Collect Data using Connected Vehicles (CV) for Real-Time and Future Use

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DISCLAIMER STATEMENT

Table of Contents

Table of Figures

List of Tables

Abbreviations

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

API	Application Programming Interface
BSM	Basic Safety Message
CAN Bus	Controller Area Network
CAV	Connected and Automated Vehicle
CRTN	California Real Time Network
CV	Connected Vehicle
DVHD	Daily Vehicle-Hours of Delay
EER	Enhanced Entity Relationship
GGA	Global Positioning System Fixed Data
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
IOO	Infrastructure Owners and Operator
ITS	Intelligent Transportation System
NMEA	National Marine Electronics Association
OBU	On-Board Unit
PVD	Probe Vehicle Data
RSP	Roadside Processor
RSU	Roadside Unit
RTCM	Radio Technical Commission for Maritime Services
RTK	Real Time Kinematic
SNMP	Simple Network Management Protocol
SPaT	Signal Phase and Timing
SRM	Signal Request Message
SSM	Signal Status Message
TMC	Traffic Management Center
UDP	User Datagram Protocol
UTC	Universal Coordinated Time
V2I	Vehicle-to-Infrastructure
V2X	Vehicle-to-Everything
VHD	Vehicle-Hours of Delay
VHT	Vehicle-Hours Traveled
VMT	Vehicle-Miles Traveled
VSP	Vehicle Side Processor
WAVE	Wireless Access for Vehicular Environment
WSMP	WAVE Short Message Protocol

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1 Introduction

Current Intelligent Transportation System (ITS) equipment used for "sensing" the operations of highways are very limited, both in geographic coverage and in the measured data they can provide. To effectively monitor, measure, and manage the Daily Vehicle-Hours of Delay (DVHD) on the transportation network, transportation agencies must again focus on actively reducing peak period travel times and delay for all modes through closer collaboration between the road and vehicles. Connected Vehicle (CV) technology can provide real-time data to Caltrans so that this data can be used not only to monitor the traffic condition on the road but also optimize the throughput in real-time, support ITS planning activities, and keep travelers informed about traffic conditions. As connected vehicles become more prevalent, CV will produce massive quantities of data that will need to be reduced, managed, analyzed, and aggregated to provide useful information for real-time traffic management and archived for offline planning and evaluation purposes. There is a need for a mechanism in place for data collection, processing, analysis, dissemination of information to the Traffic Management Center (TMC) and data archiving. Furthermore, messages transmitted between connected vehicles and connected infrastructure include mandatory and optional data elements. Some of the optional data elements would be beneficial to collect for the use of traffic management but are subject to OBU (On-Board Unit) venders' support. Conduct testing and evaluation of the mechanism for data collection, analysis, and information dissemination in a real-world setting with OBUs from different venders will help to address the interchangeability issue, leading to more robust and efficient use of CV data for TMC operations.

1.1 Project Goal

The goal of this project is to address the technology gap in gathering useful information from CV data and integrating this new information with TMC operations through real-time CV data collection, analysis, and information dissemination between connected infrastructure and the TMC. The test site to carry on this project is the connected Interstate 15 (I-15) at Caltrans District 11 (D-11). CV roadside equipment consists of a Roadside Unit (RSU), a Roadside Processors (RSP), and roadside backhaul.

- The RSU is an infrastructure communications device that provides Vehicle-to-Everything (V2X) connectivity between OBUs and the transportation infrastructure.
- The RSP (also called edge processor) hosts CV roadside applications that collect CV data via the RSU, processes the data and estimates the metrics that measure traffic conditions, and transmits the estimated metrics to D-11 TMC via the roadside backhaul.

The TMC could utilize the estimated metrics in traffic management algorithms and functions, generate V2X messages such as roadside alert and speed advisory, and transmit the V2X messages to the RSP for sending back to connected vehicles via the RSU.

