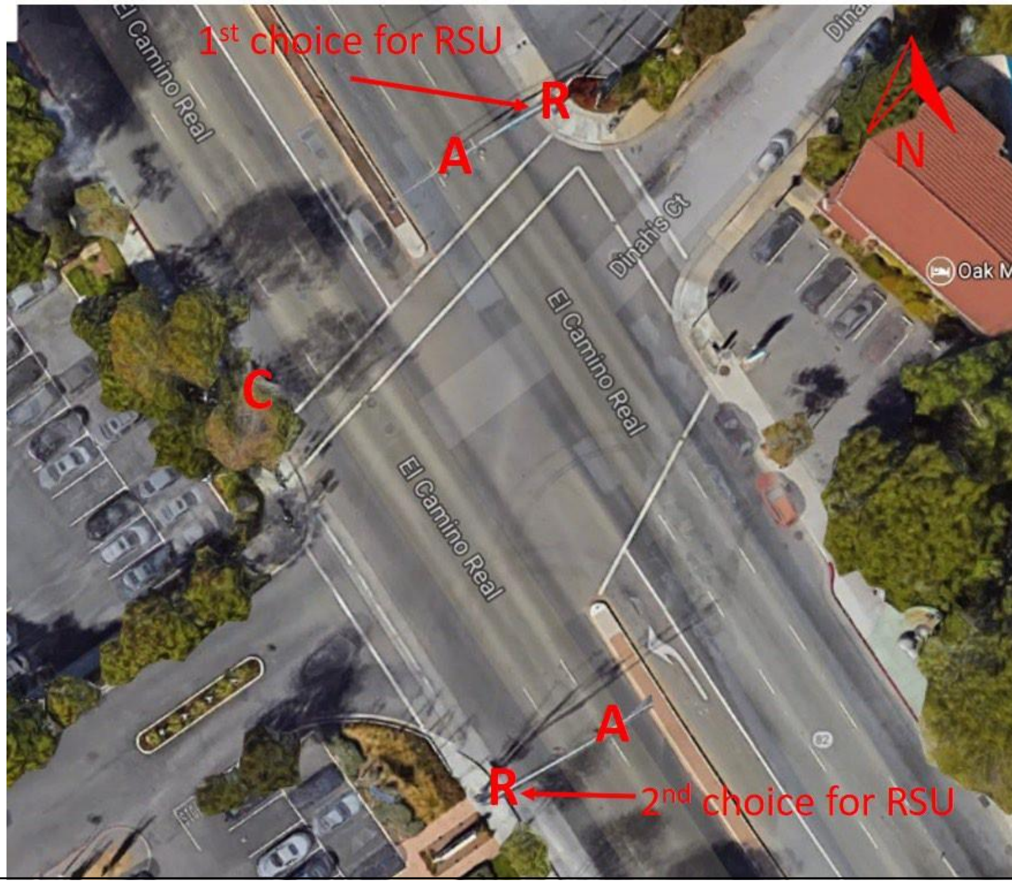
1. Determine best RSU (R) location based on conduit capacity.
2. Install antenna (A) on mast arm with bracket.
3. Install RSU on upright above mast arm.
4. Connect RSU to antenna with 20' coax cables.
5. Connect RSU to cabinet (C) through pole and pull boxes with PoE cable.
6. Install new 2070 controller in existing controller cabinet.
7. Install CV equipment in existing auxiliary cabinet and connect to new 2070 controller and other equipment per cabinet diagram.

Site #4: El Camino Real and Park Blvd/Serra St.

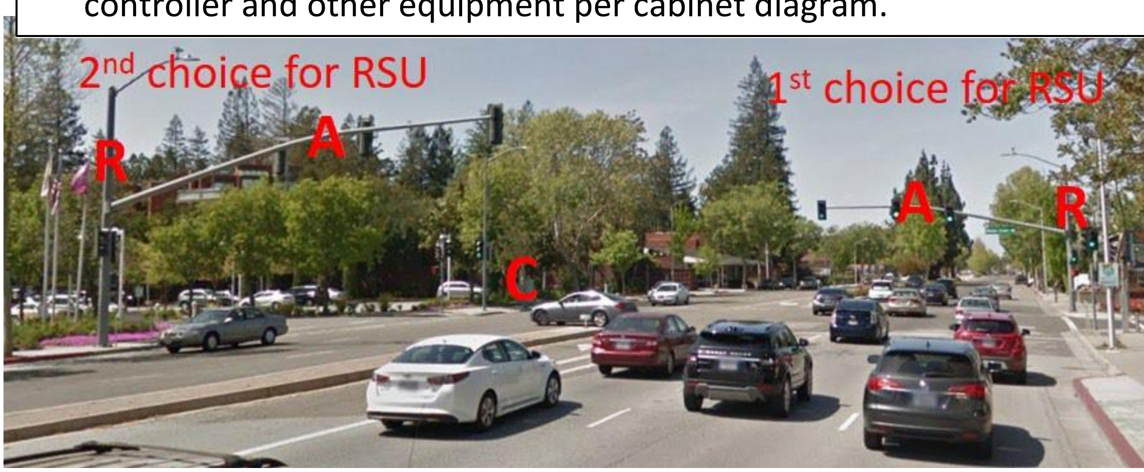


1. Install antenna (A) on mast arm with bracket.
2. Install RSU (R) on upright above mast arm.
3. Connect RSU to antenna with 40' coax cables.
4. Connect RSU to cabinet (C) through pole and pull boxes with PoE cable.
5. Install auxiliary cabinet on street side of controller cabinet #E37G5.
6. Install new 2070 controller in existing controller cabinet.
7. Install CV equipment in auxiliary cabinet and connect to new 2070 controller and other equipment per cabinet diagram.

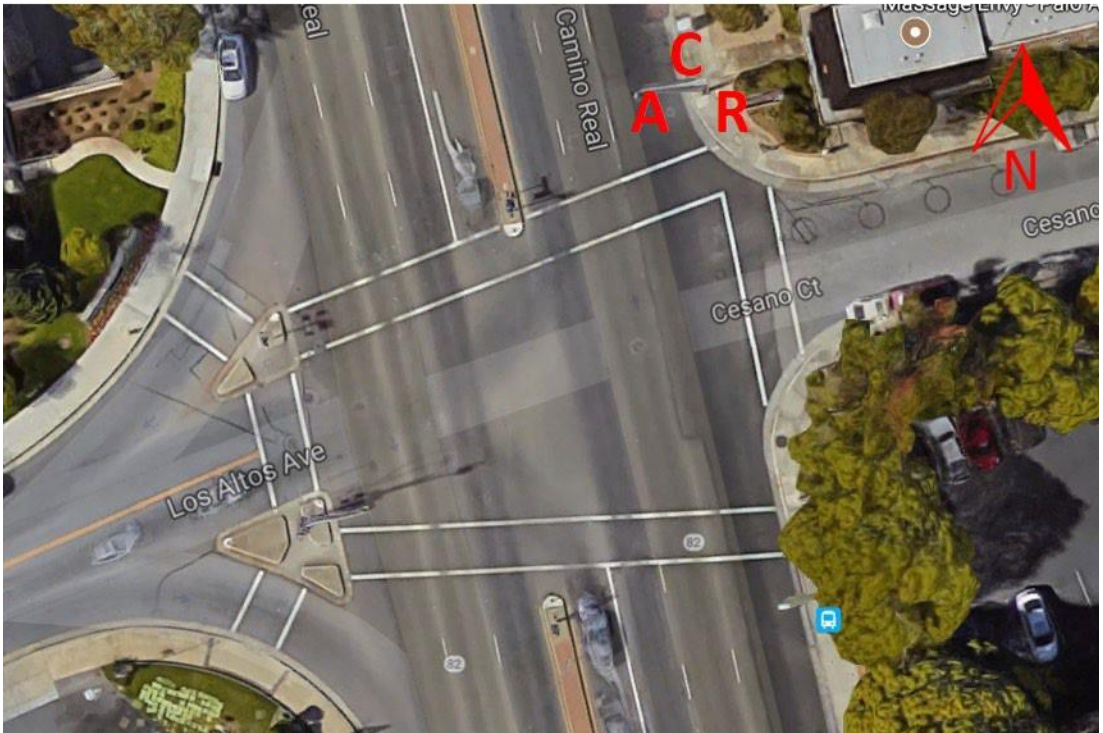
Site #5: El Camino Real and Dinah CT.



1. Determine best RSU (R) location based on conduit capacity.
2. Install antenna (A) on mast arm with bracket.
3. Install RSU on upright above mast arm.
4. Connect RSU to antenna with 20’ coax cables.
5. Connect RSU to cabinet (C) through pole and pull boxes with PoE cable.
6. Install new 2070 controller in existing controller cabinet.
7. Install CV equipment in existing auxiliary cabinet and connect to new 2070 controller and other equipment per cabinet diagram.



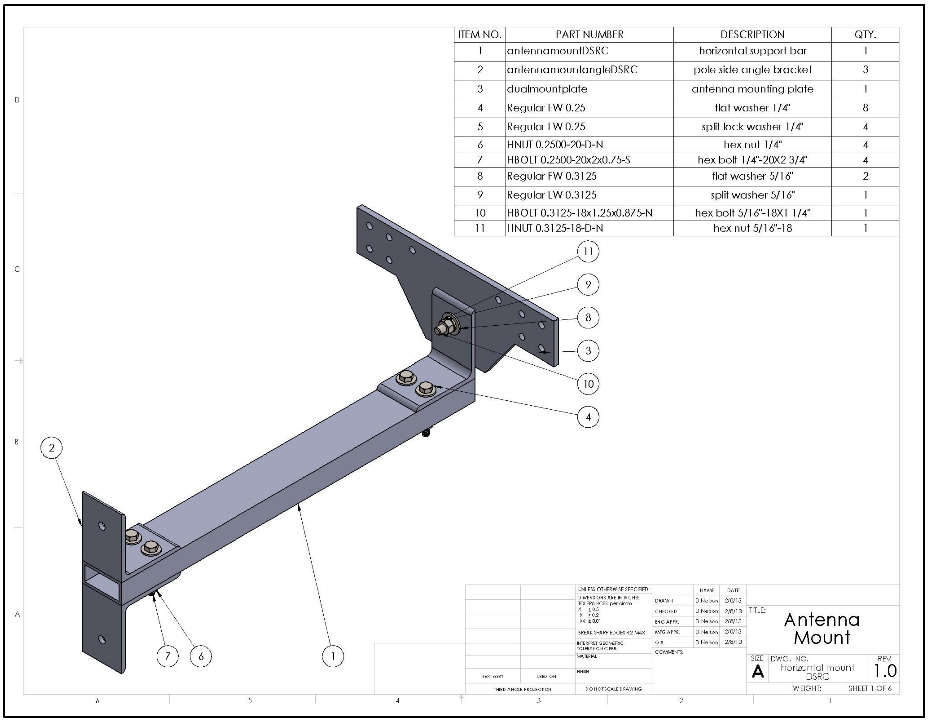
Site #6: El Camino and Los Altos Ave.



