One California Deployment Support

Final Report

July 2023

Kun Zhou (Principal Investigator)

California Partners for Advanced Transportation Technology (PATH)

University of California, Berkeley

Alexander Vu, Guoyuan Wu

Nigel Williams, Matthew Barth

Center for Environmental Research and Technology (CE-CERT)

University of California at Riverside

Submitted to

California Department of Transportation under Contract No. 65A0601

DISCLAIMER STATEMENT

Table of Contents

Table of Figures

List of Tables

List of Abbreviations

The abbreviations and acronyms used in this document are defined below.

Abbreviation	Definition
BSM	Basic Safety Message
CV	Connected Vehicle
C-V2X	Cellular Vehicle-to-Everything
DGPS	Differential Global Positioning Systems
DSRC	Dedicated Short Range Communications
EAD	Eco-Approach and Departure
FSP	Freight Signal Priority
GNSS	Global Navigation Satellite System
HSM	Hardware Security Module
IFM	Immediate Forward Message
MMITSS	Multi-Modal Intelligent Traffic Signal System
MOE	Measure of Effectiveness
MRP	MMITSS Roadside Processor
Ntrip	Networked Transport of RTCM via Internet Protocol
OBU	On-Board Unit
PED-SIG	Mobile Accessible Pedestrian Signal System
PSCWT	Pedestrian in Signalized Crosswalk Warning
RSU	Roadside Unit
RTCM	Radio Technical Commission for Maritime Services
RTK	Real-Time Kinematic
SPaT	Signal Phase and Timing
SRM	Signal Request Message
SSM	Signal Status Message
TSP	Transit Signal Priority
V2I	Vehicle-to-Infrastructure
V2V	Vehicle-to-Vehicle
V2X	Vehicle-to-Everything
WAAS	Wide Area Augmentation System
WAVE	Wireless Access in Vehicular Environments

Acknowledgements

The authors thank the California Department of Transportation (Caltrans) for their support, in particular - Jose Camacho Jr., the contract manager for this task, as well as Supanpreet Kaur and Jagtar Dhaliwal, all from the Division of Research, Innovation and System Information (DRISI). The Authors would also like to thank Hector Garcia, Harris Zaw, Melissa Chee, Min Yin Lee, and Einar Acuna from Caltrans District 4 for their support and advice throughout this work. The authors thank Dr. Peggy Wang from UC Berkeley PATH for her help on preparing this document.

1 Introduction

The California Department of Transportation (Caltrans), three of California's largest metropolitan regions, and the University of California have developed a partnership named *One California* with an intention to implement and demonstrate Connected Vehicle (CV) technology that can benefit the traveler, the environment, and the economy of California.

Over the last decade or so, the United State Department of Transportation (USDOT) has been sponsoring research to develop nearly 100 CV applications that have at their core the ability to exchange data wirelessly between vehicles (Vehicle-to-Vehicle or V2V) and between vehicle and road infrastructure (Vehicle-to-Infrastructure or V2I). These nearly 100 applications span six specific categories including V2V Safety, V2I Safety, Agency Data, Environment, Road Weather, Mobility, and Smart Roadside.

This *One California* team is led by Caltrans and supported by three regional transportation partners, including:

- The Metropolitan Transportation Commission of the San Francisco Bay Area (MTC),
- The Los Angeles County's Metropolitan Transportation Authority (LA Metro), and
- The San Diego Association of Governments (SANDAG).

The *One California* team is supported by its academic partners at UC Berkeley PATH and UC Riverside CE-CERT. *One California* seeks to spur innovation, promote economic vitality, and protect precious natural resources through early adoption of CV systems and applications. Specifically, the *One California* team intends to improve traveler safety, mobility, and the productivity of goods movement while improving California's environment through the implementation, demonstration, and evaluation of a variety of previously developed CV applications, at various locations within California.

Specific CV applications under consideration by the *One California* Team include:

- Intelligent Traffic Signal Control – CV can enable Multi-Modal Intelligent Traffic Signal System (MMITSS) to better estimate the traffic condition from the intersection level to the overall network level. Various intelligent traffic control strategies such as section level coordination and control can enable smooth traffic with reduced delays to all travelers.
- Intelligent Signal Priority – Creating a more reliable and on-time transit service and efficient freight is a recurring need of many transportation agencies in California and critical to California's economy and environment. Particularly in urban environments, traffic congestion and traffic signal queues can cause route delays, transit reliability issues, bus bunching, and other issues that lead to unreliable service and longer wait and travel times for transit users. Transit Signal Priority (TSP) and Freight Signal Priority (FSP) that grant priority requests to enrolled transit and freight fleet vehicles, based upon approved

scenarios and in areas where there is the greatest need for improved transit on-time service and freight mobility.

- Mobile Accessible Pedestrian Signal System (PED-SIG) and Pedestrian in Signalized Crosswalk Warning (PSCWT) – Pedestrian safety is a high priority goal in California. *One California* is considering the deployment of the PED-SIG and PSCWT applications to further improve pedestrian safety by delivering safe crossing messages to the visually and hearing-impaired pedestrians. The PED-SIG and PSCWT applications can enhance mobility of all users by extending walk times for pedestrians, issuing alerts to drivers, and reducing incidents between pedestrians and transit vehicles in high-risk areas.
- Connected Eco-Driving – The *One California* team has considered the use of CV applications that are focused on several impactful environmental applications. Some of which, such as the Eco-Approach and Departure (EAD) at signalized intersections, can help to determine the most eco-friendly route (in terms of minimum fuel consumption or emissions) for both passenger and heavy-duty truck participants.

The goals of this project are two folds, including:

- To develop, implement and field test a set of critical CV applications in the California CV Test Bed ([3]) to establish technological foundations for California CV deployment, and
- To support the development of CV in California.

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

- Section 2 – Roadside Unit Upgrade and Test Bed Expansion
  Describes the efforts to upgrade the Roadside Unit (RSU) at eleven (11) existing test-bed intersections to be compliant with the 2016-version of IEEE 1609 family of standards and expand the test bed with five (5) additional intersections.
- Section 3 – Development of CV Applications
  Describes the CV applications developed under this project.
- Section 4 – Prepare California CV Test Bed for Field Testing
  Describes the efforts conducted to prepare the California CV Test Bed to be ready for the system test.
- Section 5 – Field Operation Test and System Performance Evaluation
  Presents field operation test procedure and evaluation results.
- Section 6 – Conclusions and Recommendations
- Section 7 – References

2 Roadside Unit Upgrade and Test Bed Expansion

2.1 Upgrade of Roadside Units

Prior to this project, the California CV Test Bed consists of eleven (11) intersections between Stanford Ave and W Charleston Rd along El Camino Real (green circular symbols in Figure 1). RSU installation at these eleven intersections was completed in June 2014, under Task 2297 – Vehicle-Infrastructure Cooperation Using Dedicated Short-Range Communications (DSRC) ([2]). These DSRC RSUs are in the process of upgrading to Cellular Vehicle-to-Everything (C-V2X) RSUs under Task 3904 – Maintenance, Operations and Enhancement of V2X Communications Infrastructure Phase III.

