Assessment of the Infrastructure Readiness for Connected Vehicle to Infrastructure Applications on Arterial Streets

Final Report

Florida Department of Transportation (FDOT) Project

Contract Number: BDV29-977-58

Prepared for
Florida Department of Transportation

Prepared by
Florida International University

February 22, 2023

DISCLAIMER

The opinions, findings, and conclusions expressed in this publication are those of the authors and not necessarily those of the State of Florida Department of Transportation.

METRIC CONVERSION CHART

Approximate Conversions to SI* Units					Approximate Conversions from SI Units				
Symbol	When You Know	Multiply By	To Find	Symbol	Symbol	When You Know	Multiply By	To Find	Symbol
LENGTH					**LENGTH**				
in	inches	25.4	millimeters	mm	mm	millimeters	0.039	inches	in
ft	feet	0.305	meters	m	m	meters	3.28	feet	ft
yd	yards	0.914	meters	m	m	meters	1.09	yards	yd
mi	miles	1.61	kilometers	km	km	kilometers	0.621	miles	mi
AREA					**AREA**				
in^2	square inches	645.2	millimeters squared	mm^2	mm^2	millimeters squared	0.0016	square inches	in^2
ft^2	square feet	0.093	meters squared	m^2	m^2	meters squared	10.764	square feet	ft^2
yd^2	square yards	0.836	meters squared	m^2	m^2	meters squared	1.196	square yards	yd^2
ac	acres	0.405	hectares	ha	ha	hectares	2.47	acres	ac
mi^2	square miles	2.59	kilometers squared	km^2	km^2	kilometers squared	0.386	square miles	mi^2
VOLUME					**VOLUME**				
fl oz	fluid ounces	29.57	milliliters	ml	ml	milliliters	0.034	fluid ounces	fl oz
gal	gallons	3.785	liters	L	L	liters	0.264	gallons	gal
ft^3	cubic feet	0.028	meters cubed	m^3	m^3	meters cubed	35.315	cubic feet	ft^3
yd^3	cubic yards	0.765	meters cubed	m^3	m^3	meters cubed	1.308	cubic yards	yd^3
NOTE: Volumes greater than 1000L shall be shown in m^3.									
MASS					**MASS**				
oz	ounces	28.35	grams	g	g	grams	0.035	ounces	oz
lb	pounds	0.454	kilograms	kg	kg	kilograms	2.205	pounds	lb
T	short tons (2000 lb)	0.907	megagrams	Mg	Mg	megagrams	1.102	short tons (2000 lb)	T
TEMPERATURE (exact)					**TEMPERATURE (exact)**				
°F	Fahrenheit	(F-32)/1.8	Celsius	°C	°C	Celsius	1.8C+32	Fahrenheit	°F
*SI is the symbol for the International System of Measurement									

TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No. *FHWA Report #, if applicable*	2. Government Accession No. *Leave blank*	3. Recipient's Catalog No. *Leave blank*
4. Title and Subtitle Assessment of the Infrastructure Readiness for Connected Vehicle to Infrastructure Applications on Arterial Streets		5. Report Date September, 2022
		6. Performing Organization Code *Leave blank*
7. Author(s) Mohammed Hadi, Ph.D., PE; Mahmoud Arafat, Ph.D; and Tao Wang, Ph.D.		8. Performing Organization Report No.
		10. Work Unit No. *Leave blank*
9. Performing Organization Name and Address Florida International University 10555 W Flagler St Miami, FL 33174		11. Contract or Grant No. BDV29-977-58
12. Sponsoring Agency Name and Address Florida Department of Transportation 605 Suwannee Street, MS 30 Tallahassee, FL 32399		13. Type of Report and Period Covered Final Report March 2020 to September 2022
		14. Sponsoring Agency Code *Leave blank*
15. Supplementary Notes The Project Manager from FDOT was Derek Vollmer, P.E.		

16. Abstract

This project has developed functional requirements of connected vehicle (CV) applications and testing plan for the vendor implementations of these applications. The project focuses on message level requirements and testing, which is needed to ensure that the messages generated by the roadside equipment (RSE) are received by the on-board unit (OBU), completely encoded in the required format, and the received information is complete and correct. The project demonstrated the testing according to the test plan using wired connection scenarios and open sky connection scenarios. It then demonstrated the use of hardware-in-the-loop simulation analysis to evaluate the performance of CV-based applications under actuated signal control.

17. Key Words Connected Vehicles, Message-Level Testing, SAE Standards, Red-Light Violation Warning	18. Distribution Statement No restrictions.		
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 200	22. Price

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the contribution of Mr. Derek Vollmer, the Florida Department of Transportation (FDOT) project manager to the project activities through many discussions during the course of this project. We would also like to thank the FDOT Research Center for providing funding for this project and for the FDOT Research Center staff for supporting the project.

EXECUTIVE SUMMARY

An important component of connected vehicle (CV) applications is the infrastructure support of these applications.. The vendors of the CV devices have incorporated in their products various applications that can be utilized to enhance mobility and safety of the transportation system. In addition, signal controller vendors have started to produce processors to interface with the CV roadside equipment (RSE) to provide functionalities that support CV applications. There is a need to test the functionality and performance of various applications supported by the RSE. The Florida Department of Transportation (FDOT) has developed specifications for the road side units (RSUs) required for the communications between the infrastructure and road users. The specifications address the hardware and communication aspects of these devices, but do not cover the CV applications themselves and whether these applications are successfully supported by the devices provided by different vendors

This project developed functional requirements of CV applications and testing plan for these applications. The project focused on message level requirements and testing, which is needed to ensure that the messages generated by the RSE are received by the on-board unit (OBU), encoded in the required format, and the received information is complete and correct. The project demonstrated the testing according to the test plan using wired connection scenarios and open sky connection scenarios. It then demonstrated the use of hardware-in-the-loop simulation analysis to evaluate the performance of CV-based applications under actuated signal control.

The project started with a review of the state of practice associated with the utilization and testing of CV applications combined with signal controllers. The review included documents related to the concepts of operation (ConOps), functional requirements, design, testing, and evaluation of the applications, in addition to lessons learned, guidance, standards, and other relevant documents produced as part of CV application deployments and testing. The state of the practice review also involved interviews with CV product vendors to get more information about their products.

Next, the project developed message level requirements of three CV applications. The three applications are Red Light Violation Warning (LRVW) utilizing Signal Phase And Timing (SPaT) and Map (MAP) messages; Emergency Vehicle Preemption (EVP) using service request messages (SRM) and service status messages (SSM) messages, and work zone warning (WZW) and reduced speed zone warning and lane closure (RSZW/LC) using traveler information messages (TIM). All messages follow the society of Automotive Engineers (SAE) message standards.

The project then developed test plans for the three applications mentioned above. The test plans were developed based on the developed requirements and follow the Institute of Electrical and Electronics Engineers (IEEE) Standard for Software and System Test Documentation (IEEE Std 829-2008). The test objectives were to verify the completeness and correctness of the format of the data produced by the RSE according to SAE J2735 message format, verify that the values in the messages generated and received by the CV equipment are identical to those in the data source, test/verify positive outcomes/results when correct inputs are provided to the RSE, test/verify correct error handling when negative (incorrect) inputs are provided to the RSE, test/verify correct error handling for boundary conditions (values) inputs are provided to the RSE, and allow the verification that the messages generated by the RSE are received correctly by the OBU.

The test plan considered two alternative configuration of the RSE. The first configuration utilizes an open source middleware developed by the Federal Highway Administration (FHWA), referred to as the V2X Hub, to convert, processes, and forward messages between the traffic controller and the RSU. The second configuration is to use build-in features in the RSE (signal controller or the CV RSU) to convert, processes, and forward messages without the need for a middleware. In addition, the test plan describes two variations of the data capture. The first uses wired connection, in which the messages are obtained as a log on a computer that is connected through the Ethernet interface to the RSE equipment within a subnet. Another possible option of the wired connection is to obtain the Unaligned Packed Encoding Rules (UPER Hex) messages as a log on the RSU. The second variation of the data capture is the use of a mobile tool to capture the wireless packets transmitted over the air (open sky connection).

This project then demonstrates the message-level verification of the three CV-based applications to ensure that the messages transmitted and received by the RSE and OBU conform to the requirements developed in this project and the applicable standards. The verification was done according to the developed test plans using the different configuration and data capture options mentioned above. The results show that while most of the tested fields of the SPaT and MAP message passed the verification, there can also be some differences in the SPaT data item and minor differences in the values of the MAP field values. The results also show that all the tested fields of the TIM message passed the verification.

The research team of this project coordinated with the FDOT project manager on demonstrating the testing procedures developed in this project at the FDOT Traffic Engineering Research Laboratory (TERL). The research team showcased and demonstrated the following:

- Describing building a laboratory environment for message level testing of CV applications.
- Describing the system overview; data flow; and methods of installation, configuration, and demonstration of the CV environment.
- Demonstrating the successful communication between the CV devices
- Presenting testing scenarios using wired and wireless communication with and without utilizing the V2X Hub.
- Demonstrating methods that were applied in this project for encoding, capturing, and decoding the SPaT, MAP, and SRM messages.

This project built a laboratory environment for testing of CV applications using software-in-the-loop simulation (SILS) and hardware-in-the-loop simulation (HILS). The project used the environment to evaluate the performance of the Red-Light Violation Warning application (RLVW) as an example of CV-based applications under actuated signal controller and to assess a method to mitigate the uncertainty in identifying the end-of-green. In the case of actuated control, the study results showed significantly higher differences in the assessed performance when using the EILS compared to the use of the other two platforms. The SILS and the HILS produced similar results.

The differences can be attributed to the variations in the communication latencies between the EILS and the other two simulation platforms The study found that in the case of actuated control, there are differences in the estimated impacts when comparing the built-in signal control emulation in the utilized simulation tool compared to the use of the SILS and the HILS. The differences can be attributed to the variations in the communication latencies between the emulation and the other two simulation platforms. Based on the analysis in this study, it can be concluded that the provision of an assured green period (AGP) to mitigate the impact of uncertainty in the end of green can improve the performance of the CV-based RLVW application. The combination of the CV-based RLVW application on the on-board equipment and the AGP on the actuated controller can reduce the overall intersection red-light running (RLR) by approximately 92% and improve the overall safety of the signalized intersection as measured by the RLR events, rear-end conflicts, and right-angle conflicts. However, the results showed that the application of the AGP, as applied and assessed in this paper, can increase stopped delay, number of stops, and approach delay. This issue will need to be further investigated to determine the optimal setting of the AGP considering both mobility and safety impacts.

.

TABLE OF CONTENTS

DISCLAIMER .... **I**
METRIC CONVERSION CHART .... **III**
TECHNICAL REPORT DOCUMENTATION PAGE .... **IV**
ACKNOWLEDGEMENTS .... **V**
EXECUTIVE SUMMARY .... **VI**
TABLE OF CONTENTS .... **IX**
LIST OF FIGURES .... **XIII**
LIST OF TABLES .... **XIV**
LIST OF ABBREVIATIONS AND ACRONYMS .... **XV**
1 INTRODUCTION **1**
2 STATE OF PRACTICE REVIEW **3**
2.1 RELATIONSHIP TO THE ITS ARCHITECTURE 3
2.2 CONCEPT OF OPERATIONS AND DESIGN DOCUMENTS 4
2.2.1 Tampa (THEA) Pilot 5
2.2.2 New York City Pilot 6
2.2.3 Wyoming Pilot 8
2.2.4 Lessons Learned 9
2.3 EXISTING AND ON-GOING TESTING AND TESTING PLANS 10
2.3.1 FDOT Connected Vehicle RSU Specifications 10
2.3.2 FDOT FRAME Roadside and Onboard Units Testing (5) 11
2.3.3 Tampa Bay (THEA) Pilot Test Plan 11
2.3.4 New York City Pilot Test Plan 13
2.3.5 Wyoming Pilot Test Plan 13
2.3.6 FHWA Testing of SPaT Message Communication Using NTCIP Standards 14
2.3.7 FHWA Testing of SPaT Message Communication based on SAE J2735 Standards 16
2.3.8 FHWA Testing of MAP Message Communication Using SAE J2735 Standards . 17
2.3.9 CAMP SPaT Challenge Verification Document 19
2.3.10 OmniAir Consortium Basic Safety Message Verification 20
2.3.11 Connected Vehicle Pilots Phase 2 Interoperability Test (12, 13) 20
2.3.12 New Hampshire’s Response to AASHTO’s SPaT Challenge 21
2.3.13 Southeast Michigan Connected Vehicle Test Bed-Michigan 21

2.3.14 Texas Transportation Institute (TTI) Test Bed at the Campus Deployment 21
2.3.15 USDOT DSRC Roadside Unit (RSU) Specifications v4.1.................................... 22
2.3.16 National Electrical Manufacturers Association (NEMA) TS 10-2019 Standards .. 23
2.4 RSE PRODUCT VENDORS 23
2.4.1 TrafficCast 24
2.4.2 Savari 24
2.4.3 Kapsch.. 25
2.4.4 Cohda 25
2.4.5 Siemens.. 25
2.4.6 Danlaw 26
2.4.7 Commsignia 26
2.5 SIGNAL CONTROLLER PRODUCT VENDORS... 27
2.5.1 Econolite 27
2.5.2 Siemens.. 27
2.5.3 Intelight.. 28
2.5.4 Cubic/Trafficware 28
2.5.5 McCain... 29
2.6 SUMMARY.. 29
3 IDENTIFICATION OF REQUIREMENTS FOR THE SELECTD V2I APPLICATION 32
3.1 REFERENCED DOCUMENT.. 32
3.2 GENERAL REQUIREMENTS.. 33
3.3 SPaT AND MAP MESSAGES 33
3.4 PREEMPTION REQUIREMENTS 41
3.5 WORK ZONE WARNING (WZW) REDUCED SPEED ZONE WARNING AND LANE CLOSURE (RSZW/LC) APPLICATION 46
4 TEST PLAN FOR THE SELECTED V2I APPLICATIONS 55
4.1 REFERENCED DOCUMENT.. 55
4.2 TEST OBJECTIVE AND SCOPE 55
4.3 ITEMS TO BE TESTED.. 56
4.4 FEATURES TO BE TESTED... 57
4.5 TEST DESIGN OVERVIEW.. 58
4.6 TESTING PERSONNEL 59
4.7 TEST ENVIRONMENT 60
4.8 TEST ENVIRONMENT SETUP 61
4.9 SCHEDULE 63

4.10 RISK AND MITIGATION 64
4.11 TEST CASES AND PROCEDURES 64
4.11.1 SAE J2735 SPaT Messages 68
4.11.2 SAE J2735 MAP Messages 72
4.11.3 SAE J2735 SRM Messages 81
4.11.4 SAE J2735 SSM Messages 85
4.11.5 SAE J2735 TIM Messages 88
4.12 RELATIONSHIP OF TEST CASE TO REQUIREMENTS 94
5 DEMONSTRATION OF THE APPLICATIONS OF THE MESSAGE-LEVEL TEST PLAN 98
5.1 TEST OBJECTIVE AND SCOPE 98
5.2 ITEMS TESTED 98
5.3 FEATURES TESTED 100
5.4 TEST DESIGN OVERVIEW 100
5.5 TEST ENVIRONMENT SETUP 108
5.6 TEST RESULTS 112
5.6.1 SAE J2735 SPaT MESSAGES 112
5.6.2 SAE J2735 MAP MESSAGES 117
5.6.3 SAE J2735 TIM MESSAGES 125
6 UTILIZATION OF HARDWARE-IN-THE-LOOP SIMULATION TO SUPPORT THE TESTING OF CV APPLICATIONS 133
6.1 LITERATURE REVIEW 134
6.1.1 Red-Light Violation Warning Application 134
6.1.2 Hardware-in-the-Loop Simulation 135
6.2 METHODOLOGY 136
6.2.1 Actuated Signal Controller Support of RLVW 137
6.2.2 Hardware-in-the-Loop Simulation Environment Setup 139
6.2.3 CV-based RLVW Modeling and Network Calibration 141
6.2.4 Investigation of RLVW Impacts and Performance 142
6.3 RESULTS AND DISCUSSION 143
6.3.1 Mobility Measures 144
6.3.2 RLVW Safety Measures Assessment 145
6.4 CONCLUSIONS 146
7 INVESTIGATION OF ALTERNATIVE SIMULATION APPROACHES TO SUPPORT THE TESTING OF CV APPLICATIONS 148
7.1 LITERATURE REVIEW 149

7.1.1 Hardware-in-the-Loop Simulation ... 149
7.1.2 Software-in-the-Loop Simulation ... 150
7.1.3 Combined EILS, SILS, and HILS Evaluation ... 150
7.2 METHODOLOGY ... 151
7.2.1 Case Study Network and Simulation Platforms ... 151
7.2.2 EILS and SILS Platforms Setup ... 154
7.2.3 HILS Platform Setup ... 154
7.2.4 CV-based RLVW Modeling and Network Calibration ... 156
7.2.5 Investigation of RLVW Impacts and Performance ... 157
7.3 RESULTS AND DISCUSSION ... 158
7.3.1 Communication Delay and Latencies ... 158
7.3.2 Signal Timing Measures of Effectiveness ... 159
7.3.3 Safety Enhancement Assessment ... 160
7.4 CONCLUSIONS ... 162
8 DEMONSTRATION OF OPEN SKY TESTING OF THE MESSAGE-LEVEL TSETS 163
8.1 TEST OBJECTIVE AND SCOPE ... 163
8.2 ITEMS TESTED ... 163
8.2.1 Kapsch RIS-9260 RSU ... 165
8.2.2 Kapsch ACV-330 OBU ... 166
8.3 FEATURES TESTED ... 168
8.4 TEST DESIGN OVERVIEW ... 169
8.4.1 SAE J2735 SPaT MESSAGES CONFIGURATION ... 169
8.4.2 SAE J2735 MAP MESSAGES CONFIGURATION ... 170
8.4.3 SAE J2735 SRM MESSAGES CONFIGURATION ... 174
8.5 TEST ENVIRONMENT SETUP ... 175
8.6 TEST RESULTS ... 176
8.6.1 SAE J2735 SPaT MESSAGES ... 177
8.6.2 SAE J2735 MAP MESSAGES ... 177
8.6.3 SAE J2735 SRM MESSAGES ... 177
8.7 TESTING AT THE FDOT TRAFFIC ENGINEERING RESEARCH LABORATORY (TERL) ... 180
REFERENCES ... 181

LIST OF FIGURES

Figure 2-1 Setup of the 3M J2735 Message Sniffer in the TTI Vehicle 22
Figure 4-1 Test Environment Setup of Scenario 1 62
Figure 4-2 Test Environment Setup of Scenario 2 62
Figure 4-3 Test Environment Setup of Scenario 3 63
Figure 4-4 Test Environment Setup of Scenario 4 (for SRM only) 63
Figure 5-1 Siemens ESCoS Roadside Unit (Source: Siemens RSU Brochure) 99
Figure 5-2 Signal Timing Configuration of TrafficWare Commander ATC Controller 101
Figure 5-3 Interface of USDOT MAP Creator Tool 102
Figure 5-4 Interface of USDOT TIM Creator Tool 103
Figure 5-5 Interface of the V2X Hub Map Plugin 104
Figure 5-6 Interface of Message Sender within the Web App of Siemens ESCoS RSU 105
Figure 5-7 Interface of Log Management within the Web App of Siemens ESCoS RSU 105
Figure 5-8 Interface of Wireshark for Message Capture 106
Figure 5-9 Interface of Wireshark for the UDP Stream 107
Figure 5-10 Interface of Free Online Automotive ASN.1 Message Decoder 108
Figure 5-11 Connected Vehicle-to Infrastructure Applications Testing Environment 109
Figure 5-12 Test Environment Setup of Scenario 1 110
Figure 5-13 Test Environment Setup of Scenario 2 110
Figure 5-14 Test Environment Setup of Scenario 3 111
Figure 5-15 Test Environment Setup of Scenario 4 (for SRM only) 111
Figure 6-1 Case study signalized intersection for modeling RLVW application. 138
Figure 6-2 Data flow between the HILS hardware and software components 140
Figure 6-3 HILS middleware interface and detector setup 141
Figure 6-4 Impacts of the AGP on the number of Red-light running events 145
Figure 6-5 Surrogate safety assessment vs mobility benefits for the RLVW application 146
Figure 7-1 (a-b) Case study network and major components of EILS Platform 152
Figure 7-2 (a-b) SILS and HILS platforms 153
Figure 7-3 Data flow between the HILS hardware and software components 155
Figure 7-4 HILS middleware and SNMPWALK queries 156
Figure 7-5 Signal timing MOEs results 159
Figure 8-1 Devices Under Test and Software Applications 164
Figure 8-2 Kapsch RIS-9260 Roadside Unit 165
Figure 8-3 Kapsch ACV-330 On-board Unit 167
Figure 8-4 Kapsch Assist CV-based Vehicle-to-Infrastructure V2I warnings (Source: Kapsch OBU User Manual) 168
Figure 8-5 J2735 SPaT Configuration of TrafficWare Commander ATC Controller 170
Figure 8-6 Logging into Kapsch RIS-9260 RSU using Secure Shell command line 171
Figure 8-7 Kapsch Insight Application on the Samsung A-8 Tablet 172
Figure 8-8 Interface of Wireshark for Wireless Message Capture 173
Figure 8-9 Kapsch ACV-330 OBU SRM Logs 175
Figure 8-10 Open Sky CV-based Applications Testing Environment 176

LIST OF TABLES

Table 2-1 An Example of the Test Procedures of the THEA Pilot 12
Table 2-2 Enable/Disable SPaT Data 15
Table 2-3 Status (IntersectionStatusObject) Input Verification 16
Table 2-4 laneID input verification 18
Table 2-5 Test Suit Structure 20
Table 2-6 Test Cases for CV Interface Triplets Presented in NEMA TS 10-2019 Standards 23
Table 3-1 Required Data for SPaT Message Transmission for the RLVW Application 39
Table 3-2 Required Data for MAP Message Transmission for the RLVW Application 39
Table 4-1 Test Personnel 59
Table 4-2 Test activities 64
Table 4-3 Ranges of the Valid Value for Each Field 65
Table 4-4 Data Specification of SPaT Message 69
Table 4-5 SPaT Message Test Case – Fields Existence 71
Table 4-6 SPaT Message Test Case – Fields Valid 71
Table 4-7 Data Specification of MAP Message 73
Table 4-8 MAP Message Test Case – Fields Existence 80
Table 4-9 MAP Message Test Case – Fields Valid 81
Table 4-10 Data Specification of SRM Message 82
Table 4-11 SRM Message Test Case – Fields Existence 84
Table 4-12 SRM Message Test Case – Fields Valid 85
Table 4-13 Data for SSM Message Transmission 86
Table 4-14 SSM Message Test Case – Fields Existence 87
Table 4-15 SSM Message Test Case – Fields Valid 88
Table 4-16 Data Specification of TIM Message 89
Table 4-17 TIM Message Test Case – Fields Existence 93
Table 4-18 TIM Message Test Case – Fields Valid 94
Table 4-19 Relationship of Test Cases to Requirements for SPaT and MAP Messages 95
Table 4-20 Relationship of Test Cases to Requirements for SRM and SSM Messages 96
Table 4-21 Relationship of Test Cases to Requirements for TIM Message 97
Table 5-1 SPaT Message Test Results 114
Table 5-2 MAP Message Test Result (V2X Hub) 118
Table 5-3 MAP Message Test Result (RSU) 121
Table 5-4 TIM Message Test Result (RSU) 126
Table 6-1 Impacts of Vehicle Detector Extend Parameter on Network Delay Measures 144
Table 7-1 Impacts of Simulation Platform on RLVW Under Pre-timed Signal Control 160
Table 7-2 Impacts of Simulation Platform on RLVW Under Actuated Signal Control. 161
Table 8-1 SRM Message Test Result 178

LIST OF ABBREVIATIONS AND ACRONYMS

AASHTO	American Association of State Highway and Transportation Officials
ACC	Adaptive Cruise Control
ARC-IT	Architecture Reference for Cooperative and Intelligent Transportation
ATC	Advanced Transportation Controller
AV	Autonomous Vehicle
BSM	Basic Safety Message
CACC	Cooperative Adaptive Cruise Control
CAMP	Crash Avoidance Metrics Partners
CAV	Connected and Automated Vehicle
ConOps	Concept of Operations
CV	Connected Vehicle
DSRC	Dedicated Short-Range Communications
EILS	Emulator-in-the-loop Simulation
EVP	Emergency Vehicle Preemption
FDOT	Florida Department of Transportation
FHWA	Federal Highway Administration
FRAME	Florida's Regional Advanced Mobility Element
HILS	Hardware-in-the-loop Simulation
IEEE	Institute of Electrical and Electronics Engineers
ITE	Institute of Transportation Engineers
ITS	Intelligent Transportation System
NEMA	National Electrical Manufacturers Association
NTCIP	National Transportation Communications for ITS Protocol
OBE	On-board Equipment
OBU	On-board Unit
RLVW	Red Light Violation Warning
RSE	Roadside Equipment
RSU	Roadside Unit
RSZW/LC	Reduced Speed Zone Warning and Lane Closure
SAE	Society of Automotive Engineers
SILS	Software-in-the-loop Simulation
SPaT	Signal Phasing and Timing
SRM	Signal Request Message
SSAM	Surrogate Safety Assessment Model
SSM	Signal Status Message
SUMO	Simulation of Urban Mobility
TERL	Traffic Engineering Research Laboratory
THEA	Tampa Hillsborough Expressway Authority
TIM	Traffic Information Message
TSP	Transit Signal Priority
TTI	Texas Transportation Institute
USDOT	United State Department of Transportation
V2I	Vehicle-to-Infrastructure
V2P	Vehicle-to-Pedestrian

1 INTRODUCTION

An important component of connected vehicle (CV)-based applications is the infrastructure support of these applications. A critical infrastructure element is the roadside equipment (RSE) that allows, when combined with other devices such as a traffic signal controller, the delivery of the needed functionality of CAV-based vehicle-to-infrastructure (V2I) applications. The Florida Department of Transportation (FDOT) has developed specifications for the Road Side Units (RSUs), which address the hardware and communication aspects of these devices, but it does not cover the applications themselves and whether these applications are successfully supported by the devices provided by different vendors.

The vendors of the CV devices have incorporated in their products various V2I applications that can be utilized to enhance mobility and safety of the transportation system. In addition, signal controller vendors have started to produce processors to interface with the RSE to provide functionalities that support CV applications. There is a need to test the functionality and performance of various applications supported by the RSE.