1. Install antenna (A) on mast arm with bracket.
2. Install RSU (R) on upright above mast arm.
3. Connect RSU to antenna with 30’ coax cables.
4. Connect RSU to cabinet (C) through pole and pull boxes with PoE cable.
5. Install new 2070 controller in existing controller cabinet.
6. Install CV equipment in existing auxiliary cabinet and connect to new 2070 controller and other equipment per cabinet diagram.

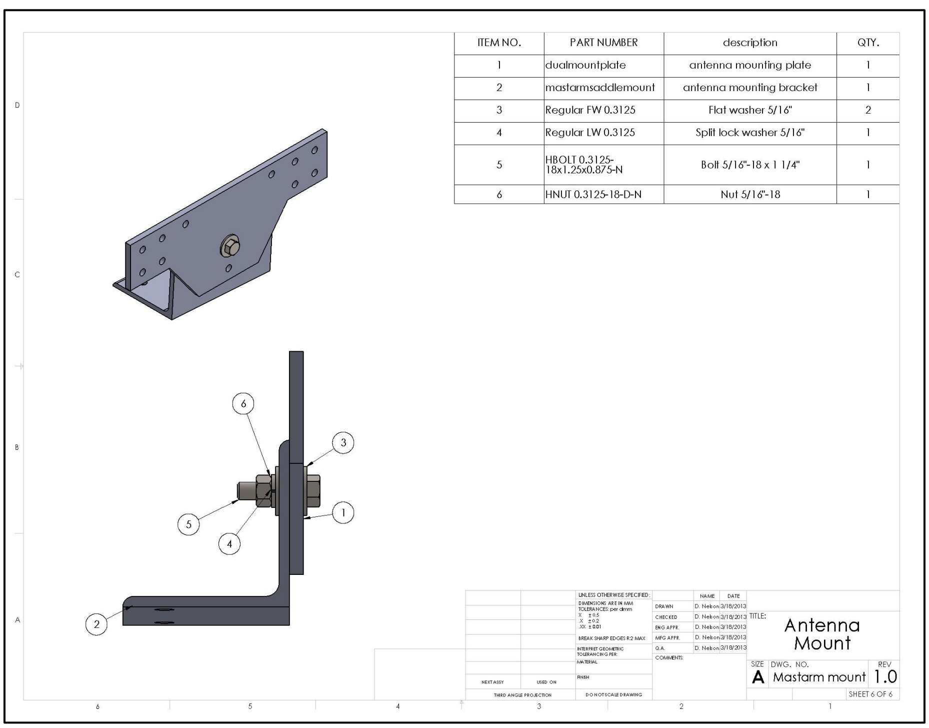
Appendix A: Design Specifications for DSRC Antenna Bracket(s)

A1: Pole Mount:



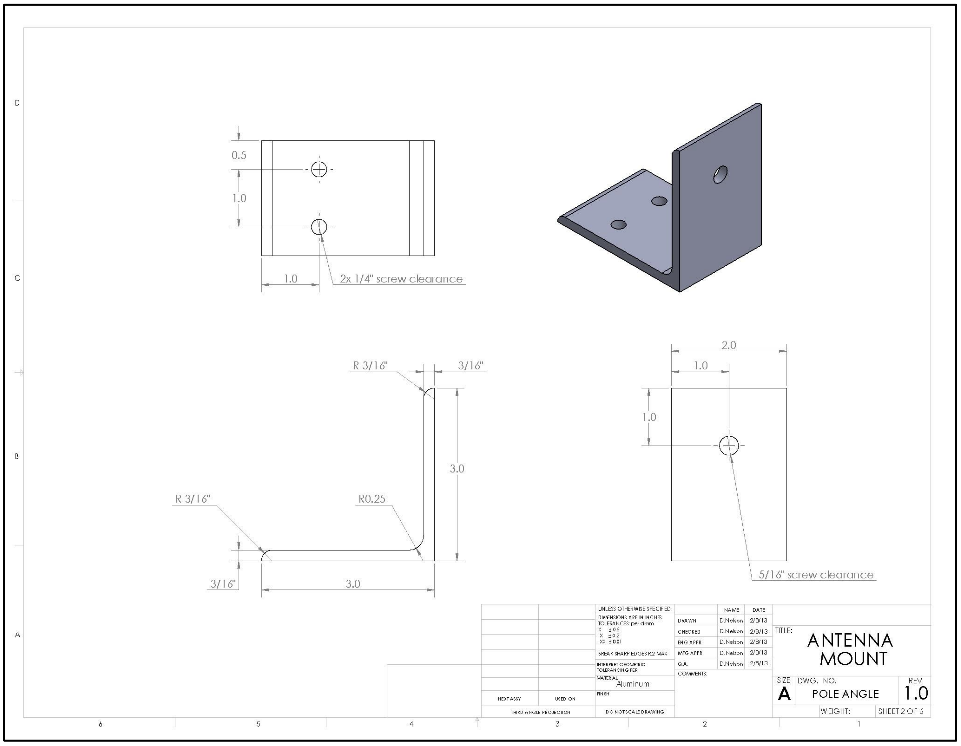
ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	antennamountDSRC	horizontal support bar	1
2	antennamountangleDSRC	pole side angle bracket	3
3	dualmountplate	antenna mounting plate	1
4	Regular FW 0.25	flat washer 1/4"	8
5	Regular LW 0.25	split lock washer 1/4"	4
6	HNUT 0.2500-20-D-N	hex nut 1/4"	4
7	HBOLT 0.2500-20x2x0.75-S	hex bolt 1/4"-20X2 3/4"	4
8	Regular FW 0.3125	flat washer 5/16"	2
9	Regular LW 0.3125	split washer 5/16"	1
10	HBOLT 0.3125-18x1.25x0.875-N	hex bolt 5/16"-18X1 1/4"	1
11	HNUT 0.3125-18-D-N	hex nut 5/16"-18	1

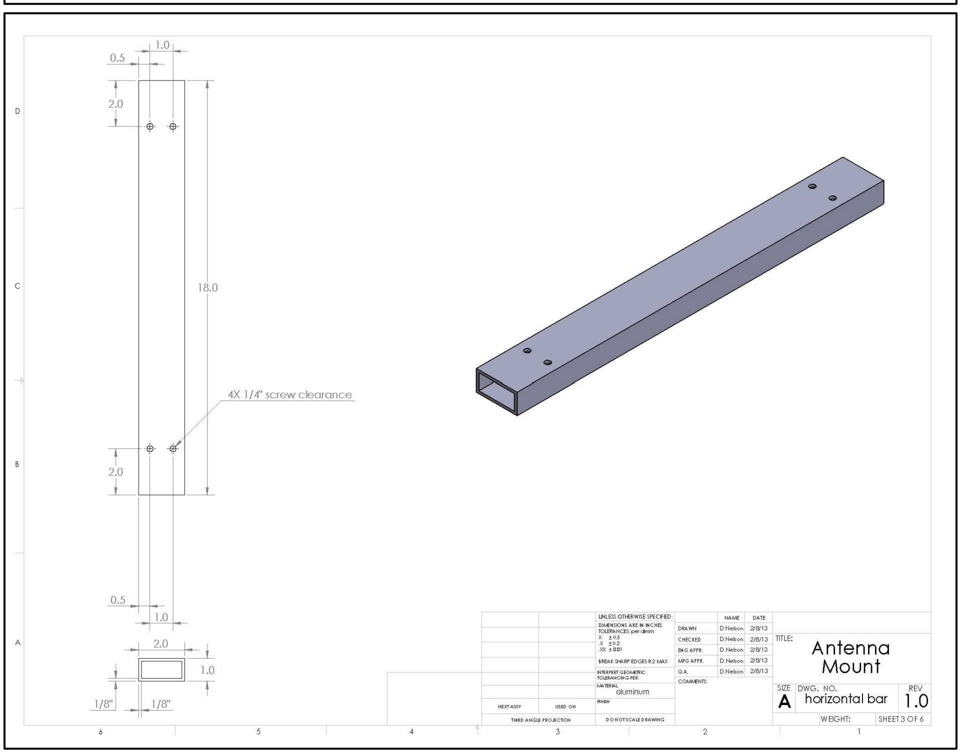
A2: Mast Arm Mount:

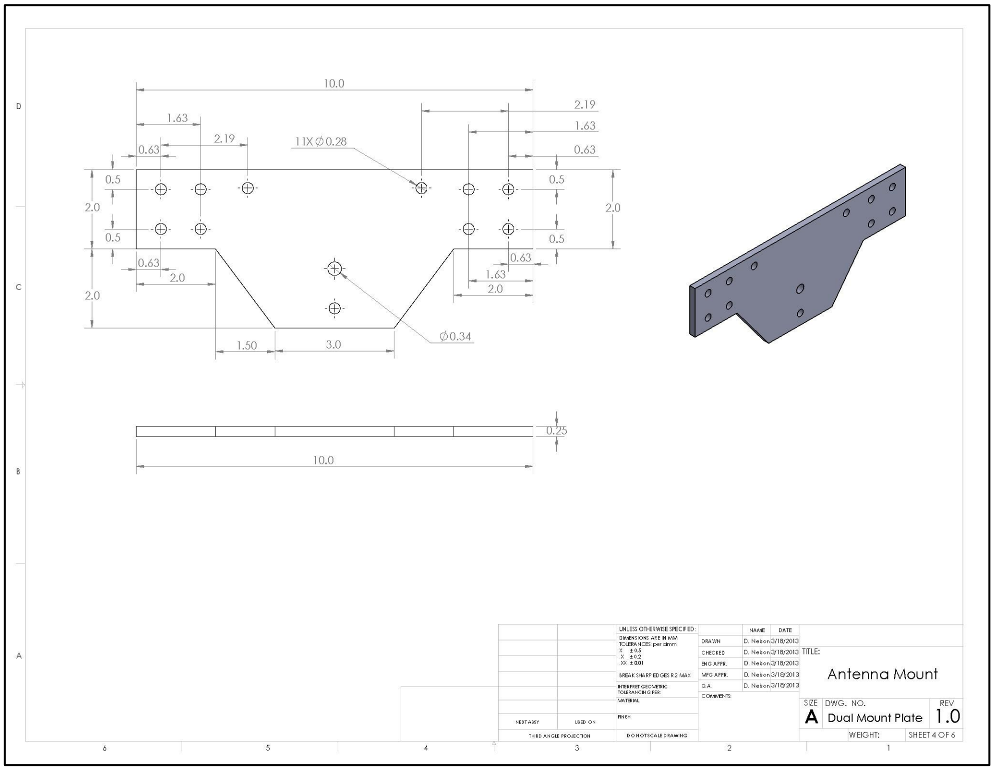


ITEM NO.	PART NUMBER	description	QTY.
1	dualmountplate	antenna mounting plate	1
2	mastarmsaddlemount	antenna mounting bracket	1
3	Regular FW 0.3125	Flat washer 5/16"	2
4	Regular LW 0.3125	Split lock washer 5/16"	1
5	HBOLT 0.3125-18x1.25x0.875-N	Bolt 5/16"-18 x 1 1/4"	1
6	HNUT 0.3125-18-D-N	Nut 5/16"-18	1