1.2 Project Objectives

The objective of this project is to use CV to collect the following real-time data so that this data can be used by TMC in the future to monitor the traffic condition on the road and to optimize the throughput in real-time:

- Travel speed/travel time,
- Origin and destination,
- Vehicle classification, and
- Vehicle lane position

1.3 Organization of the Report

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

- Section 2 – Selection of V2X Messages for CV Data Collection
  Describes the V2X messages selected for this project and for future use.
- Section 3 – Development of the CV Data Collection and Data Processing System
  Describes the developed CV data collection and data processing system.
- Section 4 – Bench Testing
  Describes the efforts conducted in bench testing of applications developed.
- Section 5 – Conclusions and Recommendations
- Section 6 – References

2 Selection of V2X Messages for CV Data Collection

This project selects the use of two SAE J2735 V2X messages ([5]), i.e., Basic Safety Message (BSM) and Probe Vehicle Data (PVD) message, for CV data collection to generate the measures described in Section 1.2. In a CV environment, an equipped vehicle broadcasts BSMs at 10 Hz (one BSM in every 100 milliseconds). When the vehicle is within the communication range with a RSU, the RSP collects BSMs from the vehicle via the RSU and generates the measures of traffic conditions. When the vehicle is outside the communication range with any RSUs, the PVD message is designed for transportation Infrastructure Owners and Operators (IOOs) to collect vehicle traveling behavior data along a segment of road. A PVD message contains a sequence (up to 32) of snapshots with each snapshot containing similar data as a BSM. When outside the communication range with any RSUs, the vehicle buffers the snapshots; and when within the communication range with a RSU, the vehicle transmits the PVD message to the RSU and clears the snapshots buffer to start buffering snapshots for downstream vehicle traveling behavior data.

Table 1 summarizes the data category and data source used for this project as well as for future use, when OBUs are widespread deployed.

Table 1 Data Category and Data Source

Measures	Description	Category	Data Source	Contained In
Timestamp	An instance in time when the data is collected on the vehicle	Real-Time	Global Navigation Satellite System (GNSS) Receiver	BSM PVD
Position	An instant in position (latitude, longitude, and elevation) when the data is collected on the vehicle			
Heading	Instant direction of travel			
Speed	Instance speed			
Hard Breaking	Decelerating at a level greater than 0.4 g		Vehicle CAN Bus	
Vehicle Classification	A composite set of common classification systems used in ITS	OBU Configuration	OBU Configuration	
Distance Traveled	Length of the road segment	Aggravated	Position SAE J2735 MAP	Individual trip-based travel behavior data along a road segment (Covered in this Project)
Origin	Vehicle's entry point to the road segment			
Destination	Vehicle's exit point of the road segment			
Vehicle Lane Position	Vehicle's lane(s) of travel along the road segment			
Travel Time	Duration the vehicle remained on the road segment		Timestamp	
Travel Speed	Distance traveled divided by travel time		Distance Traveled Travel Time	
Traffic Volume	Annual average daily traffic	Aggravated	Loop Detectors CV Penetration Rate	System-level performance measure with widespread OBU deployment
Vehicle-Miles Traveled (VMT)	Volume times distance traveled	Aggravated	Traffic Volume Distance Traveled	
Vehicle-Hours Traveled (VHT)	VTM divided by Travel Speed	Aggravated	VMT Travel Speed	
Vehicle-Hours of Delay (VHD)	VHT at free flow speed - VHT	Aggravated	VHT Free Flow Speed	
Congestion Level	$1 - \frac{\text{Travel Speed}}{\text{Free Flow Speed}}$	Aggravated	Travel Speed Free Flow Speed	
Duration of Congestion	Period of congestion	Aggravated	Congestion Level Timestamp	
Traffic Incidents	Spatiotemporal distribution of traffic incidents	Aggravated	Hard Braking Timestamp SAE J2735 MAP	

The first section of Table 1 lists data elements required and available for CV data collection to generate measures described in Section 1.2, i.e., individual trip-based travel behavior data along a road segment (also depicted in the second section of Table 1). The third (last) section of Table

1 lists the potential system-level performance measures when OBUs are widespread deployed in the future.

Spatiotemporal instant (or real-time) data that is collected across both space and time from the vehicle equipped with OBU include:

- Timestamp when the data is collected on the vehicle,
- Vehicle's position (latitude, longitude, and altitude) when the data is collected, and
- Data attributes related to travel behaviors, such as speed, heading, vehicle classification, and hard braking events, etc.

These data elements are available and contained in both BSM and PVD messages (see Table 2).