This project has been initiated to assist the FDOT in developing functional requirements of CV applications and testing the vendor implementations of these applications. This project focuses on message level requirements and testing, which is needed to ensure that the messages generated by the RSE are received by the on-board unit (OBU), completely encoded in the required format, and the received information is complete and correct.   The specific objectives are:

- Providing a review of the state of practice associated with the utilization and testing of CV hardware and software combined with signal controllers to support mobility and safety
- Identification of the requirements for selected V2I applications on arterial streets
- Development of test plan for the selected applications
- Demonstration of the testing according to the test plan using wired connection scenarios
- Demonstration of the testing according to the test plan using open sky connection scenarios
- Assessment of the use of simulation analysis is to evaluate the performance of CV-based V2I applications under actuated signal controller

To start with, it is recognized that there has been confusion about the terms RSE and RSU, with some references saying that the RSU and RSE refer to the same thing or that the RSU is the newer name. However, the “ITS Standards for Project Managers” module produced by the Intelligent Transportation System (ITS) Professional Capacity Building Program of the United State Department of Transportation (USDOT)) (*1*) differentiates between these two terms, as follows:

1) **Road Side Equipment (RSE)** is a term used to describe the complement of equipment to be located at the roadside; the RSE will prepare and transmit messages to the vehicles and receive messages from the vehicles for the purpose of supporting the V2I applications. This is intended to include the dedicated short-range communications (DSRC) radio, traffic signal controller where appropriate, interface to the backhaul communications network necessary to support the applications, and support such functions as data security,

encryption, buffering, and message processing. It may also be referred to as the roadside ITS station. When only speaking of the DSRC radio, the correct term is RSU (see below).

2) **Road Side Unit (RSU)** is a connected device that is only allowed to operate from a fixed position (which may, in fact, be a permanent installation or from temporary equipment brought on-site for a period of time associated with an incident, road construction, or other events). Some RSEs may have connectivity to other nodes or the Internet.

Section 2 of this document includes a review of the state of practice associated with the utilization and testing of CV hardware and software combined with signal controllers to support the required V2I mobility and safety applications on urban arterials. It then identifies the lessons learned from CV application deployments and testing as well as a review of available testing guidance and standards produced at the national or state levels. Section 3 presents the message-level application requirements, validation and verification based on the requirements developed by other entities. Section 4 identifies the message-level testing plan for CV-based applications. The test plan was developed based on the requirements developed in Section 3 of this project and follows the Institute of Electrical and Electronics Engineers (IEEE) Standard for Software and System Test Documentation (IEEE Std 829-2008). Section 5 of the project demonstrates elements of the message-level test plan presented in Section 4. It then reports the results from the demonstration of the message-level verification of the CV-based applications to ensure that the messages conform to the requirements developed in this project and the applicable standards.

Section 6 presents an assessment of the use of simulation analysis as to evaluate the performance of the Red-Light Violation Warning application (RLVW) as an example of CV-based applications under actuated signal controller and to assess a method to mitigate the uncertainty mentioned above. A microscopic simulation environment is utilized as a primary tool for assessing the benefits of the RLVW application. The utilized simulation environment allows the interface of the simulation software and hardware elements in a hardware-in-the-loop simulation (HILS) platform. The platform integrates a physical actuated traffic signal controller for better evaluation of the performance of the RLVW application. Section 7 assessed the use of different approaches to emulate signal control in V2I applications. Such emulation can affect the assessment of the performance of the V2I applications using simulation.

Section 5 of this document includes only a laboratory environment testing results using wired connection scenarios. Meaning, the CV messages were captured using an Ethernet interface and listening to a particular port on a wired network switch. Section 8 reports on the demonstration of the applications elements of the message-level test plan presented in Section 4 of this report that involves open sky testing of the message sets using wireless communications. This testing captures and analyzes the messages wirelessly by listening to the wireless communication of the commercial device under test (i.e., RSU and OBU). This wireless capture needs to be tested because it replicates real-world communication scenarios and will be discussed in Section 8.

2 STATE OF PRACTICE REVIEW

This section presents a review of the state of practice associated with the utilization and testing of CV hardware and software combined with signal controllers to support the required mobility and safety V2I applications on urban arterials. The state of practice is identified based on the following:

- Review of documents related to the ConOps, functional requirements and design of the applications
- Lessons learned from CV application deployments and testing.
- Review of any available testing guidance and standards produced at the national or state levels
- Review of RSE vendor equipment and supporting applications
- Other existing presentations and publications on the subject

2.1 RELATIONSHIP TO THE ITS ARCHITECTURE

The Regional Architecture Development for Intelligent Transportation (RAD-IT) presented a high-level list of the functionalities to be provided by the RSE and the on-board equipment (OBE). Overall, 19 functionalities were listed for the RSE in RAD-IT. These functionalities can be used as a starting point for the identification of the functional requirements of these units.

Connected vehicle applications were included as services in the Architecture Reference for Cooperative and Intelligent Transportation (ARC-IT) (*2*). Overall, 19 functionalities were listed for the RSE. A combination of some of these functionalities may be needed to deliver a single application. These functions are categorized as follows:

- **Traffic Monitoring** – supports performance measurement and incident detection based on Basic Safety Messages (BSM). This function monitors the BSM that are shared between CVs to allow the estimation of performance measures and detecting incidents in combination with or in lieu of traffic data collected by infrastructure-based sensors.
- **Situation Monitoring –** supports performance measurement and incident detection based on snapshots of traffic and emissions data from passing vehicles equipped to send probe vehicle messages. The data is collected, filtered, and forwarded based on parameters provided by the back office. Parameters are provided to passing vehicles.
- **Intersection Management –** supports applications that manage signalized intersection control. It involves the communication with approaching vehicles and ITS and other equipment in the cabinet such as the traffic signal controller to enhance traffic signal operations.
- **Intersection Safety -** alerts and warns drivers of a potential stop sign, red light, and non-motorized user crossing conflicts or violations.
- **Map Management -** provides current map and geometry data to connected vehicles.
- **Speed Management** - provides infrastructure information, including road grade, roadway geometry, road weather information, and current speed recommendations.
- **Speed Warning -** notifies connected vehicles that are approaching a reduced speed zone.
- **Incident Scene Safety -** warns responders and drivers of imminent encroachment.

- **Infrastructure Restriction Warning** - warns vehicles of infrastructure dimensional and weight restrictions.
- **Queue Warning -** identifies and monitors queues in real-time and provides information to vehicles about upcoming queues.
- **Restricted Lanes Application -** provides lane restriction information and signage data to the vehicles and optionally identifies vehicles that violate the current lane restrictions.
- **Rail Crossing Warning -** provides rail crossing warnings and train arrival information to approaching vehicles and monitors connected vehicles that may intrude on the crossing.
- **Traffic Gap Assist -** facilitates gap selection to proceed through the intersection in yield situations.
- **RSE Traveler Information Communications -** includes field elements that distribute traveler information to vehicles for in-vehicle display.
- **RSE Work Zone Safety -** communicates with connected vehicles and Personal Information Devices carried or worn by the work crew to detect vehicle intrusions in work zones and warn crew workers and drivers of imminent encroachment. Crew movements are also monitored so that the crew can be warned of movement beyond the designated safe zone.
- **Position Correction Support** - broadcasts differential positioning data to enable precise locations to be determined by passing vehicles.
- **RSE Trust Management** - manages the certificates and associated keys that are used to sign, encrypt, decrypt, and authenticate messages.
- **RSE Privacy Services** - replaces the mobile device's network address
- **RSE Support -** provides the control and monitoring of the RSE hardware and installed software applications to detect and report fault conditions. The following RSE support is specified in ARC-IT:
  - Allow the monitoring of the operational status (state of the device, configuration, and fault data)
  - Send operational status to the center
  - A local interface that provides operational status and fault data to field personnel
  - Provide operational status information to the Service Monitor
  - Implement configuration commands received from an authorized Center
  - Implement configuration commands received from authorized Field Support Equipment

2.2 CONCEPT OF OPERATIONS AND DESIGN DOCUMENTS

This section presents the relevant aspects of the concept of operations (ConOps), requirements, and design documents produced for the three CV pilots (Tampa, New York, and Wyoming). The focus is on the V2I applications and the functionality of the RSEs in these applications. Thus, the functionalities of the OBEs, vehicle-to-vehicle (V2V), and vehicle-to-pedestrian (V2P) applications are not discussed in this section.

2.2.1 Tampa (THEA) Pilot

Below is a description of the related applications and functionality of the Tampa Hillsborough Expressway Authority (THEA) CV Pilot.

End of Ramp Deceleration Warning: This application produces the location of the queue using the computation of the I-SIG software, which is part of a suite of mobility applications referred to as Multimodal Intelligent Transportation Systems Signal (MMITSS). The application reports the queue information using what is referred to as an Infrastructure Sensor Message (ISM) for the end of the longest lane queue. The RSE sends a Traffic Information Message (TIM) that specifies the recommended speed for each zone based on the minimum of the posted speed or the safe stopping distance calculated according to the Florida Driver's License Handbook.

RSE Function: RSE stores previously configured TIM messages, each describing a series of recommended speed zones. These RSE broadcast these messages under certain queue length limits (minimum and maximum). The I-SIG estimates queue lengths based on BSMs from OBU equipped vehicles approaching the intersection and radar detector data received in the form of an ISM, which contains the timestamps, locations, and speeds of the detected vehicles.

Wrong Way Entry: This application identifies zones with changeable allowed direction of travel and provides this information to passing connected vehicles. The RSE sends the direction, plus an indication of whether each lane is active or revoked. An infrastructure-based detection point is used to generate a warning to the traffic management center (TMC), in case of violation.

RSE Function: The RSE broadcasts the MAP and Signal and Phasing Timing (SPaT) message according to J2735. The SPaT message for each revocable zone (if exists) contains the direction information of that zone by time of day. The wrong way direction by time-of-day is treated as a red signal. When a vehicle is going the wrong way is detected, the RSE provides an alert to the TMC and provides a warning to upstream RSEs. The RSEs broadcast wrong way vehicle ahead to be received by CV.

Pedestrian Crash Warning: With this application, a LiDAR system detects the locations and tracks the movements of pedestrians. The RSE converts this information into Personal Safety Messages (PSMs) and broadcast these PSMs to be received by the equipped vehicles. The RSE also receives the BSM information from CV and forwards the information to a pedestrian safety app on smartphones in the vicinity of the intersection using Wi-Fi. The smartphone application collects logs of the smartphone location and collision warnings and forward the logs to the RSE.

RSE Function: The RSE receives the locations of vehicles and pedestrians and provides warnings to both. In addition, it collects the log information from the pedestrian's smartphone application.

Intelligent Signal System (I-SIG): This application utilizes the Siemens implementation of the MMITSS system. This implementation communicates with the traffic controller using NTCIP standards, receiving information about the controller configuration, current signal plan, and vehicle detection. The implementation then produces control commands including phase calls, holds, omits, and force offs to control the phase execution. MMITSS receives BSMs from CV for use in estimating the queue lengths. The application uses this information as input to I-SIG for signal timing. MMITSS also has pedestrian, freight, and transit components, as described next. Traffic detection devices (e.g., radar or video) can be used to supplement the vehicle information in estimating the length of the queue at the intersection.

<u>RSE Function:</u> The RSE estimates the queue length based on CV messages and infrastructure sensors and provide timing allocation to the signal phases.

Transit Signal Priority (TSP): This application provides signal priority to transit at intersections and is implemented as part of MMITSS (freight signal priority could also be implemented). The OBE sends a Signal Request Message (SRM) to the RSE. The RSE forwards the request to a server at the TMC to determine if the bus is behind schedule. The RSE then determines the priority of all received SRMs and sends a command for an extension of the green to the controller using NTCIP standards. The RSE also communicates the Signal Status Message (SSM) to the approaching vehicles that request the priority to confirm whether the priority is granted.

<u>RSE Function:</u> The RSE receives SRM requests, forwards to the TMC to get confirmation regarding bus not meeting schedule, grants priority to one of the vehicles requesting priority, and communicates to the request vehicles which one is granted the priority.

Pedestrian Mobility (PED-SIG): The utilized PED-SIG application receives the SPaT messages from the controller and broadcast the SPaT and MAP messages to a smartphone app. In addition, the application receives the pedestrian calls for a phase via the smartphone app when it is near the crosswalk in lieu of pushing a pedestrian button and forward the call to the controller.

<u>RSE Function:</u> The RSE receives the SPaT messages from controllers, sends SPaT and MAP information to the smartphone app, and receives ped calls and communicates the calls to the controller using NTCIP.

Probe Data Enable Traffic Monitoring (PDETM): With this application, the central server receives travel time information from RSEs along a corridor. These RSEs receive BSMs from connected vehicles and uses these BSMs to calculate travel times along the corridor.

<u>RSE Function:</u> The RSE receives the BSM from the CV, estimates the travel time based on the information, and communicates the travel time information to the center.

2.2.2 New York City Pilot

Below is a description of the V2I applications of the New York City (NYC) CV Pilot with focus on the functionality of the RSUs in these applications.

Speed Compliance Warning: This application uses the static speed limit and the speed/location of the vehicle to provide speeding warnings. The stored speed limit information includes a schedule and geographic boundaries. The OBE receives this information and warns the driver when exceeding the speed limit by a configurable amount of time. In addition to static zones, this application is extended to allow the warning for dynamic zones for example for construction activities with the RSE installed on the barrier truck for example. .

RSE Function: The RSE delivers MAP or TIM messages described in SAE J2735 of the speed limit configured by geographic boundaries, time-of-day, and day-of-week.

Oversize Vehicle Compliance: This application communicates a height restriction with over-height trucks approaching at a bridge underpass or tunnel entrance. The OBE compares the received height restriction information with the stored vehicle height. In this application, unlike the one described in ARC-IT, RSE does not incorporate the detection of the vehicle height.

RSE Function: The RSE delivers MAP or TIM messages described in SAE J2735 of the speed restriction and receives an encrypted event log for the alerts from the OBE to track the driver response.

Emergency Communications and Evacuation Information: This application transmits to the vehicle's emergency information including zone-specific evacuation directions, routes, areas to avoid, restrictions, global emergency information, and route-specific information. The messages are first reviewed at the TMC before sending to the RSEs.

RSE Function: The RSE receives and broadcasts the emergency-related information in the areas of interest. In addition, it receives an encrypted event log from the OBE to track the driver response to the alerts.

Pedestrian in Signalized Crosswalk: This implementation includes two applications: 1) a warning to vehicles of the presence of pedestrians and 2) support for visually impaired pedestrians. The implementation uses infrastructure sensors for pedestrian detection. An app on smartphone is also able to communicate with the RSE. The pedestrian detection information communicated to the RSE are broadcasted to be received by the CV.

RSE Function: The pedestrian's Personal Information Device (PID) sends BSM to the RSE and receives SPaT and MAP messages from the RSE. The RSE receives the pedestrian detection information from the infrastructure. The RSE alerts the CV that a pedestrian is crossing.

Intelligent Signal System CV Data: This application utilizes CV data as an input to the existing Adaptive Control Decision Support System augmenting or replacing the existing travel time data from other sources. The ConOps include limited details about this application. The New York City Pilot document is still not available. More details will be available when the design document becomes available.

Red light violation warning: The ConOps include limited details about this application. The New York City Pilot document is still not available. More details will be available when the design document becomes available.

Support Functions: The New York City deployment implement a number of support applications related to the RSE including the monitoring of the RSE.

2.2.3 Wyoming Pilot

Below is a description of the V2I applications of the Wyoming Pilot with focus on the functionality of the RSUs in these applications.

Infrastructure-to-Vehicle (I2V) Situational Awareness: This application gathers important travel information from the central systems and communicates the information to vehicles using both DSRC and satellite communications. The communicated information includes relevant downstream road conditions including weather alerts, speed restrictions, vehicle restrictions, road conditions, incidents ahead, truck parking, and road closures.

RSE Function: The RSE receives information from the TMC and broadcasts the information to the CV using DSRC.

Distress Notification (DN): With this application, CV communicates a distress message to the system when detecting events such as air bag deployed, and vehicle disabled or when the vehicle's operator manually initiates a distress status. The vehicle broadcasts a DN message including the location, time of message, distress message explanation, and vehicle category. The RSE forwards the information to the central location. This application utilizes a higher priority TIM communication using SAE J2735 standards.

RSE Function: The RSE receives DN messages from the CV and communicates the information to the center.

Work Zone Warning (WZW): The WZW Application broadcasts information about the conditions of an approached work zone including unsafe conditions for the workers or the approaching vehicle. Such information may include lane obstructions and closures, lane shifts, speed reductions, and/or vehicles entering/exiting the work zone. The provided messages use the TIM WZW message standards of SAE J2735.

RSE Function: The RSE receives the work zone information and broadcasts the information to the CV and workers.

Spot Weather Impact Warning (SWIW): In this application, RSEs communicate hazardous road condition information due to weather, such as fog or icy roads. Localized information at the segment level is provided utilizing the TIM advisory messages defined in SAE J2735.

RSE Function: The RSE receives spot weather information and broadcasts the information to the CV using DSRC.

2.2.4 Lessons Learned

Presented below are lessons learned related to the subject of this study based on information provided in the USDOT CV pilot website (*3*).

- The CV Pilot teams found ambiguity in the CV standards and worked together to update the data elements of the SPaT and MAP messages considering this ambiguity. An example is the definition of the crosswalks in the MAP message. To address this, the Tampa pilot and NYC pilot initially used different approaches that were compliant with the SAE J2735 standards. Later, the Tampa Pilot team decided to utilize the NYC approach. Other issues were identified with the standards. Another example is that the NYC pilot identified an issue with the SAE J2945/1 Standard's Certificate Change criteria, which is required as a part of the Security Credential Management System (SCMS) resulting in privacy risk. The above points to the need to continuously examine the CV standards and the related experience and lessons learned.
- The USDOT and the three CV Pilot sites conducted a limited test of interoperability of CV equipment (more on this is presented later in this document). The test was to determine if a vehicle with an OBU from one of the three sites is able to interact with OBUs and/or RSUs from the other sites according to the standards and to identify potential interoperability issues. The CV Pilot sites had to harmonize data elements to allow these interactions. Results of the testing indicated successful transfer of messages between the configured devices from the different sites.
- The Wyoming CV Pilot has used OBUs that utilize both DSRC and satellite communication to communicate TIMs messages. Satellite communication enable a vehicle to receive TIM when the vehicle is in specific target geographic zones.
- For pedestrian applications, the Tampa CV Pilot is using Wi-Fi communications for the interface between the RSUs and the pedestrian mobile application. The smartphone application can receive SPaT, MAP, and BSM messages from the surrounding RSUs through Wi-Fi.
- The CV Pilot program demonstrated the interaction of the RSU and Advanced Transportation Controller (ATC) signal controller using ITS standards. The RSU network address was programmed into the ATC allowing the RSU to receive messages from the ATC to enable SPaT messages over the air (DSRC and Wi-Fi).
- The software development for the three CV Pilot sites built on the software developed by other programs, in many cases, the existing software required modification or customization. For the example, the Wrong Way Entry application developed in the Tampa Pilot is based on the existing Red Light Violation Warning (RLVW) application.
- The NYC pilot augmented the Global Navigation Satellite System (GNSS) location technology with triangulation from the RSU signals. The OBUs also use Tethering by linking to the CAN BUS to acquire speed data from the vehicle allowing the use of dead reckoning. This was done because the project team found during demonstrations at a site with thick tree coverage that the lack of open sky disrupted the GNSS signals and therefore the applications were unreliable.
- It was reported that testing based on individual products is no substitute for testing on the integrated systems. This will have to be specified in the planning stage of the project in a formal testing strategy. This strategy should include unit/component testing, subsystem

testing, and system testing. The strategy should apply testing principles of IEEE 829 or ISO 29119-3.

2.3 EXISTING AND ON-GOING TESTING AND TESTING PLANS

A number of existing and on-going testing plans have been recently developed or are about to be developed. The Crash Avoidance Metrics Partners (CAMP) produced a document for the testing of Red-Light Violation Warning (RLVW) (*4*). The CAMP document pointed out that there are three levels of verification:

- System-Level Verification: This is a required verification to ensure that the system is "built according to the required architecture and that it correctly implements support protocols." The verification focuses on meeting requirements such as the FHWA RSU specification and possibly the SCMS requirements.
- Message-Level Verification and Validation: This verification is also required to verify that the messages generated by the RSE are received by the OBU, the encoding format is done, and information completeness is performed. The test is also to validate the correctness of the information in the received data. The document recommends that the verification shall be performed using equipment and personnel from a source other than from the vendor that manufactured or installed the RSE equipment.
- Application-Level Verification: This verification is marked as optional and focuses on ensuring the correct operation of the completed installation functionality at the application level using a vehicle.

In the current research project, the main focus is on the Message Level Verification and Validation and the infrastructure support of the applications. Below is an overview of the plans reviewed in this study.

2.3.1 FDOT Connected Vehicle RSU Specifications (*5*)

FDOT added CV RSU developmental Specification as Section 681of the Florida Department of Transportation Standard Specifications for Road and Bridge Construction (*5*). The specifications specify that the CV equipment must be compatible with the USDOT approved Security Credential Management System (SCMS) message security solution for V2I communications and meet listed industry standards. In addition, it specifies that the CV equipment must be Federal Communications Commission (FCC) certified. The equipment must be capable of remote firmware updates and has both DSRC and C-V2X communication capabilities, although concurrent DSRC and C-V2X operation is not required. The RSU must be configurable to account for the specific site including MAP data input. The RSUs shall also be interoperable with all FDOT APL approved Advanced Traffic Controllers (ATC). The RSU must include a wired Ethernet interface. The RSU shall allow access to all user-programmable features, health and status monitoring, event logging, and diagnostic utilities.

Of specific interest to this study, the specification specified in the Field-Testing section to verify over the air RSU broadcasts using a multi-channel test tool (MCTT) and verify that the MCTT received TIMs, including SPaT and MAP data, where applicable. However, no further details are provided regarding this testing. As discussed later in this section, other testing procedures have received vendor-independent and vendor provided tools to receive, decode, and in some cases log the messages.

2.3.2 FDOT FRAME Roadside and Onboard Units Testing (*6*)

The evaluation team of the Florida's Regional Advanced Mobility Elements (FRAME) performed interoperability testing of equipment received from CV vendors combined with FDOT approved controllers. The testing was performed in the lab as well as at two field sites. At the lab, multiple controllers were used in the testing including Trafficware ATC, Intelight X3, Siemens M60, Econolite ASC/3, and Econolite Cobalt. One of the two field sites was equipped with a Trafficware ATC controller. The second location was equipped with an Intelight X3 controller.

A total of ten (10) vendors participated in the FRAME CV equipment testing. The vendors were asked to test their units to ensure the successful transmitting and receiving of various messages (BSMs, MAP, TIM, SPaT, SRM, and SSM). The test also included interoperability testing with OBUs and RSUs from other vendors.

As an example of the testing, the evaluation team was able to view the SPaT, MAP, and TIM messages using the TrafficCast application on the tablet they provided while driving through the intersection. The application provided a graphical view of the messages in addition to viewing the individual packets (individual packets was also shown by other vendors). When testing the Siemens RSE, a 3M DSRC Sniffer box was utilized to sniff the DSRC. The SPaT, BSM, MAP, and TIM messages were verified by a utilized OBU as well as the packets being displayed by the sniffer box. The team was able to verify the SRM with the sniffer as well as see the controller go into Preemption call. The call was manually requested through the unit.

The evaluation team was also able to use Commsignia tablet and their preloaded application which produce a graphical view of the intersection and signal head displays to confirm the SPaT data. The evaluation team was successful in testing all SPaT, BSM, MAP, TIM, and emergency vehicle preemption through the application on the tablet as well as seeing the packets using the Wireshark program.

Additional information was stored on the FDOT District 5 FRAME SharePoint Site. It will be useful if the research team on this study is provided access to this site.

2.3.3 Tampa Bay (THEA) Pilot Test Plan (*7*)

The test plan of the Tampa Bay (THEA) pilot consisted of five levels, as shown below. Among these levels, Levels 3 and 4 are the most relevant to this study. Level 3 is more directly related to this study. Up to now, we were successful in getting a document describing Level 4 but not Level 3. We will try to get a version of Level 3.

- Level 1- Existing Hardware/Software Investigation

- Level 2 - Unit/Device Test: This test ensure conformance to standards, project requirements, and security requirements
- Level 3 - Subsystem Integration Test: After passing Level 2 testing, the OBU, RSU, PID, and Master Server subsystems software are integration tested as individual Subsystems
- Level 4 - System Verification: After passing Level 3, the subsystems are integrated into systems to satisfy the requirements for each use case. Each use case is tested for conformance to requirements. Testing verifies that the subsystems operate correctly when connected as systems:
- Level 5 – Field Test: At this level, the equipment is deployed at the roadside and test vehicles for end-to-end conformance to requirements.

In Level 4, four units are identified as Golden subsystems, defined as RSU or OBU devices that were verified that they implement the interface protocols. Devices from other vendors are then tested with the golden device, as would be the case of using commercial test equipment. An example of the test procedure steps is given below in Table 2-1. This example provides the steps for the Level 4 test of the End-of-Ramp Deceleration Warning (ERDW) use case.

Table 2-1 An Example of the Test Procedures of the THEA Pilot (*7*)

STEP	ACTION	REQ	EXPECTED RESULTS	P/F/I
Test Case UC1 ERDW_A				
1	Set the queue length via the RSU browser UI.	THEA-UC1-024	ERDW displays entered queue length and uses it to select the TIM associated with that queue length based on ERDW configuration.	P
2	Verify with 3M Tester that RSU broadcasts the selected TIM and compare to OBU.	THEA-UC1-022 THEA-UC1-026a	3M Tester receives and logs broadcast TIM. TIM content (speed zones) equals the TIM configured for the queue length.	P
3	Repeat steps 1 -2 for the second queue length and compare to OBU.	THEA-UC1-024 THEA-UC1-022 THEA-UC1-026A	ERDW picks a different TIM that is associated with the second queue length based on ERDW configuration. TIM content (speed zones) equals the TIM configured for the second queue length.	P
Test Case UC1 ERDW_B				
1	A vehicle approaches 40 MPH zone but has not reached it yet (a).	THEA-UC1-002 THEA-UC1-023 THEA-UC1-025	No warning is shown to the driver.	P
2	The vehicle reaches a 40 MPH zone (b).	THEA-UC1-002 THEA-UC1-023 THEA-UC1-025	ERDW safety application issues a "40 MPH" warning to the driver per the HMI	P

STEP	ACTION	REQ	EXPECTED RESULTS	P/F/I
Test Case UC1 ERDW_A				
			specification. 	
3	The vehicle reaches a 30 MPH zone (c).	THEA-UC1-002 THEA-UC1-023 THEA-UC1-025	ERDW safety application issues a "30 MPH" warning to the driver per the HMI specification. 	P
4	The vehicle reaches 20 MPH zone (d).	THEA-UC1-002 THEA-UC1-023 THEA-UC1-025	ERDW safety application issues a "20 MPH" warning to the driver per the HMI specification. 	P
5	The vehicle reaches the stop bar at the intersection with Twiggs.	THEA-UC1-002 THEA-UC1-023 THEA-UC1-025	No warning is shown to the driver.	P
6	Repeat steps 1-5 with differing queue lengths.	THEA-UC1-002 THEA-UC1-023 THEA-UC1-025	Same as steps 1-5.	P

2.3.4 New York City Pilot Test Plan

The testing document of the NYC pilot is in the production stage. The research team will summarize it when it becomes available.

2.3.5 Wyoming Pilot Test Plan (*8*)

The end-to-end system operational readiness testing of the Wyoming Department of Transportation (WYDOT) pilot discussed two types of test procedures and test cases:

End-to-end Message Communication Tests: These tests include the testing of the communications of key messages and data files including V2I Basic Safety Messages, I2V Situational Awareness (I2V SA) TIMs, Distress Notification (DN) TIMs, V2I Environmental Sensor Data, and V2I Log file. Communication Test Cases also include testing DSRC and satellite communication range and coverage.