A3: Antenna Mount Assembly Part Details:







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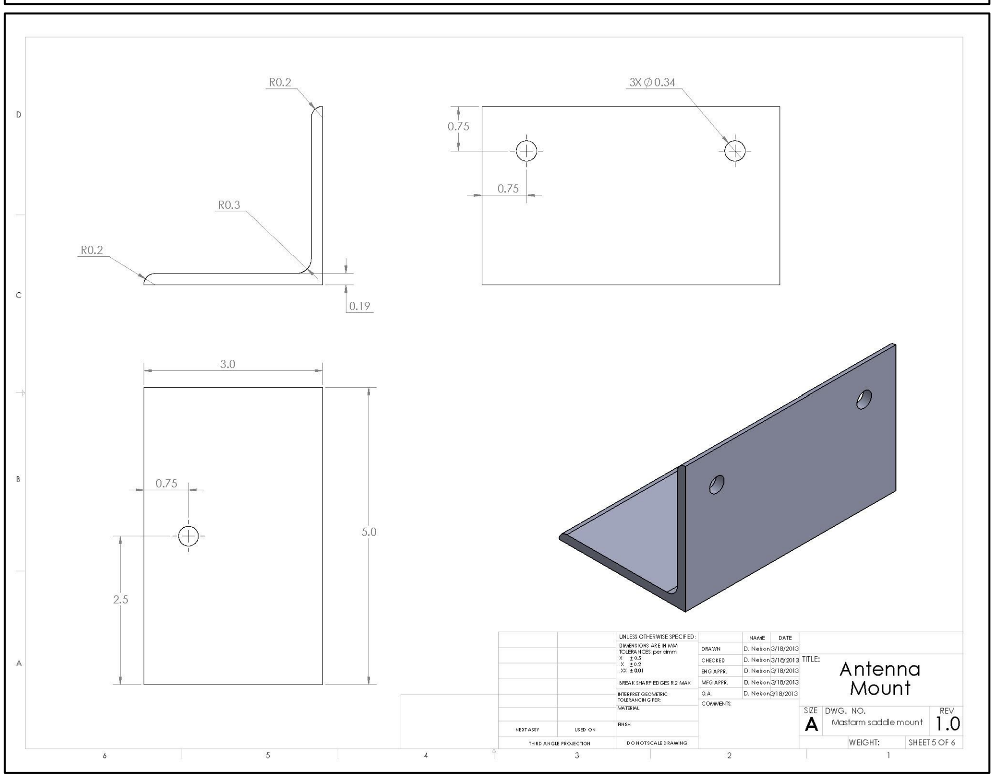
2.19
1.63
0.63
11X ∅0.28
0.5
2.0
0.63
2.0
1.63
∅0.34
1.50
3.0
0.25
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MM
TOLERANCES: per dimm
BREAK SHARP EDGES R2 MAX
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
NEXT ASSY
USED ON
THIRD ANGLE PROJECTION
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
D. Nelson 3/18/2013
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
Antenna Mount
SIZE
DWG. NO.
REV
A
Dual Mount Plate
1.0
WEIGHT:
SHEET 4 OF 6



R0.2
R0.3
R0.2
0.19
3X ∅0.34
0.75
0.75
3.0
0.75
5.0
2.5
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MM
TOLERANCES: per dimm
BREAK SHARP EDGES R2 MAX
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
NEXT ASSY
USED ON
THIRD ANGLE PROJECTION
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
D. Nelson 3/18/2013
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
Antenna Mount
SIZE
DWG. NO.
REV
A
Mastarm saddle mount
1.0
WEIGHT:
SHEET 5 OF 6

Appendix B: Pictures and dimensions of Road Side Equipment (RSE)

Arada RSE:

Dimensions: 9 ¼" (L) x 9 ¼" (H) x 3" (D)

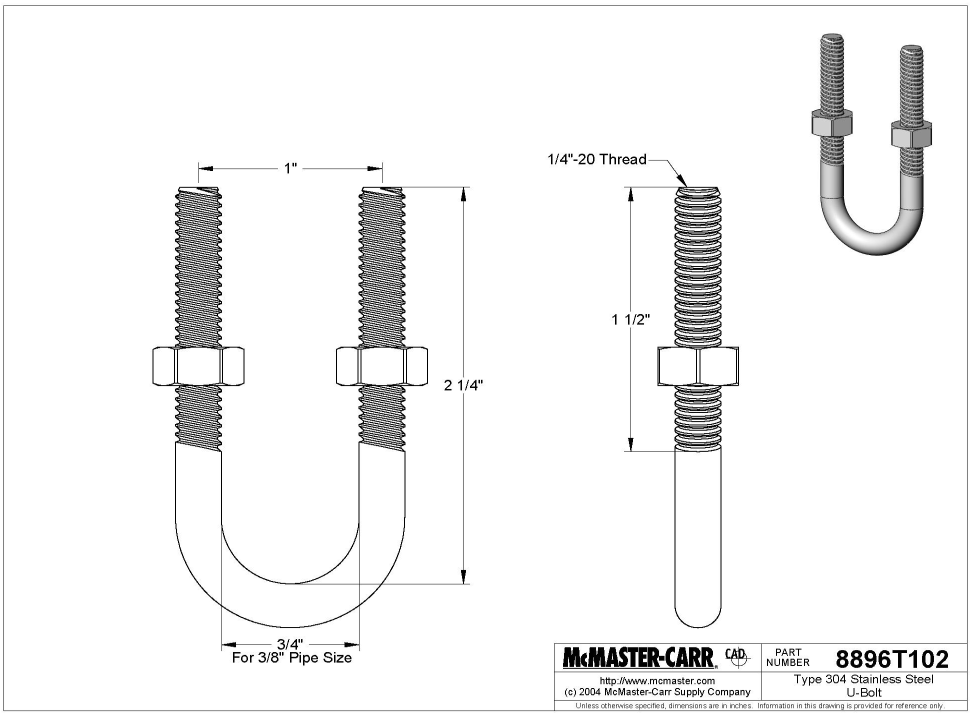
Savari RSU:

Dimension: 8" (L) x 8 1/2"(H) x 2 3/4" (D)

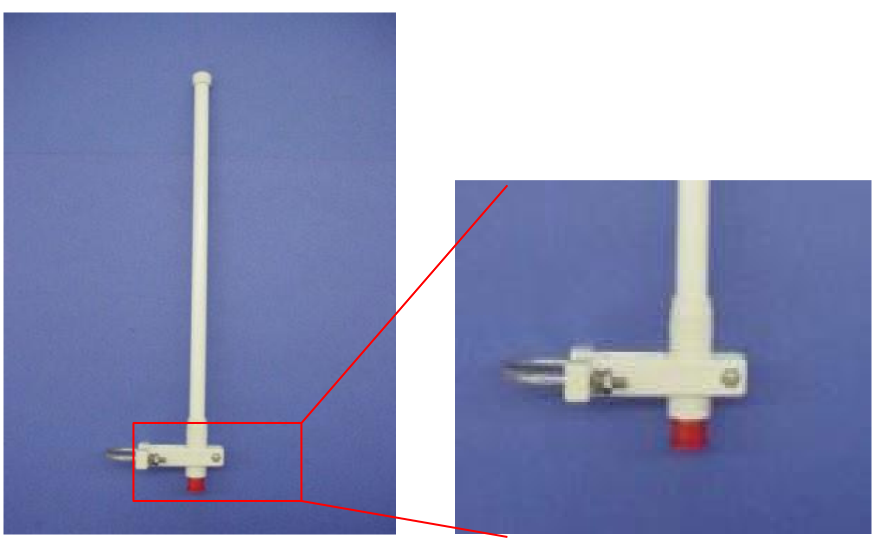
Appendix C: Design Specifications for Savari and Arada DSRC RSU Mounting Accessories

There are some accessories required to secure the antennas to the Pole Mount and the Mast Arm Mount. They are listed below as needed by the different brand of RSUs.

Arada: U-Bolts (Part # - McMaster-Carr 8896T102) – 4 per site, 2 per antenna



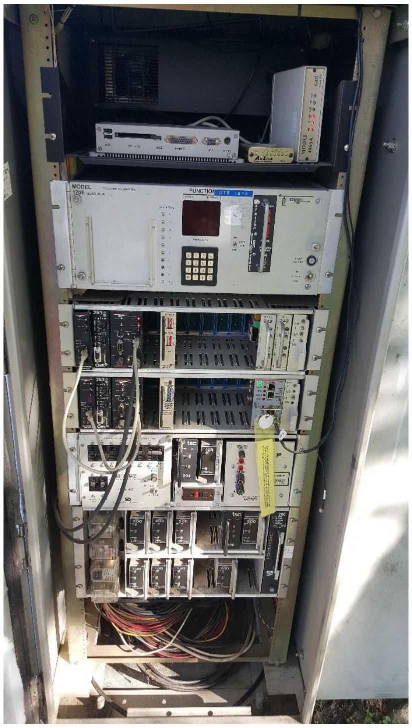
Savari: Mobilemark mounts (Part # - ECO-MK) – 2 per site, 1 per antenna

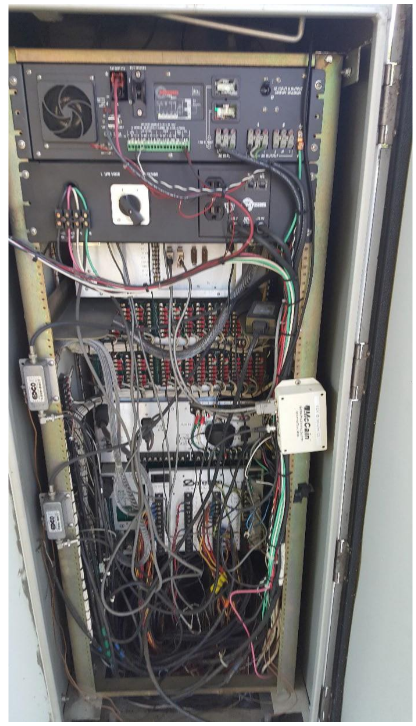


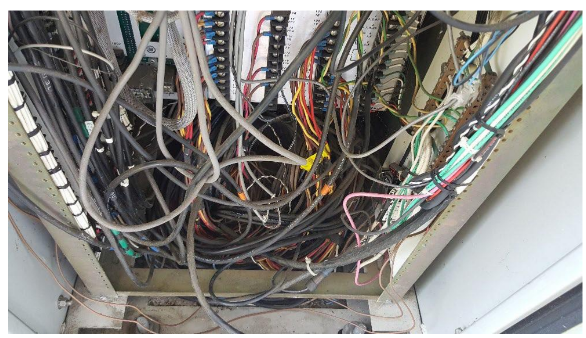
Appendix D: Two Intersections in the South of Charleston Ave

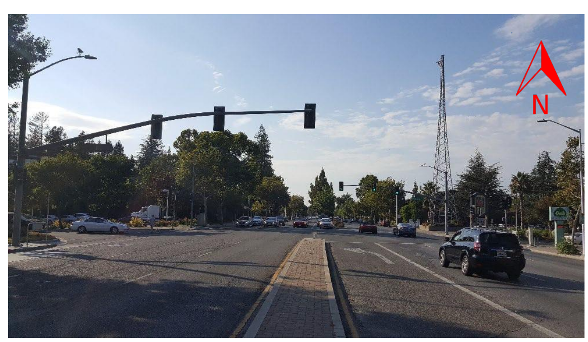
Both intersections of Dinah CT @ ECR and Los Altos Ave @ ECR have a 170E controller and a side cabinet. Both side cabinets have enough room to put inside-cabinet devices (e.g., Linux PC, router, etc.). It looks like the conduits have space for additional wires for RSU but need D4 engineers to confirm.