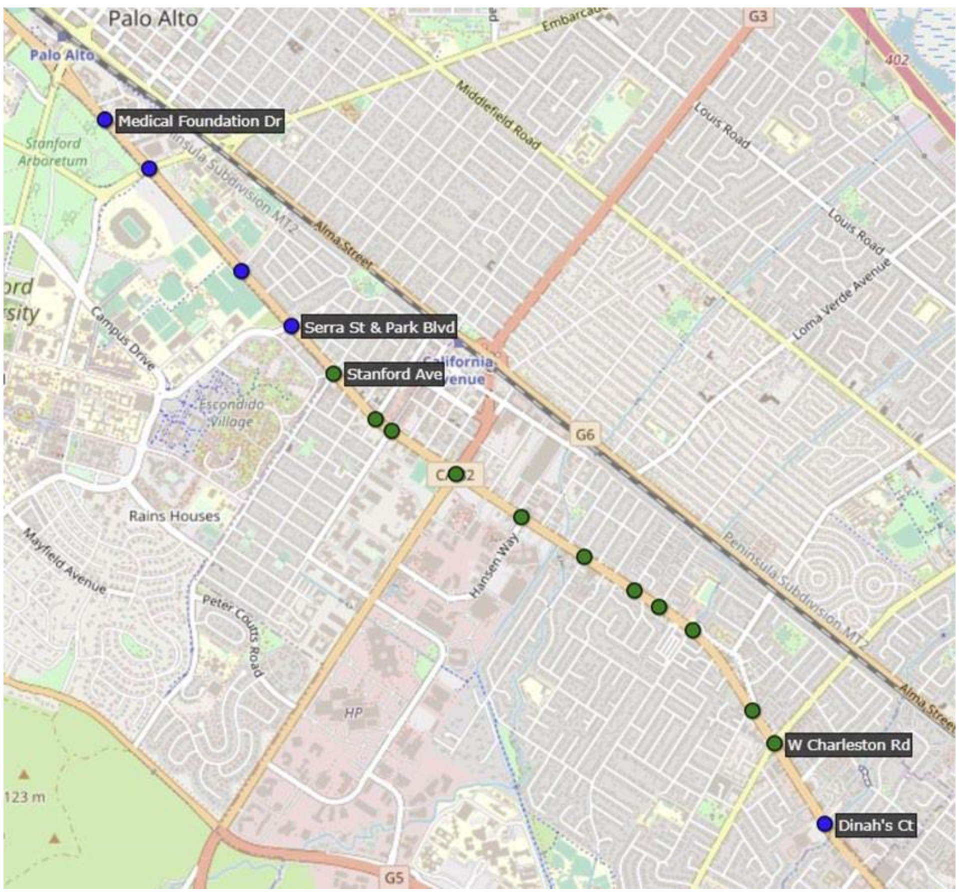


Figure 1 California CV Test Bed (February 2019)

The IEEE 1609 family of standards for Wireless Access in Vehicular Environments (WAVE) defines the architecture, communications model, management structure, security mechanisms and physical access for high speed, short range, and low latency wireless communications in the vehicular environment. The primary architectural components defined by these standards are the On-Board Unit (OBU), Roadside Unit (RSU) and WAVE interface.

In 2016, IEEE published the revision of four (4) IEEE 1609.x standards, including:

- IEEE 1609.2-2016 ([7]) – a revision of IEEE 1609.2-2013, which defines secure message formats and processing for use by WAVE devices,
- IEEE 1609.3-2016 ([6]) – a revision of IEEE 1609.3-2010, which defines the network and transport layer options for the WAVE environment,
- IEEE 1609.4-2016 ([5]) – a revision of IEEE 1609.4-2010, which defines the data link layer of the WAVE communications stack, and
- IEEE 1609.12-2016 ([4]) – a revision of IEEE 1609.12-2012, which describes the use and allocation of identifiers for use by WAVE systems.

Due to the revision of these IEEE 1609.x standards, a 2016-version WAVE device cannot communicate with a pre-2016-version WAVE device. USDOT provided version 4.1 (v4.1) RSUs ([10]) to exchange for the older RSUs installed in the test bed. The v4.1 RSU is IEEE 1609.x-2016 compliant and has a Hardware Security Module (HSM). PATH worked in coordination with Caltrans District 4 maintenance staff swapped the older RSUs with v4.1 RSUs at the existing eleven intersections.

2.2 Test Bed Expansion to Include Five Additional Intersections

To meet the requirement of SPaT Challenge ([8]), Caltrans acquired five additional v4.1 RSUs from USDOT for expanding the test bed from eleven intersections to sixteen intersections (blue circular symbols in Figure 1). Test bed Intersection CV equipment include (see Figure 2):

- A version 4.1 RSU with radio antenna mounted on a mast arm facing El Camino Real traffic,
- A Model 2070E traffic signal controller to replace the existing Model 170E controller,
- A 4G LTE router for mobile backhaul and Local Area Network (LAN), and
- An edge processor (i.e., MMITSS Roadside Processor or MRP) for hosting roadside CV applications.

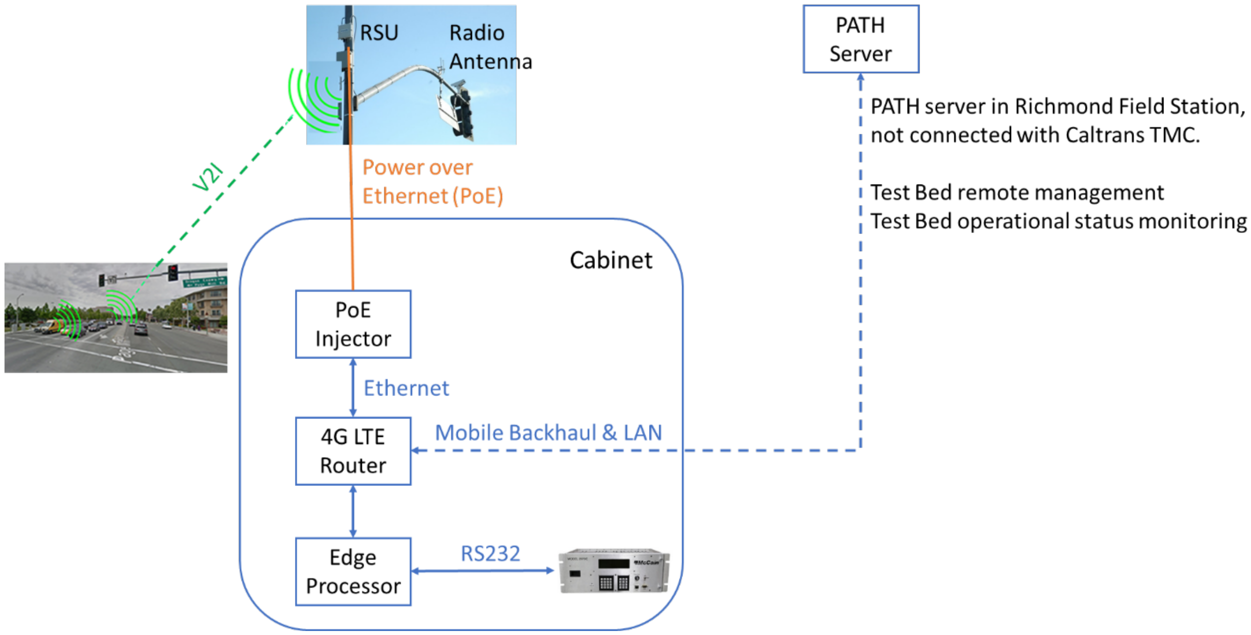


Figure 2 California CV Test Bed System Architecture

The PATH server is in PATH Headquarters at Richmond Field Station (RFS) for test bed remote management and monitoring test-bed operational status via the test-bed website.

PATH conducted field survey and developed a design guidance for installing intersection CV equipment (see Appendix A). PATH worked in coordination with Caltrans District 4 maintenance staff completed the expansion of 5 new intersections.

2.3 Revision of SAE J2735 Standard

In 2016, the SAE International (SAE) also published SAE J2735-201603 ([9]), the fifth edition of the Vehicle-to-Every (V2X) message set dictionary. V2X messages defined in SAE J2735-201603 changed significantly from that defined in SAE J2735-200911, which is the version used in the test bed prior to this project. PATH upgraded the V2X message library for decoding and encoding V2X messages to be compliant with SAE J2735-201603. V2X messages included in the V2X message library include:

- Basic Safety Message (BSM),
- Signal Phase and Timing (SPaT) message,
- MAP message,
- Signal Request Message (SRM), and
- Signal Status Message (SSM).

PATH also recreated SAE J2735-201603 compliant MAP messages for the sixteen test-bed intersections.

3 Development of CV Applications

3.1 Caltrans Traffic Signal Control Program (CTSCP) Enhancements for CV Applications

To support the deployment of CV applications in California, Caltrans Traffic Operations implemented enhancements into Caltrans Traffic Signal Control Program (CTSCP) software. CTSCP CV enhancements include (see Figure 3):

- CV data-based actuations for placing service call/request to the Model 2070E controller,
- Dynamic force-off for changing force-off points (for coordination control) on the fly, and
- Controller to push out SPaT data and coordination parameters for generation of SAE J2735 SPaT messages.

PATH worked in coordination with Caltrans Traffic Operations to test the prototype of CTSCP enhancements, revise the enhancements, and finalize the enhancements.