End-to-end Applications Performance Test Procedures and Test Cases: These tests verify the WYDOT CV Pilot applications including Forward Collision Warning, I2V Situational Awareness

(Spot Weather Impact Warning, Work Zone, Variable Speed Limit, Incident Information, Road Condition, and Truck Parking), and Distress Notification. The tests verify the correct initiation of messages at their origin and the correct parsing and implementation at the receiving end. The tests also assess the processing and communication speed performance and the correct prioritization of the messages to drivers.

The above verifications generally are done using data logs and stores on the OBE or the RSE. The above testing assumes that the device developers had already performed component and subsystem testing and requirements verification. The test cases were performed either on a "test track" or "on road."

The test plan categorizes the tests into Test Procedures and Test Cases. The test cases were defined according to ISO 29119-3 to specify preconditions, system configuration, inputs (such as driving scenarios), and expected result (pass/fail criteria). A test procedure is a collection of test cases to be executed for a particular objective.

2.3.6 FHWA Testing of SPaT Message Communication Using NTCIP Standards (*9*)

FHWA has developed a draft testing plan for the certification of the communication of SPaT information between a signal controller and the RSE. The plan considers only the data objects in NTCIP 1202v03 that are required for constructing a SPaT message, as defined in SAE J2735.

The required items have been identified as needed for the plan:

- A power source
- Physical or virtual traffic signal controller(s) - NTCIP 1202 v03 compatible
- A Simple Network Management Protocol (SNMP) browser
- A software package to monitor and collect data on the target communication layer (e.g., Wireshark)
- A computer with V2X decoder
- (optional) GPS to provide location and system time

The following are the functions addressed in the test plan:

- Enable/Disable SPaT data
- SPaT Timing including the synchronization of system time and the generation time of SPaT
- SPaT data critical elements including intersection identifier, intersection status, movement status, movement minimum end times, movement maximum end times
- SPaT data performance including maximum transmission start time, movement time point minimum transmission rate, data request transmission rate, and event reporting latency

An example is given in Table 2-2for the Enable/Disable SPaT data function below.

Table 2-2 Enable/Disable SPaT Data

(*9*)

Test Case #	**Status-01**
Test Case	**Enable/Disable SPaT data**
Reference	*NTCIP 1202 v3 (December 2018): Section 5.17.4*
Objective	Users could enable and disable SPaT data generation from a traffic signal controller
Entrance Criteria	The traffic signal controller under test complies with NTCIP 1202 v3
Data Inputs	SNMP commands generated by a user
Data Outputs	The traffic signal controller under test generates or stops generating signal phase and timing data, according to user's configuration
Exit Criteria	Users can successfully enable and disable SPaT data generation from a traffic signal controller
Test Procedures	It is assumed the SPaT message is disabled by default. If the assumption is not true, the test operator should conduct Test 2 first. Test 1 (Enable SPaT) ➢ The test conductor uses Wireshark to monitor the communication between traffic signal controller and PC in order to verify the SPaT function is disabled (i.e., no SPaT UDP package exists). If not, test 2 should be conducted first. ➢ The test conductor uses the SNMP set function to enable SPaT messages (OID: 1.3.6.1.4.1.1.1206.4.2.1.16.4; value: 1). Then, using Wireshark, the test conductor should be able to find SPaT UDP packages are sent from controller to PC. Test 2 (Disable SPaT) ➢ The test conductor uses Wireshark to monitor the communication between traffic signal controller and PC in order to verify the SPaT function is enabled (i.e., find SPaT UDP packages are sent from controller to PC). ➢ The test conductor uses the SNMP set function to disable SPaT messages (OID: 1.3.6.1.4.1.1.1206.4.2.1.16.4; value: 0). Then, using Wireshark, the test conductor should be able to find the controller stopped sending SPaT UDP packages to PC. This test case is passed when both Test 1 and Test 2 are passed.

2.3.7 *FHWA Testing of SPaT Message Communication based on SAE J2735 Standards* (*10*)

In conjunction with the effort described in Section 4.6, the FHWA has developed a draft testing plan to evaluate the SPaT output generated by the RSE to be communicated to the vehicles. The procedure tests the format, structure and encoding of the SPaT message as defined in the SAE J2735 Standard. The document mentioned that such tests "will be conducted at a Certification Test Laboratory, such as OmniAir and its affiliates."

The broadcasted messages according to SAE J2735 are in the ASN.1 format encoded in UPER Hex. The tests verify the accuracy of SPaT data in that they must be identical to the SPaT data elements from the traffic signal controller. In addition, the test verifies ASN.1 SPaT message format according to SAE J2735 to UPER Hex encoding. The ASN.1 structure is verified based on the SAE J2735 2016 ASN.1 document.

It was stated that the message may be obtained from the RSU log or middleware log before broadcast. Another option is to obtain these messages using a test tool to capture the transmitted packets. The captured packets can be converted to the ASN.1 format using an UPER to ASN.1 decoder.

The following equipment were listed as required for testing:

- A power source
- (optional) GPS
- Network backhauls
- A physical or virtual traffic signal controller
- A laptop with IP packet sniffer and UPER converter
- A test tool to log encoded packets over the available wireless technology

The functions addressed in the test plan include:

- Timestamp Verification includes test cases that verify whether the timestamp in the SPaT message broadcast from the RSE matches the RSE system timestamp
- Signal Groups Verification consists of test cases that evaluate whether the correct number of signal groups are included in the broadcasted SPaT message
- Field Existence test cases evaluate whether the mandatory fields exist in the SPaT message
- Input Verification evaluate whether mandatory fields in the SPaT message match with the input

An example is given in Table 2-3 for the Status Input Verification

Table 2-3 Status (IntersectionStatusObject) Input Verification
(*10*)

Test Case #	VERIFY-05
Test Case	status (IntersectionStatusObject) input verification
Reference	*SAE J2735 2016, section 6.37, 7.57; NTCIP 1202 v3*

Test Case #	VERIFY-05
Test Case	status (IntersectionStatusObject) input verification
Objective	Users can verify the status field in the SPaT message broadcast from the RSE matches with the input
Entrance Criteria	The RSE under test is compatible with the SAE J2735 2016 standard
Data Inputs	Encoded SPaT message and parallel listening port configured by the user for the SPaT message generating device
Data Outputs	The data received from SPaT message generating device and a report verifying the value associated with status by comparing the encoded SPaT message logs to the SPaT data obtained on the listening port
Exit Criteria	The status in the SPaT message broadcast is verified with the input and the results are documented
Test Procedures	➢ The test operator configures the device under test to produce and transmit the encoded SPaT message ➢ The test operator configures the test PC to receive the encoded SPaT messages. ➢ The test operator uses the converted SAE J2735 SPaT Message in the ASN.1 or other human readable format to compare the status value with the SPaT configuration file. ➢ The acceptable values are: ○ IntersectionStatusObject: Bitstring (SIZE(16)) ➢ The test operator repeats the test with the following values: ○ lowest acceptable value ○ highest acceptable value ○ value within acceptable range ○ value outside of range A list of recommended values to be tested is provided.

2.3.8 *FHWA Testing of MAP Message Communication Using SAE J2735 Standards* (*11*)

A third testing plan was developed as part of the FHWA effort that developed the plans described in Section 4.6 and Section 4.7. This third draft plan test the MAP messages generated by the RSE to be communicated to the vehicles and test the format, structure and encoding of the SPaT message as defined in the SAE J2735 Standard. The document mentioned that the tests “will be conducted at a Certification Test Laboratory, such as OmniAir and its affiliates.”

This plan listed the following configuration and equipment for the testing:

- A power source
- Optional) GPS
- Network backhaul to allow connection to a hardware which includes a MAP application.

- A laptop with IP packet sniffer and UPER decoder
- A test tool to log encoded packets over the available communication medium.
- Optional MAP data broadcasting device.

The test determines that the message is converted in the correct format while maintaining the mandatory standards and fields. Each value is checked to be sure it is in the acceptable range according to the standards documents.

The functions addressed in the test plan include:

- Field Existence test cases evaluate whether the mandatory fields exist in the MAP message Field Existence
- Input Verification evaluate whether mandatory fields in the SPaT message match with the input.
- Multiple MAP File Verification checks if the RSE can handle various intersection geometries

An example is given in Table 2-4.

Table 2-4 laneID input verification
(*11*)

Test Case #	**VERIFY-08**
Test Case	**laneID input verification**
Reference	*SAE J2735 2016 (Section 6.14, 7.86)*
Objective	Users can verify the laneID field under GenericLane for each lane in the MAP message broadcast from the RSE matches with the input
Entrance Criteria	The RSE under test is compatible with the SAE J2735 2016 standard and the laneID field exists
Data Inputs	Encoded MAP message and user generated MAP input source
Data Outputs	A report verifying the value associated with laneID field by comparing the encoded MAP message logs to the user generated MAP input source
Exit Criteria	The laneID data for each lane in the MAP message broadcast is verified with the input and the results are documented
Test Procedures	➢ The test operator configures the device under test to produce and transmit the encoded MAP message ➢ The test operator configures the test PC to receive the encoded MAP messages ➢ The test operator uses the converted SAE J2735 MAP Message in the ASN.1 or other human readable format to compare the laneID value for each lane with the original MAP file used for store and repeat. ➢ The acceptable values are: o LaneID: Integer (0.255) ➢ The test operator repeats the test with the following values: o lowest acceptable value

Test Case #	VERIFY-08
Test Case	**laneID input verification**
	○ highest acceptable value ○ value within acceptable range ○ value outside of range A list of recommended values to be tested is available in APPENDIX B.

2.3.9 CAMP SPaT Challenge Verification Document (*4*)

As stated earlier, CAMP produced a document that focuses on the verification of messages and the application of the Red-Light Violation Warning (RLVW). The document presents a high-level overview of the architecture used in the RLVW, requirements for the messages used by the RLVW application to deliver SPaT and MAP messages and position correction using Radio Technical Commission for Maritime Services (RTCM), and a framework for verifying the performance of an intersection to support the RLVW. The testing is to confirm that the RSE is broadcasting a properly formatted message according to SAE J2735 standard and to confirm that the data contained in the broadcast messages are accurate.

The utilized commercially available OBU unit in the test has an Ethernet interface for communication with an external device such as a laptop computer and an interface for storing logged data on a Universal Serial Bus (USB) storage device. The engineering Graphical User Interface (eGUI) enables a visual display for application status parameters and application messages. The unit has a data-logging feature to enable data from the test scenarios to be replayed and analyzed off-line. A remote access using Wi-Fi router is also possible for software updates and for downloading the logged data.

The Message-Level Verification of the plan verifies the transmitted message content. The document mentioned that it is desired to have verification equipment such as a laptop with a DSRC radio that "can receive and decode messages, perform validation tests, and display additional information for visual verification." The validation of the correctness of the MAP and SPaT messages is compared to the raw intersection map data and SPaT information from the signal controller.

According to the plan, the MAP and SPaT message packets are captured using tools provided by RSU vendors. The test then compares and verifies the MAP data received from the RSU MAP data with the data input to the RSU provided in the vendor-specific format (e.g., XML file). The test also validates the received and captured DSRC SPaT message from the RSU with the SPaT Management Information Base (MIB) from the signal controller.

To demonstrate the message-level verification, a test vehicle was driven making a total of eight runs covering the two directions of the main streets at two intersections. The test logged the received SPaT and MAP messages allowing the data elements in the message to be verified utilizing the application eGUI.

2.3.10 OmniAir Consortium Basic Safety Message Verification (*12*)

The OmniAir CV certification process determines whether the tested device conforms to the industry standards. All devices have to meet the IEEE 1609.2, 1609.3, 1609.4 test specifications, IEEE 802.11 test specification, and the WAVE V2I test specification. The OBUs also have to meet the SAE J2945/1 test specification. The test also determines whether the device can properly communicate with other vendors' devices that conform to the same standards. The tests can be found at: https://github.com/certificationoperatingcouncil/COC_TestSpecs. Among the available document at the site, the most relevant to this project is a document entitled "Conformance test specifications for SAE J2945/1 - On-board System Requirements for V2V Safety Communications Test Suite Structure and Test Purposes (TSS & TP)" (*12*). This document provides the test suite structure and test purposes for BSM structure, content, and transmission as defined in SAE J2945/1.

This clause introduces the test configurations that are used for the definition of test purposes. The test configurations cover the various scenarios of the J2945/1 test for BSM conformance. Distance between the IUT and the Test System shall not exceed five meters. In all test configurations antenna locations are located at an unspecified measured location and the test system is configured to account for the location.

Table 2-5 shows the Test Suite Structure (TSS) including its subgroups defined for conformance testing.

Table 2-5 Test Suit Structure
(*12*)

Root	Group	Category
BSM	Stationary Test	Valid
BSM	Stationary Test	Invalid
BSM	Moving Vehicle	Valid
BSM	Moving Vehicle	Invalid

2.3.11 Connected Vehicle Pilots Phase 2 Interoperability Test (*13*, *14*)

The USDOT CV Pilots Program tested the interoperability between selected OBUs and RSUs from the NYC, Tampa, and Wyoming pilot sites. The tested applications included the V2V Forward Collision Warning. The V2I testing focused on the reception of SPaT and MAP messages. NYC pilot collected the messages utilizing the native logging mechanisms of their OBUs (Savari OBU and Danlaw OBU). All messages are logged in a single log and correlated to individual test and are accessed utilizing Ethernet connection. The Tampa Pilot collected data utilizing a test laptop that has the Wireshark software, Java installed, and Siemen's remote-sniffer.jar. The laptop is connected via Ethernet to the RSU and OBU. Wireshark collects messages in a packet capture data (PCAP) file that is saved in the computer. The Wyoming Pilot site utilized the OBU data log file accessed via Ethernet (*15*). The test executes queries to extract BSM and driver alert log records and generate a keyhole markup language (KML) file for display in Google Earth. This allows each BSM and driver alert record from each test vehicle to be plotted in the Google Earth application. The test team used the Google Earth ruler tool to measure the distance in meters from the first advisory FCW (stationary vehicle alert) to the location of the stationary Remote Vehicle and recorded the Host Vehicle speed in mph that is associated with this first advisory for the forward collision warning to confirm that the time-to-collision corresponds to the standards for advisory time.

While performing testing for the RLVW application, it was observed that SPaT messages received by the OBUs were inconsistent with the observed signal display (i.e., the signal phases were swapped). This test was retested after modifications were made to update the SPaT/MAP messages. The test demonstrated that the Tampa and New York OBUs were able to receive SPaT, and MAP messages broadcasted by RSUs from the other site.

2.3.12 New Hampshire's Response to AASHTO's SPaT Challenge (*15*)

A testing procedure was produced as part of New Hampshire's response to American Association of State Highway and Transportation Officials (AASHTO)'s SPaT Challenge. A presentation made by one of the team members pointed out that the objective was to validate the RSU deployment, determine field range of RSU, determine LTE network speed with field conditions, and calibration of the MAP file. The test compared the DSRC and cellular
V2I connectivity, tested the FHWA V2I Hub Software. An email was sent to the presenter to get the final report of the study, but the email address was disabled.

2.3.13 Southeast Michigan Connected Vehicle Test Bed-Michigan (*16*)

The Southeast Michigan Connected Vehicle Test Bed-Michigan in Novi-Detroit-Oakland County was developed to test CV applications. This testbed collects data from infrastructure sensors. The deployment includes the testing of SPaT messages with a portable listener, a GUI, a Security Credential Management System (SCMS), 50 RSEs, SPaT broadcast on 22 RSEs broadcasting both J2735 and CICAS-V standards, and 30 RSEs with complete IPv4 and IPv6. The testing utilized two portable SPaT listeners along with a DSRC sniffer.

2.3.14 Texas Transportation Institute (TTI) Test Bed at the Campus Deployment (*17*)

Texas Transportation Institute (TTI) installed CV equipment at the Riverside Campus. The acquired devices included RSUs and OBUs from two vendors. The implemented I2V messages included SPaT, MAP, and TIM messages. The implemented V2I messages are the BSM. The RSUs were configured to listen and broadcast messages on the same DSRC channel that the OBU is configured to broadcast and receive the messages on. A J2735 messages sniffer tool (as shown in Figure 2-1) was acquired from 3M to capture DSRC messages broadcast over the air by the OBUs and RSUs and decode them. The sniffer has a Wireshark plugin that can decode the J2735 messages and display the contents of each message in real-time. Wireshark was also used to capture and save the messages received into a .pcap log file. The J2735 sniffer was configured to listen to the messages sent by the devices on DSRC channel 172. The J2735 sniffer was able to capture and decode the BSM messages that were sent by both devices. The RSU was also configured to log the messages received. The researchers verified manually that the messages were received and logged.

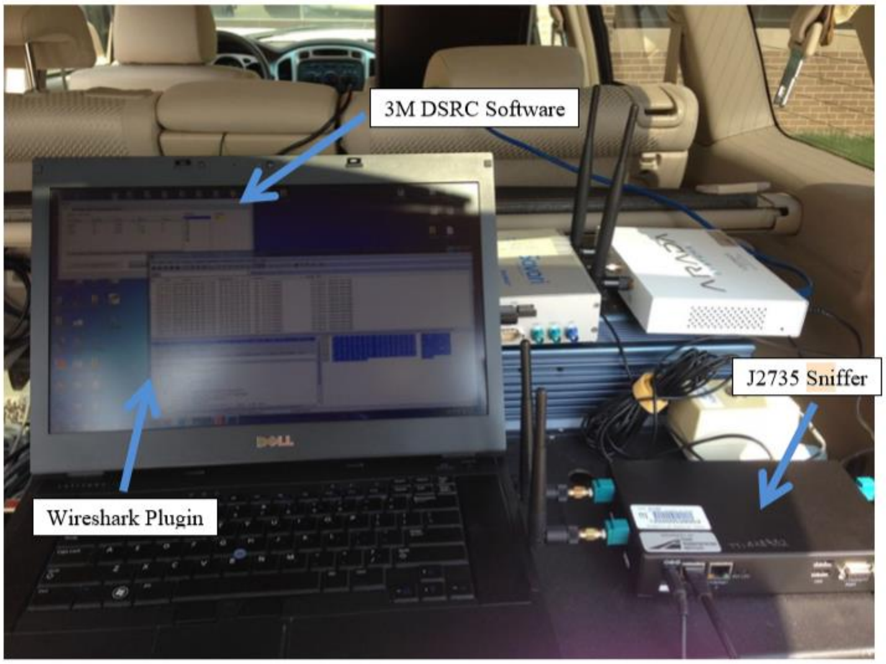


Figure 2-1 Setup of the 3M J2735 Message Sniffer in the TTI Vehicle

2.3.15 USDOT DSRC Roadside Unit (RSU) Specifications v4.1 (*18*)

The USDOT DSRC Roadside Unit (RSU) Specifications V4.1 document specifies the minimum requirements for RSUs for the 5.9 GHz DSRC infrastructure. This document is currently being updated and will include RSUs that support other communication media. The specification specifies the exchange of data over DSRC according to ITS standards such as IEEE 802.11, IEEE 1609.x, SAE J2735, and SAE J2945. The specification also recognizes that the RSU can be integrated with a backhaul system for remote management service provision and interfaced with local traffic control systems (*19*). The specification stated that the two core functions of a RSU are the provision of IPv6 access to remote network hosts and the broadcasting and receiving of messages as defined in SAE J2735. In general, the USDOT RSU 4.1 specifications are related to the System-Level Verification, which is above the level that is the focus of this study.

The requirements specified by the USDOT DSRC RSU Specifications include:

- System Requirements
- Power Requirements
- Environmental Requirements
- Physical Requirements
- Functional Requirements
- Behavioral Requirements
- Performance Requirements
- Interface Requirements

2.3.16 National Electrical Manufacturers Association (NEMA) TS 10-2019 Standards (*19*)

The NEMA TS 10-2019 standard describes the physical, performance, and functionality requirements of the RSE. The proposed RSU device standard allows for the implementation of future wireless technologies and application. A large proportion of the standard is related to the System-Level Verification, which is not subject of this study. The most relevant part of the specifications to the present study is the specification of the data elements that are communicated on each of the interfaces. The NEMA TS 10-2019 identifies the functional requirements based on the user needs that were a bases for the Concept of Operations. The standard presents the minimum requirements for the RSU to support safety applications utilizing a message format for use by mobile devices. It was stated that the RSU and mobile application suppliers can expand the message flows beyond the mandatory flows standardized by NEMA TS 10-2019. Verification Method is associated with each requirement. With regard to the interface requirements, the standard presents the Test Cases listed in Table 2-6. However, no details are given about these use cases. In this table, TSC is the traffic signal controller, *TSCBM is the* Traffic Signal Controller Broadcast Message, PSM is the Personal Safety Message, and other acronyms are as defined before.

Table 2-6 Test Cases for CV Interface Triplets Presented in NEMA TS 10-2019 Standards (*19*)

Test Case Number	Flow	Source	Destination	Flow	Standard
RSU-INT-F1	F1	TSC	RSU	TSCBM	NTCIP 1202 v3
RSU-INT-F2	F2	RSU	OBU	MAP	SAE J2735 2016
RSU-INT-F3	F3	RSU	OBU	SPaT	SAE J2735 2016
RSU-INT-F4	F4	RSU	OBU	TIM	SAE J2735 2016 SAE J2540-2 2009
RSU-INT-F5	F5	RSU	OBU	PSM	SAE J2735 2016
RSU-INT-F6	F6	OBU	RSU	BSM	SAE J2735 2016
RSU-INT-F7	F7	OBU	RSU	SRM	SAE J2735 2016
RSU-INT-F8	F8	RSU	TSC	SET	NTCIP 1202 v3
RSU-INT-F9	F9	RSU	OBU	SSM	SAE J2735 2016
RSU-INT-F10	F10	TSC	RSU	GET	NTCIP 1202 v3
RSU-INT-F11	F11	RSU	TMC	Unpublished	NTCIP 1218
RSU-INT-F12	F12	TMC	RSU	Unpublished	NTCIP 1218

2.4 RSE PRODUCT VENDORS

This section includes an initial review of the RSE vendors. The research team will expand this section based on phone calls with these vendors. The reviewed vendors are:

- TrafficCast
- Savari
- Kapsch

- Cohda
- Siemens
- Danlaw
- Commsignia

2.4.1 TrafficCast

TrafficCast CV offering combines their RSUs with OBUs from DENSO. The provided platform has implemented a number of applications including emergency vehicle preemption, TSP/FSP, Traveler Information System utilizing TIM for construction zones, emergencies and/or school zones, and pedestrian safety project. The RSU can interface with controllers that has Ethernet-based input/out, comply with NTCIP standards, and comply with priority message definitions. The BlueTOAD® Spectra RSE combines the BlueTOAD Travel Time detector with a 5.9 GHz Dedicated Short Range Communications system allowing the provision of the CV data with the provision travel time and origin/destination estimation based on Bluetooth.

The TIM broadcasted messages can be received by smart phone app. The information in the TIM messages can include weather conditions, emergency response vehicle movement, construction zone safety, travel times, lane closures, reduced speed limits, school zone safety, pedestrian (children) crossing, parking restriction, short- and long-term construction projects, and detours.

The BlueTOAD® Spectra RSU firmware also enables broadcasting SPaT messages with pedestrian and cyclist detection using infrastructure standards. The TrafficCarma App is used to exchange information between the driver, pedestrians and the traffic management system

2.4.2 Savari

Savari is a vendor of OBUs and RSUs with the Savari StreetWAVE® SW2000 being capable of providing C-V2X (PC5) as well as DSRC connectivity. It offers multiple configuration options for V2X radios, optional Wi-Fi and GNSS, and is based on the USDOT RSU v4.1a specification. The device is FCC certified (Currently for DSRC only). It allows remote management support including remote device and application health monitoring. It also supports message and event logging. The supported messages include TIM, SPaT, SRM, SSM, GID/MAP, RTCM messages Standard support. It also interfaces with select traffic controllers using NTCIP 1202 standards. The device supports IPv6 and IPv4 and is interoperable with US-DOT CAMP SCMS.

StreetWAVE™ can receive and load new versions of software, new configurations and credentials, and instructions to perform logging functions and download log messages to an external device. V2X applications include Vehicle-to-Vehicle (V2V), Vehicle-to-Infrastructure (V2I) and Vehicle-to-Phone (V2P). Examples of the supported I2V/V2I applications are traffic signal violation warning, curve speed warning, left turn assistant, red light violation warning, reduced speed zone warning, SPaT messages, and traffic signal priority. All apps are developed in collaboration with the CAMP consortium.

2.4.3 Kapsch

Kapsch RIS-9260 is the latest generation of Kapsch RSU offering that supports DSRC and 3GPP C-V2X wireless communication. The unit provides a software development kit (SDK) allowing a third party to create software applications running on the device. The RSU is based on a Linux driven dual-core 64 Bit single board computer platform. The applications currently available includes:

- Collision Risk Warning
- Stationary Vehicle Warning
- Emergency Vehicle Warning
- Road Condition Warning
- Green Light Optimal Speed Advice
- Public Transport Prioritization
- Multi-Modal Information
- Travel Time Information
- Intersection Safety
- In-Vehicle Information
- Signal Priority for Emergency Vehicles
- Road Works Warning
- Probe Vehicle Data
- Traffic Condition Warning

2.4.4 Cohda

Cohda RSU and OBU supports V2V, V2I, and V2P communications supporting both DSRC and 5G mobile networks. Both Development Licenses and Production Licenses are available to developers of automotive V2X equipment. Kit is provided with multiple connectivity options to allow third party to develop their own V2X applications and use-cases.

2.4.5 Siemens

Siemens RSU meets the USDOT RSU 4.1 specification and supports DSRC V2I communications in addition to a local Wi-Fi hot spot for remote maintenance or travel time applications and an optional LTE cellular back-haul for data upload/download. The Roadside Unit also includes internal data storage for intersection map geometry without need to replace controllers. The central software is available as an option to manage the RSUs.

The RSU has a browser-based service interface for easy configuration, diagnosis and remote software update. The unit includes GPS receiver for location and time and offer local Wi-Fi hot spot for communications to nearby smart devices such as laptops, tablets and smart phones for pedestrian and cyclist safety applications.