Table 2 Comparison of BSM and PVD Messages

	BSM	PVD Message
OBU Requirement	Mandated	Optional (depending on OBU vendors)
Travel Time	Yes*	Yes
Travel Speed	Yes*	Yes
Vehicle Classification	Yes	Yes
Origin and Destination	Yes*	Yes
Lane of Travel	Yes**	Yes**
*	Loss of CV data when there are coverage gaps between RSUs	
**	Require SAE J2735 MAP message that describes the geometry of a freeway segment	

Note that, vehicle parameters such as vehicle classification is not a real-time measurement rather than a configuration parameter, i.e., the parameters are set on the OBU when the OBU is installed on a particular vehicle; the vehicle event flags such as hard braking require the OBU to connect with the vehicle CAN bus (Controller Area Network) and may not be available for aftermarket devices.

This project focuses on collecting BSM and PVD messages from connected vehicles via RSU and processing the messages to generate individual trip-based performance measures. The outcome of this project will lay the groundwork for system-level performance measures when OBUs are widespread deployed.

The Probe Data Management (PDM) message broadcasted by the RSU is used to control the type of data collected and sent by OBUs to the local RSU, taken at a defined snapshot event to define RSU coverage patterns. PDM message works together with PVD message, and it is also included in this project.

3 Development of the CV Data Collection and Data Processing System

3.1 System Architecture

Figure 1 illustrates the system architecture for the CV data collection and processing system.

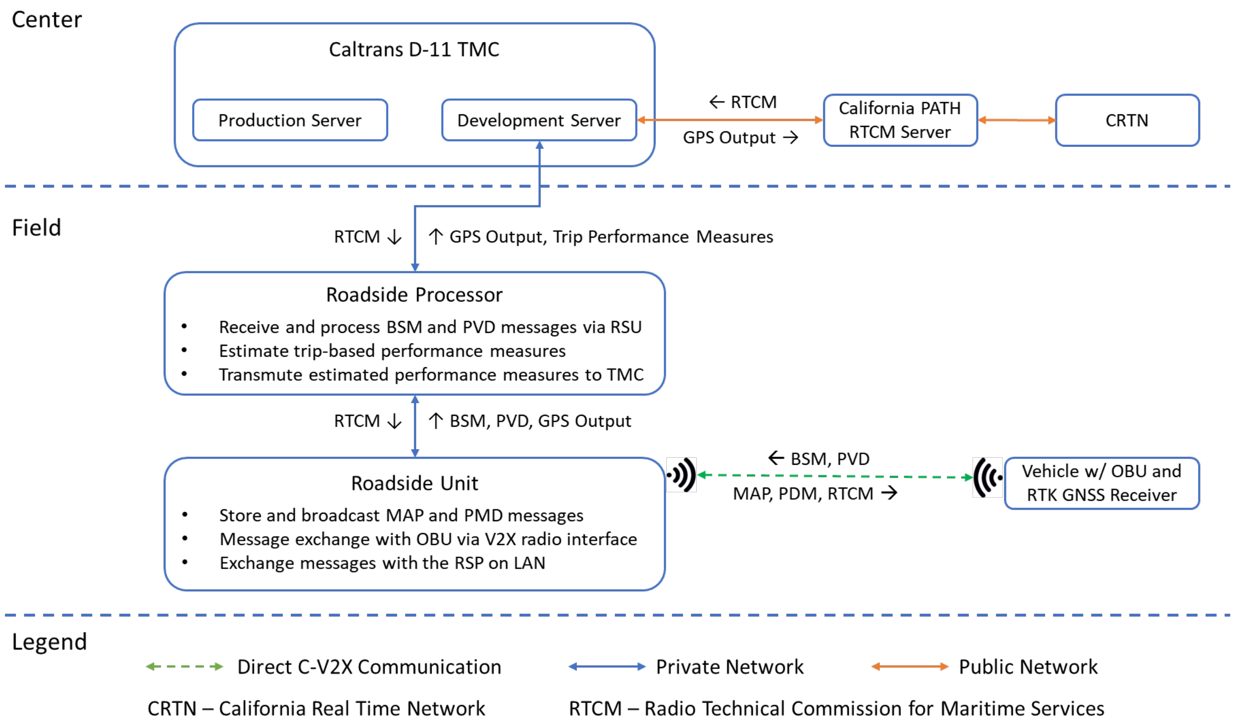

Figure 1 System Architecture for the CV data collection and processing system

The system consists of the following physical components:

3.1.1 CV Field Devices

- RSU and RSP installed on I-15 freeway,
- Roadside backhaul (private network) that provides connectivity between field RSU/RSP and Caltrans D-11 TMC, and
- Vehicles equipped with OBU and RTK (Real Time Kinematic) GNSS (Global Navigation Satellite System) receiver that are traveling along the I-15 segment.