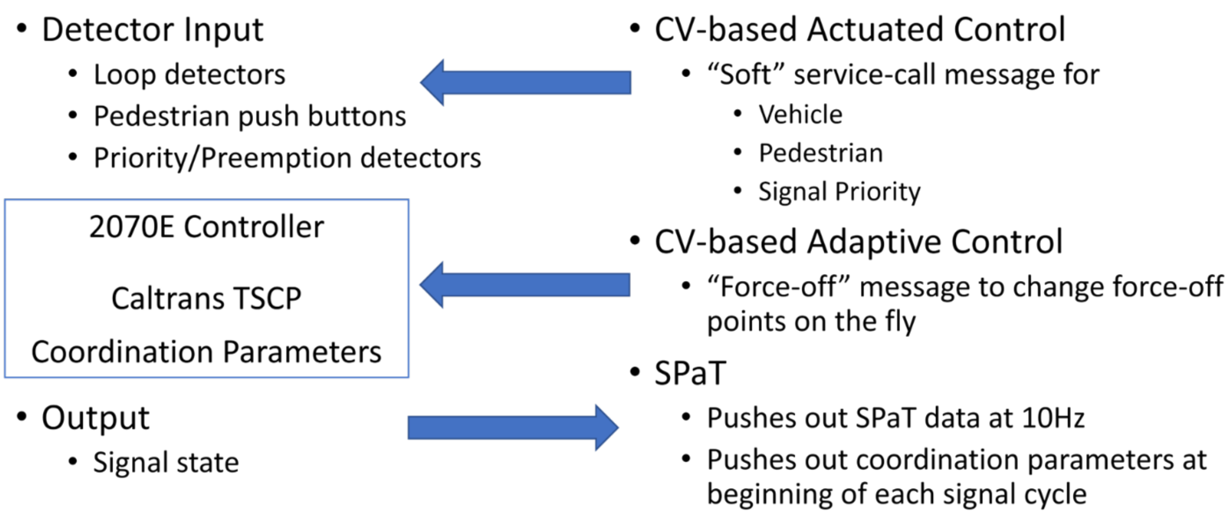


Figure 3 CTSCP Enhancements for CV Applications

3.2 SPaT Application

As shown in Figure 3, Model 2070E controller pushes out SPaT data to the MRP at 10 Hz. The SPaT data contains the information about active phase and active interval that the controller is currently timing. SAE J2735 SPaT message requires to include state of all permitted phases (vehicles and pedestrians) as well as estimated time-to-change of the state.

PATH developed SPaT processing tool to generate SAE J2735-201603 compliant SPaT messages. SPaT processing steps are illustrated in Figure 4:

1) Model 2070E pushes out SPaT data and coordination parameters to the MAP,
2) The MRP determines state of all permitted phases and estimate phase time-to-change,
3) The MRP encodes SPaT payload using the V2X message library,

4) The MRP generates SPaT Immediate Forward Message (IFM) and send it to the RSU,
5) The RSU broadcasts SPaT message over its radio interface to OBUs.

The IFM file format is defined in Appendix C in USDOT RSU Specification v4.1.

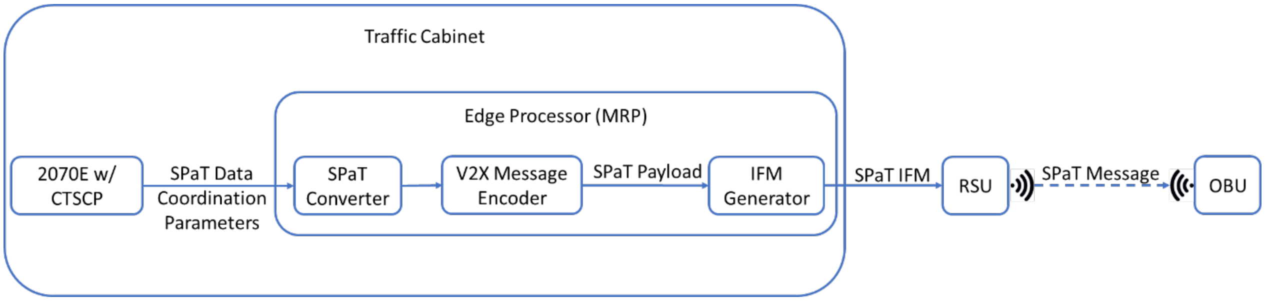


Figure 4 SPaT Message Processing Flow

3.3 MAP Engine Library

The MAP Engine library provides functions to locate a vehicle (i.e., BSM) on the MAP to determine the approaching intersection and lane-of-travel. PATH improved the algorithms of the MAP Engine library and made the library compliant with SAE J2735-201603. For testing and validating the new algorithms, PATH collected GPS traces with an OBU and took notes of the lanes-of-travel and compared with the output of an offline version of the MAP Engine library.

3.4 Mobile Accessible Pedestrian Signal System (PED-SIG)

PATH worked in coordination with Savari Inc. (now Harman Automotive) to develop PED-SIG application for the California CV Test Bed, by leveraging Savari SmartCross application. As illustrated in Figure 5, the Savari Pedestrian Application Server exchanges data with the Savari SmartCross mobile app and the intersection MRP mobile networks. Based on mobile user's position and intent to cross, the Savari Pedestrian Application Server sends a pedestrian SRM to the intersection MAP; the MAP places a pedestrian service request to the Model 2070E controller; and the 2070E controller servers the pedestrian request.

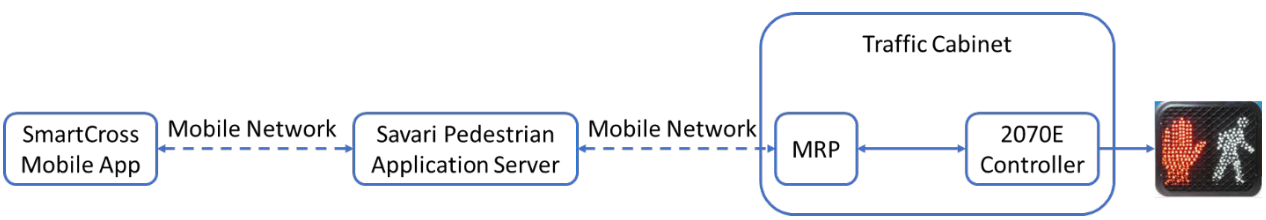


Figure 5 Data Flow of PED-SIG Application

3.5 Eco-Approach and Departure (EAD)

UC Riverside CE-CERT developed a refined set of in-situ real-world EAD algorithms for a variety of vehicle types, including a light-duty vehicle and a heavy-duty class 8 truck. The EAD algorithm deals with preceding vehicles and has a new trajectory planning methodology. CE-CERT also developed a new EAD application tailored to the transit bus. This new application has been coded in the DriverModel.dll through Application Programming Interfaces in VISSIM (a microscopic traffic flow simulation software). In addition, a machine-learning based module which mainly relies on inputs from on-board sensors (e.g., Radar) to predict the speed trajectory of preceding vehicle has been developed and verified in numerical simulation. This module was integrated into the new EAD algorithm for enhancement.

These new algorithms are tested primarily in microscopic traffic simulation environment. UC Riverside planned limited on-road testing in Riverside.

3.6 RTCM Position Correction

PATH and CE-CERT jointly developed broadcasting of RTCM (Radio Technical Commission for Maritime Services) Corrections messages in the California CV Test Bed.

CE-CERT developed an architecture for broadcasting RTCM position corrections messages using the Networked Transport of RTCM via Internet Protocol (Ntrip) to relay correction data from a referenced base station to the RSU and tested the architecture at CE-CERT lab. CE-CERT provided PATH an instruction regarding the implementation of Ntrip using open source Ntrip Server and Ntrip Caster packages. CE-CERT also provided PATH with a Python Ntrip Client program.

PATH obtained a Ntrip account from Berkeley Seismology Lab for accessing real-time RTCM correction data stream from the JRSC station ([1]). The JRSC station is about 5 miles west of the test bed and is managed by Berkeley Seismology Lab. PATH developed a C++ Ntrip Client program to receive data stream from the JRSC station, encode correction data into SAE J2735 Corrections message, and sends the message to test-bed intersections for broadcasting at the RSU. RTCM processing steps are illustrated in Figure 6. The California CV testbed started broadcasting RTCM Corrections messages in December 2017.