2.4.6 Danlaw

Danlaw's RouteLink RSU applications provide alerts to drivers about adverse driving conditions, enables pre-emption for first responders, and grants signal priority to buses and service vehicles. RouteLink can be configured to utilize either C-V2X or DSRC). Typical message support includes WSA broadcasts, SSM and SRM messages, SPaT and MAP messages, RTCM message. Applications reported to be implemented utilizing the Danlaw platform includes:

- Traffic Signal Coordination
- Emergency Vehicle Management
- Traffic Monitoring and Control
- Access and Parking Systems
- Transit Signal Priority
- Platooning Eco-Speed Harmonization
- Forward Collision Warning
- Intersection Movement Assistance
- Emergency Electronic Brake Lights Warning
- Left Turn Assist
- Control Loss Warning
- Blind Spot & Lane Change Warning
- Curve Speed Warning
- Emergency Communications & Evacuation Information
- Pedestrian Warning
- Icy Road Warning

Interestingly Danlaw offers a system referred to as Mx-Drive, which is described as a multi-vehicle and infrastructure mobility simulator to generate and run real-world conditions to test connected vehicle applications. Mx-Drive is combined with the Mx-Suite, which is a platform for automated embedded software verification and validation to support the testing of Advanced Driver Assistance Systems (ADAS), Sensor Fusion, Radar, and V2X (V2V, V2I, V2P) applications. Mx-Drive simulates the movement of objects such as vehicles and people, as well as the data messages for RSUs and OBUs. It generates a GPS signal with simulated time and position data for the unit under test and delivers synchronized CAN data, or other vehicle bus alternatives. The application uses the Danlaw DSRC modem to transmit messages such as BSM, MAP and SPAT and perform the message data packing, encoding, and security in conformance with industry standards. It is stated that the platform supports verification of application algorithms in MIL, SIL and HIL test environments and offers a graphical and a programmatic approach to creating tests

2.4.7 Commsignia

Commsignia supports DSRC and C-V2X (PC5) communication interface, 3G/HSDPA broadband connectivity, and WLAN access for smart-devices. The Commsignia V2X Software Stack supports Linux and RTOS operating systems and provides API features and tools for the development and integration process to any hardware platform. API bindings are available for multiple platforms including embedded C and Android Java.

2.5 SIGNAL CONTROLLER PRODUCT VENDORS

This section includes an initial review of the signal controller vendors of CV applications. The research team will expand this section based on phone calls with these vendors. The reviewed vendors are:

- Econolite
- Siemens
- Intelight
- Cubic/Trafficware
- McCain

2.5.1 Econolite

Econolite's controllers provide the fundamental capability required for connected vehicle applications through their Connected Vehicle Co-Processor (CVCP) module and controller software EOS. According to Econolite, their lineup of controllers combined with the CVCP module and matched with their controller software EOS can provide an open architecture to support connected vehicle programs and expand traffic control and safety capabilities.

Connected Vehicle Co-Processor (CVCP)
The CVCP module is a hardened, Linux based embedded computing platform that provides supplemental application processing power for the controller. It is intended to allow third-party developed and CPU-intensive connected vehicle applications. The module plugs into the communications slot of the Econolite Cobalt or any other properly equipped ATC-compliant traffic controller such as 2070E and 2070C. The CVCP module communicates through backplane Ethernet and SP2 and provides a processing platform that supports connections between the controller and RSEs and other sensors. It includes three Power over Ethernet (PoE) ports capable of directly driving RSUs, SB1 & SB2 Serial Motherboard interfaces, one micro-SD card slot and an EIA-232 Linux console port.
The CVCP module provides a critical V2I communications capability including the provision of SPaT and MAP information. The CVCP also works indirectly with Ethernet-capable NEMA traffic controller with the CVCP Module Enclosure and communicates through the front panel Ethernet. It can also be used in its stand-alone enclosure, making it an ideal tool for connected vehicle Research & Development (R&D).

EOS
EOS is Econolite's ATC controller software designed for Econolite Cobalt and other properly configured ATC controllers. It currently supports SPaT, MAP, and BSM messages according to the latest SAE J2735 standards.

2.5.2 Siemens

Siemens supports the connected vehicle applications through their SEPAC traffic controller software and their Sitraffic Vehicle2x technology utilizing the Cooperative Management System (CMS) providing central integration and comprehensive monitoring for all RSEs.

SEPAC
SEPAC is a traffic signal priority software that is designed for Siemens "m" series and Caltrans 2070 style controllers, as well as for ATC (Linux based) controllers. It Supports V2I Signal Phase and Timing (SPaT) data for connected vehicles.

Cooperative Management System (CMS)
CMS is the core element of the Sitraffic Vehicle2x intelligent communication technology from Siemens Mobility that establishes connectivity between the infrastructure systems and vehicles. It can be integrated into existing Siemens traffic control centers such as Sitraffic Scala and Sitraffic Concert or deployed as standalone solution. The CMS provides the central linkup of the RSUs and manages basic functionality such as equipment monitoring, remote support functions or hazard warnings and general information. According to Siemens, the CMS can communicate with the RSUs "over the air" or via existing cabling.

2.5.3 Intelight

Intelight's Connected Vehicle applications, MAXTIME cv and MAXVIEW cv, are built upon the latest ATC, NTCIP and DSRC J2735 standards. MAXTIME cv is built as a stand-alone embedded firmware application designed to run on ATC 5.2b or above compliant controller hardware. In addition, by leveraging the Linux kernel and the ATC API Standard v2.06b, MAXTIME cv can run on the same physical ATC engine board as the existing MAXTIME intersection firmware, thereby reducing the overall hardware cost of the connected vehicle deployment.

MAXTIME cv communicates directly with the signal firmware utilizing NTCIP 1201, 1202 and 1211 message sets. MAXTIME cv then creates valid J2735 messages including SPaT, MAP, and Signal Status Message (SSM) to be broadcast on a connected DSRC radio or via a connected MAXVIEW cv server application over the internet. Intelight's in-car CV App (Android and Apple devices supported) provides real-time connected vehicle data from MAXVIEW cv (Cellular) or MAXTIME cv (DSRC Radio). The application currently displays real-time position and lane tracking, time to green/time to red, actual/suggested speed, preempt/EV notification, and traveler information messages.

2.5.4 Cubic/Trafficware

Cubic/Trafficware supports the connected vehicle applications through their Version 76 (V76) and SCOUT controller software. Their controller firmware also has a module to addresses the requirements for connected vehicle. They also launched a subscription-based Connected Vehicle Module as part of their ATMS.now central management software.

V76 and SCOUT Controller Software
Cubic/Trafficware's V76 controller software is available in both OS 9 and Linux OS platforms. It can be used with ATC class controllers including NEMA and 2070. SCOUT is the company's controller software built upon the V76 controller software with enhancements. It is available in the Linux OS platform and can be matched for the latest in ATC class controllers including NEMA, 2070 and ITS. There is also connected vehicle firmware module preinstalled in the firmware of

the vendor controllers, requiring a software key to enable the feature according to the vendor.

ATMS.now central management software
Cubic/Trafficware launched its subscription-based Connected Vehicle Module as part of their ATMS.now central management software. The module allows transportation agencies to selectively publish traffic intersection data to any third party for the growing number of Connected Vehicle applications, which provide valuable intersection data to the driver.

2.5.5 McCain

McCain supports the connected vehicle applications through their FLeX Controller and Omni eX 2.0 Intersection Control Software.

FLeX Controller
McCain's FLeX Controller represents the latest design in the company's ATC eX series of advanced transportation controllers. Leveraging a Linux engine board, the controller has a real-time, open-source operating system that supports ITS applications including high-resolution data collection and V2X connected vehicle applications. It is available in both shelf and rack mount version and supports both ATC and Caltrans cabinet configurations.

Omni eX 2.0 Intersection Control Software
McCain's Omni eX 2.0 Intersection Control Software is a NTCIP-compliant program that is compatible with any ATC standard traffic controller. It is capable of operating on Model 2070 and NEMA based controllers and interfacing with Caltrans, NEMA TS2 Type 1 and Type 2, ITS and ATC cabinets. It provides the connected vehicle SPaT interface, and can be integrated with the vendor central software, Transparity TMS, or any other NTCIP-compliant central system.

2.6 SUMMARY

The infrastructure support including the functionality provided by the RSE is critical to the success of connected vehicle applications and cooperative automated vehicle applications. RAD-IT identified 19 functionalities of the RSE.

The review of the ConOps, requirements, and design documents produced for the three USDOT CV pilots (Tampa, New York, and Wyoming) provided more detailed information about several V2I applications and the RSE support of these applications. The Tampa (THEA) pilot us implementing the End of Ramp Deceleration Warning, Wrong Way Entry, Pedestrian Crash Warning, Intelligent Signal System (I-SIG), Transit Signal Priority (TSP), Pedestrian Mobility (PED-SIG), and Probe Data Enable Traffic Monitoring (PDETM). The New York City pilot is implementing Speed Compliance Warning, Oversize Vehicle Compliance, Emergency Communications and Evacuation Information, Pedestrian in Signalized Crosswalk: Intelligent Signal System CV Data, Red light Violation Warning, and RSE support functions. The related to the RSE including the monitoring of the RSE. The Wyoming Pilot is implementing Infrastructure-to-Vehicle (I2V) Situational Awareness, Distress Notification (DN), Work Zone Warning (WZW), and Spot Weather Impact Warning (SWIW).

The CV Pilot teams found ambiguity in the CV standards and worked together to update the data elements of the SPaT and MAP messages considering this ambiguity. The USDOT and the three CV Pilot sites conducted a limited test of interoperability of CV equipment from the three sites and demonstrated successful transfer of messages between the configured devices from the different sites. The CV Pilot program demonstrated the interaction of the RSU and Advanced Transportation Controller (ATC) signal controller using ITS standards. The test sites reported that testing based on individual products is no substitute for testing on the integrated systems. This will have to be specified in the planning stage of the project in a formal testing strategy.

The review conducted in this study indicates significant national and state interests in developing standards to test the infrastructure support of CV-applications including those associated with a connected intersection. There are two efforts that just started recommending or developing testing procedures. The first is referred to as the Connected Intersection effort and is sponsored by the USDOT and contracted to the Institute of Transportation Engineers (ITE). The second is an effort that is being conducted by the V2I Coalition. The review of existing and on-going testing and testing plans indicates that there is a number of existing and on-going testing plans have been recently developed or are about to be developed. The research team of this study is following these efforts. Overall, this study reviewed 16 documents related to RSE specifications and testing. The review will provide valuable inputs to the future tasks of the project including the development of the specification and testing for three selected applications.

There are three types of verifications: system level verification, message level verification, and end-to-end supplication verification. The FDOT recently produced a RSU developmental specification to add to the FDOT Standard Specifications for Road and Bridge Construction (FDOT, 2020). This specification mostly addresses the System Level standards. This research focuses on extending the specifications and associated testing to verify that the RSE provide the required support of the applications including the required messages.

Some of the reviewed tests used applications provided by CV device vendors either installed on a tablet or a laptop computer or by downloading and examining the logs and stores of the RSE and the OBE using the native logging mechanisms of the devices. In this way, the project teams were able to verify the communication of SPaT, MAP, TIM, BSM, SRS, SMS messages. Some of the applications provided a graphical view of the messages in addition to allowing the viewing the individual packets. In some cases, a DSRC Sniffer box such as that from 3M was utilized to sniff the DSRC messages to verify these messages. The teams were also able to verify the SRM with the controller go into Preemption or Priority calls.

The Tampa Pilot collected data utilizing test laptop that has the Wireshark software, Java installed, and Siemen's remote-sniffer.jar. The laptop is connected via Ethernet to the RSU and OBU. Wireshark collects messages in a packet capture data (PCAP) file that is saved in the computer. The Wyoming Pilot site utilized the OBU data log file accessed via Ethernet.

In the Tampa test procedure, units from specific venders were verified to meet the required specifications. Devices from other vendors were then tested with the golden device, as would be the case of using commercial test equipment.

FHWA has developed a draft testing plan for the certification of the communication of SPaT information between a signal controller and the RSE. The plan considers only the data objects in NTCIP 1202v03 that are required for constructing a SPaT message, as defined in SAE J2735. The test procedure utilizes SNMP browser and software package to monitor and collect data on the target communication layer (e.g., Wireshark). In the same effort, the FHWA developed draft testing plans for to evaluate the SPaT and MAP output generated by the RSE. The procedures test the format, structure and encoding of the SPaT and MAP messages as defined in the SAE J2735 Standard. The tests use a laptop with IP packet sniffer and UPER converter and a test tool to log the encoded packets.

In a test procedure produced by CAMP of the RLVW application, the document mentioned that the verification equipment can include a laptop with a DSRC radio that can receive and decode messages, perform validation tests, and display additional information for visual verification. However, according to the plan, the MAP and SPaT message packets are captured using tools provided by RSU vendors.

Several of the reviewed tested test documents will be very beneficial to this effort. In particular, the following test efforts were found to be the most useful among the 16 plans.

- FDOT FRAME Roadside and Onboard Units Testing
- The three USDOT CV Pilot test plans
- FHWA Testing of SPaT Message Communication Using NTCIP Standards
- FHWA Testing of SPaT Message Communication based on SAE J2735 Standards
- FHWA Testing of MAP Message Communication Using SAE J2735 Standards
- CAMP SPaT Challenge Verification Document
- Connected Vehicle Pilots Phase 2 Interoperability Test

The research team conducted an initial review of the RSE vendors. The reviewed vendors are TrafficCast, Savari, Kapsch, Cohda, Siemens, Danlaw, and Commsignia. The research team also conducted an initial review of the signal controller vendors of CV applications. The reviewed vendors are: Econolite, Siemens, Intelight, Cubic/Trafficware, and McCain. The research team will expand these reviews based on phone calls with the RSE and controller vendors and any additional documents provided by the vendors.

3 IDENTIFICATION OF REQUIREMENTS FOR THE SELECTD V2I APPLICATION

This section includes the identification the requirements for three selected applications. In discussion and coordination with the FDOT project manager, the project team selected the three applications based on the review of the state of practice and state of the art conducted as part of Task 1. The three applications are SPaT/MAP messages to support Red Light Violation Warning (RLVW), Emergency Vehicle Preemption (EVP), and Work Zone Warning (WZW) Reduced Speed Zone Warning and Lane Closure (RSZW/LC). Requirements for additional applications can be developed in future projects.

The requirements were developed based on the requirements developed by other entities, listed in the Reference Documents Section (Section 3-1 in this document). The requirements are based on the latest versions of the Society of Automotive Engineers (SAE) J2735 standards, SAE J2945 standards, and NTCIP 2012 v03 standards.

It should be mentioned that while working on the project tasks, the research team became aware of an effort referred to as the Connected Intersection (CI) project by the Institute of Transportation Engineers (ITE) funded by the United States Department of Transportation (USDOT) to develop detailed requirements for the RLVW. Thus, it was decided to use these requirements that are being develop by a number of consultants and volunteers as one of the basis for the RLVW requirements, although other existing requirements were also used in this study.

The remaining of this section is structured in five sections. Section 3.1 presents the referenced documents. Section 3.2 presents the general requirement that are applicable to all of the three applications. Sections 3.3 to 3.5 present the requirements for the SPaT/MAP/RLVW, EVP, and RSZW/LC applications, respectively.

3.1 REFERENCED DOCUMENT

Below is a list of the documents that are used in the development of the requirement in this report. Reference(s) are associated with each requirement presented in the rest of Section 3 where appropriate to indicate the source(s) of the requirements.

1. IEEE Guide for Developing System Requirements Specifications , IEEE Std 1233, 1998 Edition (R2002) (*20*)
2. Dedicated Short Ragne Communications (DSRC) Message Set Dictionary, SAE J2735_201603, 2016 Edition, Society of Automotive Engineers (SAE): Troy, Michigan, USA, 2016. (*21*)
3. On-Board System Requirements for V2V Safety Communications, SAE J2945/1 V5, Society of Automotive Engineers (SAE): Troy, Michigan, USA, 2016.
4. SPaT Challenge SPaT Infrastructure System Model Functional Requirements Draft Version 1.1, Vehicle to Infrastructure Deployment Coalition (V2I DC), March 2018. (*22*)
5. Multi-Modal Intelligent Traffic Signal System Final System Requirements Document University of Arizona (Lead) University of California PATH Program Savari Networks,

Inc. SCSC Econolite Kapsch Volvo Technology CDRL 130 Version 4.0, March 7, 2012. (*23*)

6. Connected Vehicle Pilot Deployment Program Phase 1, System Requirements Specification (SyRS) - Tampa (THEA) www.its.dot.gov/index.htm Final Report – August 2016 FHWA-JPO-16-315. (*24*)
7. Connected Vehicle Pilot Deployment Program Phase 1, System Requirements Specification (SyRS) – New York City, July 28, 2016, FHWA-JPO-16-303. (*25*)
8. Connected Vehicle Pilot Deployment Program Phase 1, System Requirements Specification (SyRS) – WYDOT, May 11, 2018, FHWA-JPO-16-291. (*26*)
9. Vehicle-to-Infrastructure (V2I) Safety Applications System Requirements Document www.its.dot.gov/index.htm Final Report – March 8, 2013, FHWA-JPO-13-061. (*27*)
10. Vehicle-to-Infrastructure Program V2I Safety Applications Connected Work Zone Warning Application Deployment Guideline. Developed by CAMP – Vehicle-to-Infrastructure Consortium the United States Department of Transportation Federal Highway Administration (FHWA) Date: May 23, 2019. (*28*)
11. SPaT Challenge Verification Document Revised - October 30, 2017, Version 1.2. Developed by CAMP - V2I Consortium Proprietary for SPaT Challenge Participants, October 2017. (*4*)
12. SPaT V2I Interface for Red Light Violation Warning System Requirements Specification. Ongoing Effort Conducted as Part of the ITE Connected Intersection Project, April 2020. (*29*)
13. SPaT Challenge SPaT Infrastructure System Model Concept of Operations Draft Version 1.6, Prepared by the SPaT Challenge Resource Team, March 2018.

3.2 GENERAL REQUIREMENTS

The following are general requirements for the three applications addressed in this study. It should be noted that some of the reviewed documents include additional support requirements that specify infrastructure functions to support the monitoring and logging of the application and RSU status and activity and the configuring of the system. However, these requirements are not listed in this report since the focus of this project is on message-level verification and validation.

1) For messages that include time, a RSE shall provide time that is accurate to within 10 milliseconds (ms) of Coordinated Universal Time (UTC). (*4*, *22*, *29*)
2) The RSE shall receive and broadcast messages such that they can be received from and received by the OBUs in each lane approaching the intersection. (*29*)
3) The RSE shall identify the time that the data provided by the infrastructure was generated. This allows an application using the same time source to determine the timeliness of the data. (*29*)
   a) The RSE shall provide a timestamp indicating the minute of the year when the message was created.
   b) The RSE shall provide a timestamp indicating the milliseconds within the current minute when the SPaT information was created.
4) The utilized RSU shall meet the latest USDOT and FDOT specifications.

3.3 SPaT AND MAP MESSAGES

Signal Phase and Timing (SPaT) and MAP messages are used to support several V2I connected vehicle applications. Such applications include Red Light Violation Warning (RLVW), Pedestrian in Signalized Crosswalk Warning, Eco-Approach and Departure at Signalized Intersections within the vehicle. Additionally, Mobile Accessible Pedestrian Signal System (PED-SIG) application on a mobile Personal Information Device (PID) and Left-Turn Assist.

The followings are the recommended requirements for the SPaT and MAP messages.

1) The RSE shall allow configuring the SpaT and MAP messages using the user interface. (*22*)**.**
    a) The user interface shall allow configuring a MAP message for each intersection. (For example, this will typically be the creation of an XML file that contains the MAP data for each intersection).
    b) The user interface shall allow configuring the SPaT message from the controller to the RSE, depending upon the applications to be supported at the intersection
    c) The user interface shall allow configuring the SPaT message broadcasted or communicated by the RSE.
2) The RSE shall receive traffic signal data from the Traffic Signal Controller that is compliant in NTCIP 1202 v3 format or SAE J2735 format. (*22*)
    a) The RSE shall receive an updated data set from the Traffic Signal Controller at a frequency of 10 Hz or more regardless of whether there is a state change.
3) The RSE shall assemble the content needed for standard SPaT and MAP messages. (*22*)
    a) The RSE shall process the message containing SPaT data obtained from the Traffic Signal System and generate a SPaT message.
    b) The RSE shall combine the data received from the SPaT Data Source with additional data to complete the SPaT messages.
4) The RSE shall broadcast SPaT messages that conform with J2735 standards
5) The RSE shall broadcast SPaT messages that conform to the latest version of SAE J2735, as indicated below. (*29*)
    - timeStamp MinuteOfTheYear
    - intersections IntersectionStateList (Sequence of IntersectionState)
        - IntersectionState
            - id IntersectionReferenceID
            - revision MsgCount
            - status IntersectionStatusObject
            - timeStamp DSecond
            - states MovementList (Sequence of MovementState)
                - MovementState
                - signalGroup SignalGroupID
                - state-time-speed MovementEventList (Sequence of MovementEvent)
                    - MovementEvent
                        - eventState MovementPhaseState
                        - timing TimeChangeDetails
                            - minEndTime TimeMark
                            - maxEndTme TimeMark
                            - likelyTime TimeMark
6) The RSE shall broadcast MAP messages that conform to the latest version of SAE J2735, as indicated below. (*29*)

- msgIssueRevision MsgCount
- intersections IntersectionGeometryList (Sequence of IntersectionGeometry)
    - IntersectionGeometry
        - id IntersectionReferenceID
            - id IntersectionID
        - revision MsgCount
        - refPoint Position3D-2
            - lat Latitude
            - long Longitude
        - laneWidth
        - LaneList (Sequence of GenericLane)
            - GenericLane
                - laneID
                - maneuvers AllowedManeuvers
                - NodeList2
                    - nodes NodeSet (Sequence of Node)
                        - Node
                            - delta NodeOffsetPoint
                                - [Any representation Node-XY-20b through Node-XY-32b]
                - connectsTo ConnectsToList (Sequence of Connection)
                    - Connection
                        - connectingLane
                            - lane LaneID
                            - maneuver AllowedManeuvers
                        - signalGroup SignalGroupID

7) The RSE shall broadcast the changes in signal state, timing and physical geometry with low latency to allow CV applications to react in a timely and correct manner. (*4*, *22*, *29*)
    a. The RSE shall broadcast MAP messages periodically at 1 Hz.
    b. The RSE shall broadcast SPaT messages periodically at 10 Hz.
    c. The RSE provide SPaT information that reflects the actual signal indications of the intersection within a latency of 100 ms.
8) The RSE shall increment a message counter for a signalized intersection message whenever the value of any data element describing the signalized intersection in the message except the time stamp changes. (*4*, *29*)
9) The RSE shall provide an intersection reference identifier unique within North America for each SPaT enabled intersection included in the MAP message. (*4*, *22*, *29*)
10) The RSE shall provide the movement state and state time change detail for each signal group identified in the MAP message. (*29*)
    a. The RSE shall identify the current interval state for the signal group as defined in the latest version of SAE J2735.
        i) Each SPaT will contain a “states” field, which is a list of one or more MovementStates. The number of MovementStates shall correspond to the number of controller traffic phases that are currently active at the intersection.
        ii) The RSE movement shall broadcast whether a currently allowed movement is protected or permitted.

iii) The RSE shall broadcast if the pedestrian WALK interval in the current state, is a protected movement.
iv) The RSE shall broadcast if the pedestrian WALK interval in the current state, is a permissive movement.
v) The RSE shall broadcast the pedestrian DON'T WALK interval as being stop and remain for pedestrians.

b. The RSE shall identify the next future interval state to follow the current interval state if allowed by the latest version of SAE J2735.
c. The RSE shall provide information about when the current signal interval (state) for each movement at the intersection, including pedestrian intervals (states), will change in tenths of a second in the current or next hour.
d. The provided state and state change information shall be accurate under all conditions such as under TSP (transit signal priority) and EVP (emergency vehicle preemption).
e. The RSE shall provide the earliest time, in tenths of a second that the current and any future interval in the SPaT message for the signal group could end in the absence of unpredictable events such as preemption or priority calls.
f. The time difference between minEndTime (in the UTC reference system) and the earliest possible physical phase change shall be no larger than 100 ms.
g. The RSE shall provide the latest time, in tenths of a second that the current interval could end in the absence of unpredictable events such as preemption or priority calls.
    i. In a situation where a RSE cannot determine a latest end time, a RSE shall identify the latest end time as being undefined or unknown.
    ii. The time difference between latest end time (in the UTC reference system) and the earliest possible physical phase change shall be no larger than 100 ms.
    iii. If allowed by the latest version of J2735, the RSE shall provide a Minimum Assured Time (MAT) before the movement changes to a stop (red) interval. During the MAT, the time of the beginning of the upcoming stop (red) interval shall be known and shall not change in the absence of unpredictable events such as preemption or priority calls. The MAT may be entirely within the clearance (yellow) interval or may include the clearance (yellow) interval plus all or a portion of a movement allowed (green) interval.
h. The RSE shall provide a confidence indicator for the predicted time when the current signal interval (state) for each movement at the intersection.
i. The RSE shall provide the estimated time that the current movement will next be in the allowed (green) state in the absence of unpredictable events such as preemption or priority calls.
j. The RSE shall provide signal timing data that is synchronized with signal indication changes on the roadway within a defined tolerance.
k. The RSE shall provide Intersection Status.
    i) The Intersection Status shall indicate whether the intersection is operated as fixed time or actuated control.
    ii) The Intersection Status shall indicate whether the intersection is currently operating in preemption or priority.
    iii) The Intersection status shall include whether the intersection is operating in failure flash.

11) The Infrastructure System shall manage a MAP database. (*4*, *29*)

a. The Infrastructure System shall include a database to store MAP data.
b. The Infrastructure System shall have a mechanism to configure the MAP data to be applied to the intersection associated with the SPaT Infrastructure System.
c. The SPaT Infrastructure System shall assemble the content for standard MAP messages.
d. Each MAP message shall uniquely identify the intersection for which it applies.
e. The SPaT Infrastructure System shall store a unique MAP message for each SPaT intersection.
f. The Intersection Geometry revision shall be changed only if the map information was updated.

12) The RSE shall provide the intersection geometry for one or more intersections using SAE J2735 MAP message standards. (*22*, *29*)
    a. Each MAP message shall contain a laneList. Each lane in the laneList shall be identified as an ingress lane or an egress lane through the laneAttributes->directionalUse field.
    b. The MAP Message shall provide an intersection reference point that includes latitude, longitude and elevation with a minimum of six significant decimal places for better than 0.11132-meter precision.
    c. A connected intersection shall provide an intersection reference point that is accurate to +/- half a meter.
    d. The MAP Message shall provide the default lane width at the intersection.
    e. The MAP Message shall provide a lane identifier unique within the intersection for each lane.
    f. The MAP message shall describe the geometry of the center of each vehicle lane approaching (ingress) and departing (egress) the intersection. (*4*, *22*, *29*)
        i. The MAP Message shall describe the geometry of the center of the lane by identifying at least two node points that define at least one line segment depicting the center of the lane.
        ii. The MAP Message shall describe the first node point at the stop bar of the ingress vehicle lane, with each subsequent node being farther from the intersection.
        iii. All ingress lanes shall be described in the map with each ingress lane shall contain a maneuvers field and a connectsTo field. The connectsTo field describes one or more connections to egress lanes.
        iv. Each connection shall contain the lane, maneuver, and signalGroup associated with the connection. The signalGroup identifies which signal group in the SPaT controls the flow of traffic from the ingress lane to the egress lane.
        v. If a single physical lane has multiple different signals assigned (e.g., for straight and for right-turn movement), it shall be represented by a single ingress lane and multiple connections that specify the relevant movements and the associated signal groups.
        vi. All egress lanes may be described and mapped in the MAP message. This makes it possible to connect each ingress lane to the corresponding egress lane and also to describe the allowed maneuvers on all ingress lanes. The egress lanes (if included) may optionally contain a maneuvers field or a connectsTo field.

vii. Each ingress and egress lane shall be depicted by enough nodes such that the distance between the actual curved lane center line and the straight-line connecting nodes shall not be more than half of the lane width.

g. The MAP message shall describe the geometry of the center of each crosswalk at the intersection.
h. The MAP Message shall describe the X and Y offsets of node points using a 16-bit representation of each offset, 32 bits per node according to J2735 standards.
i. The Map Message shall describe the width of the lane at the node position.