D-1 Intersection of Dinah CT @ ECR

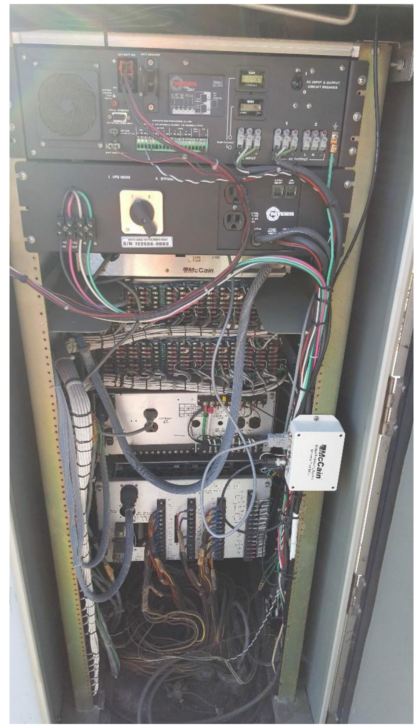


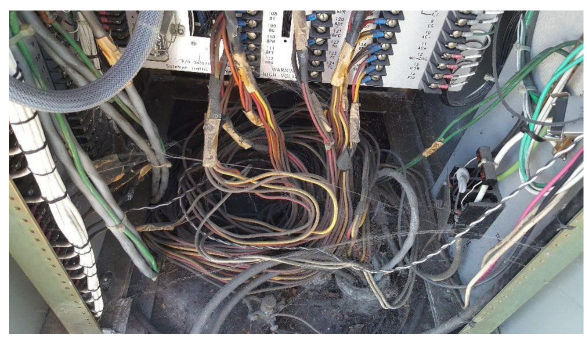


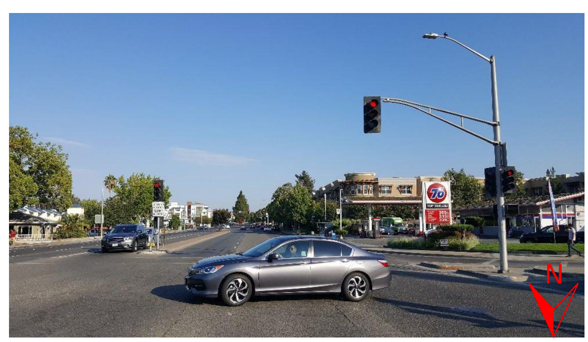




D-2 Intersection of Los Altos Ave @ ECR







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payload ecr-embarcadero
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payload ecr-churchill
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payload ecr-serra-park
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payload ecr-stanford

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payload ecr-cambridge

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payload ecr-california

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payload ecr-page-mill
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payload ecr-portage-hansen
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C3109800800001F8045A000705A080000010001 6A806505E023C411CB2186665B3D80444400105D80020C00003572EB9C
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payload ecr-matadero
0012837C280B3019000003F200A5F94FA3913EC8988832015E0288BC68B0045000000E40031C27F0CA3B966BD0949EDBB
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payload ecr-curtner

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000821B000581AE80000028001246952704788 42FB88E348E520423AE470A409000152202000A381D0400000400 0129CF
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04800800001F90E084100000100006 13B7D40636FC110CA0574119936C843311D9E8620B001000003F2088C000E08C100
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000002561358BAE158FEAE0AF037E0

payload ecr-ventura

0012822F280B3019000003F400A5F92216113F1F500837014A0288BC44B00450000000640031 5EFF1C929EDBB9495BE61D
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160E29098000208 6C001606BA000000A000490F968811E219E92AF83206DFF847F51DE2902400054880800 28E07410000
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448800381049800 20C0002BC164924129612141000 9348C441222800200

payload ecr-los-robles

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payload ecr-maybell

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payload ecr-charleston

0012850F280B3019000003F700A5F8A510913FA384084B014A0288BC90B0045000000A40051D35F2DE3B515CD076DEBDB
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payload ecr-dinahs-court

00128311280B3019000003F800A5F85C29113FDE04085A012C0288BC58B0045000000E40011CF830084B6AAF02262919C
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payload ecr-los-altos

00128389280B3019000003F900A5F833BC9140080F885F014A0288BC6CB0045000000E400215E0F800F701AD01642E120
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Design Guidance for Installation of CV Infrastructure Equipment

Fifteen Expansion Intersections at El Camino Real Testbed

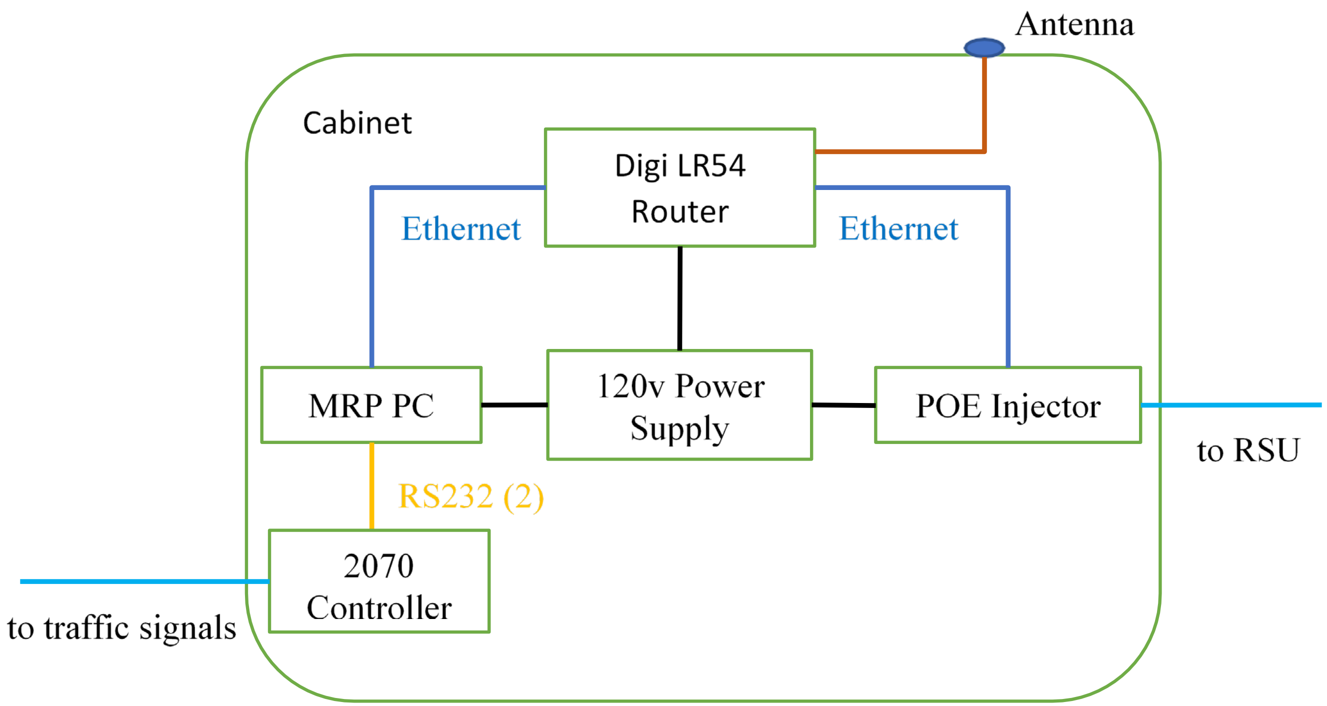
December 2019

El Camino Real (ECR) CV Test Bed

Connected Vehicle (CV) Intersection Equipment

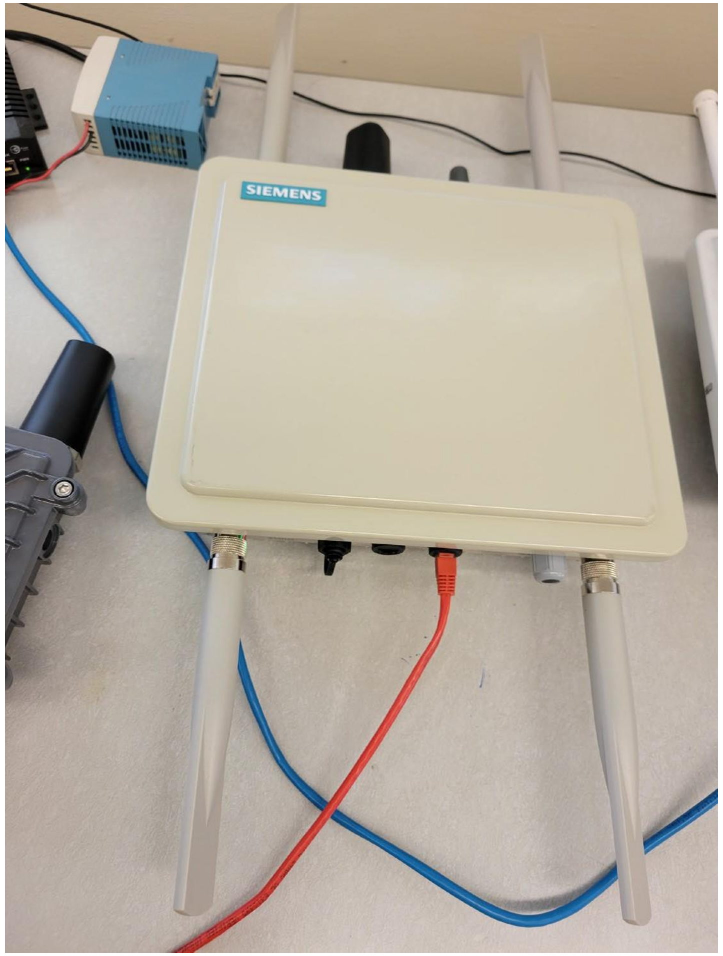
Equipment	Install Location	Note
Siemens Dual-mode RSU	Mast arm facing ECR traffic	• Pull CAT6 PoE cable from the cabinet to the RSU
2070E Controller	Main cabinet	• With CV TSCP firmware
Surge Protector		• Rack mount
Power Strip	Backpack cabinet	• Power source from the main cabinet surge protector
PoE Injector		• DIN rail mount • PoE cable needs to reach the backpack cabinet
4G Modem/Router		• Provide communications backhaul and LAN networking
4G Modem Antenna		• Mount on the top of the main or backpack cabinet
Roadside Processor (RSP)		• Use two serial cables or an Ethernet cable to connect with the 2070E controller
DIN rail		• 35 mm (1.4 in) wide