3.1.2 CV Center Devices (Systems)

- Caltrans D-11 TMC,
- RTCM (Radio Technical Commission for Maritime Services) server located in California PATH Headquarters at Richmond Field Station (RFS), and
- California Real Time Network (CRTN) that provides raw RTCM position correction data ([3]).

This project leveraged the RTCM broadcast system that has been developed under Task 3687 (Contract No. 65A0775) to provide lane-level position accuracy to connected vehicles, which is essential for estimating vehicle lane position. More detailed information about the RTCM broadcast system (RTCM server and CRTN) can be found in [2].

To connect the public network with RTCM server and CRTN with Caltrans D-11 private network, this project proposed to install a development server in D-11 TMC, which connects to CV roadside field devices via the private network and connects to the RTCM server via the public network (see Figure 1). In this project (development stage), the development server does not directly connect to the D-11 production server.

3.2 Communication Interface and Protocol

Table 3 lists the communication interface and protocol between physical devices.

Table 3 Communication Interface and Protocol

Interface		Protocol	Description
From	To		
RSU	OBU	WAVE Short Message Protocol (WSMP)	MAP, PDM, and RTCM messages
OBU	RSU		BSM and PVD messages
RSP	RSU	Store-and-Repeat (SNMP – Simple Network Management Protocol)	Configuring the RSU for broadcasting MAP and PDM messages
RSP	RSU	Immediate Forward (UDP – User Datagram Protocol)	RSU to transmit messages received from the RSP on its radio interface
RSU	RSP	V2X Message Forward (UDP)	RSU to forward V2X messages received from OBUs to the RSP
RSU	RSP	GPS (Global Positioning System) Output (UDP)	RSU to send the GGA (GPS Fixed Data) NMEA (National Marine Electronics Association) string to the RSP
RSP	Development Server	GPS Output (UDP)	RSP to forward GPS output received from the RSU to the development server
RSP	Development Server	Individual Trip-Based Performance Measures (UDP)	RSP to send estimated trip performance measures to the development server via the private network
Development Server	RTCM Server	GPS Output (UDP)	Development server forwards GPS output received from the RSP to the RTCM server via the public network
Development Server	RSP	RTCM Message (UDP)	Development server forwards RTCM message received from the RTCM server to the RSP via the private network

The Store-and-Repeat, Immediate Forward, V2X Message Forward, and GPS Output interfaces on the RSU are described in ITE RSU Standard ([1]) and USDOT RSU v4.1 Specifications ([7]).

The RSP processes BSM and PVD messages, estimates trip-based performance measures, and sends the estimated measures to the development server. Byte map of the performance measures message is depicted in Table 4 to Table 7.

Table 4 Byte MAP of Trip Data

Trip Data			
Tag	**Index**	**Format**	**Description**
vehicleID	0	uint32_t	Same value used in the BSM
vehicleClassification	4	uint8_t	Basic vehicle class, integer (0 - 255)
numOfSegments	5	uint8_t	Each trip can include multiple segments in term of vehicle lane position
segments	6	SegmentData[]	An array of segment data (see Table 5)

Table 5 Byte MAP of Segment Data

Segment Data			
Tag	**Index**	**Format**	**Description**
startTime	0	timestamp	Time with millisecond precision in Universal Coordinated Time (see Table 6)
startPosition	8	position	Vehicle's position, speed, heading, and lane position at *startTime* (see Table 7)
travelDist	29	uint16_t	Units of decimeters
travelTime	31	uint16_t	Units of milliseconds

Table 6 Byte MAP of Timestamp Data

Timestamp Data			
Tag	**Index**	**Format**	**Description**
year	0	uint16_t	Units of years
month	2	uint8_t	Integer (1 - 12), units of months
day	3	uint8_t	Integer (1 - 31), units of days
hour	4	uint8_t	Integer (0 - 23), units of hours
minute	5	uint8_t	Integer (0 - 59), units of minutes
second	6	uint16_t	Milliseconds within a minute