13) The RSE shall provide information about the allowed use of each lane at an intersection. **(***27*)
    a. The MAP Message shall identify the direction of travel allowed for each lane.
    b. At intersections having lanes with usage that is different at different times, such as lanes that by time of day are reversible, have turn restrictions, or have parking restrictions.
    c. The MAP needs to identify lanes that are revocable. An IOO may define the same physical lane for different uses or with different restrictions depending on the time of day or on specific days. (Note: The SPaT message will then identify which revocable lane is currently is active.)
14) The RSE shall provide information about the allowed maneuvers of each lane at an intersection. **(**27)
    a. The RSE shall identify for each lane each maneuver that is allowed for that lane at the stop bar for ingress lanes and at the downstream point for egress lanes.
15) The RSE shall provide information about the permitted connections between ingress lanes and egress lanes at an intersection **(***27)*
    a. The MAP Message shall allow identifying each possible connection between each ingress and an egress lane.
    b. For each connection between an ingress lane and an egress lane, a MAP Message shall identify the egress lane that the ingress lane connects to.
    c. For each connection between an ingress lane and an egress lane, a MAP Message shall identify the maneuver the connection allows.
    d. For each connection between an ingress lane and an egress lane, the RSE shall identify the SPaT signal group that provides traffic signal control for that movement.
16) If a lane connects to a lane defined for an adjacent SPaT enabled intersection, the MAP Message shall provide the intersection reference identifier of the remote intersection.
17) The RSE shall provide the posted or statutory speed limit, whichever is applicable. **(***27*)

Table 3-1 and Table 3-2 provides a list of data elements/frames for transmitting SPaT and MAP message, respectively. They are identified as either optional or required based on the definition in the SAE J2735-201603 data dictionary and the RLVW application requirements. (*29*)

Table 3-1 Required Data for SPaT Message Transmission for the RLVW Application

SPaT Message	SAE J2735 (201603)	RLVW Application
• timeStamp MinuteOfTheYear	Optional	Required
• intersections IntersectionStateList (Sequence of IntersectionState)	Required	Required
○ IntersectionState		
▪ id IntersectionReferenceID	Required	Required
▪ revision MsgCount	Required	Required
▪ status IntersectionStatusObject	Required	Required
▪ timeStamp DSecond	Optional	Required
▪ states MovementList (Sequence of MovementState)	Required	Required
♦ MovementState		
¤ signalGroup SignalGroupID	Required	Required
¤ state-time-speed MovementEventList	Required	Required
+ MovementEvent		
− eventState MovementPhaseState	Required	Required
− timing TimeChangeDetails	Optional	Required
› minEndTime TimeMark	Required	Required
› maxEndTme TimeMark	Optional	Optional
› likelyTime TimeMark	Optional	Optional

Table 3-2 Required Data for MAP Message Transmission for the RLVW Application

MAP Message	SAE J2735 (201603)	RLVW Application
• msgIssueRevision MsgCount	Required	Required
• intersections IntersectionGeometryList (Sequence of IntersectionGeometry)	Optional	Required
○ IntersectionGeometry		
▪ id IntersectionReferenceID	Required	Required
♦ id IntersectionID		
▪ revision MsgCount	Required	Required
▪ refPoint Position3D-2	Required	Required

MAP Message	SAE J2735 (201603)	RLVW Application
♦ lat Latitude	Required	Required
♦ long Longitude	Required	Required
▪ laneWidth	Optional	Required
▪ LaneList (Sequence of GenericLane)	Required	Required
♦ GenericLane		
¤ laneID	Required	Required
¤ maneuvers AllowedManeuvers	Optional	Required
¤ NodeList2	Required	Required
+ nodes NodeSet (Sequence of Node)		
− Node		
› delta NodeOffsetPoint		
# [Any representation Node-XY-20b through Node-XY-32b]		
¤ connectsTo ConnectsToList (Sequence of Connection)	Optional	Required
+ Connection		
− connectingLane	Required	Required
› lane LaneID	Required	Required
› maneuver AllowedManeuvers	Optional	Required
− signalGroup SignalGroupID	Optional	Required

3.4 PREEMPTION REQUIREMENTS

This application provides signal preemption to emergency vehicles. The Onboard equipment (OBE) of connected vehicles (CV) sends a Signal Request Message (SRM) to the RSE. The RSE forwards the request to the central controller or the roadside signal controller. The RSE also communicates the Signal Status Message (SSM) to the approaching vehicles that request the preemption to confirm whether the priority is granted. Although the EVP has not been implemented as part of the three United States Department of Transportation (USDOT) CV pilot projects, the Tampa Bay pilot implemented Transit Signal Priority (TSP) Application, which is applied in a similar manner to the EVP.

The following are the recommended requirements for the EVP CV application. Please note that some of the functional requirements may be performed by the traffic signal controller. This will be confirmed in the testing stage of the project.

1) The RSE shall receive valid Signal Request Messages (SRM) messages that adhere to the SAE J2735 standard from emergency vehicle OBUs that are within communication control range of an intersection. (*22*) (*23*)
   a) The received SRM shall include a timestamp, vehicle ID, vehicle type, and intersection ID. It is understood that the OBU will send SRM to RSU when the vehicle matches the location of the approached intersection. (*22*) (*24*)
   b) Each SRM shall define a path through the intersection which is desired in terms of lanes and approaches to be used.(*21*)
   c) The received messages from the emergency vehicle OBU shall include the preemption eligibility as determined by the OBU. The messages shall indicate that the emergency vehicle is in active response mode while traversing the intersection and an appropriate preemption strategy is needed. (*22*)
   d) The received messages from the emergency vehicle OBUs shall include the desired level of priority as determined by the OBUs. (*22*)
   e) The received messages from the OBU shall specify the emergency vehicle current speed, heading, and location. (*21*)
   f) Optional: The received message from the emergency vehicle OBUs shall contain the time of arrival. (*21*)
   g) The received message from the emergency vehicle OBUs shall contain the expected duration of the service. (*21*)
   h) **Optional:** The RSE shall be able to acquire active emergency vehicle priority requests for priority on a segment or section of multiple intersections. This request can be used in determining section-based priority strategies. (*22*)
2) The RSE shall process the SRM from an emergency vehicle.
   a) The RSE will determine the traffic signal phase and desired time of service associated with the request. (*22*)
   b) The RSE shall process preemption/priority request cancellations received from the OBUs. (*23*)
   c) The RSE shall be able to prioritize the SRMs received from multiple vehicles, and multiple vehicle classifications. (*23*)
3) The RSE shall request preemption to be provided by the traffic control system.

a) The RSE shall generate and send SRMs to the Traffic Signal Controller that complies with NTCIP 1202v3 (*22*)
b) In case of a higher priority, such as rail gates, the RSE shall not grant priority. (Note: This requirement may be performed by the traffic signal controller.
c) The RSE shall send requests with a maximum latency of 100 ms from receiving the preemption or priority request. (*23*)

4) The RSE shall obtain preemption status from the Traffic Signal Controller using Signal Status Messages (SSM) that comply with NTCIP 1202v3 standards**.** (*22*)
   a) The RSE shall obtain preemption status from the Traffic Signal Controller with a maximum latency of 100 ms.
5) When there are active priority requests, the RSE shall assemble and broadcast SSM that conform to the SAE J2735 March 2016 standard to the vehicles within the communication range.
   a) The SMS shall relate the current status of the signal and the collection of pending or active preemption or priority requests acknowledged by the controller. (*21*)
   b) The SMS shall include information about preemption or priority requests which were denied. (*21*)
   c) The SMS shall allow users to determine their "ranking" for any request they have made as well as to see the currently active events. (*21*)
   d) When there have been no recently received requests for service messages, this message may not be sent. (*21*)
   e) The current active event (if any) shall also be reflected in the SPaT message contents. (*21*)
   f) The RSE shall assemble and broadcast SSM with a maximum latency of 100 ms from the time the RSE receives information from the Traffic Signal System. (*23*)
6) The RSE shall track equipped vehicles within communication control range of the intersection to determine the time for the provision of the traffic signal phase that serves the approach (movement) to the intersection. (*23*)
   a) The RSE shall track the emergency vehicles using the basic safety messages (BSM) broadcast by the vehicles as they move about the intersection. (*23*)
   b) The RSE shall estimate the expected time of arrival of an emergency vehicle at specified locations within communication control range of the intersection. (*23*)
   c) The RSE shall calculate the time of the intersection departure of an equipped emergency vehicle. (*23*)
7) **Optional:** The RSE shall provide intersection signal phase and timing data and geometric description data to equipped vehicles within communication control range of the intersection consistent with the FDOT Signal Phase and Timing data (SPaT) and MAP requirements. (*23*)
8) The SRM messages received by the RSE from the OBU shall be provided using the following ASN.1 Representation. (*21*)

```
SignalRequestMessage ::= SEQUENCE {
    timeStamp MinuteOfTheYear OPTIONAL,
    second DSecond,
    sequenceNumber MsgCount OPTIONAL,
    requests SignalRequestList OPTIONAL,
```

```
        -- Request Data for one or more signalized
        -- intersections that support SRM dialogs
    requestor RequestorDescription,
        -- Requesting Device and other User Data
        -- contains vehicle ID (if from a vehicle)
        -- as well as type data and current position
        -- and may contain additional requestor data
    regional SEQUENCE (SIZE(1.4)) OF
    RegionalExtension {{REGION.Reg-SignalRequestMessage}} OPTIONAL,
    …
}
```

a) The SRM shall include Data Frame: DF_SignalRequestPackage. The DF_SignalRequestPackage data frame contains both the service request itself (the preemption and priority details and the inbound-outbound path details for an intersection) and the time period (start and end time) over which this service is sought from one single intersection. One or more of these packages are contained in a list in the Signal Request Message (SRM).

```
ASN.1 Representation:
SignalRequestPackage ::= SEQUENCE {
    request SignalRequest,
        -- The specific request to the intersection
        -- contains IntersectionID, request type,
        -- requested action (approach/lane request)
        -- The Estimated Time of Arrival (ETA) when the service is requested
    minute MinuteOfTheYear OPTIONAL,
    second DSecond OPTIONAL,
    duration DSecond OPTIONAL,
        -- The duration value is used to provide a short interval that
        -- extends the ETA so that the requesting vehicle can arrive at
        -- the point of service with uncertainty or with some desired
        -- duration of service. This concept can be used to avoid needing
        -- to frequently update the request.
        -- The requester must update the ETA and duration values if the
        -- period of services extends beyond the duration time.
        -- It should be assumed that if the vehicle does not clear the
        -- intersection when the duration is reached, the request will
        -- be cancelled and the intersection will revert to
        -- normal operation.
    regional SEQUENCE (SIZE(1..4)) OF
    RegionalExtension {{REGION.Reg-SignalRequestPackage}} OPTIONAL,
    ...
}
```

b) The SRM shall include Data Frame: DF_SignalRequest. The DF_SignalRequest is used (as part of a request message) to request either a priority or a preemption service from a signalized intersection. It relates the intersection ID as well as the specific request information. Additional information includes the approach and egress values or lanes to be used.

```
ASN.1 Representation:
SignalRequest ::= SEQUENCE {
        -- the unique ID of the target intersection
    id IntersectionReferenceID,
        -- The unique requestID used by the requestor
    requestID,
        -- The type of request or cancel for priority or preempt use
        -- when a prior request is canceled, only the requestID is needed
    requestType PriorityRequestType,
        -- In typical use either an approach or a lane number would
        -- be given, this indicates the requested
        -- path through the intersection to the degree it is known.
    inBoundLane IntersectionAccessPoint,

        -- desired entry approach or lane
    outBoundLane IntersectionAccessPoint OPTIONAL,
        -- desired exit approach or lane
        -- the values zero is used to indicate
        -- intent to stop within the intersection
    regional SEQUENCE (SIZE(1..4)) OF
        RegionalExtension {{REGION.Reg-SignalRequest}} OPTIONAL,
    ...
}
```

Used By: This entry is used directly by one other data structure in this standard, a DF called DF_SignalRequestPackage <ASN>. In addition, this item may be used by data structures in other ITS standards.

9) The SSM messages sent by the RSE to the OBU shall be provided using the following ASN.1 Representation. (*21*)

```
ASN.1 Representation:
SignalStatusMessage ::= SEQUENCE {
    timeStamp MinuteOfTheYear OPTIONAL,
    second DSecond,
    sequenceNumber MsgCount OPTIONAL,
        -- Status Data for one of more signalized intersections
    status SignalStatusList,
    regional SEQUENCE (SIZE(1..4)) OF
            RegionalExtension {{REGION.Reg-SignalStatusMessage}} OPTIONAL,
```

```
    ...
}
```

a) The SSM shall include Data Frame: DF_SignalStatusList. The DF_SignalStatusList data frame consists of a list of SignalStatus entries.

ASN.1 Representation:
SignalStatusList ::= SEQUENCE (SIZE(1..32)) OF SignalStatus

Used By: This entry is used directly by one other data structure in this standard, a MSG called MSG_SignalStatusMessage (SSM) <ASN>. In addition, this item may be used by data structures in other ITS standards.

b) The SSM shall include Data Frame: DF_SignalStatusPackageList. The SignalStatusPackageList data frame consists of a list of SignalStatusPackage entries.

ASN.1 Representation:
SignalStatusPackageList ::= SEQUENCE (SIZE(1..32)) OF SignalStatusPackage

Used By: This entry is used directly by one other data structure in this standard, a DF called DF_SignalStatus <ASN>. In addition, this item may be used by data structures in other ITS standards.

c) The SSM shall include Data Frame: DF_SignalStatusPackage. The DF_SignalStatusPackage data frame contains all the data needed to describe the preemption or priority state of the signal controller with respect to a given request and to uniquely identify the party who requested that state to occur. It should be noted that this data frame describes both active and anticipated states of the controller. A requested service may not be active when the message is created and issued. A requested service may be rejected. This structure allows the description of pending requests that have been granted (accepted rather than rejected) but are not yet active and being serviced. It also provides for the description of rejected requests so that the initial message is acknowledged (completing a dialog using the broadcast messages).

ASN.1 Representation:

```
SignalStatusPackage ::= SEQUENCE {
        -- The party that made the initial SRM request
    requester SignalRequesterInfo OPTIONAL,
        -- The lanes or approaches used in the request
    inboundOn IntersectionAccessPoint,
        -- estimated lane / approach of vehicle
    outboundOn IntersectionAccessPoint OPTIONAL,
        -- The Estimated Time of Arrival (ETA) when the service is requested
        -- This data echos the data of the request
    minute MinuteOfTheYear OPTIONAL,
    second DSecond OPTIONAL,
```

```
        duration DSecond OPTIONAL,
            -- the SRM status for this request
        status PrioritizationResponseStatus,
            -- Status of request, this may include rejection
        regional SEQUENCE (SIZE(1..4)) OF
            RegionalExtension {{REGION.Reg-SignalStatusPackage}} OPTIONAL,
        ...
    }
```

Used By: This entry is used directly by one other data structure in this standard, a DF called
DF_SignalStatusPackageList <ASN>. In addition, this item may be used by data structures in other ITS standards.

d) The SSM shall include Data Frame: DF_SignalStatus. The DF_SignalStatus data frame is used to provide the status of a single intersection to others, including any active
e) preemption or priority state in effect.

ASN.1 Representation:

```
SignalStatus ::= SEQUENCE {
    sequenceNumber MsgCount,
        -- changed whenever the below contents have change
    id IntersectionReferenceID,
        -- this provides a unique mapping to the
        -- intersection map in question
        -- which provides complete location
        -- and approach/movement/lane data
        -- as well as zones for priority/preemption
    sigStatus SignalStatusPackageList,
        -- a list of detailed status containing all
        -- priority or preemption state data, both
        -- active and pending, and who requested it
        -- requests which are denied are also listed
        -- here for a short period of time
    regional SEQUENCE (SIZE(1..4)) OF
        RegionalExtension {{REGION.Reg-SignalStatus}} OPTIONAL,
    ...
}
```

3.5 WORK ZONE WARNING (WZW) REDUCED SPEED ZONE WARNING AND LANE CLOSURE (RSZW/LC) APPLICATION

Work Zone Warning (WZW) and Reduced Speed Zone Warning: The WZW Application broadcasts information about the conditions of an approached work zone including unsafe conditions for the workers or the approaching vehicle. Such information may include lane obstructions and closures, lane shifts, speed reductions, and/or vehicles entering/exiting the work zone. This application uses the speed limit and the speed/location of the vehicle to provide speeding warnings. The stored speed limit information includes a schedule and geographic boundaries. The OBE receives this information and warns the driver when exceeding the speed limit by a configurable amount of time. In addition to static zones, this application is extended to allow the warning for dynamic zones for construction activities with the RSE installed on the barrier truck for example. This application has been implemented in the New York pilot and Tampa pilot.

The RSZW/LC application communicates with the driver approaching the work zone and warns the drivers when vehicle speed is higher than the work zone speed limit. The application also warns the drivers of lane closures associated with the work zone and worker presence. The application used information based on measured and/or communicated vehicle speed, work zone lane configuration, and the distance to the start of work zone. Two types of messages are usually provided: an “Inform” and a “Warn” messages. The “Inform” message is generated at configurable time (e.g., 15 seconds before the work zone) and “Warn” is generated at a configurable time that is shorter than the one used for the “Inform” message (e.g., 5 seconds before the work zone) (*28*).

It should be noted that the SAE is currently working on the Road Safety Applications (J2945/4) standard (https://www.sae.org/standards/content/j2945/4/) that will serve to re-work and extend the existing SAE J2735 message elements to include additional V2I messages, which are applicable to RSZW/LC. The standard will revise the structure of the existing “TIM” message to reflect the lessons learned from the various deployment activities such as the work conducted by CAMP on the subject. It is also anticipated that the J2735 document will be revised based on this work. The standards are expected to be published in March 2021. The requirements presented in this section will be revised based on the released document.

Below are the recommended requirements for the RSZW/LC.

1) The RSE shall be able to acquire and store the required work zone information collected from other infrastructure equipment (*25*) (*27*)
    a) The RSE shall be able to receive and store the reduced static speed limit that can be time variant
    b) The RSE application shall be able to receive and store the roadway work zone geometric information required to be broadcasted according to Requirement 3 below.
    c) The acquired and stored information shall be associated with a period of time for issuing the messages (*25*)
    d) The RSE shall determine if there is a reduced speed zone ahead. (*25*)
2) The RSE Application shall acquire data from the equipped vehicle (Note: Optional - the determination of the need for warning can be done by the onboard units).
    a) The acquired data shall include the vehicle’s lane-level position based on the work zone geometry received from the infrastructure. (*25*) (*27*)
    b) The acquired data shall include vehicle speed (*25*) (*27*)
3) The RSE shall provide advisories, alerts and/or warnings to deliver the information in order for the driver to take action (*25*) (*27*) (*28*)
    a) The RSE application shall broadcast to the drivers a reduced speed zone ahead. (*25*)
    b) The provided work zone geometry shall include the reference point that indicates start of the work zone (e.g., location where the taper for lane closure begins/end of taper to

indicate end of closed lane), start of lane open indicating lane for possible lane change for a closed lane, approach lanes (the lanes that lead to the work zone), work zone lanes (lanes within the work zone), and total length of the work zone (*28*)

   c) The RSE shall broadcast workers presence/absence of workers in the section(s) of the work zone where a lower speed limit applies. (*28*)
   d) The RSE shall broadcast posted speed limits (in the work zone), normal speed limit, and speed limit in the work zone when workers are present.
   e) The RSE Application shall be able to provide lane-level information including high-fidelity work zone map data elements for each lane including the geometry of the work zone represented by waypoints that describe the layout of reach lane, lane closure location(s) (start and end of tapers for lane closure(s) in the work zone, workers present location(s), and the posted speed limit(s) in the work zone according to SAE J2735 specifications and specification being defined in SAE J2945/4 (Road Safety Applications). (*28*)
   f) The RSE shall provide advisories, and/or warnings to vehicles in time for the driver to take action. Example: An "Inform" message is generated at configurable time (with default set at 15 seconds) and "Warn" messages are also generated (with default set at 5 seconds) prior to reaching the Reference Point. When approaching a RS zone, the application displays an RS Inform message on the Driver Vehicle Interface (DVI) at a configurable distance corresponding to typical response time and comfortable deceleration rate of 0.3g (does not account for weather and pavement conditions) for the driver to reduce speed before entering a work zone. (*28*)

4) The RSE application shall provide information, warning and alerts when the detected vehicle speed is determined to be unsafe. (**Note: Optional , this can be done by the On-Board Unit).** (*25*) (*27*)
   a) The RSE application shall determine the speed of the host vehicle based on accuracy and threshold per J2945/1. (*25*)
   b) The RSE application shall determine the difference between the posted speed on the upcoming reduced speed zone and the vehicle's current speed. (*25*)
   c) The RSE Application shall determine when an alert/warning is warranted based on the reduced speed zone speed limit and the detected vehicle's speed. (*25*) (*27*)
      i) The RSE application shall determine if the vehicle exceeds the Work Zone Posted Speed plus the Excessive Zone Speed Amount Threshold, for a period exceeding the Excessive Zone Speed Time Threshold. (*25*) (*27*)
   d) If the vehicle speed is greater than the reduced speed zone, the RSE application shall advise the driver in time for the driver to reduce vehicle speed to the posted speed limit before the vehicle enters the zone. (*25*) (*27*)
   e) If the driver continues to travel in the closing lane a Warning will be issued, which is also based on distance to the start of taper for the lane closure in the work zone.
   f) While the vehicle is in the speed zone, the RSE application shall trigger a driver alert when the vehicle speed exceeds the Work Zone Posted Speed plus the Excessive Zone Speed. (*25*)
5) **Optional:** The RSE shall support the display of messages on roadside signage to provide information for unequipped vehicles.

a) The RSE Application shall determine, if applicable, the appropriate message pertaining to roadway configuration changes and speed to be provided on Roadside Dynamic Message Sign.

6) The broadcasted messages shall follow SAE J2735 and SAE J2945/4 standards. (Note: the followings are the requirements given in the Wyoming Pilot System Requirements for the messages (*26*). They will be updated after the release of J2945/4 standards.)
   a) The RSE shall include a packet identifier for the traveler information packet broadcasted to connected devices.
   b) The RSE shall identify each message transmitted as part of a traveler information packet broadcasted to connected devices.
   c) For each traveler information message in a traveler information packet, the RSE shall include the duration from the start time that the traveler message is valid for.
   d) For each traveler information message in a traveler information packet, RSE shall include the importance of the message relative to other traveler information messages being broadcasted as part of a traveler information packet broadcasted to connected devices.
   e) The RSE shall be able to broadcast the information to travelers within specific geographic (spatial) regions and/or a direction of travel. **(Note: Optional – the Onboard units may be able to resolve this.)**
      i. For each traveler information message in a traveler information packet, a connected device shall include the geographic location (latitude, longitude, elevation) of the default anchor point for which valid regions are determined as part of a traveler information packet broadcasted to connected
      ii. For each traveler information message in a traveler information packet, a connected device shall include the direction of motion (of the connected device) that the message is valid for as part of a traveler information packet broadcasted to connected devices.
      iii. A spatial region for which a traveler information message is valid for may be a circular region around an anchor point. The connected device should be located within the circular region for the traveler information message to be presented to the traveler. Each traveler information message in a traveler information packet a connected device shall include the radius for the circular region.
      iv. A spatial region for which a traveler information message is valid for may be a polygon, which may represent the jurisdictional boundaries of a specific transportation agency or a work zone. The connected device should be located within this polygon region for the traveler information message to be presented to the traveler.
      v. A spatial region for which a traveler information message is valid for may be a shape point set, which allows a spline-like representation of a geographic area such as a road segment. A connected device should be located within the shape point set region for the traveler information message to be presented to the traveler.
   f) For traveler advisory message in a traveler information packet, a connected device shall include the contents of the travel advisory information
      i) For each traveler information message, a connected device shall include the vehicle types that the traveler advisory or road sign is valid for as part of a traveler information message broadcasted to connected vehicles.

ii) An RSE shall broadcast a traveler information message to connected devices no more than once per second. If the specification does not indicate a default transmission rate, the suggested default transmission rate for an RSU to broadcast a traveler information message to connected devices is once per second.

iii) If there is no need for an RSU to broadcast a message, then it recommended that no messages be transmitted from the RSU. Otherwise, it is recommended that an RSU transmit a broadcast message frequently enough to ensure that the connected device for which the message is intended, traveling at the expected percentile speed would be within the transmission zone for at least three or four broadcasts.

7) The RSZW/LC application TIM messages shall be provided using the following ASN.1 representation. (*21*)

```
TravelerInformation ::= SEQUENCE {
    msgCnt MsgCount,
    timeStamp MinuteOfTheYear OPTIONAL,
    packetID UniqueMSGID OPTIONAL,
    urlB URL-Base OPTIONAL,
            -- A set of one or more self contained
            -- traveler information messages (frames)
    dataFrames TravelerDataFrameList,
    regional SEQUENCE (SIZE(1..4)) OF
            RegionalExtension {{REGION.Reg-TravelerInformation}} OPTIONAL,
    ...
}
```

Data Frame: DF_TravelerDataFrame

Use: The DF_TravelerDataFrame is used to send a single "message" in a TIM message. The data frame allows sending various advisory and road sign types of information to equipped devices. It uses the ITIS encoding system to send well-known phrases but allows limited text for local place names. The supported message types specify several sub-dialects of ITIS phrase patterns to further reduce the number of octets to be sent. The expressed messages are active at a precise start and duration period, which can be specified to a resolution of a minute. The affected local area (or set of areas) can be expressed using either a radius system or one of the two systems of short defined regions. This expression is similar to the way roadway geometry is defined in the map fragment messages. The ability to send this message is controlled by the SSPIndex which links back to the sender’s CERT.