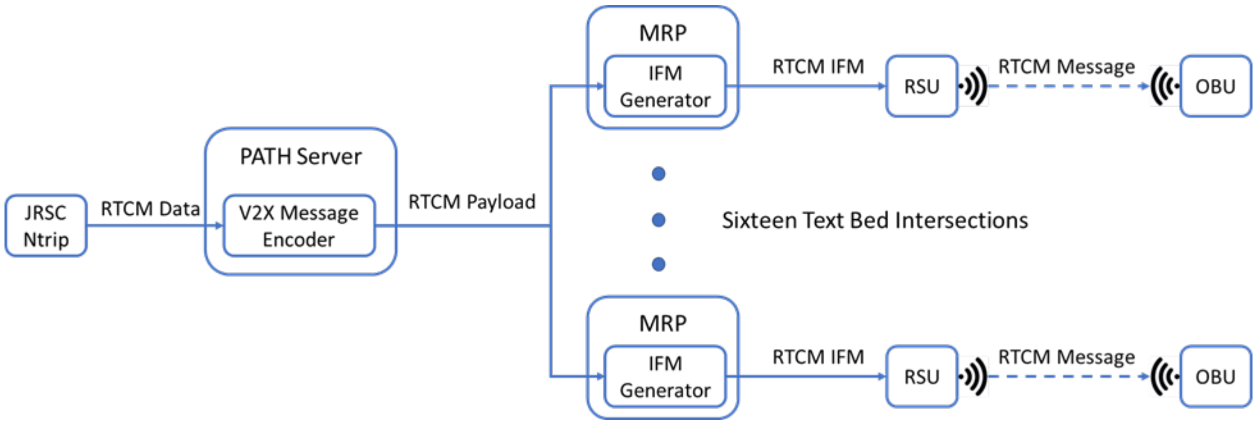


Figure 6 RTCM Message Processing Flow

4 Prepare California CV Test Bed for Field Testing

4.1 Installation of MMITSS Software in California CV Test Bed

PATH worked in coordination with Caltrans District 4 traffic engineers to upload the finalized CTSCP firmware with CV enhancements into field 2070E controllers and upload MMITSS software with developed applications described in Section 3 into field MRPs. PATH conducted communication tests between the MRP and the 2070E controller at each test-bed intersection.

4.2 Field Integration and Operational Testing in the California CV Test Bed

PATH conducted field integration and operational tests using a testing vehicle equipped with an OBU. The objective of the tests is to ensure that communications among MRP, RSU, OBU, and Model 2070E controller function for the specific applications described in Section 3.

PATH also conducted tests of communications between the MRP and the PATH server. PATH found out the Internet connectivity provided by the 3G router that is used for intersection communications backhaul is not reliable and not stable. PATH acquired 4G routers and worked in coordination with Caltrans District 4 traffic engineers to replace the router and installed router antenna at each test-bed intersection.

5 Field Operation Test and System Performance Evaluation

5.1 MMITSS and Signal Priority

Five passenger cars temporarily instrumented with an OBU were used as testing vehicles. The five OBUs include 2 Savari MobiWave units and 3 Arada LocoMate mini 2 units. Each OBU is mounted on the vehicle's dashboard and is programed to be either a transit vehicle, a freight vehicle, or a general car. A transit or freight vehicle can request TSP or FSP from test-bed intersections. A general car is not illegible for priority and does not request signal priority.

5.1.1 Test Procedure

A field-testing plan was developed to provide the experimental protocol for MMITSS field testing and data collection at the California CV Test Bed. The drivers, including PATH researchers and Caltrans employees, were instructed to travel at a speed that is judged to be representative of the speed of general traffic at the time. Vehicle trajectory data were stored on the OBU. Priority granting data were stored on the MRP. These data were retrieved after the field operation test and were used for system performance evaluation.

To collect the "before" data, the five vehicles were driven to keep circling around the test bed along El Camino Real, with priority request turned off. Another set of tests were conducted with the same vehicle settings but with priority request function tuned on to collect "after" data.

5.1.2 Test Results

Table 1 summarizes the sample size of collected vehicle trips by mode.

Table 1 Sample Size of Test Trips

Mode	No. of	No. of "Before" Trips (Without Priority)		No. of "After" Trips (With Priority)	
		Southbound (SB)	Northbound (NB)	Southbound (SB)	Northbound (NB)
Transit	2	14	16	18	18
Freight	2	19	20	17	18
Car	1	7	9	3	4

Table 2 shows a comparison between "before" and "after" scenarios by measure of effectiveness (MOE). As shown in Table 2, signal priority helped to reduce 7.3% on number of stops at red signal, 7.4% on trip time, and 12.5% on stopped time at red signal.

Table 2 Summary of Benefits of Priority Treatments

Measure of Effectiveness (MOE)	Without Priority			With Priority			Improvement (Percentage)
	SB	SB	NB	SB	SB	NB	
No. of Trips	33	36	69	35	36	71	N/A
No. of Stops at Red Signal	3.9 ± 1.5			3.6 ± 1.4			7.3%
Total Stopped Time at Red Signal (Seconds)	132.1s ± 74.2s			115.7s ± 54.5s			12.5%
Total Trip Time (Seconds)	386.4s ± 82.1s			358.1s ± 67.6s			7.4%

5.2 RTCM Position Correction

A Real-Time Kinematic (RTK) capable Global Navigation Satellite System (GNSS) receiver is required to utilize RTCM corrections. Figure 7 shows a picture of CE-CERT Nissan Altima Test Vehicle with three GNSS antennas (circled in red, from left to right: Trimble, u-blox, and Savari).