Table 7 Byte MAP of Position Data

Position Data			
Tag	Index	Format	Description
latitude	0	int32_t	Units of 1/10th microdegrees
longitude	4	int32_t	Units of 1/10th microdegrees
elevation	8	int32_t	Units of decimeters
speed	12	uint16_t	Units of 0.02 m/s
heading	14	uint16_t	Units of 0.0125 degrees
roadSegRefID	16	uint32_t	MAP road segment reference ID
laneID	20	uint8_t	MAP lane ID

3.3 Development of RSP Applications

3.3.1 Expanding the V2X Message Library

This project leveraged the existing V2X message library that provides application programming interfaces (APIs) for encoding and decoding common V2X messages such as BSM, Signal Phase and Timing (SPaT), MAP, Signal Request Message (SRM), and Signal Status Message (SSM). For BSM, the existing V2X message library only processes *BSMcoreData* (i.e., BSM Part I data). For MAP, the existing V2X message library only processes intersection map (*intersectionData*).

The V2X message library has been expanded to include:

- BSM Part II Extension (*supplementalVehicleExt*) that contains vehicle classification data,
- PVD message,
- PMD message, and
- MAP for freeway (*roadwaySectionData*).

3.3.2 Expanding the MAP Engine Library

The MAP engine library provides APIs to project vehicle position (latitude, longitude, elevation, speed, and heading) onto MAP for determining vehicle lane position (*laneID*). The MAP Engine Library has been expanded to work with freeway MAP in addition to intersection MAP.

3.3.3 Estimation Trip-Based Performance Measures

A RSP software module has been developed to process BSM and PVD messages, estimate the aggregate trip-based performance measure, and pack the estimated measures into serialized data message as described in Table 4 to Table 7. Each vehicle position measurement (BSM or PVD snapshot) is projected onto MAP to determine vehicle lane position. The projected trajectory data is then used to estimate the aggregated performance measures.

3.4 Development of Development Server Applications

The development server has three functionalities:

- To interface with the RTCM server for obtaining RTCM correction data stream,
- To forward the received RTCM data stream to the RSU for broadcasting over-the-air, and
- To unpack the trip data message received from the RSP.

The first two functionalities are already in place and are using in the California CV Test Bed in Palo Alto. Unpacking the trip data message has been developed under this project.

A MySQL relational database (*tb_map*) with twenty-one (21) tables has been developed for managing intersection MAP and freeway MAP. Figure 2 depicts the enhanced entity-relationship (EER) diagram of database *tb_map*.