ASN.1 Representation:

```
TravelerDataFrame ::= SEQUENCE {
    -- Part I, Frame header
    sspTimRights SSPindex,
    frameType TravelerInfoType, -- (enum, advisory or road sign)
    msgId CHOICE {
            furtherInfoID, -- links to ATIS msg
            roadSignID -- an ID to other data
```

```
    },
     startYear DYear OPTIONAL, -- only if needed
     startTime MinuteOfTheYear,
     duratonTime MinutesDuration,

     priority SignPrority,


     -- Part II, Applicable Regions of Use
     sspLocationRights SSPindex,
     regions SEQUENCE (SIZE(1..16)) OF GeographicalPath,

     -- Part III, Content
     sspMsgRights1 SSPindex, -- allowed message types
     sspMsgRights2 SSPindex, -- allowed message content
     content CHOICE {
             advisory ITIS.ITIScodesAndText, -- typical ITIS warnings
             workZone, -- work zone signs and directions
             genericSign GenericSignage, -- MUTCD signs and directions
             speedLimit, -- speed limits and cautions
             exitService -- roadside avaiable services
             -- other types may be added in future revisions
    },
     url URL-Short OPTIONAL, -- May link to image or other content
     ...
}
```

Used By: This entry is used directly by one other data structure in this standard, a DF called DF_TravelerDataFrameList<ASN>. In addition, this item may be used by data structures in other ITS standards.

```
WorkZone ::= SEQUENCE (SIZE(1..16)) OF SEQUENCE {
    item CHOICE {
             itis ITIS.ITIScodes,
             text ITIStextPhrase
    }
}
```

SpeedLimit ::= SEQUENCE (SIZE(1..16)) OF SEQUENCE { item CHOICE { itis ITIS.ITIScodes, text ITIStextPhrase } }

```
ITIScodes ::= INTEGER (0.. 65535)
    -- The defined list of ITIS codes is too long to list here
    -- Many smaller lists use a sub-set of these codes as defined elements
    -- Also enumerated values expressed as text constant are very common,
```

```
    -- and in many deployments the list codes are used as a shorthand for
    -- this text. Also, the XML expressions commonly use a union of the
    -- code values and the textual expressions.
    -- Consult SAE J2540 for further details.
```

ITIStextPhrase ::= IA5String (SIZE(1..16))

Use: The DE_ITIStextPhrase data element is used to provide very short sections of text interspersed between the IT IS codes to create phrases. In general, this is used for expressing proper nouns, such as street names reflecting local expressions that do not appear in the ITIS tables.

```
ValidRegion ::= SEQUENCE {
    direction HeadingSlice, -- field of view over which this applies,
    extent OPTIONAL,
            -- the spatial distance over which this
            -- message applies and should be presented
            -- to the driver
    area CHOICE {
            shapePointSet, -- A short road segment
            circle, -- A point and radius
            regionPointSet -- Wide area enclosed regions
    }
}

HeadingSlice ::= BIT STRING {
    -- Each bit 22.5 degree starting from
    -- North and moving Eastward (clockwise) as one bit
    -- a value of noHeading means no bits set, while a
    -- a value of allHeadings means all bits would be set
    from000-0to022-5degrees (0),
    from022-5to045-0degrees (1),
    from045-0to067-5degrees (2),
    from067-5to090-0degrees (3),
    from090-0to112-5degrees (4),
    from112-5to135-0degrees (5),
    from135-0to157-5degrees (6),
    from157-5to180-0degrees (7),
    from180-0to202-5degrees (8),
    from202-5to225-0degrees (9),
    from225-0to247-5degrees (10),
    from247-5to270-0degrees (11),
    from270-0to292-5degrees (12),
    from292-5to315-0degrees (13),
    from315-0to337-5degrees (14),
    from337-5to360-0degrees (15)
```

```
 } (SIZE (16))
Extent ::= ENUMERATED {
      useInstantlyOnly (0),
      useFor3meters (1),
      useFor10meters (2),
      useFor50meters (3),
      useFor100meters (4),
      useFor500meters (5),
      useFor1000meters (6),
      useFor5000meters (7),
      useFor10000meters (8),
      useFor50000meters (9),
      useFor100000meters (10),
      useFor500000meters (11),
      useFor1000000meters (12),
      useFor5000000meters (13),
      useFor10000000meters (14),
      forever (15) -- very wide area
 } -- Encoded as a 4-bit value

Circle ::= SEQUENCE {
      center Position3D,
      radius Radius-B12,
      units DistanceUnits
 }

ShapePointSet ::= SEQUENCE {
      anchor Position3D OPTIONAL,
      laneWidth OPTIONAL,
      directionality DirectionOfUse OPTIONAL,
      nodeList NodeListXY, -- XY path details of the lane and width
      ...
 }

 RegionPointSet ::= SEQUENCE {
      anchor Position3D OPTIONAL,
      scale Zoom OPTIONAL,
      nodeList RegionList, -- path details of the regions outline
      ...
 }

AdvisorySpeed ::= SEQUENCE {
      type AdvisorySpeedType, -- the type of advisory which this is.
      speed SpeedAdvice OPTIONAL,
```

```
            -- See Section 11 if SAE J2735 for converting and translating speed
            -- expressed in mph into units of m/s
            -- This element is optional ONLY when superseded
            -- by the presence of a regional speed element found in
            -- Reg-AdvisorySpeed entry
   confidence SpeedConfidence OPTIONAL, -- A confidence value for the above speed
   distance ZoneLength OPTIONAL,
            -- Unit = 1 meter,
            -- The distance indicates the region for which the advised speed
            -- is recommended, it is specified upstream from the stop bar
            -- along the connected egressing lane
   class RestrictionClassID OPTIONAL,
            -- the vehicle types to which it applies
            -- when absent, the AdvisorySpeed applies to
            -- all motor vehicle types
   regional SEQUENCE (SIZE(1..4)) OF
   RegionalExtension {{REGION.Reg-AdvisorySpeed}} OPTIONAL,
   ...
}
AdvisorySpeedList ::= SEQUENCE (SIZE(1..16)) OF AdvisorySpeed
   -- The AdvisorySpeedList data frame consists of a list of AdvisorySpeed entries.
```

Used By: This entry is used directly by one other data structure in this standard, a DF called DF_MovementEvent

4 TEST PLAN FOR THE SELECTED V2I APPLICATIONS

This section identifies the test plan for the three selected applications. As reported in Section 3, in discussion and coordination with the FDOT project manager, the project team selected the three applications based on the review of the state of practice and state of the art conducted as presented in Section 2. The three applications are SPaT/MAP messages to support Red Light Violation Warning (RLVW), Emergency Vehicle Preemption (EVP), and Work Zone Warning (WZW) Reduced Speed Zone Warning and Lane Closure (RSZW/LC). Requirements for additional applications can be developed in future projects.

The test plan in this document were developed based on the requirements reported in Section 3 of this document and follows the *Institute of Electrical and Electronics Engineers (IEEE)* Standard for Software and System Test Documentation (IEEE Std 829-2008**).** The plan identifies the items to be tested, features to be tested, test design overview, testing personnel, test environment and setup, schedule, risk and mitigation, and test cases and procedures.

4.1 REFERENCED DOCUMENT

Below is a list of the documents that are used in the development of the requirement in this report:

1. IEEE Standard for Software and System Test Documentation, IEEE Computer Society Sponsored by the Software & Systems Engineering Standards Committee, /July 2008 (Revision of IEEE Std 829-1998)
2. Vehicle-to-Infrastructure (V2I) Connected Vehicle Pilots Phase 2 Interoperability Test – Test Plan https://rosap.ntl.bts.gov/view/dot/36715 Final Report – August 13, 2018, FHWA-JPO-18-691.
3. Infrastructure Connectivity Certification Test Procedures for Infrastructure-based CAV Components, Test Procedures, MAP – SAE J2735 Developed by Leidos, Inc. Date: December 23, 2019.
4. Infrastructure Connectivity Certification Test Procedures for Infrastructure-based CAV Components, Test Procedures, Signal Phase and Timing – NTCIP 1202v03 developed by Leidos, Inc. Date: December 23, 2019.
5. Infrastructure Connectivity Certification Test Procedures for Infrastructure-based CAV Components, Signal Phase and Timing – SAE J2735 Developed by Leidos, Inc. Date: December 23, 2019.
6. Deliverables of the on-going Connected Intersection project manager for the USDOT by the ITE.
7. ITS Standards for the Data Capture and Management Program – Test Plan for the SAE Submittal Developed by Consensus Systems Technologies Corporation (ConSysTec), FreeAhead Inc., and TransCore Inc Ltd March 9, 2017

4.2 TEST OBJECTIVE AND SCOPE

The objective of this document is to identify a process for the message-level verification of the RLVW, EVP, and RSZW/LC connected vehicle-based applications to ensure that the messages conform to the requirements developed in this project and the applicable standards. The described process is to verify the format, structure, values, and completeness of the messages generated by the RSE for the three applications. The scope for testing includes various messages and associate data elements to support the requirements presented in Section 3. As such, the testing process will:

- Verify completeness of the data produced by the RSE according to Society of Automotive Engineers (SAE) J2735 message format for the messages and data elements that are needed to support the identified requirements in Section 3
- Verify the correctness of the format conversions between the National Transportation Communications for Intelligent Transportation System Protocol (NTCIP) and the SAE J2735 message formats
- Verify that the generated values of all data elements data encoded to messages are identical as those in the data source (Example: SPaT data elements broadcasted by the RSE are identical to those received from the traffic signal controller)
- Test/verify outcomes/results when correct inputs are provided to the RSE
- Test/verify correct error handling for boundary conditions (values) inputs are provided to the RSE
- Allow the verification that the messages generated by the RSE are received correctly by the OBU

4.3 ITEMS TO BE TESTED

The Device Under Test (DUT) will be a physical or virtual device that implement CV-based applications to communicate with the traffic signal controller and generate messages according to the J2735 standard for broadcast to equipped vehicles. The DUT will be a RSE that meets the latest FDOT and USDOT RSU standards and has one or more of the following functionalities depending on the tested application(s), according to the FDOT requirements:

- Receive Signal Phase and Timing data (SPaT) information from a traffic signal controller and MAP information and broadcast intersection signal phase and timing data and geometric description data to equipped vehicles within communication control range of the intersection in accordance with SAE J2735 SPaT and MAP standards
- Receive valid Signal Request Messages (SRM) messages that adhere to the SAE J2735 standard from emergency vehicle OBUs that are within communication range of an intersection and forward the requests to the traffic signal controller
- Assemble and broadcast Signal Status Messages (SSM) that conform to the SAE J2735 standard to the vehicles within the communication range when there are active priority requests
- Broadcast work zone advisories, alerts and/or warnings following SAE J2735 and SAE J2945/4 traveler information standards to the vehicles within the communication range.

This document utilizes two variations of the test plan developed in the study:

- Testing of commercially available RSE that provides the above functionality
- Testing utilizing the V2X Hub developed by the USDOT, which converts, processes, and forwards messages between the traffic controller and the RSU

The second variation in the above is meant to demonstrate and verify the different steps of the testing process. In this case, the RSU is used only to verify that the messages have the security credentials before transmitting the messages to the on-board units or the V2X Hub. The V2X Hub functions as a middleware between the controller and the RSU.

The commercially tested equipment must meet the latest FDOT Standard Specifications for Road and Bridge Construction (*5*) and USDOT RSU standards and has the required communication capabilities. According to the FDOT specifications, the equipment must be compatible with the USDOT approved Security Credential Management System (SCMS) message security solution for vehicle-to-infrastructure (V2I) communications and meet listed industry standards. In addition, the FDOT specifies that the CV equipment must be Federal Communications Commission (FCC) certified. The equipment must be capable of remote firmware updates. The RSUs shall also be interoperable with all FDOT APL approved Advanced traffic Controllers (ATC). The RSU must include a wired Ethernet interface. The RSU shall allow access to all user-programmable features, health and status monitoring, event logging, and diagnostic utilities. The specification specified in the Field-Testing section to verify over the air RSU broadcasts using a multi-channel test tool (MCTT) and verify that the MCTT receives the messages.

4.4 FEATURES TO BE TESTED

This section identifies the features of the DUT that will be tested. It also identifies any features of the DUT that will not be tested. The test addressed in this document is a message level testing of SPaT, MAP, SRS, SMS, and work zone TIM messages. The verification will include:

a) Conformance with SAE J2735 data dictionary message structure
b) Conformance with SAE J2735 data dictionary message data element value specified limits (e.g., value ranges, string lengths, enumerated list values)
c) Conformance with SAE J2735 optional data items and message constructions that are required in the FDOT CV application requirements
d) Conformance with data and reference integrity with SPaT and MAP messages (e.g., intersection ID in SPaT and MAP represent the same intersection).

The conformance testing is limited to messages and associated performance established by SAE J2735 and relevant J2945 Standards. The system-level testing and end-to-end testing are not within the scope of this test, as discussed earlier, in addition, the following items are not within the scope of this test plan:

- Physical tests of RSE and controller hardware
- Wireless communication protocols for message transmission (e.g., IEEE 1692 standards)
- Global Navigation Satellite System (GNSS) accuracy and related interfaces
- Radio Technical Commission for Maritime Services *(RTCM*) generation and accuracy
- Security assurance/SCMS
- MAP Accuracy
- MAP Security Profile

4.5 TEST DESIGN OVERVIEW

This section provides an overview of the test strategy for the message-level testing of CV applications including the activities to be performed and the types of the utilized tools in the testing. This project uses alternative methods in the testing. This includes the testing of RSE messages with and without the V2X Hub developed by the USDOT, as mentioned earlier and explained below. Two alternative configurations will be used to capture the messages; the first is by using a hardwire connection between the DUT and a computer, and the second is by capturing over-the-air messages using a mobile device.

First, the test plan will be demonstrated and tested using the V2X Hub, which converts, processes, and forwards messages between the RSU and the traffic signal controller (TSC). The received information from the TSC can be in NTCIP 1202 v03A format or Traffic Signal Controller Broadcast Message (TSCBM) format. Please note that Section 671-2 of the FDOT Specifications specifies the following requirements for the TSC: "Provide and make Management Information Bases (MIBs) available for Traffic Signal Controller Broadcast Messages (TSCBM) to local agencies and FDOT that are compatible with Society of Automotive Engineer (SAE) J2735 201603. 3. Support programming of destination Internet Protocol (IP) addresses via controller front panel for interface with Dedicated Short-Range Communication (DSRC) Roadside Units (RSU), also called Vehicle to Infrastructure (V2I) Hubs." (Note: V2I Hub is the earlier version of the V2X Hub described earlier).

The configuration of the test with the V2X Hub will allow the testing team to examine various test cases and procedures and will inform and verify the testing process before its use with commercial unit applications. If this configuration is used as part of an over-the-air testing, the RSU will be used to sign the messages received by the V2X and transmit the messages without further processing of the messages. The V2X Hub can also be used when the purpose of the test is to verify the communication requirements, physical requirements, and other requirements of a commercially available RSU, without testing a specific message generation by CV applications that are implemented by the RSU vendor.

The second variation of test will be done without the use of the V2X Hub. In this case, all of the conversion, processing, and forwarding of messages will be done utilizing commercially available equipment. The RSU will encode the messages, process the data as necessary, sign, and broadcast the messages upon receiving the information from the traffic signal controller (TSC) or the OBU. The received information from the TSC can be in NTCIP 1202 v03A format or TCBM format. It is anticipated that the testing of the RSE applications at TERL will utilize this type of testing when testing vendor-specific CV application support that does not require a middleware like the V2X Hub. It should be noted that the testing can benefit from using the V2X Hub even in this case as the V2X Hub can be used as a baseline to compare the performance of the commercial unit to the requirements. There is a potential of using both the V2X Hub and commercial CV applications incorporated in the unit, depending on the component being testing.

As stated above, the testing will use two variations for data capture, as explained:

- In the first alternative, the messages are obtained as a log on a computer that is connected through the Ethernet interface to the RSE equipment within a subnet by using an Ethernet cable or a network switch. If the V2X hub is installed on a computer, it is also possible to capture the data on the same computer. Another possible option is to obtain the Unaligned Packed Encoding Rules (UPER Hex) messages as a log on the RSU.
- In the second alternatives, the messages are obtained using a mobile tool to capture the wireless packets transmitted over the air. This wireless capture is the preferred method for collecting the output data.

When capturing the data, a utilized tool will be used to decode the captured packets from the UPER Hex to human readable XML or JSON format for verification. The verification will include the existence, completeness, and correctness of the required messages according to SAE J2735 standards. The structure of the captured messages will be verified based on the SAE J2735 2016 ASN.1 document, which provides the details of the various message sets, data frames, and data elements.

4.6 TESTING PERSONNEL

Error! Reference source not found. shows recommended the number and qualifications of staff to complete the testing activities for each of the tested messages. These recommendations are based on the information provided in the three test documents produced by the USDOT as part of the "Infrastructure Connectivity Certification Test Procedures for Infrastructure-Based Connected Automated Vehicle Components" effort (*10*).

Table 4-1 Test Personnel
(*10*)

Title	**Minimum Number**	**Description**
Test director/manager	1	The test director supervises and controls all tests, reviews and approves test procedures, has authority to direct all test activities, and is responsible for communicating test status to all stakeholders. The test director notifies key stakeholders of the test schedule in advance of the scheduled start.
Test conductor	1	The test conductor is responsible for running the daily test activities and remains in contact with vendors, as needed, to communicate which tests are being run and receive support input during testing. The test conductor distributes test scripts, forms, and any other pertinent information, and answers questions. The test conductor can also be the test operator Throughout the test day, the test conductor verifies that entrance criteria have been met for each test run, verifies readiness of test participants and equipment, and announces

Title	Minimum Number	Description
		the start and end of each testing period. The test conductor also ensures other participants execute tests according to procedures. At all times, the test conductor is responsible for judging how to proceed if incidents or exceptions occur and canceling and rescheduling tests in the event a failure prevents a test from being executed. At the end of the test period, the test conductor will write up the results of various test runs completed and any incidents or exceptions that occurred. The status report will be provided to relevant stakeholders
Test operator	1–2	The test operator defines and executes test procedures to evaluate each device and records the outputs and overall results of each test.
Roadside equipment technology expert	1	The technology expert has extensive knowledge of the technology under test. This includes the use cases, underlying and enabling technologies, communication protocols, data transfer mechanism(s), and security. The technology expert advises the test conductor, as needed.
Vendor representative	1 per vendor	The vendor representative supports the test conductors and test operators during all testing phases, as required. Support is provided in person or remotely. A representative of the vendor of each device being certified should be involved in the testing.
Test observers	As desired	Test observers witness test runs at the certification test lab's (CTL) discretion.

4.7 TEST ENVIRONMENT

The Test Environment will need to have the following equipment in order to conduct the tests:

- A power source appropriate to the device under test (DUT)
- Traffic signal controller(s) that are NTCIP 1202 v03 or TSCBM compatible
- Software that provides inputs to signal controller to set timing plans for the test
- RSU hardware
- OBU hardware for over-the-air testing
- A Linux (Ubuntu) computer running V2X Hub
- A test tool to log encoded packets over the available wireless technology (e.g., the tool currently available from Kapsch)

- A computer running a software package such as Wireshark to capture and save the encoded messages into .pcap files
- A computer with vehicle-to-everything (V2X) decoder to visualize and analyze the decoded messages

4.8 TEST ENVIRONMENT SETUP

This section presents the basic test environment setup. Depending on the connection type (wired or wireless) to the RSU, with/without V2X Hub, and the tested message types (SRM or not), there are four scenarios of test environment setup:

- **Scenario 1 – Wireless Connection with V2X Hub**: As shown in Figure 4-1, a Linux computer running V2X Hub software (this could be a regular computer or a small single board computer) is used between the signal controller and the RSU, and the connections among these three components are wired Ethernet connections. There will be wireless interface between the RSU and the packet capture tool (currently planned to be the Kapsch tool).
- **Scenario 2 – Wireless Connection without V2X Hub**: As shown inFigure 4-2, in this scenario, the signal controller is connected to the RSU through Ethernet connection. As with scenario 1, there will also be wireless interface between the RSU and the packet capture tool.
- **Scenario 3 – Wired Connection**: As shown in Figure 4-3, in this scenario, the signal controller is connected to either the RSU or V2X Hub through Ethernet connection, and the RSU or V2X Hub is also connected to a control/logging device (computer).
- **Scenario 4 – Wireless Connection with OBU (SRM only)**: While Scenarios 1 to 3 are to test the SPaT, MAP, SSM, and TIM messages, Scenario 4 is to test SRM messages only. As shown in Figure 4-4, the message transmission direction from the OBU to the RSU and then to the signal controller, which is the reversed direction compared to the other four messages. There is wireless connection between the OBU and RSU. The SRM messages can be logged to the control/logging device (computer) from signal control system and/or RSU.

After configuring the DUT, the data capture tool, and logging computers; any two devices communicating through the Ethernet interface must be connected within a subnet by using an Ethernet cable or a network switch. The test operator must ensure communication between two devices are properly set up. A software package (e.g., Wireshark) will be used to decode the SAE J2735 user datagram protocol (UDP) packets to unpack the various layers and retrieve the payload. The payload will be further decoded and converted to human readable XML or JSON format for analysis using a decoder software that are commonly available or written specifically for this testing.

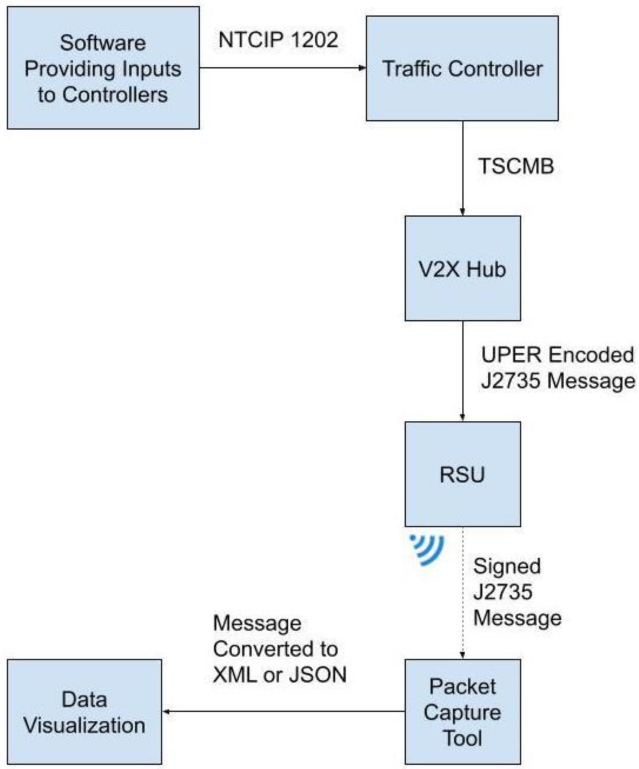


Figure 4-1 Test Environment Setup of Scenario 1

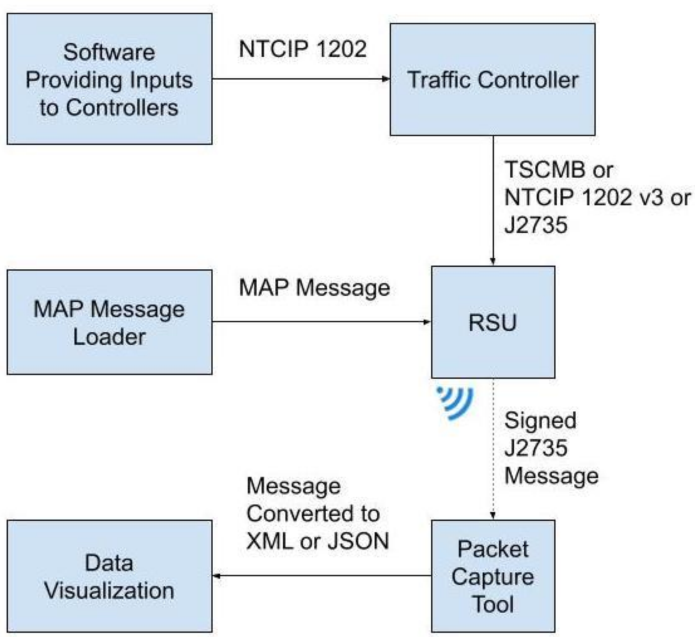


Figure 4-2 Test Environment Setup of Scenario 2

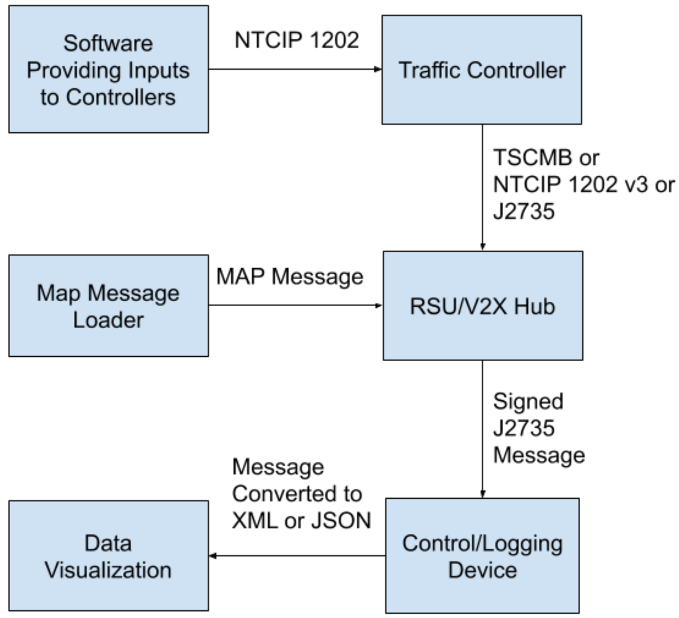


Figure 4-3 Test Environment Setup of Scenario 3

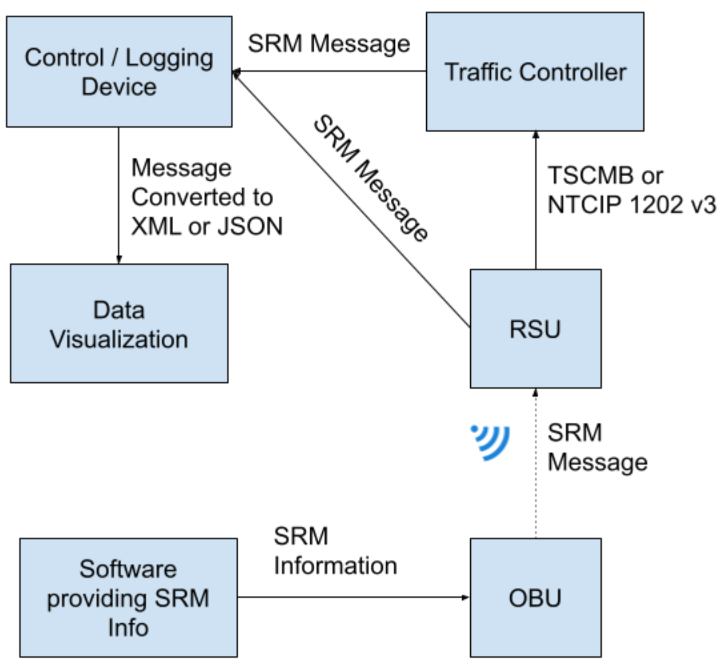


Figure 4-4 Test Environment Setup of Scenario 4 (for SRM only)

4.9 SCHEDULE

Error! Reference source not found. lists the anticipated duration for the activities of the evaluation process of each of the messages tested (SPaT, MAP, SRS and SMS, and work zone

TIM messages). This is based on the information provided in the three test documents produced by the USDOT as part of the "Infrastructure Connectivity Certification Test Procedures for Infrastructure-Based Connected Automated Vehicle Components" effort (*10*).

Table 4-2 Test activities
(*10*)

ID	Activity	Estimated Duration
1	Initial hardware inspection	1 day
2	Initial configuration to operate in the applicable test environment	1 day
3	Full evaluation	2 weeks
4	Document results and submit a final report	1 week

4.10 RISK AND MITIGATION

This section is meant to identify the overall risks to the project with emphasis on the test processes. A main issue is that the Society of Automotive Engineers (SAE) standards and to a lesser degree NTCIP standards are continuously changing. In fact, new SAE J2945 standards are being or will be released, in addition to major updates to existing SAE J2945, J2735, and NTCIP 1202 standards. Thus, these standards should be continuously monitored, and this document should be updated accordingly.