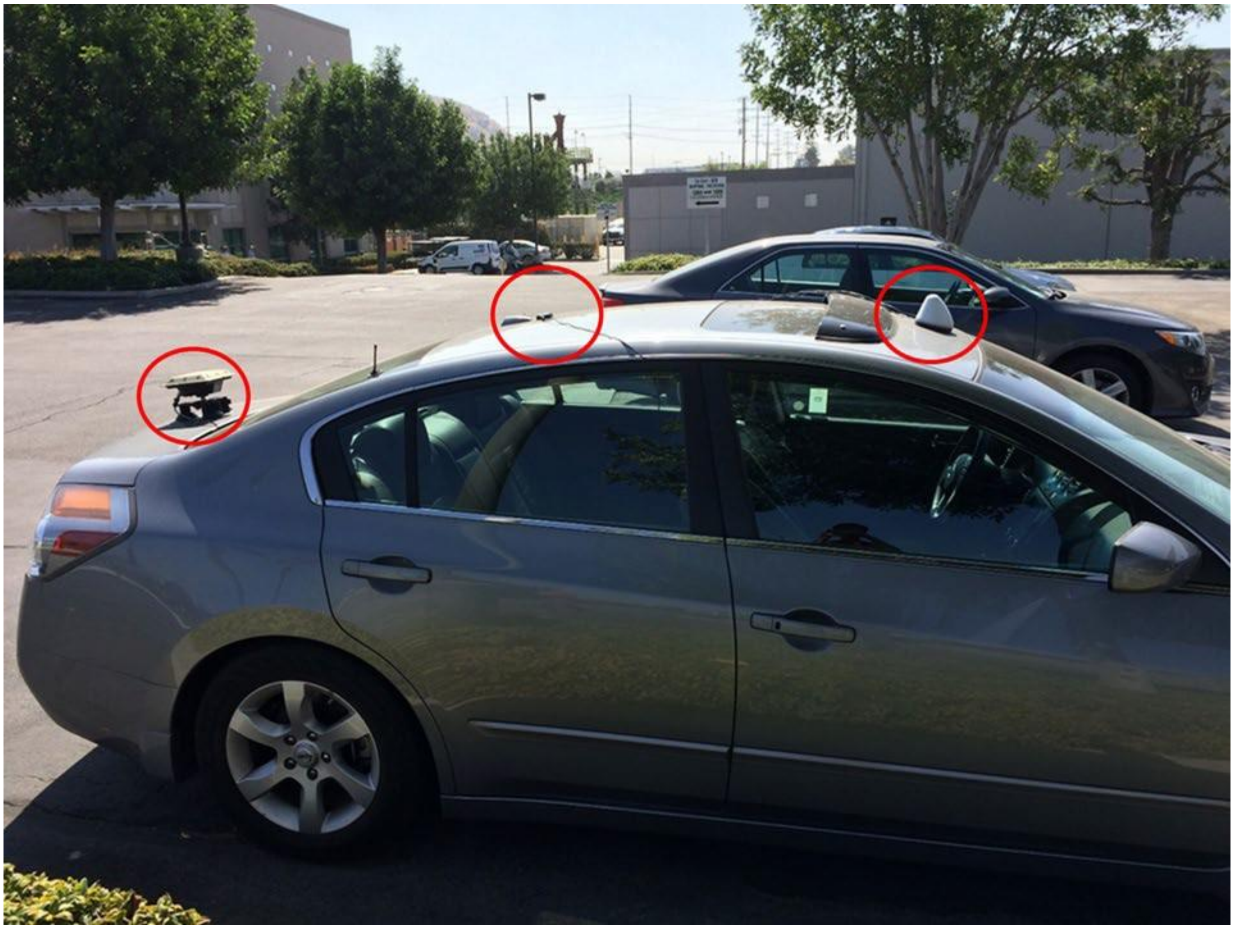


Figure 7 CE-CERT Nissan Altima Test Vehicle and GNSS Antennas

Figure 8 GNSS Receivers (from left to right: Savari, u-blox, and Trimble)

The three GNSS receivers mounted on the CE-CERT test vehicle include (see Figure 8):

- Trimble 5700, a dual-frequency receiver capable of operating in autonomous, Differential Global Positioning Systems (DGPS) (code-differential), or RTK (phase-differential) mode.
- u-blox M8P, a single-frequency receiver capable of operating in autonomous or RTK mode.
- Savari OBU with embedded a Wide Area Augmentation System (WAAS) GPS receiver.

Both the Trimble and u-blox receivers are RTK capable while the Savari GPS receiver is not.

5.2.1 Test Procedure

CE-CERT research engineers drove the test vehicle to the California CV Test Bed and conducted static test (with the vehicle stationary) and dynamic test (drove the test vehicle to keep circling around the test bed along El Camino Real).

5.2.2 Test Results

Figure 9 illustrates the results of the static test in the California CV Test Bed.

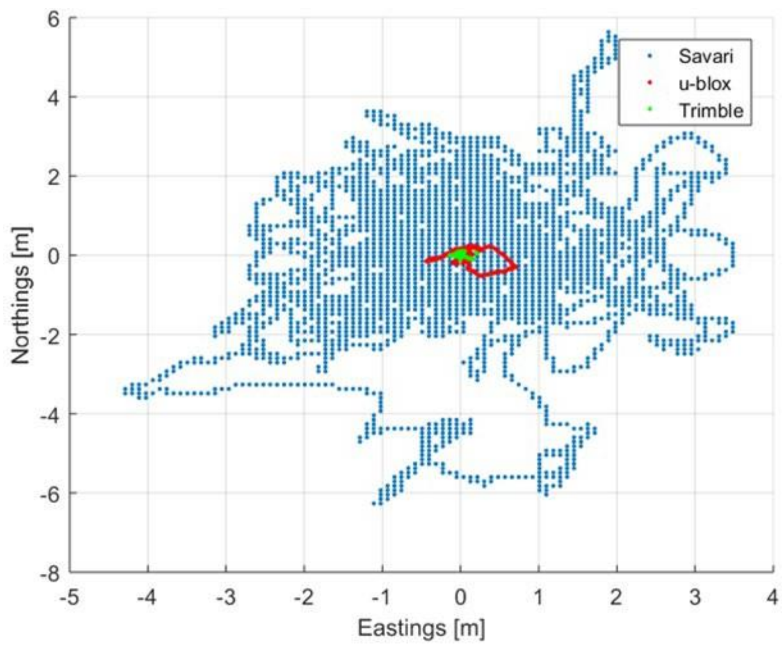


Figure 9 Static Test in the California CV Test Bed

On average, position error for the high-end RTK GNSS receiver (Trimble) is 2 centimeters, 4 centimeters for the low-cost RTK GNSS receiver (u-blox), and 1.88 meters for the WAAS GPS receiver (Savari).

Figure 10 illustrates the results of the dynamic test, using Trimble GPS as the ground truth. It clearly shows that utilizing RTCM corrections can significantly increase the positioning accuracy.

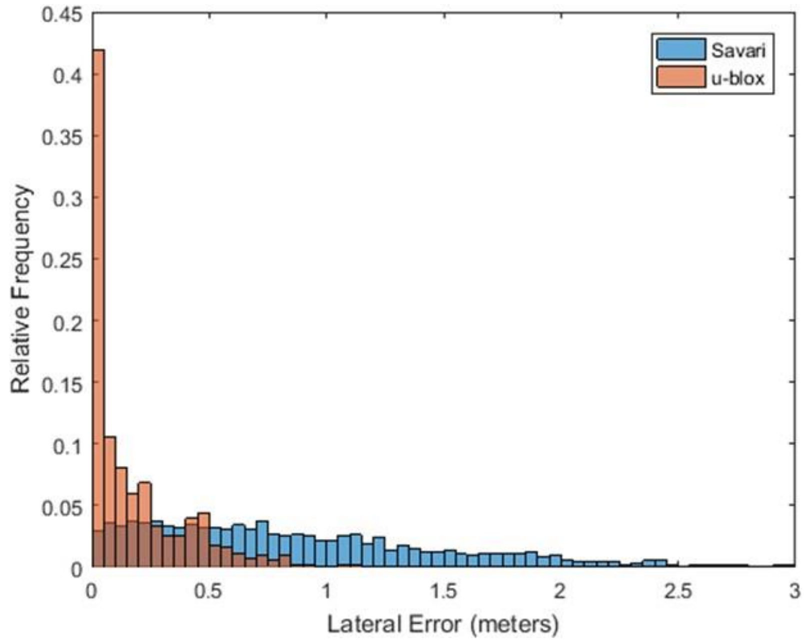


Figure 10 Dynamic Test in the California CV Test Bed

5.2.3 Effectiveness of RTCM Corrections on Lane-Level Vehicle Positioning

To evaluate the effectiveness of RTCM correction on lane-level vehicle positioning, PATH obtained the raw dynamic test data collected in the California CV Test Bed from CE-CERT and conducted the evaluation of the effectiveness of RTCM broadcasts at the application level by using the MAP Engine library to locate the vehicle (i.e., GNSS position estimate) on the MAP and determine vehicle's lane-of-travel, and comparing the performance of correct detection of lane-of-travel with and without RTCM correction.

Figure 11 illustrates an example where the WAAS GNSS provided consistent measurements with the RTK GNN receivers. All three GPS receivers reported the same lane-of-travel. Figure 12 shows an example where the WAAS GNSS reported a wrong lane-of-travel while the RTK GNSS reported the correct lane-of-travel.

(a) Straight through at Maybell Ave (b) Left-turn at Charleston Rd

Figure 11 WAAS GNSS Consistent with RTK GNSS

(a) Straight through at Maybell Ave (b) Left-turn at Charleston Rd

Figure 12 WAAS GNSS not Consistent with RTK GNSS

Figure 13 plots the distribution of vehicle lateral position with respect to the center of the lane-of-travel. It shows the intersection MAP is accurate and the RTK GNSS receivers provide much more reliable (high and narrow peak) and accurate (peak near the center) position estimate than the WAAS GNSS receiver.