Cabinet Devices



Siemens Dual-Mode RSU (1/3)

- Dual C-V2X and DSRC radios
- To be mounted on mast arm facing ECR traffic
- Dimension: 65 cm x 31 cm x 12 cm
- Weight: 4.1 kg
- Seven antennas
  - Two DSRC antennas
  - One C-V2X antenna
  - One LTE antenna
  - Two GNSS antenna
  - One Wi-Fi/Bluetooth antenna



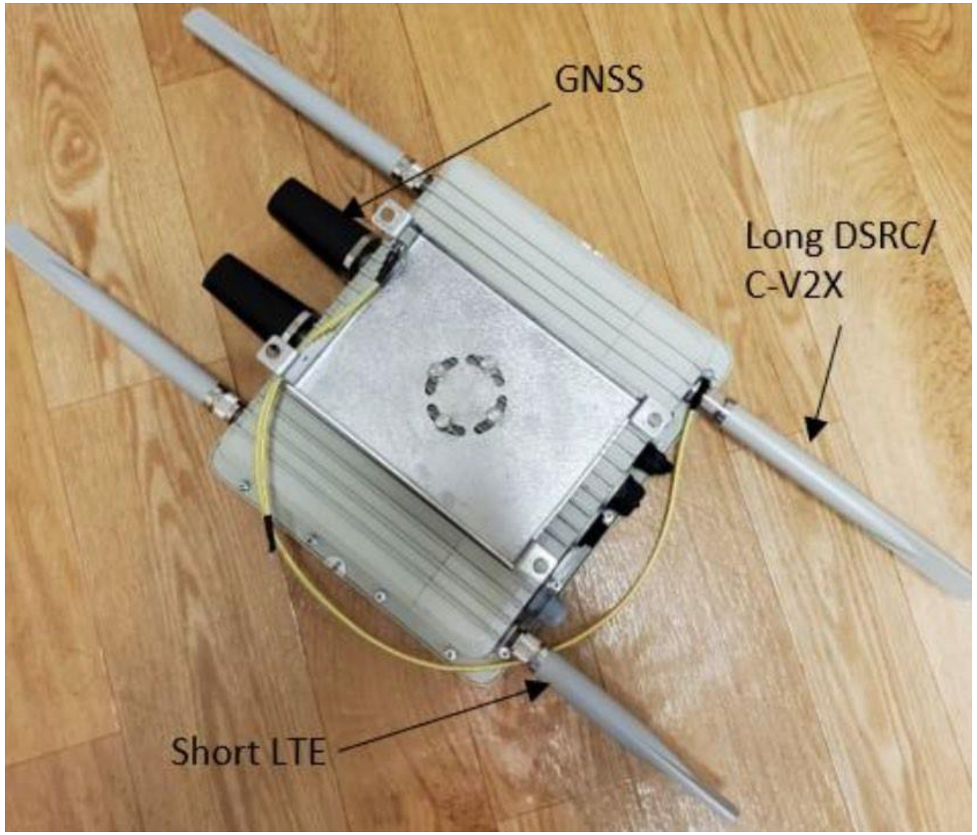
Siemens Dual-Mode RSU (2/3)

Top View

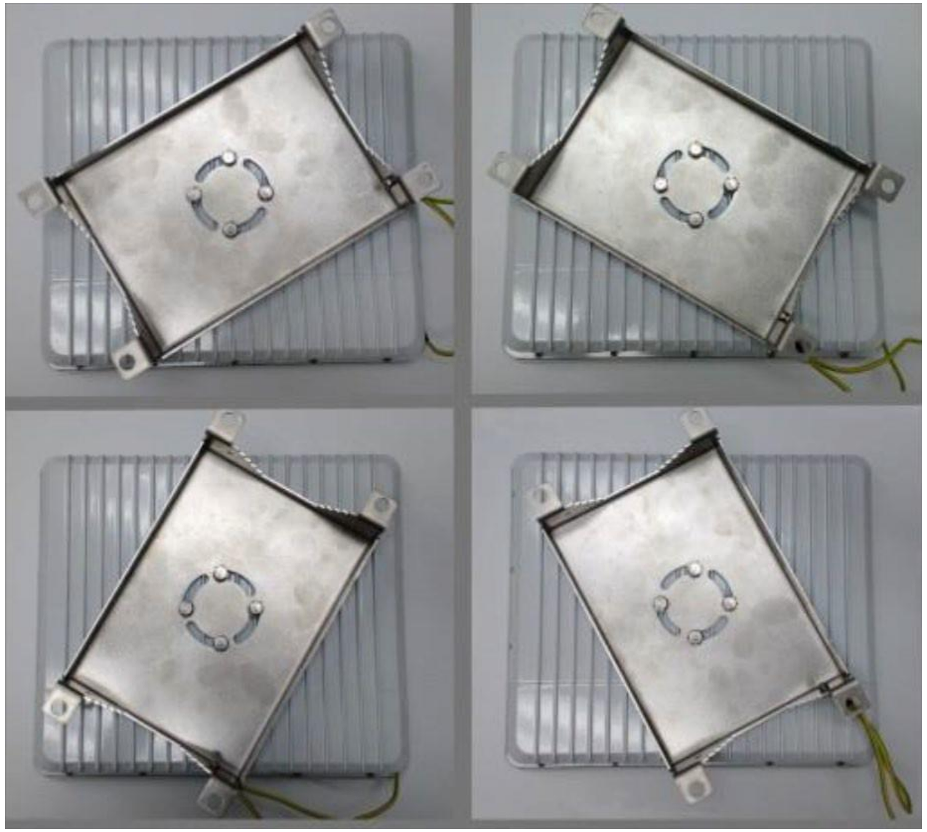
Bottom View

Siemens Dual-Mode RSU (3/3)

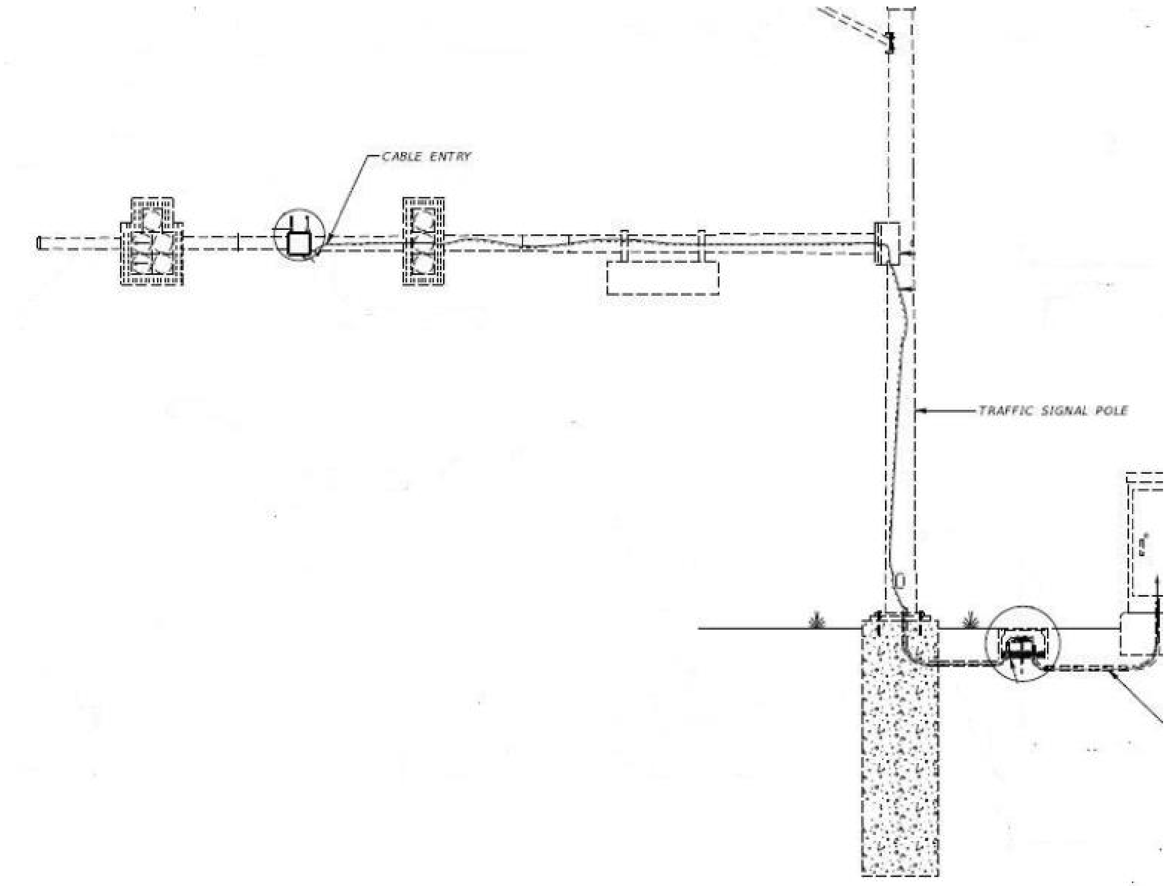
Back View with Mounting Bracket



Mounting Bracket Adjustment Range



Siemens Recommended RSU Installation

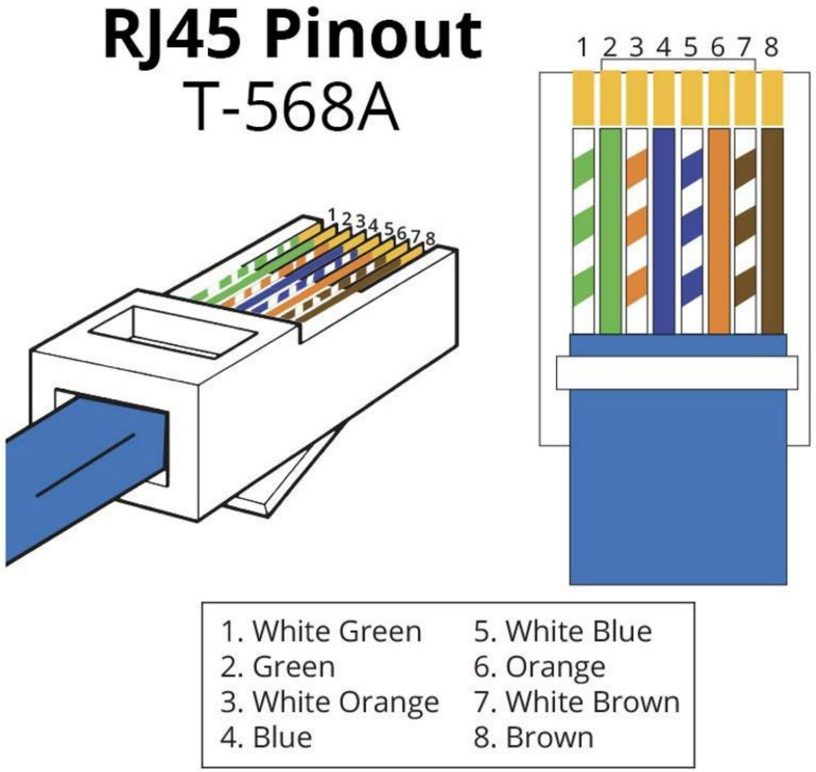


- The RSU is required to be mounted vertically orientated within +/- 5 degrees maximum
- Length of the PoE cable within 100 meters