Other national efforts such as the Connected Intersection Project, the Connected Vehicle Pooled Fund Study, and various USDOT projects will identify requirements and associated testing that can be adopted to supplement the testing plan in this document.

The CV applications and associated testing are emerging concepts that are expected to be updated as they are implemented, and lessons learned gathered. Newly developed testing tools will also become available and such tools may allow easier implementations of the testing plan. This will be another reason to have this testing plan continuously monitored and updated.

Since the standards can be updated frequently, vendors need time to fully implement these standards, which may result in devices that follow different versions of the standards. This may be mitigated by FDOT specifications.

4.11 TEST CASES AND PROCEDURES

This section includes the Test Case Specification (TCS) and for each of the tested messages. The validation of the message includes two aspects. One is to validate the existence of the data fields of the tested message, and the second is to validate the content and structure of the tested message. Therefore, there are two types of test case for each message:

- **Fields Existence**: to verify all the fields of the message configured by input exist after transmission
- **Fields Valid**: to verify all the fields of a message after transmission are valid and match with the input configuration

Each test case consists of a case number name, reference, objective, inputs, expected outcomes, pass/fail criteria, and test procedures. The verification and validation of the data fields are according to the definition of each tested message based on J2735 (201603).

Table 4-3 lists the ranges of all the data element types used by all five tested message sets (SPaT, MAP, SRM, SSM, and TIM). There are six types of data elements as listed below.

- **INTEGER**: integer variable
- **BIT STRING**: binary data of arbitrary length
- **BOOLEAN**: logical, two-state variable
- **ENUMERATED**: values of variables with at least three states
- **IA5String**: values that are strings of characters from the International Alphabet 5 (International ASCII) character set
- **OCTET STRING**: binary data whose length is a multiple of eight

The data and test case specifications for each tested message are provided in the remainder of this section.

Table 4-3 Ranges of the Valid Value for Each Field

Item Under Test	Type	Lowest Acceptable Value	Highest Acceptable Value
Angle	INTEGER	0	28800
ApproachID	INTEGER	0	15
DeltaAngle	INTEGER	-150	150
DeltaTime	INTEGER	-122	121
DrivenLineOffsetLg	INTEGER	-32767	32767
DrivenLineOffsetSm	INTEGER	-2047	2047
DSecond	INTEGER	0	65535
DYear	INTEGER	0	4095
Elevation	INTEGER	-32768	32767
IntersectionID	INTEGER	0	65535
Iso3833VehicleType	INTEGER	0	100
LaneConnectionID	INTEGER	0	255
LaneID	INTEGER	0	255
LaneWidth	INTEGER	0	32767
Latitude	INTEGER	-900000000	900000001
LayerID	INTEGER	0	100
Longitude	INTEGER	-1799999999	1800000001
MergeDivergeNodeAngle	INTEGER	-180	180
MinuteOfTheYear	INTEGER	0	527040
MinutesDuration	INTEGER	0	32000
MsgCount	INTEGER	0	127
Offset-B10	INTEGER	-512	511
Offset-B11	INTEGER	-1024	1023
Offset-B12	INTEGER	-2048	2047

Item Under Test	Type	Lowest Acceptable Value	Highest Acceptable Value
Offset-B13	INTEGER	-4096	4095
Offset-B14	INTEGER	-8192	8191
Offset-B16	INTEGER	-32768	32767
PrioritizationResponseStatus	INTEGER	0	7
RequestID	INTEGER	0	255
RestrictionClassID	INTEGER	0	255
RoadRegulatorID	INTEGER	0	65535
RoadSegmentID	INTEGER	0	65535
RoadwayCrownAngle	INTEGER	-128	127
Scale-B12	INTEGER	-2048	2047
SignalGroupID	INTEGER	0	255
SignPrority	INTEGER	0	7
SpeedAdvice	INTEGER	0	500
SSPindex	INTEGER	0	31
SSPindex	INTEGER	0	31
StationID	INTEGER	0	4294967295
TimeIntervalConfidence	INTEGER	0	15
TimeMark	INTEGER	0	36001
Velocity	INTEGER	0	8191
ZoneLength	INTEGER	0	10000
Zoom	INTEGER	0	15
AllowedManeuvers	BIT STRING (SIZE(12))	0b000000000000	0b111111111111
HeadingSlice	BIT STRING (SIZE(16))	0b0000000000000000	0b1111111111111111
IntersectionStatusObject	BIT STRING (SIZE(16))	0b0000000000000000	0b0011111111111111
LaneAttributes-Barrier	BIT STRING (SIZE(16))	0b0000000000000000	0b0000001111111111
LaneAttributes-Bike	BIT STRING (SIZE(16))	0b0000000000000000	0b0000000001111111
LaneAttributes-Crosswalk	BIT STRING (SIZE(16))	0b0000000000000000	0b0000000111111111
LaneAttributes-Parking	BIT STRING (SIZE(16))	0b0000000000000000	0b0000000001111111
LaneAttributes-Sidewalk	BIT STRING (SIZE(16))	0b0000000000000000	0b0000000000001111
LaneAttributes-Striping	BIT STRING (SIZE(16))	0b0000000000000000	0b0000000000111111
LaneAttributes-TrackedVehicle	BIT STRING (SIZE(16))	0b0000000000000000	0b0000000000011111
LaneAttributes-Vehicle	BIT STRING	0b00000000	0b11111111

Item Under Test	Type	Lowest Acceptable Value	Highest Acceptable Value
	(SIZE(8))		
LaneDirection	BIT STRING (SIZE(2))	0b01	0b10
LaneSharing	BIT STRING (SIZE(10))	0b0000000000	0b1111111111
TransitVehicleStatus	BIT STRING (SIZE(8))	0b00000000	0b00111111
PedestrianBicycleDetect	BOOLEAN	false	true
WaitOnStopline	BOOLEAN	false	true
AdvisorySpeedType	ENUMERATED	0	3
BasicVehicleRole	ENUMERATED	0	22
DirectionOfUse	ENUMERATED	0	3
LayerType	ENUMERATED	0	7
MovementPhaseState	ENUMERATED	0	9
MUTCDCode	ENUMERATED	0	6
NodeAttributeXY	ENUMERATED	0	11
PriorityRequestType	ENUMERATED	0	3
RequestImportanceLevel	ENUMERATED	0	15
RequestSubRole	ENUMERATED	0	15
RestrictionAppliesTo	ENUMERATED	0	13
SegmentAttributeXY	ENUMERATED	0	37
SpeedConfidence	ENUMERATED	0	7
SpeedLimitType	ENUMERATED	0	12
TransitVehicleOccupancy	ENUMERATED	0	7
TransmissionState	ENUMERATED	0	7
TravelerInfoType	ENUMERATED	0	3
VehicleType	ENUMERATED	0	15
URL-Base	IA5String (SIZE(1..45))	IA5String (SIZE(1))	IA5String (SIZE(45))
DescriptiveName	IA5String (SIZE(1..63))	IA5String (SIZE(1))	IA5String (SIZE(63))
FurtherInfoID	OCTET STRING (SIZE(2))	‘0000000000000000’H	‘EEEEEEEE’H
MsgCRC	OCTET STRING (SIZE(2))	‘0000000000000000’’H	‘EEEEEEEE’H
TemporaryID	OCTET STRING (SIZE(4))	‘0000000000000000’H	‘EEEEEEEEEEEEEEEE’H
UniqueMSGID	OCTET STRING (SIZE(9))	‘000000000000000000000000000000000000’H	‘EEEEEEEEEEEEEEEEEEEEEEEEEEEEEEEEEEEE’H

4.11.1 SAE J2735 SPaT Messages

The SPaT message is used to send the current movement state of each active phase of one or more signalized intersections in the system. Table 4-4 provides a list of data elements/frames for transmitting SPaT messages. They are identified as either optional or required based on the definition in the SAE J2735-201603 data dictionary. The test cases of SPaT message are presented in Table 4-5 and Table 4-6. Please, note that the Connected Intersection Project is identifying some of the optional data elements in the standards as required for the RLVW applications.

Table 4-4 Data Specification of SPaT Message

SPaT Message	SAE J2735 (201603)
• timeStamp MinuteOfTheYear	Optional
• name DescriptiveName	Optional
• intersections IntersectionStateList (Sequence of IntersectionState)	Required
○ IntersectionState	
▪ name DescriptiveName	Optional
▪ id IntersectionReferenceID	Required
♦ region RoadRegulatorID	Optional
♦ id IntersectionID	Required
▪ revision MsgCount	Required
▪ status IntersectionStatusObject	Required
▪ moy MinuteOfTheYear	Optional
▪ timeStamp DSecond	Optional
▪ states MovementList (Sequence of MovementState)	Required
♦ MovementState	
¤ movementName DescriptiveName	Optional
¤ signalGroup SignalGroupID	Required
¤ state-time-speed MovementEventList	Required
+ MovementEvent	
− eventState MovementPhaseState	Required
− timing TimeChangeDetails	Optional
› startTime TimeMark	Optional
› minEndTime TimeMark	Optional
› maxEndTme TimeMark	Optional
› likelyTime TimeMark	Optional
› confidence TimeIntervalConfidence	Optional
› nextTime TimeMark	Optional
− speedsAdvisorySpeedList	Optional
› AdvisorySpeed	
# type AdvisorySpeedType	Required
	Optional

SPaT Message	SAE J2735 (201603)
# speed SpeedAdvice	Optional
# confidence SpeedConfidence	Optional
# distance ZoneLength	Optional
# class RestrictionClassID	Optional
▪ maneuverAssistList	
♦ ConnectionManeuverAssist	Required
¤ connectionID LaneConnectionID	Optional
¤ queueLength ZoneLength	Optional
¤ availableStorageLength ZoneLength	Optional
¤ waitOnStop WaitOnStopline	Optional
¤ pedBicycleDetect PedestrianBicycleDetect	

Table 4-5 SPaT Message Test Case – Fields Existence

Test Case #	TC-SPaT-1
Test Case	**SPaT Test - Fields Existence**
Reference	*SAE J2735 2016: Section 5.13*
Objective	Verify all the SPaT information configured in traffic controller exists in the SPaT message broadcasted from the RSU
Inputs	SPaT message broadcasted from the RSU and received by packet capture tool (Scenarios 1 and 2) and control/logging device (Scenario 3)
Expected Outcome(s)	All SPaT information configured in traffic controller exist after transmission. Output Data Specification • Table 4-4 contains a complete SPaT message data specification.

Pass/Fail Criteria	Data Verification Outcomes:
	• Pass:
	  o All SPaT information configured in traffic controller can be found within the SPaT messages after transmission.
	  o Message structure of SPaT is correct.
	• **Fail**: Any other outcome.

Test Procedures	• The test operator configures the DUT to produce and transmit SPaT messages under different intersection geometric configurations and signal phasing and timing parameters for at least ten signal timing cycles. • The test operator configures the packet capture tool (Scenario 1 and 2), and control/logging device (Scenario 3) to receive the encoded SPaT messages. • The test operator uses the converted SAE J2735 SPaT message in human readable format (XML or JSON) to verify the presence of all SPaT information configured with SPaT message fields.

Table 4-6 SPaT Message Test Case – Fields Valid

Test Case #	TC-SPaT-2
Test Case	**SPaT Test – Fields Valid**
Reference	*SAE J2735 2016: Section 5.13*
Objective	Verify all the fields of the SPaT message broadcasted from the RSU are valid and match with the inputs from traffic controller
Inputs	SPaT message broadcasted form the RSU and received by packet capture tool (Scenarios 1 and 2) and control/logging device (Scenario 3) Input Data Specification • **Error! Reference source not found.** contains the valid value ranges of data types that will be tested in this test case.

Test Case #	TC-SPaT-2
Test Case	**SPaT Test – Fields Valid**
Expected Outcome(s)	All fields of SPaT messages transmitted are valid and match with the inputs from traffic controller. Output Data Specification • Table 4-4 contains a complete SPaT message data specification.

Pass/Fail Criteria	Data Verification Outcomes:
	• Pass:
	  o All data elements within the SPaT message are verified as valid and match with the traffic controller inputs.
	  o Message structure of SPaT is correct.
	• **Fail**: Any other outcome.

Test Procedures	• The test operator configures the DUT to produce and transmit SPaT messages under different intersection geometric configurations and signal phasing and timing parameters for at least ten signal timing cycles. • The test operator configures the packet capture tool (Scenario 1 and 2), and control/logging device (Scenario 3) to receive the encoded SPaT messages. • The test operator uses the converted SAE J2735 SPaT message in human readable format (XML or JSON) to verify all SPaT message fields are valid and match with the traffic controller inputs.

4.11.2 SAE J2735 MAP Messages

The MAP message is used to convey geographic road information of one or more signalized intersection in the system. Table 4-7 provides a list of data elements/frames for transmitting MAP messages. The data elements are identified as either optional or required based on the definition in the SAE J2735-201603 data dictionary. Table 4-8 and Table 4-9 present the test cases for MAP message.

Table 4-7 Data Specification of MAP Message

MAP Message	SAE J2735 (201603)
• timeStamp MinuteOfTheYear	Optional
• msgIssueRevision MsgCount	Required
• layerType LayerType	Optional
• layerID LayerID	Optional
• intersections IntersectionGeometryList (Sequence of IntersectionGeometry)	Optional
○ IntersectionGeometry	
▪ id IntersectionReferenceID	Required
♦ region RoadRegulatorID	Optional
♦ id IntersectionID	Required
▪ revision MsgCount	Required
▪ refPoint Position3D-2	Required
♦ lat Latitude	Required
♦ long Longitude	Required
▪ laneWidth	Optional
▪ LaneList (Sequence of GenericLane)	Required
♦ GenericLane	
¤ laneID	Required
¤ name DescriptiveName	Optional
¤ ingressApproach ApproachID	Optional
¤ egressApproach ApproachID	Optional
¤ laneAttributes	Required
+ directionalUse LaneDirection	Required
+ sharedWith LaneSharing	Required
+ laneType LaneTypeAttributes	Required
− vehicle LaneAttributes-Vehicle	Choice
− crosswalk LaneAttributes-Crosswalk	Choice
− bikeLane LaneAttributes-Bike	Choice
− sidewalk LaneAttributes-Sidewalk	Choice
	Choice

MAP Message	SAE J2735 (201603)
− median LaneAttributes-Barrier	Choice
− striping LaneAttributes-Striping	Choice
− trackedVehicle LaneAttributes-TrackedVehicle	Choice
− parking LaneAttributes-Parking	Optional
¤ maneuvers AllowedManeuvers	Required
¤ nodeList NodeListXY	Choice
+ nodes NodeSetXY	
− NodeXY	Required
› delta NodeOffsetPointXY	Choice
# node-XY1 Node-XY-20b	Choice
# node-XY2 Node-XY-22b	Choice
# node-XY3 Node-XY-24b	Choice
# node-XY4 Node-XY-26b	Choice
# node-XY5 Node-XY-28b	Choice
# node-XY6 Node-XY-32b	Choice
# node-LatLon Node-LLmD-64b	Optional
› attributes NodeAttributeSetXY	Optional
# localNode NodeAttributeXYList ❖ NodeAttributeXY	Optional
# disabled SegmentAttributeXYList ❖ SegmentAttributeXY	Optional
# enabled SegmentAttributeXYList ❖ SegmentAttributeXY	Optional
# data LaneDataAttributeList	Choice
❖ LaneDataAttribute	Choice
➢ pathEndPointAngle DeltaAngle ➢ laneCrownPointCenter RoadwayCrownAngle ➢ laneCrownPointLeft RoadwayCrownAngle	Choice

MAP Message	SAE J2735 (201603)
➢ laneCrownPointRight	Choice
RoadwayCrownAngle	Choice
➢ laneAngle MergeDivergeNodeAngle	
➢ speedLimits SpeedLimitList	Choice
✓ RegulatorySpeedLimit	
* type SpeedLimitType	Required
* speed Velocity	Required
# dWidth Offset-B10	Optional
# dElevation Offset-B10	Optional
+ computed ComputedLane	Required
− referenceLaneId LaneID	Required
− offsetXaxis	Required
› small DrivenLineOffsetSm	Choice
› large DrivenLineOffsetLg	Choice
− offsetYaxis	Required
› small DrivenLineOffsetSm,	Choice
› large DrivenLineOffsetLg	Choice
− rotateXY Angle	Optional
− scaleXaxis Scale-B12	Optional
− scaleYaxis Scale-B12	Optional
¤ connectsTo ConnectsToList	Optional
+ Connection	
− connectingLane	Required
› lane LaneID	Required
› maneuver AllowedManeuvers	Optional
− remoteIntersection IntersectionReferenceID	Optional
› region RoadRegulatorID	Optonal
› id IntersectionID	Required
− signalGroup SignalGroupID	Optional
− userClass RestrictionClassID	Optional

MAP Message	**SAE J2735 (201603)**
− connectionID LaneConnectionID	Optional
¤ overlays OverlayLaneList	Optional
+ LaneID	
• roadSegments RoadSegmentList	Optional
○ RoadSegment	
▪ name DescriptiveName	Optional
▪ id RoadSegmentReferenceID	Required
♦ region RoadRegulatorID	Optional
♦ id RoadSegmentID	Required
▪ revision MsgCount	Required
▪ refPoint Position3D	Required
♦ lat Latitude	Required
♦ long Longitude	Required
♦ elevation	Optional
▪ laneWidth	Optional
▪ speedLimits SpeedLimitList	Optional
♦ RegulatorySpeedLimit	
¤ type SpeedLimitType	Required
¤ speed Velocity	Required
▪ roadLaneSet RoadLaneSetList	Required
♦ GenericLane	
¤ laneID	Required
¤ name DescriptiveName	Optional
¤ ingressApproach ApproachID	Optional
¤ egressApproach ApproachID	Optional
¤ laneAttributes	Required
+ directionalUse LaneDirection	Required
+ sharedWith LaneSharing	Required
+ laneType LaneTypeAttributes	Required
− vehicle LaneAttributes-Vehicle	Choice

MAP Message	SAE J2735 (201603)
– crosswalk LaneAttributes-Crosswalk	Choice
– bikeLane LaneAttributes-Bike	Choice
– sidewalk LaneAttributes-Sidewalk	Choice
– median LaneAttributes-Barrier	Choice
– striping LaneAttributes-Striping	Choice
– trackedVehicle LaneAttributes-TrackedVehicle	Choice
– parking LaneAttributes-Parking	Choice
¤ maneuvers AllowedManeuvers	Optional
¤ nodeList NodeListXY	Required
+ nodes NodeSetXY	Choice
– NodeXY	
› delta NodeOffsetPointXY	Required
# node-XY1 Node-XY-20b	Choice
# node-XY2 Node-XY-22b	Choice
# node-XY3 Node-XY-24b	Choice
# node-XY4 Node-XY-26b	Choice
# node-XY5 Node-XY-28b	Choice
# node-XY6 Node-XY-32b	Choice
# node-LatLon Node-LLmD-64b	Choice
› attributes NodeAttributeSetXY	Optional
# localNode NodeAttributeXYList	Optional
❖ NodeAttributeXY	
# disabled SegmentAttributeXYList	Optional
❖ SegmentAttributeXY	
# enabled SegmentAttributeXYList	Optional
❖ SegmentAttributeXY	
# data LaneDataAttributeList	Optional
❖ LaneDataAttribute	Choice
➢ pathEndPointAngle DeltaAngle	Choice

MAP Message	SAE J2735 (201603)
➢ laneCrownPointCenter	
RoadwayCrownAngle	Choice
➢ laneCrownPointLeft	
RoadwayCrownAngle	Choice
➢ laneCrownPointRight	Choice
RoadwayCrownAngle	Choice
➢ laneAngle MergeDivergeNodeAngle	
➢ speedLimits SpeedLimitList	Required
✓ RegulatorySpeedLimit	Required
* type SpeedLimitType	Optional
* speed Velocity	Optional
# dWidth Offset-B10	Required
# dElevation Offset-B10	Required
+ computed ComputedLane	Required
– referenceLaneId LaneID	Choice
– offsetXaxis	Choice
› small DrivenLineOffsetSm	Required
› large DrivenLineOffsetLg	Choice
– offsetYaxis	Choice
› small DrivenLineOffsetSm,	Optional
› large DrivenLineOffsetLg	Optional
– rotateXY Angle	Optional
– scaleXaxis Scale-B12	Optional
– scaleYaxis Scale-B12	
¤ connectsTo ConnectsToList	Required
+ Connection	Required
– connectingLane	Optional
› lane LaneID	Optional
› maneuver AllowedManeuvers	Optonal
– remoteIntersection IntersectionReferenceID	Required

MAP Message	SAE J2735 (201603)
› region RoadRegulatorID	Optional
› id IntersectionID	Optional
– signalGroup SignalGroupID	Optional
– userClass RestrictionClassID	Optional
– connectionID LaneConnectionID	
¤ overlays OverlayLaneList	Optional
+ LaneID	Optional
• dataParameters	Optional
○ processMethod IA5String(SIZE(1..255))	Optional
○ processAgency IA5String(SIZE(1..255))	Optional
○ lastCheckedDate IA5String(SIZE(1..255))	Optional
○ geoidUsed IA5String(SIZE(1..255))	
• restrictionList RestrictionClassList	Required
○ RestrictionClassAssignment	Required
■ id RestrictionClassID	
■ users RestrictionUserTypeList	Choice
♦ RestrictionUserType	
¤ basicType RestrictionAppliesTo	

Table 4-8 MAP Message Test Case – Fields Existence

Test Case #	**TC-MAP-1**
Test Case	**MAP Test - Fields Existence**
Reference	*SAE J2735 2016: Section 5.6*
Objective	Verify all MAP information configured exists in the MAP message broadcasted from RSU
Inputs	MAP message broadcasted from the RSU and received by packet capture tool (Scenarios 1 and 2) and control/logging device (Scenario 3)
Expected Outcome(s)	All MAP information configured exists after transmission. Output Data Specification • Table 4-7 contains a complete MAP message data specification.

Pass/Fail Criteria	Data Verification Outcomes:
	• Pass:
	  o All MAP information configured can be found within the MAP messages after transmission.
	  o Message structure of MAP is correct.
	• **Fail**: Any other outcome.

Test Procedures	• The test operator configures the DUT to produce and transmit MAP messages under different intersection geometric configurations. • The test operator configures the packet capture tool (Scenarios 1 and 2), and control/logging device (Scenario 3) to receive the encoded MAP messages. • The test operator uses the converted SAE J2735 MAP message in human readable format (XML or JSON) to verify the presence of all MAP information configured with MAP messages.

Table 4-9 MAP Message Test Case – Fields Valid

Test Case #	TC-MAP-2
Test Case	**MAP Test – Fields Valid**
Reference	*SAE J2735 2016: Section 5.6*
Objective	Verify all the fields of the MAP message broadcasted from the RSU are valid and match with the inputs
Inputs	MAP message broadcasted from the RSU and received by packet capture tool (Scenarios 1 and 2) and control/logging device (Scenario 3) Input Data Specification • Table 4-3 contains the valid value ranges of data types that will be tested in this test case.
Expected Outcome(s)	All fields of MAP messages transmitted are valid and match with the inputs. Output Data Specification • Table 4-7 contains a complete MAP message data specification.

Pass/Fail Criteria	Data Verification Outcomes:
	• Pass:
	  ○ All data elements within the MAP messages are verified as valid and match with the inputs.
	  ○ Message structure of MAP is correct.
	• **Fail**: Any other outcome.

Test Procedures	• The test operator configures the DUT to produce and transmit MAP messages under different intersection geometric configurations. • The test operator configures the packet capture tool (Scenarios 1 and 2) and control/logging device (Scenario 3) to receive the encoded MAP messages. • The test operator uses the converted SAE J2735 MAP message in human readable format (XML or JSON) to check all MAP message fields are valid and match with the inputs.

4.11.3 SAE J2735 SRM Messages

The SRM message is used for either a priority signal request or a preemption signal request. Different from other tested messages included in this document, a SRM message is initiated by the OBU equipped in a vehicle and received by the RSU. The messages are then forwarded to the signalized intersection controller. Table 4-10 provides a list of data elements/frames for transmitting SRM messages. They are identified as either optional or required based on the definition in the SAE J2735-201603 data dictionary. The test cases of SRM message are presented in Table 4-11 andTable 4-12.

Table 4-10 Data Specification of SRM Message

SRM Message	SAE J2735 (201603)
• timeStamp MinuteOfTheYear	Optional
• second DSecond	Required
• sequenceNumber MsgCount	Optional
• requests SignalRequestList (Sequence of SignalRequestPackage)	Optional
o SignalRequestPackage	
▪ request SignalRequest	Required
♦ id IntersectionID	Required
♦ requestID RequestID	Required
♦ requestType PriorityRequestType	Required
♦ inBoundLane IntersectionAccessPoint	Optional
♦ outBoundLane IntersectionAccessPoint	Optional
▪ minute MinuteOfTheYear	Optional
▪ second DSecond	Optional
▪ duration DSecond	Optional
• requestor RequestorDescription	Required
▪ id VehicleID	Required
♦ entityID TemporaryID	Choice
♦ stationID StationID	Choice
▪ type RequestorType	Optional
♦ role BasicVehicleRole	Required
♦ subrole RequestSubRole	Optional
♦ request RequestImportanceLevel	Optional
♦ iso3883 Iso3833VehicleType	Optional
♦ hpmsType VehicleType	Optional
▪ position RequestorPositionVector	Optional
♦ position Position3D	Required
¤ lat Latitude	Required
¤ long Longitude	Required
¤ elevation	Optional

SRM Message	**SAE J2735 (201603)**
♦ heading Angle	Optional
♦ speed TransmissionAndSpeed	Optional
¤ transmisson TransmissionState	Required
¤ speed Velocity	Required
▪ name DescriptiveName	Optional
▪ routeName DescriptiveName	Optional
▪ transitStatus TransitVehicleStatus	Optional
▪ transitOccupancy TransitVehicleOccupancy	Optional
▪ transitSchedule DeltaTime	Optional

Table 4-11 SRM Message Test Case – Fields Existence

Test Case #	**TC-SRM-1**
Test Case	**SRM Test - Fields Existence**
Reference	*SAE J2735 2016: Section 5.14*
Objective	Verify all the signal request information broadcasted by OBU can be received by the RSU and signal controller.
Inputs	SRM message broadcasted from OBU and received by RSU and signal controller
Expected Outcome(s)	All signal request information exists after transmission. Output Data Specification • Table 4-10 contains a complete SRM message data specification.

Pass/Fail Criteria	Data Verification Outcomes:
	• Pass:
	    o All signal request information broadcasted by OBU can be found in the data elements of SRM messages received by RSU and signal controller.
	    o Message structure of SRM is correct.
	• **Fail**: Any other outcome.

Test Procedures	• The test operator configures the OBU to produce SRM messages under different intersection configurations. • The test operator configures the DUT to receive and capture the SRM messages (Scenario 4). • The test operator uses the converted SAE J2735 SRM message in human readable format (XML or JSON) to verify the presence of all signal request information with SRM messages decoded.