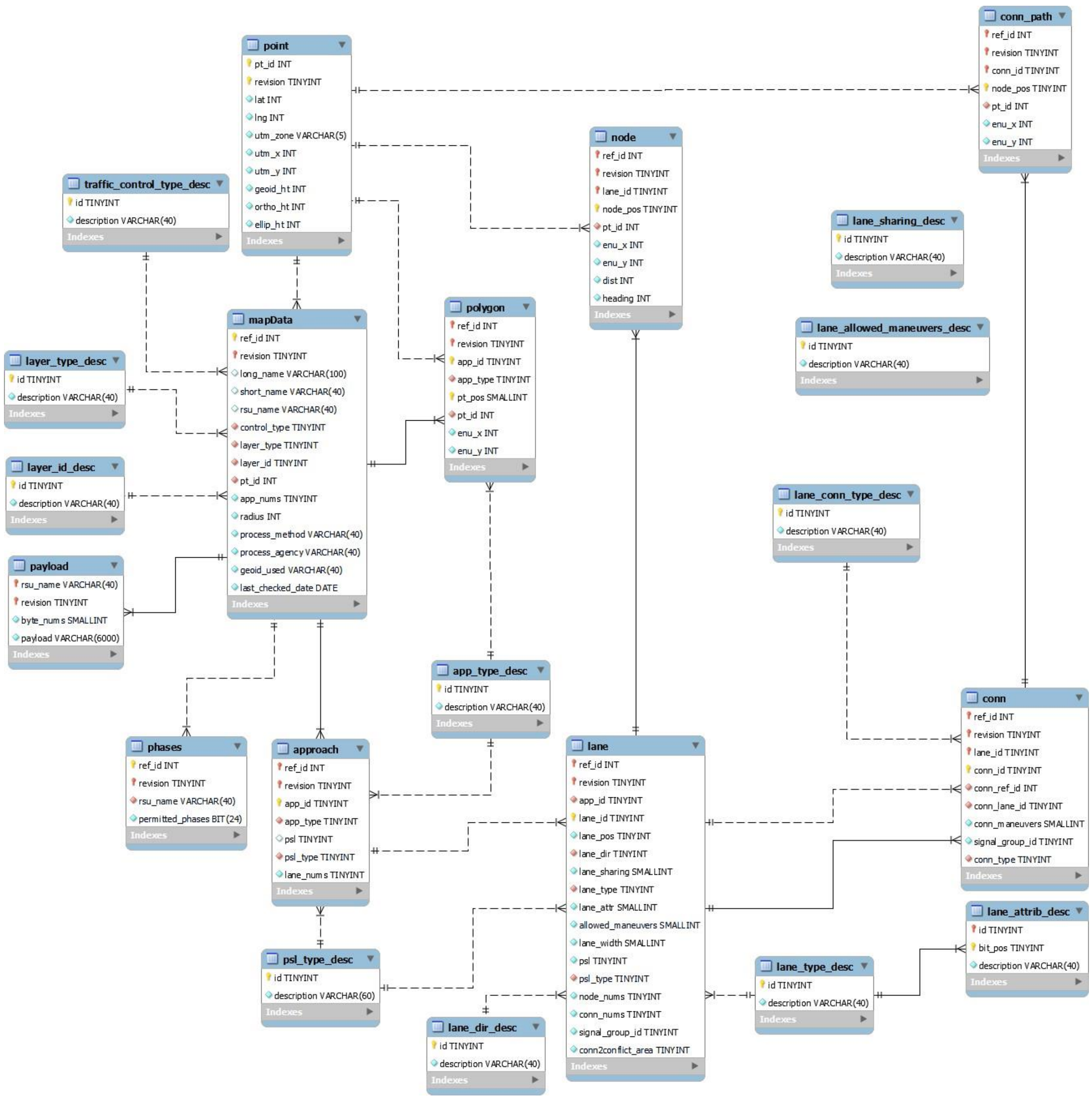

Figure 2 tb_map Database Diagram

3.5 Development of Vehicle-Side Applications

To ensure the desired interoperability and data integrity to support the performance of safety and mobility applications, the SAE J3161/1 Standard ([6]) and SAE J2945/1 Standard ([4]) on On-Board System Requirements for V2X Safety Communications only specify the minimum functional requirements on transmitting and receiving the BSM and do not mandate any vehicle-side applications enabled by V2X communications. Vehicle-side applications that process PDM message and pack PVD message is vendor specific. Vehicle-side applications have been developed under this project to achieve the project objectives.

Figure 3 depicts the architecture of the developed vehicle-side applications, using a vehicle-side processor (VSP). Message flow of vehicle-side applications are as follows:

- The OBU forwards PDM and RTCM messages to the VSP.
- The VSP decodes the received PDM and RTCM messages using V2X message library.
- The VSP sends the decoded RTCM correction data to an external RTK GNSS receiver which applies the RTCM correction to get high-precision position estimate and output NMEA messages to the OBU and VSP PVD generator.
- The OBU uses the NMEA messages to generate BSM and broadcast it to the RSU.
- The VSP sends the decoded PDM data to VSP PVD generator which applies the control parameters contained in PDM and uses NMEA messages to generate PVD data.
- The VSP encode the PVD message and forwards it to the OBU to broadcast to the RSU.