Connect CAT6 Cable to the RSU

Connect to ETH0/PoE+ Port (RSU bottom)

RJ45 Pinout (T-568A)



Location to Mount the RSU

ID	Cross Street	Intersection Type	Location of Cabinet	Location of RSU
1	Los Altos Ave	Four-legged	NE Corner	ECR NB mast arm
2	Del Medio Ave	Four-legged	NE Corner	ECR NB mast arm
3	San Antonio Rd	Four-legged	SE Corner	ECR NB mast arm
4	Showers Dr	Four-legged	NE Corner	ECR NB mast arm
5	Jordan Ave	Four-legged	SE Corner	ECR NB mast arm
6	Ortega Ave	Four-legged	NE Corner	ECR NB mast arm
7	Distel Dr	T-intersection	NE Corner	ECR NB mast arm
8	S Rengstorff Ave	Four-legged	SE Corner	ECR NB mast arm
9	Clark Ave	T-intersection	SW Corner	ECR SB mast arm
10	Escuela Ave	Four-legged	NE Corner	ECR NB mast arm
11	El Monte Ave	T-intersection	NW Corner	ECR NB mast arm
12	S Shoreline Blvd	Four-legged	SE Corner	ECR NB mast arm
13	Castro St	Four-legged	SE Corner	ECR NB mast arm
14	Calderon Ave	Four-legged	NW Corner	ECR NB mast arm
15	Grant Rd	Four-legged	SE Corner	ECR NB mast arm

General Guidance

- Mount the RSU on a mast arm that is facing ECR traffic (i.e., ECR NB or SB mast arm) and is closer to the traffic cabinet
- Mount the RSU towards the center of the road (increasing communications range with vehicles)

Google Maps Aerial Layout

- Abbreviation:
  - C = Cabinet
  - R = Roadside Unit (RSU)

Site #1: Los Altos Ave at El Camino Real

Site #2: Del Medio Ave at El Camino Real

Site #3: San Antonio Rd at El Camino Real

Site #4: Showers Dr at El Camino Real

Site #5: Jordan Ave at El Camino Real

Site #6: Ortega Ave at El Camino Real

Site #7: Distel Dr at El Camino Real

Site #8: S Rengstorff Ave at El Camino Real

Site #9: Clark Ave at El Camino Real

Site #10: Escuela Ave at El Camino Real

Site #11: El Monte Ave at El Camino Real

Site #12: S Shoreline Blvd at El Camino Real

Site #13: Castro St at El Camino Real

Site #14: Calderon Ave at El Camino Real

Site #15: Grant Rd at El Camino Real

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payload ecr-page-mill

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payload ecr-portage-hansen

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payload ecr-matadero

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payload ecr-curtner

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payload ecr-ventura

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payload ecr-los-robles

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payload ecr-maybell

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payload ecr-charleston
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payload ecr-dinahs-court
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payload ecr-los-altos
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BBC0927F0842181FD0A465000292364001408 36C00106800219541AB21F41018591BC302C1ED59148C10006246900 0300

payload ecr-del-medio

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payload ecr-san-antonio

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payload ecr-showers

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payload ecr-jordan

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8CF64CEE15D9F2D8ACBF4481228800200

payload ecr-ortega

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payload ecr-distel-circle

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8ADFF564122680020

payload ecr-rengstorff

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payload ecr-clark

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payload ecr-escuela

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payload ecr-el-monte

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payload ecr-shoreline
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payload ecr-castro
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payload ecr-calderon
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payload ecr-grant

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00020CE56A4D2250C4768D66A8431A0B06BC45064CDC226D46178C0F3100000100008342CA68889ED96A834F0176467D3
1B291447344089BD1818383EC400000400020D32E90F226C85378D4A06EC19F885EA44F94CF22276460B8048600070818
800000800022B3F6AC698900060C4A2073C00C16B008FC000C10B100000080004553123A510BFE32C24441D71A30C7F65
844E80000052002ACB8AF67048786817A3B88C12C08443F78833AC57C4675CADB10B58B410523A40004912800022C2374
000002000146654832 0D0A948A119856F88756FA067A3AF30CF3B5D3215AD68C0244E00008B091D0000008000519C0E2D
43449D1F445D5618221ABB819D9EBC23342DA2485D3D90E291480002092C001612BA0000008000AB3E34A6C11E210A9DF
408A82CE06721ACF0D2714A31A3269CC13570CC52128000A1268002C267400000240010684A9DD0D10944119D16AB2333
DD88043098C4119343052142000A929800051C2782000002000096AB7C038243C33D7526C866357D4561E692D30882C00
40000101870A20800000800021A896D6A33DFD1BC8657D810561B5932508834004000010 1870A60800000800021A5CEAF
033F0D2588670571C5615793AA0883C0040000101810A980020C0002B6C8EE8C11E21DFF163E2E955CF14959000724B50
003810AD80020C00023E394C4C6A703F608F5889052548002092C20010042C60008000008E5705231A11E7D421E7B2D14
95A000524B48002810B58002000002327330E87447BE88E8C97981495100062 4B100030

Connected Vehicle Application Development (CVAD)

Task 3 Development of CV Applications: User Guide for SPaT Application

California PATH Program

12/27/2021

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References

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[2] AASHTO, ITE, NEMA and SAE International. (2021). *Roadside Unit (RSU) Standard* (CTI 4001 v01.00). https://www.ite.org/technical-resources/standards/rsu-standardization/.

[3] AASHTO, ITE, NEMA and SAE International. (2021). *Connected Intersections Implementation Guide* (CTI 4501 v01.00). https://www.ite.org/technical-resources/standards/connected-intersections/.

Abbreviations and Definitions

Abbreviation	Definition
AASHTO	American Association of State Highway and Transportation Officials
API	Application Programming Interface
ATC	Advanced Transportation Controller
CI	Connected Intersection
CTSCP	Caltrans Traffic Signal Control Program
CV	Connected Vehicles
CVAD	Connected Vehicle Application Development
GID	Geographic Intersection Description
GNSS	Global Navigation Satellite Systems
IOO	Infrastructure Owner Operator
ITE	Institute of Transportation Engineers
MMITSS	Multimodal Intelligent Traffic Signal System
MRP	MMITSS Roadside Processor
NEMA	National Electrical Manufacturers Association
OBU	On-Board Unit
RSU	Roadside Unit
RTCM	Radio Technical Commission for Maritime Services
SDO	Standards Development Organization
SPaT	Signal Phase and Timing
UDP	User Datagram Protocol
V2I	Vehicle-to-Infrastructure
WAVE	Wireless Access in Vehicular Environments
WSM	WAVE Short Message

1 Introduction

Signal Phase and Timing (SPaT) message is one type of the primary vehicle-to-infrastructure (V2I) messages that are broadcasted by a roadside unit (RSU) installed at a connected intersection (CI). Other types of RSU broadcast V2I messages include MAP/GID (Geographic Intersection Description) message and RTCM Corrections message for differential GNSS services.

The SPaT message defines the current intersection signal light phases (Ref. [1]). The current state of all lanes at the intersection are provided, as well as any active preemption or priority.

Sponsored by USDOT, the Standards Development Organizations (SDOs), including AASHTO, ITE, NEMA and SAE International, developed and published a RSU Standard (Ref. [2]) and an Implementation Guide (Ref. [3]) that define the key capabilities and interfaces which a connected intersection must support to ensure interoperability for state and local infrastructure owner/operators (IOOs).

This user guide describes procedures to install and configure a SPaT application that interfaces with a Caltrans 2070 signal controller and a RSU to broadcast SPaT messages.

Figure 1 illustrates the CV roadside equipment for SPaT broadcasts, including:

- A *CTSCP Processor* that hosts Caltrans traffic signal control program (CTSCP) for the Mode 2070 ATC controller and controls the traffic.
- A *CV Roadside Processor* that hosts the SPaT application, which receives SPaT data from the *CTSCP Processor* via UDP, generates SAE J2735 SPaT message, and sends SPaT immediate forward message (IFM) to the *RSU* via UDP.
- An *RSU* that wirelessly transmits SPaT WAVE short message (WSM) to connected vehicles (e.g., on-board units).

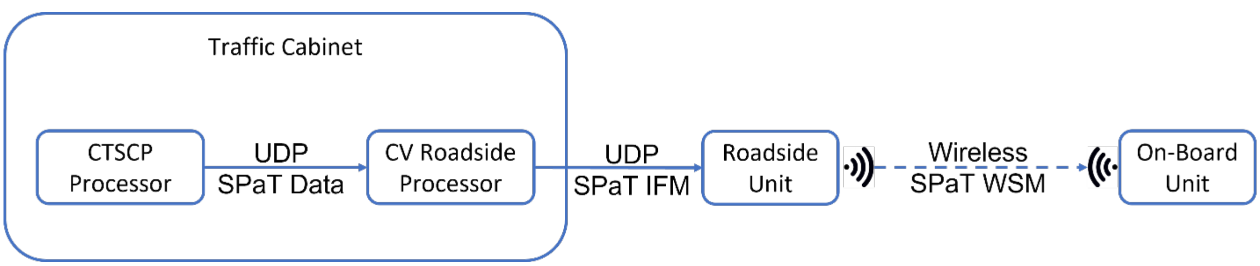


Figure 1 CV Roadside Equipment for SPaT Broadcasts

The CV roadside processor can be a standalone edge Linux computer or a Linux CPU module of a dual-processor ATC controller. Table 1 lists the operating system distribution that have been tested to support the SPaT application.

Table 1 Supported Operating System

Operating System Distribution	Example	Installation File
Ubuntu Linux 5.4.0-91-generic x86_64	MMITSS Roadside Processor	*spat.ubuntu-20.04.tar.gz*
Debian Linux 4.9.0-8-amd64 x86_64	MH Corbin devices	*spat.debian-9.13.tar.gz*
PowerPC Linux 3.12.74 ppc	2070-1C CPU module	*spat.ppc-3.12.tar.gz*

It is recommended to assign *CTSCP Processor* and *RSU* on separate subnets so that they do not interface with each other, to improve security. Table 2 shows an example of subnets and UDP ports setting.