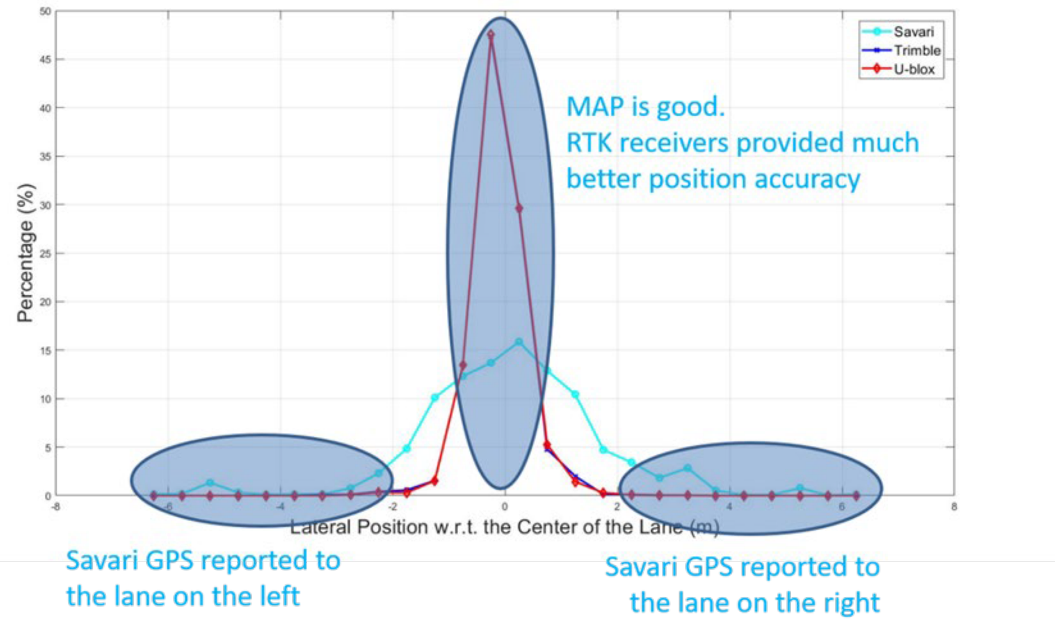


Figure 13 Vehicle Lateral Position with respect to the Lane Center

Figure A.1 compares the rate of correct lane detection between RTK GNSS and WAAS GNSS receivers. The RTK GNSS receivers achieved 100% correct detection of lane-of travel while the WAAS GNSS (without RTCM corrections) achieved 86% correct detection.

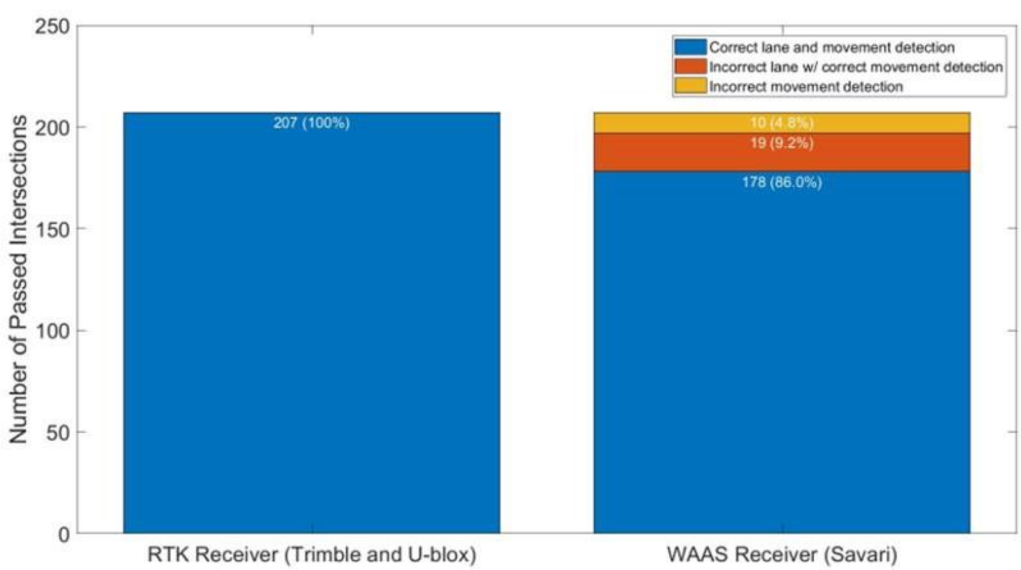


Figure 14 Rate of Correct Lane Detection

6 Conclusions and Recommendations

6.1 Conclusions

The work throughout this project showcased that:

- CV-based signal priority helped to reduce 7.3% on number of stops at red signal, 7.4% on trip time, and 12.5% on stopped time at red signal; and
- RTCM corrections increased correct detection rate of lane-of-travel from 86% without correction to 100% with correction.

The California CV Test Bed (including hardware and software) is now compliant with the latest IEEE 1608 family of standards as well as V2X message standard. In addition, expanding the test bed with five more intersections made California complete the SPaT Challenge.

6.2 Recommendations

CTSCP enhancements for CV applications, particularly the dynamic force-off points feature, have made the CTSCP capable of applying more advanced traffic signal control and priority control schemes that adaptive to the prevailing traffic conditions. However, it still needs a long time for connected vehicles to reach a high enough penetration rate so that CV data-based signal performance measures could be realistic. Research on utilizing infrastructure-based traffic detection and classification data to develop and test adaptive control schemes is needed. Alternative approaches, such as cloud-based vehicle probe data from mobile phones, need to be investigated to fill the data gap.

In the current implementation of RTCM broadcasts, the base reference station is pre-selected. To deploy RTCM broadcasts in California, research is needed to develop a RTCM broadcasts system that can automatically select the best reference station based on RSU position and automatically switch to an alternative reference station when the primary reference station has a temporary failure. In addition, network RTK can provide wider coverage area than single base RTK. Research is needed to investigate approaches to fuse single base RTK with network RTK to provide most cost-effective RTCM corrections.

This project conducted limited testing of PED-SIG (see Section 3.4) at RFS intersection and at the California CV Test Bed. When the Savari SmartCross mobile app can generate a pedestrian crossing request and once executed, PED-SIG can provide added convenience for pedestrians and potentially reduce pedestrian waiting time at a signalized intersection. However, there were more times that the app could not be able to generate a crossing request than it does, mainly due to positioning accuracy provided by mobile phone. Research is needed to investigate the effectiveness of utilizing RTCM corrections on mobile apps to improve positioning of bicyclists and pedestrians and countermeasures to improve their safety.

7 References

[1] Berkeley Seismology Lab. (2022). *JRSC Station*. Retrieved from http://seismo.berkeley.edu/station_book/jrsc.html

[2] California PATH. (2015). *Vehicle-Infrastructure Cooperation Using Dedicated Short Range Communications (DSRC) Final Report.*

[3] Caltrans and California PATH. (2022). *California Connected Vehicle Test Bed*. Retrieved from https://caconnectedvehicletestbed.org/

[4] IEEE Standard Association. (2016). *IEEE Standard for Wireless Access in Vehicular Environments (WAVE) — Identifier Allocations.* IEEE 1609.12-2016.

[5] IEEE Standards Association. (2016). *IEEE Standard for Wireless Access in Vehicular Environments (WAVE) — Multi-Channel Operation.* IEEE 1609.4-2016.

[6] IEEE Standards Association. (2016). *IEEE Standard for Wireless Access in Vehicular Environments (WAVE) — Networking Services.* IEEE 1609.3-2016.

[7] IEEE Standards Association. (2016). *IEEE Standard for Wireless Access in Vehicular Environments—Security Services for Applications and Management Messages.* IEEE 1609.2-2016.

[8] National Operations Center of Excellence. (2022). *SPaT Challenge*. Retrieved from https://transportationops.org/spatchallenge

[9] SAE International. (2016). *Dedicated Short Range Communications (DSRC) Message Set Dictionary.* SAE J2735-201603.

[10] USDOT. (2017). *Dedicated Short-Range Communications Roadside Unit Specifications v4.1.*

Appendix A Design Guidance for Installing Intersection CV Equipment

Appendix A1 Background

The California Partners for Advanced Transportation Technology (PATH) program of the University of California at Berkeley is assisting Caltrans with the installation of electrical equipment at five (5) signalized intersections along El Camino Real 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 five additional intersections, the test bed size will be increased to 16 intersections.

Figure A.1 shows the locations of existing eleven DSRC-equipped intersections (green circular symbols) and six expanding intersections (blue circular symbols).