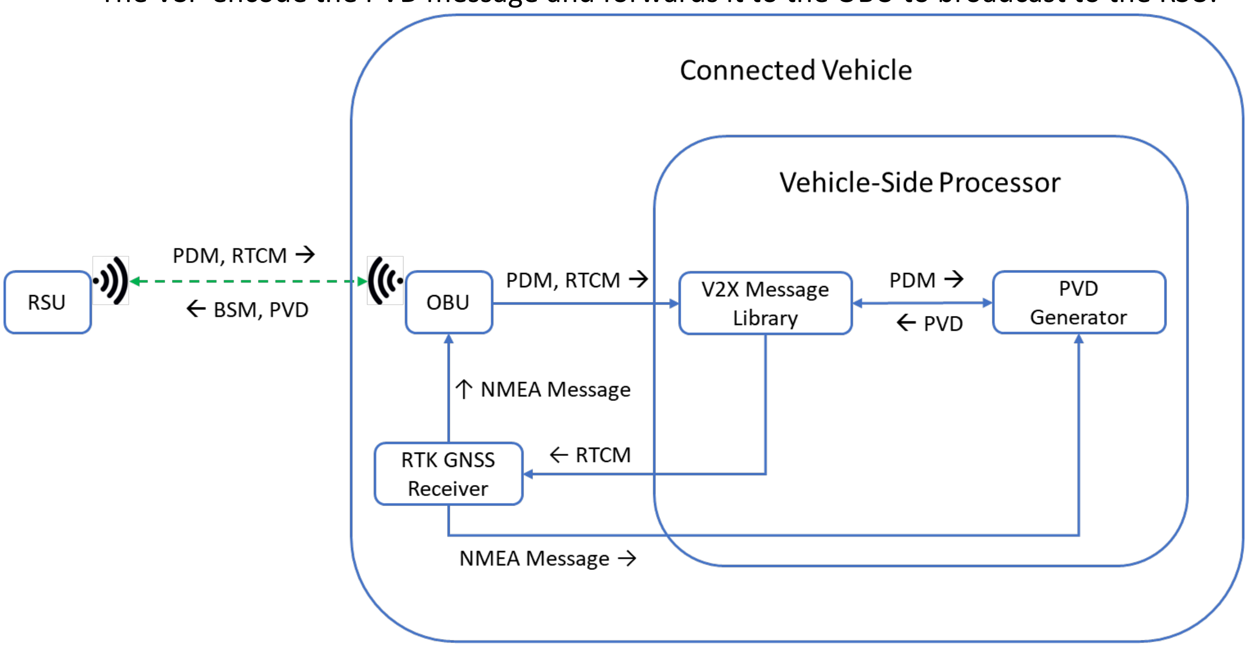

Figure 3 Vehicle-Side Applications

4 Bench Testing

Bench testing of the CV data collection and processing system (Figure 1) and vehicle-side applications (Figure 3) were performed in the PATH CAV (connected and automated vehicle) lab. RSU and OBU included in the bench testing include:

- Siemens dual-mode (DSRC and C-V2X) RSU,
- Savari DSRC RSU and OBU, and
- Cohda DSRC RSU and OBU.

C-V2X OBU was not available to this project when conducting the bench testing.

Bench testing successfully validated the performance of the developed roadside and vehicle-side applications, including:

- Receiving and transmitting V2X messages (BSM, MAP, PVD, PDM, and RTCM messages) between RSUs and OBUs.
- The expanded V2X message library to encode and decode BSM Part II extension, PVD, PMD, and freeway MAP.
- The vehicle-side applications that apply RTCM corrections to obtain high-precision position estimate, process PDM message, and apply PDM control parameters in generating PVD message.
- The RSP applications that processes BSM and PVD messages and packs the estimated trip-based performance measures message.
- The development server application that unpacks the received trip-based performance measures message.

Although the bench testing only involved DSRC RSUs and OBUs, the developed applications are communication technology neutral and are expected to work with C-V2X communications.

Due to the delay in installation of RSUs along I-15 in D-11 and creation of freeway MAPs at location where the RSU is installed, data collection and evaluation along I-15 is not performed under this project.

5 Conclusions and Recommendations

5.1 Conclusions

The work throughout this project showcased a bench system that collects and processes CV data to support freeway applications and management. Current RSU deployments focus on connected intersections. This project explored applying CV technology to connected freeways and developed some core applications on estimating freeway traffic conditions using CV data, including

- Travel speed/travel time,
- Origin and destination,
- Vehicle classification, and
- Vehicle lane position

5.2 Recommendations

Due to the delay in RSU installation, the data collection and processing system has not been evaluated in real world conditions. A data collection and evaluation phase are recommended after the completion of RSU installation along I-15 so that the developed system can be tested and refined in real world conditions and could be applied to other freeway segments.

6 References

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