Table 2 Example Subnets and UDP Ports

Device	IP Address	Port	Purpose
RSU	192.168.0.155	1516	Receive SPaT IFM from CV roadside processor
CTSCP Processor	10.20.70.50	12002	Receive *Get* message from CV roadside processor
CV Roadside Processor	192.168.0.165		Communicate with the RSU
	10.20.70.165	12001 & 12002	Receive SPaT data and *Get Response* from CRSCP processor

2 SPaT App Installation

The section describes procedures to install the SPaT App on a CV roadside processor. Installation procedures are the same regardless of the operating system distribution as listed in Table 1. For simplicity, this guide uses *Ubuntu Linux 5.4.0-91-generic x86_64* as an example. To install the SPaT App on other operating system distributions, use the Installation File listed in Table 1 for the corresponding operating system distribution.

1. Login to the CV roadside processor.
2. Create a *spat* user. We recommend avoiding running the SPaT App as *root* whenever possible. You can create a *spat* user to run the SPaT App or use an existing non-root user. The user that runs the SPaT App shall have *sudo* privilege as the App will be configured as a *systemd* service.
3. Logout and re-login as user *spat*.
4. Transfer / copy the *spat.ubuntu-20.04.tar.gz* file to the CV roadside processor using *scp*. The file can be copied to any temporary directory (e.g., */tmp*) or the user's home directory (i.e., */home/spat*).
5. Extract the *spat.ubuntu-20.04.tar.gz* file using the following command:
   `$ sudo tar -xvf spat.ubuntu-20.04.tar.gz -C /`
   The extraction will create directory */home/MMITSS-CA*. It is safe to delete the *spat.ubuntu-20.04.tar.gz* file after the extraction.
6. Change the ownership of directory */home/MMITSS-CA* to user *spat*:
   `$ sudo chown -R spat:software /home/MMITSS-CA`
7. Check the content of directory */home/MMITSS-CA*:
   `$ tree /home/MMITSS-CA`
   It will display the content of directory */home/MMITSS-CA* as shown in Figure 2.

```
spat@drisi-lab:~$
spat@drisi-lab:~$ tree /home/MMITSS-CA
/home/MMITSS-CA
└── mrp
    ├── bin
    │   └── mrpSpat
    ├── conf
    │   └── spat.conf
    ├── lib
    │   ├── libab3418.so.1.0
    │   ├── libasn.so.1.0
    │   ├── libutils.so.1.0
    │   └── libv2x.so.1.0
    ├── logs
    │   └── spat
    └── script
        ├── makelib.sh
        ├── makespat.sh
        ├── mmitss.spat.service
        ├── start-spat.sh
        └── stop-spat.sh

7 directories, 11 files
spat@drisi-lab:~$
```

Figure 2 Content of Directory /home/MMITSS-CA

- Directory *bin* contains the binary SPaT App (i.e., *mrpSpat*).
- Directory *conf* contains the configuration file for the SPaT App.
- Directory *lib* contains four dynamic libraries:
    - *libab3418* – this library provides functions to communicate with the CTSCP processor.
    - *libasn* – this library provides *C* data structures converted from the SAE J2735 ASN.1 file, using an open source ASN.1 Compiler (https://github.com/vlm/asn1c).
    - *libutils* – this library provides functionality for socket, app configuration, timestamp, and generation of immediate forward messages (IFMs).
    - *libv2x* – this library provides functions to encode and decode SAE J2735 messages.
- Directory *logs/spat* is where the SPaT App log file (*spat.err*) will be stored.
- Directory *script* contains the startup scripts for the SPaT App.

8. Make the SPaT App and script files excitable:
   $ cd /home/MMITSS-CA/mrp
   $ chmod +x bin/*
   $ chmod +x script/*
9. Create symbolic links to dynamic libraries in directory *lib*:
   $ cd /home/MMITSS-CA/mrp/script
   $ ./makelib.sh
   $ tree /home/MMITSS-CA/mrp/lib
   It will display the content of directory */home/MMITSS-CA/mrp/lib* as shown in Figure 3.

```
spat@drisi-lab:~$
spat@drisi-lab:~$
spat@drisi-lab:~$
spat@drisi-lab:~$
spat@drisi-lab:~$
spat@drisi-lab:~$
spat@drisi-lab:~$
spat@drisi-lab:~$ tree /home/MMITSS-CA/mrp/lib
/home/MMITSS-CA/mrp/lib
├── libab3418.so -> libab3418.so.1.0
├── libab3418.so.1 -> libab3418.so.1.0
├── libab3418.so.1.0
├── libasn.so -> libasn.so.1.0
├── libasn.so.1 -> libasn.so.1.0
├── libasn.so.1.0
├── libutils.so -> libutils.so.1.0
├── libutils.so.1 -> libutils.so.1.0
├── libutils.so.1.0
├── libv2x.so -> libv2x.so.1.0
├── libv2x.so.1 -> libv2x.so.1.0
└── libv2x.so.1.0

0 directories, 12 files
spat@drisi-lab:~$
```

Figure 3 Content of Directory /home/MMITSS-CA/mrp/lib

10. Change the User and Group to run the SPaT App.
    The *systemd* unit file of the SPaT App is */home/MMITSS-CA/mrp/script/mmitss.spat.service*. The default User and Group to run the SPaT App are shown in Figure 4.

```
[Unit]
Description=MMITSS-CA SPAT Service
After=network.target

[Service]
WorkingDirectory=/home/MMITSS-CA/mrp
ExecStart=/home/MMITSS-CA/mrp/script/start-spat.sh &
ExecStop=/home/MMITSS-CA/mrp/script/stop-spat.sh
Restart=on-abnormal
User=spat
Group=software

[Install]
WantedBy=multi-user.target
```

Figure 4 SPAT Systemd Unit File - mmitss.spat.service

    To change the User and Group to run the SPaT App, use a text editor to open file *mmitss.spat.service*, modify User and Group, and save the changes.

11. Create a *systemd* service to automatically start the SPaT App on boot:
    $ cd /home/MMITSS-CA/mrp/script
    $ ./makespat.sh

To check the status of *mmitss.spat.service*:

$ systemctl status mmitss.spat.service

It will display the status of *mmitss.spat.service* as shown in Figure 5.

```
spat@drisi-lab:~$
spat@drisi-lab:~$
spat@drisi-lab:~$
spat@drisi-lab:~$
spat@drisi-lab:~$
spat@drisi-lab:~$
spat@drisi-lab:~$
spat@drisi-lab:~$
spat@drisi-lab:~$
spat@drisi-lab:~$
spat@drisi-lab:~$
spat@drisi-lab:~$
spat@drisi-lab:~$
spat@drisi-lab:~$
spat@drisi-lab:~$
spat@drisi-lab:~$ systemctl status mmitss.spat.service
● mmitss.spat.service - MMITSS-CA SPAT Service
     Loaded: loaded (/etc/systemd/system/mmitss.spat.service; enabled; vendor preset: enabled)
     Active: inactive (dead)
spat@drisi-lab:~$
spat@drisi-lab:~$
spat@drisi-lab:~$
spat@drisi-lab:~$
spat@drisi-lab:~$
```

Figure 5 Status of mmitss.spat.service

12. (Optional) Delete the no-longer in use script files:

    $ cd /home/MMITSS-CA/mrp/script

    $ rm makelib.sh makespat.sh

Installing the SPaT App has completed, we are ready to configure the SPaT App.

3 SPaT App Configuration

The configuration file of the SPaT App is */home/MMITSS-CA/mrp/conf/spat.conf.*Content of *spat.conf* is shown in Figure 6, with required configuration changes marked in ▭.

```
# This provides parameters and socket configurations for MRP_SPaT (Signal Phase and Timing)
application

# parameters:
STRING_PARAMETERS    # format: variable_name  variable_value
logPath      /home/MMITSS-CA/mrp/logs/spat
refId      1000  ①
END_STRING_PARAMETERS

INTEGER_PARAMETERS  # format: variable_name  variable_value
signature   0    ② # 1 = enable SCMS message signing, otherwise disable (default 0)
encryption  0    ③ # 1 = enable message encryption, otherwise disable (default 0)
END_INTEGER_PARAMETERS

# socket configuration
SOCKETS # (IPv4 UDP) format: communication component listen_IP listen_port send_IP send_port
radio   0.0.0.0        0      192.168.0.155 1516   ④
SPAT1  10.20.70.165 12001     0.0.0.0        0
SPAT2  10.20.70.165 12002     10.20.70.50    12002 ⑥
END_SOCKETS             ⑤
```

Figure 6 SPaT App Configuration File – spat.conf

The default configuration parameters, as shown in Figure 6, are:

- SPaT *IntersectionReferenceID – refId = 1000* ①
- RSU not to sign transmitted messages – *signature = 0* ②
- RSU not to encrypt transmitted messages – *encryption = 0* ③
- RSU's IP address – *192.168.0.155* ④
- CV roadside processor's IP address – *10.20.70.165* ⑤
- *CTSCP* processor's IP address – *10.20.70.50* ⑥
- *SPAT1* UDP port number – *12001* ⑤
- *SPAT2* UDP port number – *12002* ⑤& ⑥

3.1 Record IP Addresses and UDP Port Numbers

Take note of local IP address of deployed CV devices: RSU ④, CV roadside processor⑤, and *CTSCP* processor⑥; *SPAT1* and *SPAT2* UDP port numbers ⑤& ⑥; as well as SPaT *IntersectionReferenceID* ①.

It is assumed that the MAP message is stored on the RSU and configured via the RSU's *store-and-repeat* interface (see Ref. [2]). SPaT *IntersectionReferenceID* should be set as the same as MAP *IntersectionReferenceID*.

3.2 Modify SPaT App Configuration File

Use a text editor to open file */home/MMITSS-CA/mrp/conf/spat.conf* and apply the following changes:

(1). Change the value of *refId* to MAP *IntersectionReferenceID* ①.
(2). If the RSU is going to sign transmitted messages, change the value of *signature* to 1②.
(3). If the RSU is going to encrypt transmitted messages, change the value of *encryption* to 1③.
(4). Change RSU's IP address④.
(5). Change CV roadside processor's IP address and port numbers to receive messages from the *CTSCP* processor⑤.
(6). Change *CTSCP* processor's IP address and port number to communicate with the CV roadside processor⑥.

Save the changes.