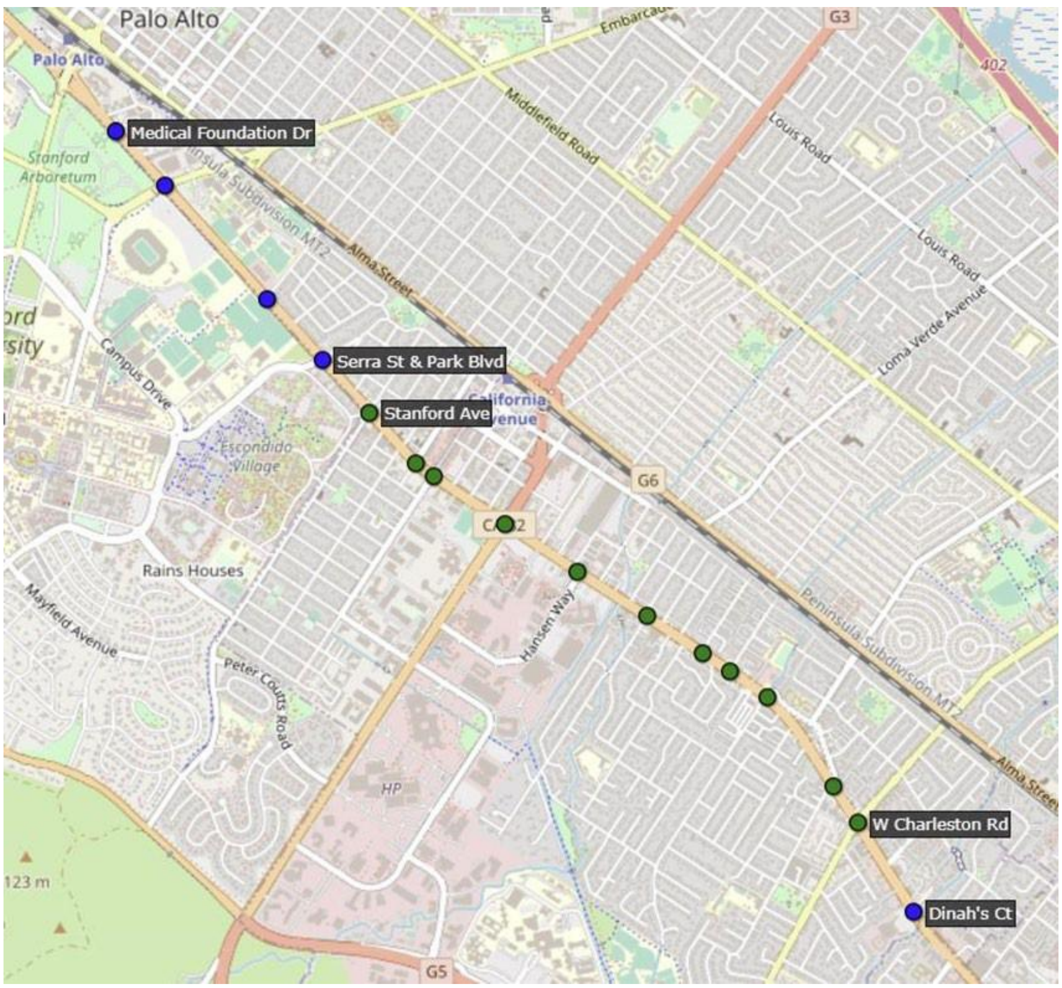


Figure A.1 Palo Alto CV Test Bed Intersections (Green – Existing, Blue – Expanding)

Appendix A2 Scope of Work

Figure A.2 shows a generic schematic for a typical installation. Each installation 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.

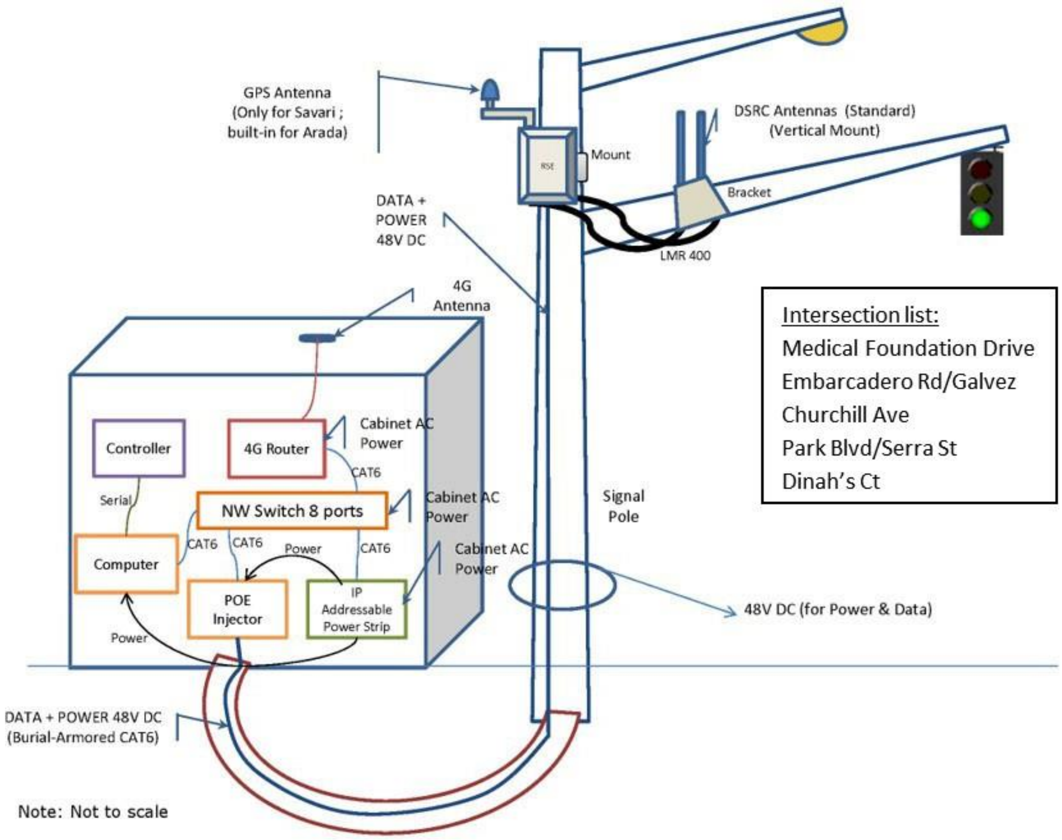


Figure A.2 Installation schematic

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

1) Procure specified CV and ancillary equipment (see Table A.1 and Table A.2).
2) Produce brackets to hold antennas (see Appendix A6 for details).
3) Attach a 2-inch flexible conduit from an opening on the host pole near the signal head to the RSU.
4) Attach RSU to the host pole (see Appendix A7 for picture and dimension of the RSU).
5) Attach antenna bracket to the mast arm.
6) Run low-loss, braided coax cables between the RSU and antenna.
7) Place antenna on the bracket attached to the mast arm.
8) Run a PoE cable from the traffic control cabinet to the RSU through Caltrans signal conduits, the host pole, and the 2-inch flexible conduit.
9) Install a new auxiliary cabinet alongside the existing traffic signal controller cabinet if one does not exist.
10) Install CV equipment (see Table A.1 and Table A.2) in auxiliary cabinet.

11) Install a 4G antenna on top of the cabinet and connect it to the 4G router inside the auxiliary cabinet.
12) Connect all the cables including those inside the cabinet and plug in all the devices.
13) Weatherproof all the connections.
14) Support an end-to-end acceptance test at each site.

Appendix A3 List of Signalized Intersections and Roadside CV Equipment

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

Table A.1 CV Equipment needed for each installation

Site #	Intersection Name	RSU	DSRC Antenna	Edge Processor	4G Router w/ Antenna	2070E w/ TSCP v2.21	Auxiliary (side) Cabinet
1	Medical Foundation Dr	1	1	1	1	1	1
2	Embarcadero Rd	1	1	1	1	1	Replace fan
3	Churchill Ave	1	1	1	1	1	Replace fan
4	Park Blvd/Serra St	1	1	1	1	1	1
5	Dinah's Ct	1	1	1	1	1	0
Total		**5**	**5**	**5**	**5**	**5**	**2**

Note: The RSUs and PoE cable, DSRC antennas and 4G antennas, 4G routers and edge processor computers will be furnished by California PATH and installed by Caltrans with assistance from PATH. The five new 2070E controllers will be furnished and installed by Caltrans. Each of the new 2070E controllers will need to have TSCP 2.2.1 firmware or above and will need a 7B serial card. Caltrans will furnish and install the auxiliary cabinet at Medical Foundation Dr and Park Blvd/Serra St, and replace the fan of the existing auxiliary cabinet at Embarcadero Rd and Churchill Ave.

Appendix A4 List of Additional Equipment

The following equipment and supplies with stated specification, lengths, and quantities will be provided by PATH for each installation. Caltrans will install all other equipment with PATH assistance.

Table A.2 Additional Equipment needed for each installation

Description of Equipment	Total Quantities
Prefab LMR 400 cables with N-Type Male and N-Type Female connectors	2-20ft, 4-30ft, 6-40ft lengths*
CAT-6 cable and connectors	Variable length*
Cat-6 Ethernet cable (2-ft long)	30
Bracket for mounting DSRC antenna on the mast arm or light pole	5
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	10
Network switch with 8 ports	5
Surge Protected power strip (6 outlets)	5
MobileMark LTM-502 antenna	5

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

Appendix A5 Installation Details for RSU and DSRC Radio Antenna

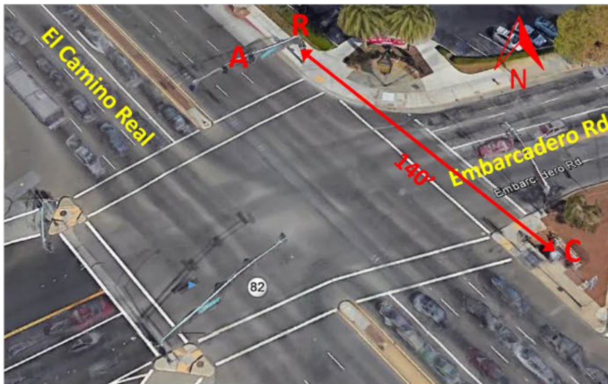
This section contains layout information for installation of RSUs and antennas at the five expansion sites. The following Google Earth aerial pictures provide a visual for the location of each major component of installation at selected intersections. Construction notes are included with each aerial.

Notation: C = Cabinet, R = Roadside Unit (RSU), and A = DSRC Radio Antenna

Site #1: El Camino Real and Medical Foundation Dr

1. Install antenna (A) on mast arm between the two signal heads 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 Model 2070E controller in the existing controller cabinet.
6. Install an auxiliary side cabinet on street side of the main controller cabinet.
7. Install CV equipment in the side cabinet and connect to 2070E controller and other equipment per cabinet diagram.

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

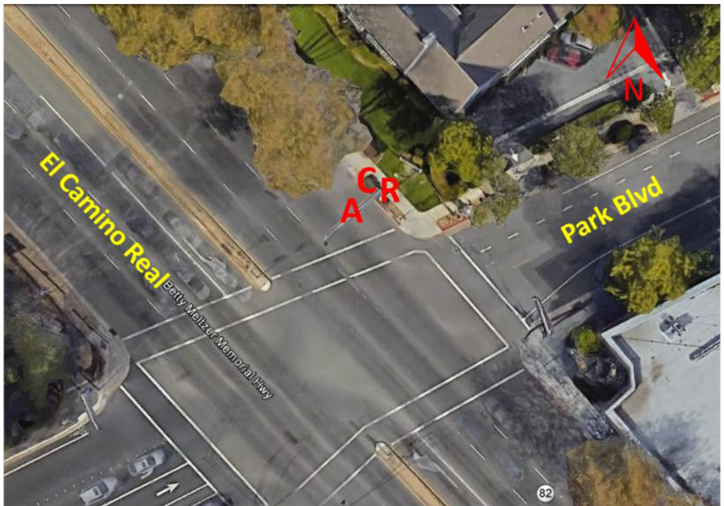


1. Install antenna (A) on mast arm between the two signal heads with bracket.
2. Install RSU (R) on upright above mast arm.
3. Connect RSU to antenna with 30' coax cables.
4. Connect RSU to cabinet (C) through pole and pull boxes with PoE cable.
5. Install Model 2070E controller in the existing controller cabinet.
6. Install an auxiliary side cabinet on street side of the main controller cabinet.
7. Install CV equipment in the side cabinet and connect to 2070E controller and other equipment per cabinet diagram.

Site #3: El Camino Real and Churchill Ave

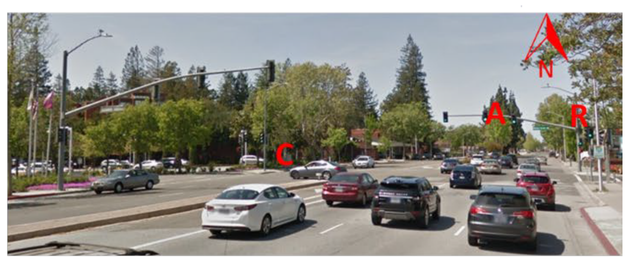
1. Install antenna (A) on mast arm between the two signal heads with bracket.
2. Install RSU (R) on upright above mast arm.
3. Connect RSU to antenna with 30' coax cables.
4. Connect RSU to cabinet (C) through pole and pull boxes with PoE cable.
5. Install Model 2070E controller in the existing controller cabinet.
6. Install an auxiliary side cabinet on street side of the main controller cabinet.
7. Install CV equipment in the side cabinet and connect to 2070E controller and other equipment per cabinet diagram.

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



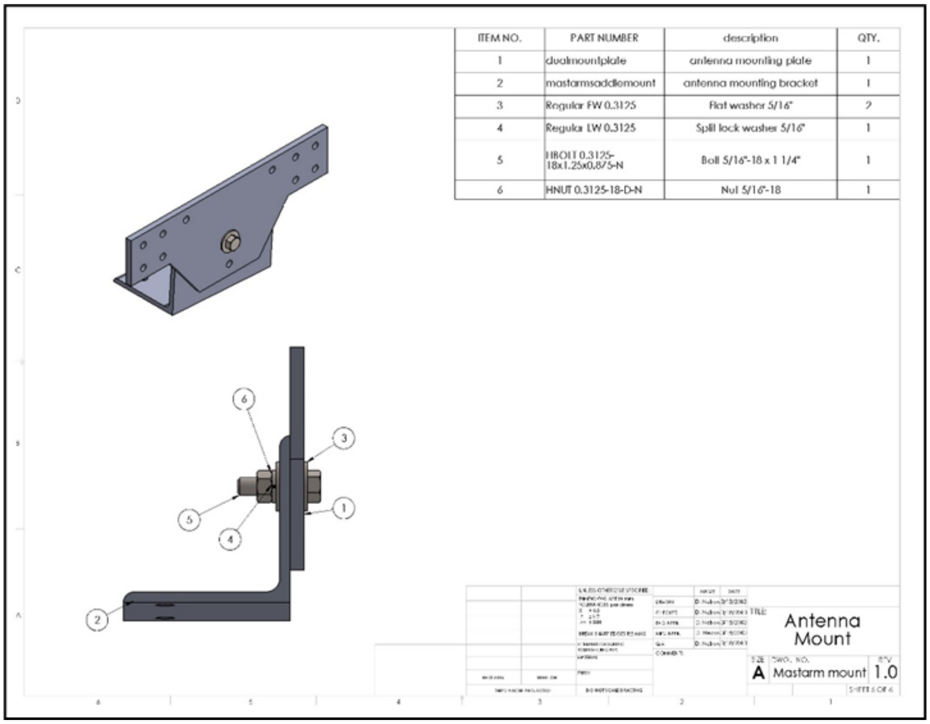
1. Install antenna (A) on mast arm between the two signal heads with bracket.
2. Install RSU (R) on upright above mast arm.
3. Connect RSU to antenna with 30' coax cables.
4. Connect RSU to cabinet (C) through pole and pull boxes with PoE cable.
5. Install Model 2070E controller in the existing controller cabinet.
6. Install an auxiliary side cabinet on street side of the main controller cabinet.
7. Install CV equipment in the side cabinet and connect to 2070E controller and other equipment per cabinet diagram.

Site #5: El Camino Real and Dinah's Ct



1. Install antenna (A) on mast arm between the two signal heads 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 Model 2070E controller in the existing controller cabinet.
6. Install an auxiliary side cabinet on street side of the main controller cabinet.
7. Install CV equipment in the side cabinet and connect to 2070E controller and other equipment per cabinet diagram.

Appendix A6 DSRC Radio Antenna Mast Arm Mount



Appendix A7 RSU Picture and Dimension

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