3.3 Open Firewall Ports for Incoming Traffic on the CV Roadside Processor

If firewall is enabled on the CV roadside processor, *SPAT1* & *SPAT2* UDP ports need to be opened in its firewall to allow the SPaT App to receive messages from the *CTSCP* processor. Use the following command to open *SPAT1* & *SPAT2* UDP ports:

```
$ sudo ufw allow 12001:12002/udp
```

3.4 Configure RSU's Immediate Forwarding Interface for SPaT Messages

Refer to RSU's user manual on configuring RSU's immediate forwarding API for SPaT messages:

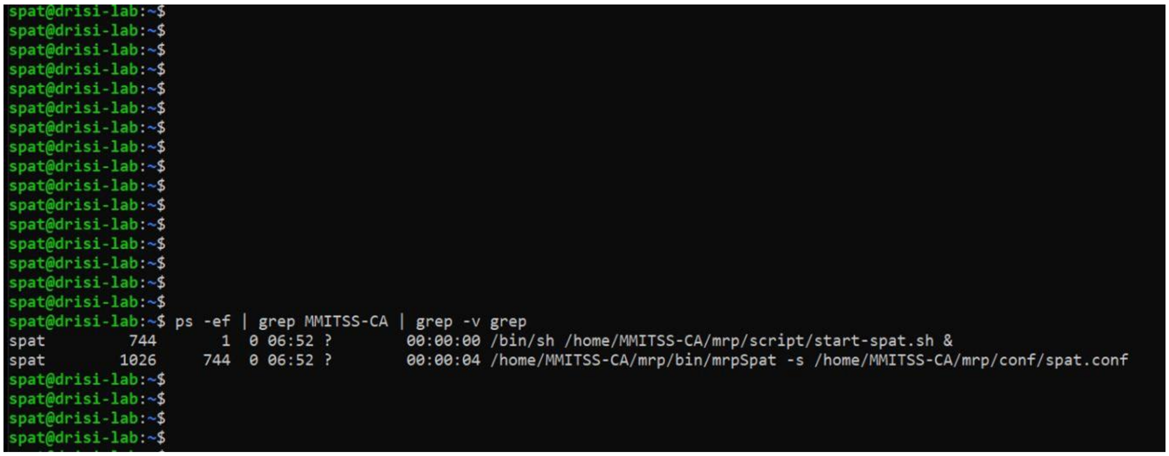
- SPaT PSID: *0x8002* (hex)
- SPaT *DSRCmsgID*: *19*
- SPaT TxChannel: *180*

Configuring the SPaT App has complete, reboot the CV roadside processor.

4 Check Running Status of SPaT App

Running status of SPaT App can be checked with three approaches.

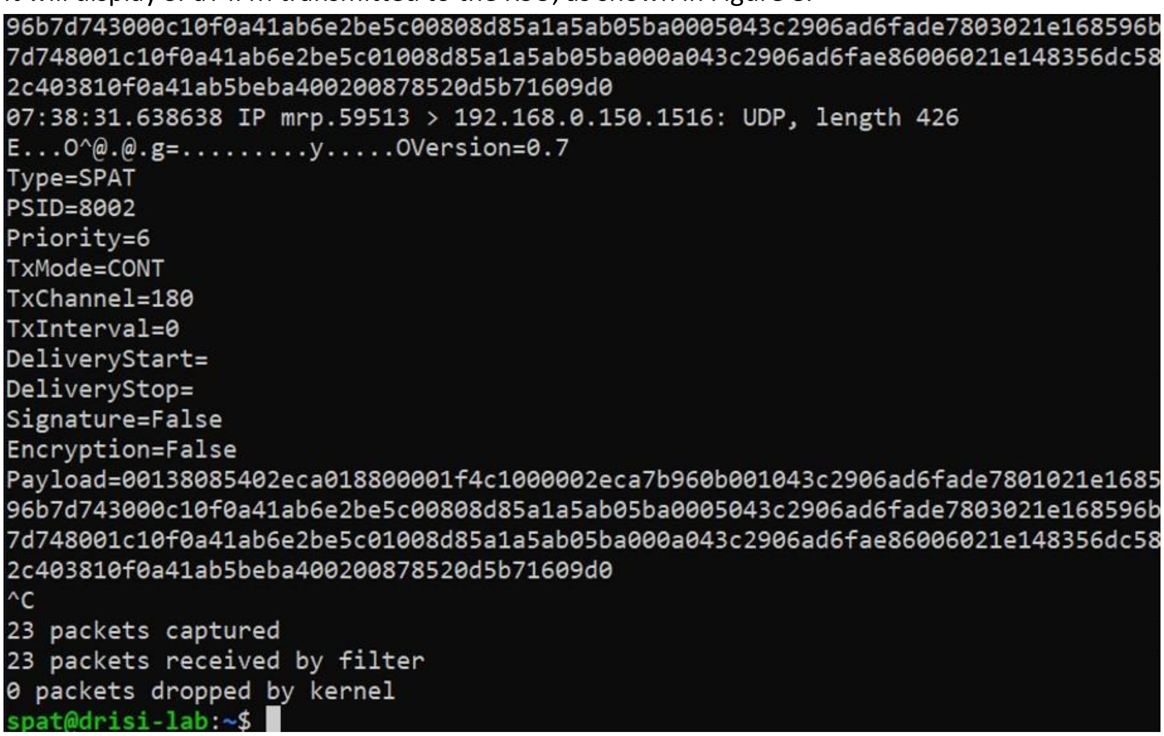
1. Use *ps* command:
   $ ps -ef | grep MMITSS-CA | grep -v grep
   It will display that the two processes, *start-spat.sh* and *rpSpat*, are running, as shown in Figure 7.



```
spat@drisi-lab:~$
spat@drisi-lab:~$
spat@drisi-lab:~$
spat@drisi-lab:~$
spat@drisi-lab:~$
spat@drisi-lab:~$
spat@drisi-lab:~$
spat@drisi-lab:~$
spat@drisi-lab:~$
spat@drisi-lab:~$
spat@drisi-lab:~$
spat@drisi-lab:~$
spat@drisi-lab:~$
spat@drisi-lab:~$
spat@drisi-lab:~$
spat@drisi-lab:~$
spat@drisi-lab:~$ ps -ef | grep MMITSS-CA | grep -v grep
spat        744       1  0 06:52 ?        00:00:00 /bin/sh /home/MMITSS-CA/mrp/script/start-spat.sh &
spat       1026     744  0 06:52 ?        00:00:04 /home/MMITSS-CA/mrp/bin/mrpSpat -s /home/MMITSS-CA/mrp/conf/spat.conf
spat@drisi-lab:~$
spat@drisi-lab:~$
spat@drisi-lab:~$
spat@drisi-lab:~$
```

Figure 7 SPaT Running Processes

2. Use *tcpdump* command (change interface *eth0* to the corresponding RSU subnet):
   $ sudo tcpdump -A -s0 -i eth0 dst port 1516
   It will display SPaT IFM transmitted to the RSU, as shown in Figure 8.



```
96b7d743000c10f0a41ab6e2be5c00808d85a1a5ab05ba0005043c2906ad6fade7803021e168596b
7d748001c10f0a41ab6e2be5c01008d85a1a5ab05ba000a043c2906ad6fae86006021e148356dc58
2c403810f0a41ab5beba400200878520d5b71609d0
07:38:31.638638 IP mrp.59513 > 192.168.0.150.1516: UDP, length 426
E...O^@.@.g=.........y.....OVersion=0.7
Type=SPAT
PSID=8002
Priority=6
TxMode=CONT
TxChannel=180
TxInterval=0
DeliveryStart=
DeliveryStop=
Signature=False
Encryption=False
Payload=00138085402eca018800001f4c1000002eca7b960b001043c2906ad6fade7801021e1685
96b7d743000c10f0a41ab6e2be5c00808d85a1a5ab05ba0005043c2906ad6fade7803021e168596b
7d748001c10f0a41ab6e2be5c01008d85a1a5ab05ba000a043c2906ad6fae86006021e148356dc58
2c403810f0a41ab5beba400200878520d5b71609d0
^C
23 packets captured
23 packets received by filter
0 packets dropped by kernel
spat@drisi-lab:~$
```

Figure 8 SPaT Immediate Forward Messages

3. Use *cat* command:
   $ cat /home/MMITSS-CA/mrp/logs/spat/spat.err
   It will display the logged errors on socket communications and configuring the SPaT App. In normal condition, the error log file is empty, as shown in Figure 9

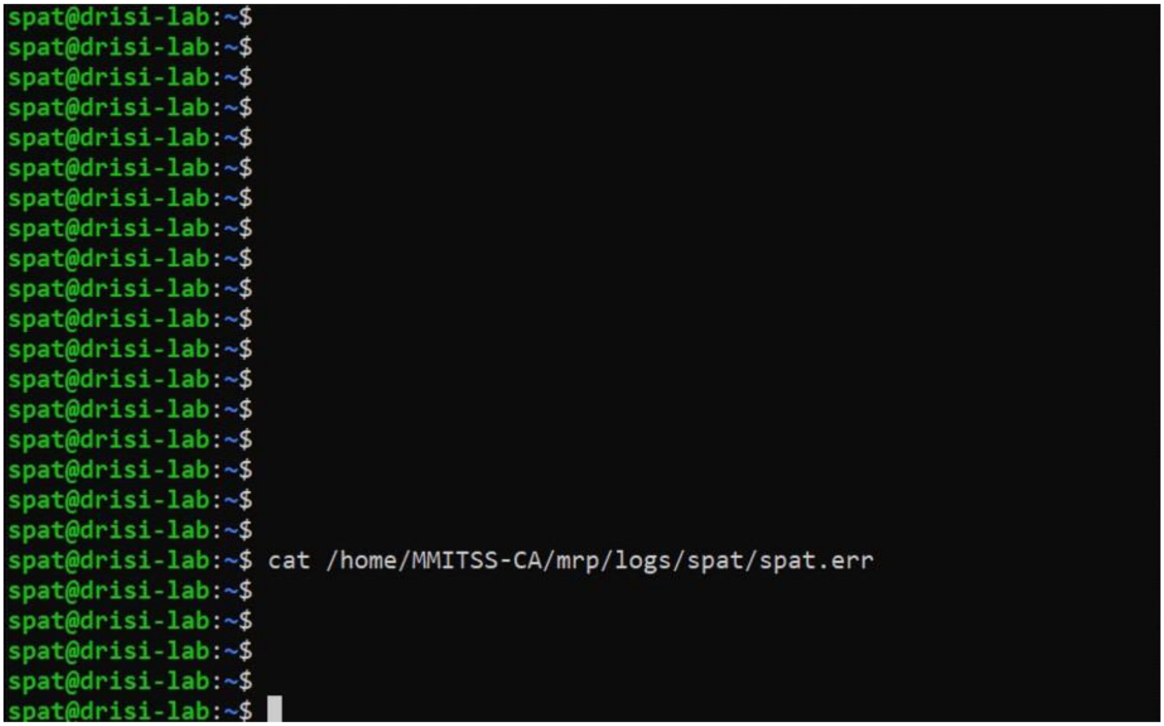


Figure 9 Content of spat.err Log File

5 Manage SPaT Service

Use *systemctl* command to manage the SPaT service.

- To check the status of SPaT service:
  systemctl status mmitss.spat.service
- To stop the SPaT service:
  systemctl stop mmitss.spat.service
- To start the SPaT service:
  systemctl start mmitss.spat.service