Table 4-12 SRM Message Test Case – Fields Valid

Test Case #	**TC-SRM-2**
Test Case	**SRM Test – Fields Valid**
Reference	*SAE J2735 2016: Section 5.14*
Objective	Verify all the fields of the SRM message received by the RSU and signal controller are valid and match with the signal request information broadcasted by OBU.
Inputs	SRM messages broadcasted form the OBU and received by RSU and signal controller Input Data Specification • Table 4-3 contains the valid value ranges of data types that will be tested in this test case.
Expected Outcome(s)	All fields of SRM messages received are valid and match with the inputs. Output Data Specification • Table 4-10 contains a complete SRM data specification.
Pass/Fail Criteria	Data Verification Outcomes: • Pass: o All data elements of SRM messages are verified as valid and match with the inputs. o Message structure of SRM is correct. • **Fail**: Any other outcome.
Test Procedures	• The test operator configures the OBU to produce the SRM messages under different intersection configurations. • The test operator configures the DUT to receive and capture the SRM messages (Scenario 4). • The test operator uses the converted SAE J2735 SRM message in human readable format (XML or JSON) to verify all SRM message fields are valid and match with signal request information of OBU.

4.11.4 SAE J2735 SSM Messages

An SSM message is a message sent by an RSU in a signalized intersection to relate the current status of the signal and the collection of pending or active preemption or priority requests acknowledged by the controller. It is also used to send information about preemption or priority requests which were denied. Table 4-13 provides a list of data elements/frames for transmitting the SSM messages. These are identified as either optional or required based on the definition in the SAE J2735-201603 data dictionary. The test cases of SSM messages are presented in Table 4-14 to Table 4-15.

Table 4-13 Data for SSM Message Transmission

SSM Message	SAE J2735 (201603)
• timeStamp MinuteOfTheYear	Optional
• second DSecond	Required
• sequenceNumber MsgCount	Optional
• status SignalStatusList (Sequence of SignalStatus)	Required
○ SignalStatus	
▪ sequenceNumber MsgCount	Required
▪ id IntersectionReferenceID	Required
♦ region RoadRegulatorID	Optional
♦ id IntersectionID	Required
▪ sigStatus SignalStatusPackageList (Sequence of SignalStatusPackage)	Required
♦ SignalStatusPackage	
¤ requester SignalRequesterInfo	Optional
+ id VehicleID	Required
+ Request RequestID	Required
+ sequenceNumber MsgCount	Required
+ role BasicVehicleRole	Optional
¤ inboundOn IntersectionAccessPoint	Required
+ lane LaneID	Choice
+ approach ApproachID	Choice
+ connection LaneConnectionID	Choice
¤ outboundOn IntersectionAccessPoint	Optional
+ lane LaneID	Choice
+ approach ApproachID	Choice
+ connection LaneConnectionID	Choice
¤ minute MinuteOfTheYear	Optional
¤ second DSecond	Optional
¤ duration DSecond	Optional
¤ status PrioritizationResponseStatus	Required

Table 4-14 SSM Message Test Case – Fields Existence

Test Case #	**TC-SSM-1**
Test Case	**SSM Test - Fields Existence**
Reference	*SAE J2735 2016: Section 5.15*
Objective	Verify all the signal status information requested exists in the SSM message broadcasted from the RSU
Inputs	SSM message broadcasted form the RSU and received by packet capture tool (Scenario 1 and 2) and control/logging device (Scenario 3)
Expected Outcome(s)	All signal status information requested exists in the SSM messages after transmission. Output Data Specification • Table 4-13 contains a complete SSM message data specification.

Pass/Fail Criteria	Data Verification Outcomes:
	• Pass:
	  ○ All signal status information requested can be found within the SSM messages after transmission.
	  ○ Message structure of SSM is correct.
	• **Fail**: Any other outcome.

Test Procedures	• The test operator configures the DUT to produce and transmit SSM messages. • The test operator configures the packet capture tool (Scenario 1 and 2) and control/logging device (Scenario 3) to receive the encoded SSM messages. • The test operator uses the converted SAE J2735 SSM message in human readable format (XML or JSON) to verify the presence of all signal status information requested with SSM messages received.

Table 4-15 SSM Message Test Case – Fields Valid

Test Case #	**TC-SSM-2**
Test Case	**SSM Test – Fields Valid**
Reference	*SAE J2735 2016: Section 5.15*
Objective	Verify all the fields of the SSM message broadcasted from the RSU are valid and match with the signal status information requested.
Inputs	SSM message broadcasted form the RSU and received by packet capture tool (Scenario 1 and 2) and control/logging device (Scenario 3) Input Data Specification • Table 4-3 contains the valid value ranges of data types that will be tested in this test case.
Expected Outcome(s)	All fields of SSM messages transmitted are valid and match with the signal status information requested. Output Data Specification • Table 4-13 contains a complete SSM data specification.
Pass/Fail Criteria	Data Verification Outcomes: • Pass: o All data elements within the SSM messages are verified as valid and match with the signal status information requested. o Message structure of SSM is correct. • **Fail**: Any other outcome.
Test Procedures	• The test operator configures the DUT to produce and transmit the SSM messages. • The test operator configures the packet capture tool (Scenarios 1 and 2) and control/logging device (Scenario 3) to receive the encoded SSM messages. • The test operator uses the converted SAE J2735 SSM message in human readable format (XML or JSON) to check all SSM message fields are valid and match with the signal status information requested.

4.11.5 SAE J2735 TIM Messages

The TIM message is used to send various types of traffic condition information to OBU of equipped vehicles. Table 4-16 provides a list of data elements/frames for transmitting TIM messages. They are identified as either optional or required based on the definition in the SAE J2735-201603 data dictionary. The test cases of TIM message are presented in Table 4-17 to Table 4-18.

Table 4-16 Data Specification of TIM Message

TIM Message	SAE J2735 (201603)
• msgCnt MsgCount	Required
• timeStamp MinuteOfTheYear	Optional
• packetID UniqueMSGID	Optional
• urlBURL URL-Base	Optional
• dataFrames TravelerDataFrameList (Sequence of TravelerDataFrame)	Required
○ TravelerDataFrame	
▪ sspTimRights SSPindex	Required
▪ frameType TravelerInfoType	Required
▪ msgId	Required
♦ furtherInfoID	Choice
♦ roadSignID	Choice
¤ position Position3D	Required
+ lat Latitude	Required
+ long Longitude	Required
+ elevation	Optional
¤ viewAngle HeadingSlice	Required
¤ mutcdCode MUTCDCode	Optional
¤ crc MsgCRC	Optional
▪ startYear DYear	Optional
▪ startTime MinuteOfTheYear	Required
▪ duratonTime MinutesDuration	Required
▪ priority SignPrority	Required
▪ sspLocationRights SSPindex	Required
▪ regions GeographicalPathList (Sequence of GeographicalPath)	Required
♦ GeographicalPath	
¤ name DescriptiveName	Optional
¤ id RoadSegmentReferenceID	Optional
+ region RoadRegulatorID	Optional

TIM Message	**SAE J2735 (201603)**
+ id RoadSegmentID	Required
¤ anchor Position3D	Optional
+ lat Latitude	Required
+ long Longitude	Required
+ elevation	Optional
¤ laneWidth	Optional
¤ directionality DirectionOfUse	Optional
¤ closedPath BOOLEAN	Optional
¤ direction HeadingSlice	Optional
¤ description	Optional
+ path OffsetSystem	Choice
− scale Zoom	Optional
− offset NodeListXY	Required
› nodes NodeSetXY (Sequence of NodeXY)	Choice
# NodeXY	
❖ delta NodeOffsetPointXY	Required
➢ node-XY1Node-XY-20b	Choice
✓ x Offset-B10	Required
✓ y Offset-B10	Required
➢ node-XY2Node-XY-22b	Choice
✓ x Offset-B11	Required
✓ y Offset-B11	Required
➢ node-XY3Node-XY-24b	Choice
✓ x Offset-B12	Required
✓ y Offset-B12	Required
➢ node-XY4Node-XY-26b	Choice
✓ x Offset-B13	Required
✓ y Offset-B13	Required
➢ node-XY5Node-XY-28b	Choice
✓ x Offset-B14	Required

TIM Message	**SAE J2735 (201603)**
✓ y Offset-B14	Required
➢ node-XY6Node-XY-32b	Choice
✓ x Offset-B16	Required
✓ y Offset-B16	Required
➢ node-LatLon Node-LLmD-64b	Choice
✓ lon Longitude	Required
✓ lat Latitude	Required
❖ attributes NodeAttributeSetXY	Optional
➢ localNode NodeAttributeXYList	Optional
✓ NodeAttributeXY	
➢ disabled SegmentAttributeXYList	Optional
✓ SegmentAttributeXY	
➢ enabled SegmentAttributeXYList	Optional
✓ SegmentAttributeXY	
➢ data LaneDataAttributeList	Optional
✓ LaneDataAttribute	
* pathEndPointAngle DeltaAngle	Choice
* laneCrownPointCenter RoadwayCrownAngle	Choice
* laneCrownPointLeft RoadwayCrownAngle	Choice
* laneCrownPointRight RoadwayCrownAngle	Choice
* laneAngle MergeDivergeNodeAngle	Choice
* speedLimits SpeedLimitList	
RegulatorySpeedLimit	Choice
⅄ type SpeedLimitType	Required
⅄ speed Velocity	Required

TIM Message	SAE J2735 (201603)
➢ dWidth Offset-B10	Optional
➢ dElevation Offset-B10	Optional
› computed ComputedLane	Choice
# referenceLaneId LaneID	Required
# offsetXaxis	Required
❖ small DrivenLineOffsetSm	Choice
❖ large DrivenLineOffsetLg	Choice
# offsetYaxis	Required
❖ small DrivenLineOffsetSm	Choice
❖ large DrivenLineOffsetLg	Choice
# rotateXY Angle	Optional
# scaleXaxis Scale-B12	Optional
# scaleYaxis Scale-B12	Optional

Table 4-17 TIM Message Test Case – Fields Existence

Test Case #	TC-TIM-1
Test Case	**TIM Test - Fields Existence**
Reference	*SAE J2735 2016: Section 5.16*
Objective	Verify all the traveler information configured exists in the TIM messages broadcasted from the RSU.
Inputs	TIM message broadcasted form the RSU and received by packet capture tool (Scenarios 1 and 2) and control/logging device (Scenario 3)
Expected Outcome(s)	All traveler information configured exists after transmission. Output Data Specification • Table 4-16 contains a complete TIM data specification.

Pass/Fail Criteria	Data Verification Outcomes:
	• Pass:
	  ○ All traveler information configured can be found within the TIM message after transmission.
	  ○ Message structure of TIM is correct.
	• **Fail**: Any other outcome.

Test Procedures	• The test operator configures the DUT to produce and transmit TIM message under different geometric configurations. • The test operator configures the packet capture tool (Scenarios 1 and 2) and control/logging device (Scenario 3) to receive the encoded TIM messages. • The test operator uses the converted SAE J2735 TIM message in human readable format (XML or JSON) to verify the presence of all traveler information configured with TIM messages.

Table 4-18 TIM Message Test Case – Fields Valid

Test Case #	**TC-TIM-2**
Test Case	**TIM Test – Fields Valid**
Reference	*SAE J2735 2016: Section 5.16*
Objective	Verify all the fields of the TIM message broadcasted from the RSU are valid and match with the inputs.
Inputs	TIM message broadcasted form the RSU and received by packet capture tool (Scenarios 1 and 2) and control/logging device (Scenario 3) Input Data Specification • Table 4-3 contains the valid value ranges of data types that will be tested in this test case.
Expected Outcome(s)	All fields of TIM messages transmitted are valid and match with the inputs. Output Data Specification • Table 4-16 contains a complete TIM data specification.
Pass/Fail Criteria	Data Verification Outcomes: • Pass: o All data elements within the TIM messages are verified as valid and match with the inputs. o Message structure of TIM is correct. • **Fail**: Any other outcome.
Test Procedures	• The test operator configures the DUT to produce and transmit TIM messages under different geometric configurations. • The test operator configures the packet capture tool (Scenarios 1 and 2) and control/logging device (Scenario 3) to receive the encoded TIM messages. • The test operator uses the converted SAE J2735 TIM message in human readable format (XML or JSON) to verify all TIM message fields are valid and match with the inputs.

4.12 RELATIONSHIP OF TEST CASE TO REQUIREMENTS

This section provides the relationship between the test cases listed in the previous section and the requirements for the three selected applications (RLVW, EVP, and RSZW/LC) identified and recommended in Section 3 of this project.

Table 4-19 presents the requirements and the corresponding test cases for the RLVW application supported by SPaT and MAP messages, Table 4-20 presents the requirements and the corresponding test cases for the EVP application supported by SRM and SSM messages, and

Table 4-21 presents the relationship between the requirements and the test cases for the RSZM/LC application supported by TIM message.

Table 4-19 Relationship of Test Cases to Requirements for SPaT and MAP Messages

Requirement #	Requirement Description	Test Case #
1	The RSE shall allow configuring the SpaT and MAP messages using the user interface	NA
2	The RSE shall receive traffic signal data from the Traffic Signal Controller that is compliant in NTCIP 1202 v3 format or SAE J2735 format	TC-SPaT-1 TC-MAP-1
3	The RSE shall assemble the content needed for standard SPaT and MAP messages	TC-SPaT-1 TC-MAP-1
4	The RSE shall broadcast SPaT messages that confirm with J2725 standards	This requirement is tested by testing other requirements.
5	The RSE shall broadcast SPaT messages that conform to the latest version of SAE J2735	TC-SPaT-1 TC-SPaT-2
6	The RSE shall broadcast MAP messages that conform to the latest version of SAE J2735	TC-MAP-1 TC-MAP-2
7	The RSE shall broadcast the changes in signal state, timing and physical geometry with low latency to allow CV applications to react in a timely and correct manner	This will be tested by comparing the time stamps of the messages at different points in its path.
8	The RSE shall increment a message counter for a signalized intersection message whenever the value of any data element describing the signalized intersection in the message except the time stamp changes	TC-SPaT-1
9	The RSE shall provide an intersection reference identifier unique within North America for each SPaT enabled intersection included in the MAP message	TC-MAP-1
10	The RSE shall provide the movement state and state time change detail for each signal group identified in the MAP message	TC-MAP-1
11	The Infrastructure System shall manage a MAP database	This requirement is tested by testing other requirements.
12	The RSE shall provide the intersection geometry for one or more intersections using SAE J2735 MAP message standards	TC-MAP-1
13	The RSE shall provide information about the allowed use of each lane at an intersection	TC-MAP-1
14	The RSE shall provide information about the allowed maneuvers of each lane at an intersection	TC-MAP-1

Requirement #	Requirement Description	Test Case #
15	The RSE shall provide information about the permitted connections between ingress lanes and egress lanes at an intersection	TC-MAP-1
16	If a lane connects to a lane defined for an adjacent SPaT enabled intersection, the MAP Message shall provide the intersection reference identifier of the remote intersection	TC-MAP-1
17	The RSE shall provide the posted or statutory speed limit, whichever is applicable	TC-MAP-1

Table 4-20 Relationship of Test Cases to Requirements for SRM and SSM Messages

Requirement #	Requirement Description	Test Case #
1	The RSE shall receive valid Signal Request Messages (SRM) messages that adhere to the SAE J2735 standard from emergency vehicle OBUs that are within communication control range of an intersection	TC-SRM-1 TC-SRM-2
2	The RSE shall process the SRM from an emergency vehicle	TC-SSM-1
3	The RSE shall request preemption to be provided by the traffic control system	TC-SSM-1
4	The RSE shall obtain preemption status from the Traffic Signal Controller using Signal Status Messages (SSM) that comply with NTCIP 1202v3 standards or J2735 standards	TC-SSM-1 TC-SSM-2
5	When there are active priority requests, the RSE shall assemble and broadcast SSM that conform to the SAE J2735 March 2016 standard to the vehicles within the communication range	TC-SSM-1 TC-SSM-2
6	The RSE shall track equipped vehicles within communication control range of the intersection to determine the time for the provision of the traffic signal phase that serves the approach (movement) to the intersection	TC-SRM-1 TC-SRM-2
7	**Optional:** The RSE shall provide intersection signal phase and timing data and geometric description data to equipped vehicles within communication control range of the intersection consistent with the FDOT Signal Phase and Timing data (SPaT) and MAP requirements	TC-SPaT-1 TC-MAP-1
8	The SRM messages received by the RSE from the OBU shall be provided using the following ASN.1	TC-SRM-1

Requirement #	Requirement Description	Test Case #
	Representation	
9	The SSM messages sent by the RSE to the OBU shall be provided using the following ASN.1 Representation	TC-SSM-1

Table 4-21 Relationship of Test Cases to Requirements for TIM Message

Requirement #	Requirement Description	Test Case #
1	The RSE shall be able to acquire and store the required work zone information collected from other infrastructure equipment	This requirement will be tested by testing other requirements.
2	The RSE Application shall acquire data from the equipped vehicle	This requirement will be tested by testing other requirements.
3	The RSE shall provide advisories, alerts and/or warnings to deliver the information in order for the driver to take action	TC-TIM-1
4	The RSE application shall provide information, warning and alerts when the detected vehicle speed is determined to be unsafe	TC-TIM-1
5	**Optional:** The RSE shall support the display of messages on roadside signage to provide information for unequipped vehicles	This requirement can be tested by integrating the system with a roadside sign. It will not be tested in this project.
6	The broadcasted messages shall follow SAE J2735 and SAE J2945/4 standards	TC-TIM-1 TC-TIM-2
7	The RSZW/LC application TIM messages shall be provided using the following ASN.1 representation	TC-TIM-1 TC-TIM-2

5 DEMONSTRATION OF THE APPLICATIONS OF THE MESSAGE-LEVEL TEST PLAN

This section summarizes a task conducted as part of this project to demonstrate the applications elements of the message-level test plan presented in Section 4 of this document. These are the elements that could be tested in the lab. The next section (Section 8) of this document demonstrates other elements of the test plan that involves open air testing of the message sets.

Section 5.1 presents the test objective and scope. Section 5.2 describes the items under test. Section 5.3 presents the features tested. Section 5.4 presents the overview of the test design. Section 5.5 presents the test environment and its setup. Section 5.6 presents the test results. Section 5.7 presents an examination of the utilization of hardware-in-the-loop simulation to support the testing of CV-based applications with focus on the red-light violation warning application in the presence of actuated signal control. Section 5.8 compares alternative simulation approaches to support the testing of CV application at signalized intersections including the use of emulator-in-the-loop, software-in-the-loop, and hardware-in-the-loop simulation.

5.1 TEST OBJECTIVE AND SCOPE

The objective of this document is to present the results from the demonstration of the message-level verification of the connected vehicle-based applications to ensure that the messages conform to the requirements developed in this project and the applicable standards. The testing was to verify the format, structure, values, and completeness of the messages generated by the RSE for the three applications. The scope of testing included various messages and associate data elements to fulfill part of the testing plan presented in Section 4. As such, the testing scope included:

- Verification of the completeness of the data produced by the RSE according to Society of Automotive Engineers (SAE) J2735 message format for the messages and data elements that are needed to support the identified requirements in Section 3
- Verification of the correctness of the format conversions between the National Transportation Communications for Intelligent Transportation System Protocol (NTCIP) and the SAE J2735 message formats
- Verification that the generated values of all data elements data encoded to messages are identical as those in the input data source
- Testing/verification of outcomes/results when correct inputs are provided to the roadside units (RSU)
- Testing/verification of correct error handling for boundary conditions (values) inputs were provided to the RSU

5.2 ITEMS TESTED

The Device Under Test (DUT) selected was Siemens ESCoS Roadside Unit, a physical device that implement CV-based applications to communicate with the traffic signal controller and central system and generate messages according to the J2735 standard for broadcasting to equipped vehicles. The Siemens RSU meets the latest FDOT and the United States Department of Transportation (USDOT) RSU standards and has the following functionality related to the tested messages:

- Receive Signal Phase and Timing data (SPaT) information from a traffic signal controller in either NTCIP or SAE J2735 standards and MAP information and broadcast intersection signal phase and timing data and geometric description data to equipped vehicles within the communication control range of the intersection in accordance with SAE J2735 SPaT and MAP standards
- Receive valid Signal Request Messages (SRM) messages that adhere to the SAE J2735 standard from emergency vehicle OBUs that are within communication range of an intersection and forward the requests to the traffic signal controller
- Assemble and broadcast Signal Status Messages (SSM) that conform to the SAE J2735 standard to the vehicles within the communication range when there are active priority requests
- Broadcast work zone advisories, alerts and/or warnings following SAE J2735 and SAE J2945/4 traveler information standards to the vehicles within the communication range.

This document discusses the demonstration of the application of two variations of the testing as presented in the test plan in Section 4:

- Testing of commercially available RSU that provides the above functionality (Siemens ESCoS RSU, shown in Figure 5-1, was selected for this purpose)
- Testing utilizing the V2X Hub developed by the USDOT, which converts, processes, and forwards messages between the traffic controller and the RSU

Figure 5-1 shows the selected Siemens ESCoS RSU. According to the brochure of the device, it has the following key features.

Figure 5-1 Siemens ESCoS Roadside Unit (Source: Siemens RSU Brochure)

- Meets USDOT FHWA 4.1 Roadside Unit specifications
- Hi-speed, low-latency DSRC to vehicle On-Board units
- Browser based service interface for easy configuration, diagnosis and remote software update
- High security level
- Compact, pole-mounting for limited space requirements
- NEMA6P enclosure and connectors for harsh environments
- Power over Ethernet connection to signal controller or cabinet network switch (Siemens ruggedized power over Ethernet injector available separately)
- GPS receiver for location and time
- Local Wi-Fi hot spot for communications to nearby smart devices such as laptops, tablets and smart phones for pedestrian and cyclist safety applications (ready for travel time applications)
- LTE cellular radio for long distance backhaul to central system
- Optional software to manage multiple Roadside Units from a central system
- Antennas and mounting hardware

5.3 FEATURES TESTED

This section presents both the tested and not tested features of the DUT. This document addresses the message level testing of SPaT, MAP, and TIM messages. The testing of SRM and SSM messages will be presented in Section 8, as mentioned previously. The test verifies the following:

a) Verification against the SAE J2735 data dictionary message structure
b) Verification against the limits of the data elements as specified in the SAE J2735 data dictionary message (e.g., value ranges, string lengths, enumerated list values)

The conformance testing was limited to the messages and associated performance established by the SAE J2735 and relevant J2945 Standards. The system-level testing and end-to-end testing were not within the scope of this test, as discussed in earlier. In addition, the following items were not within the scope of this test:

- Physical tests of RSE and controller hardware
- Wireless communication protocols for message transmission (e.g., IEEE 1692 standards)
- Global Navigation Satellite System (GNSS) accuracy and related interfaces
- Radio Technical Commission for Maritime Services *(RTCM)* generation and accuracy
- Security assurance/SCMS
- MAP Accuracy
- MAP Security Profile

5.4 TEST DESIGN OVERVIEW

This section provides an overview of the message-level testing of CV applications including the activities performed and the types of tools utilized in the testing. This project used alternative methods in the testing including the testing of messages with and without the V2X Hub developed by the USDOT, as mentioned previously. Therefore, the signal controller was connected to either the Siemens ESCoS RSU or the V2X Hub through an Ethernet connection.

The signal controller, RSU, and the Linux (Ubuntu) computer running the V2X Hub were connected and configured in the same subnetwork to allow them to communicate with one another. The SPaT messages were received from the signal controller, and the MAP and TIM messages were generated by using the USDOT web tools and downloaded to the RSU or the V2X Hub. Wireshark, a free and open-sourced packet analyzer software, was used to capture the messages between V2X Hub and the RSU. When the RSU was connected to the signal controller without V2X Hub, the messages were exported from the log of the RSU.

Figure 5-2 shows the interface of a TrafficWare Commander ATC controller that was used to configure the signal timing. The SPaT messages were changed by adjusting the different values and settings of the signal control parameters. The input changes were compared with the decoded output messages from the V2X Hub to be fed to the RSU captured via Wireshark.

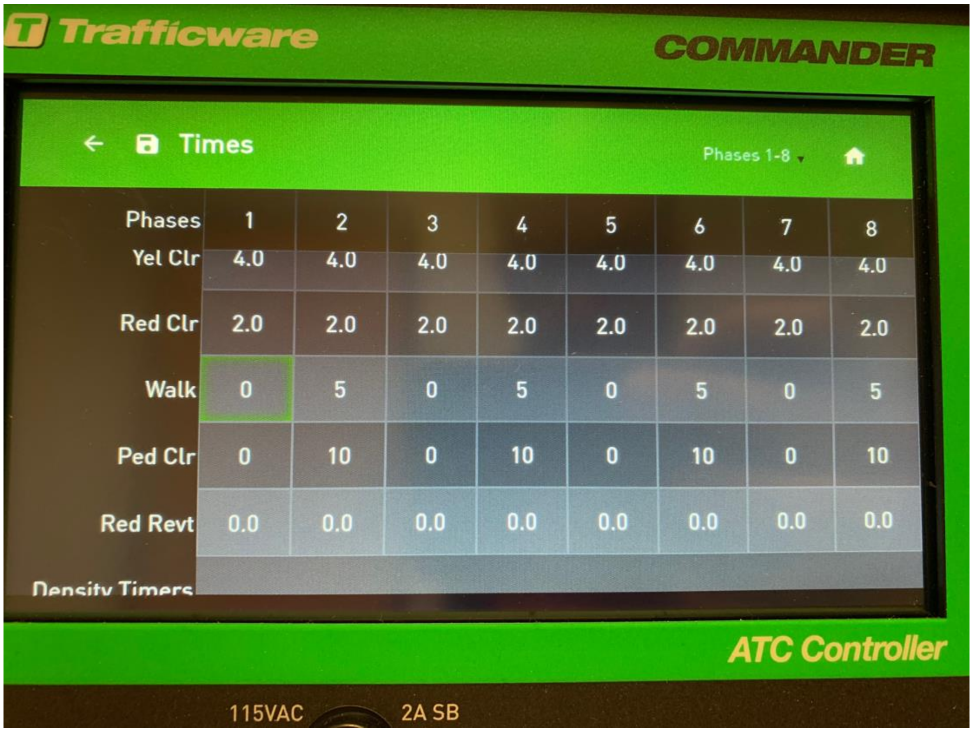


Figure 5-2 Signal Timing Configuration of TrafficWare Commander ATC Controller

Figure 5-3 shows the interface of the USDOT MAP Creator tool, which was used to generate and encode the MAP messages. This tool allows a user to define the approaches and lanes of an intersection using a graphical interface. Once defined, the user can encode an MAP message as an ASN.1 UPER Hex string. The MAP messages were input to either V2X Hub using the Map Plugin in the V2X Hub Interface or RSU using the device web application. The MAP messages captured via Wireshark or exported from the RSU log were decoded and compared with the input MAP messages to verify the correctness and completeness.

Figure 5-3 Interface of USDOT MAP Creator Tool

Figure 5-4 shows the interface of the USDOT TIM Creator tool which was used to generate and encode the TIM messages. This tool allows the user to build traveler information messages including sign and work zone details using a graphical interface. Once defined, the user can encode a TIM message as an ASN.1 UPER Hex string. The TIM messages were input to the RSU using the device web application. The TIM messages captured via Wireshark or exported from the RSU log were decoded and compared with the input TIM messages to verify the correctness and completeness.

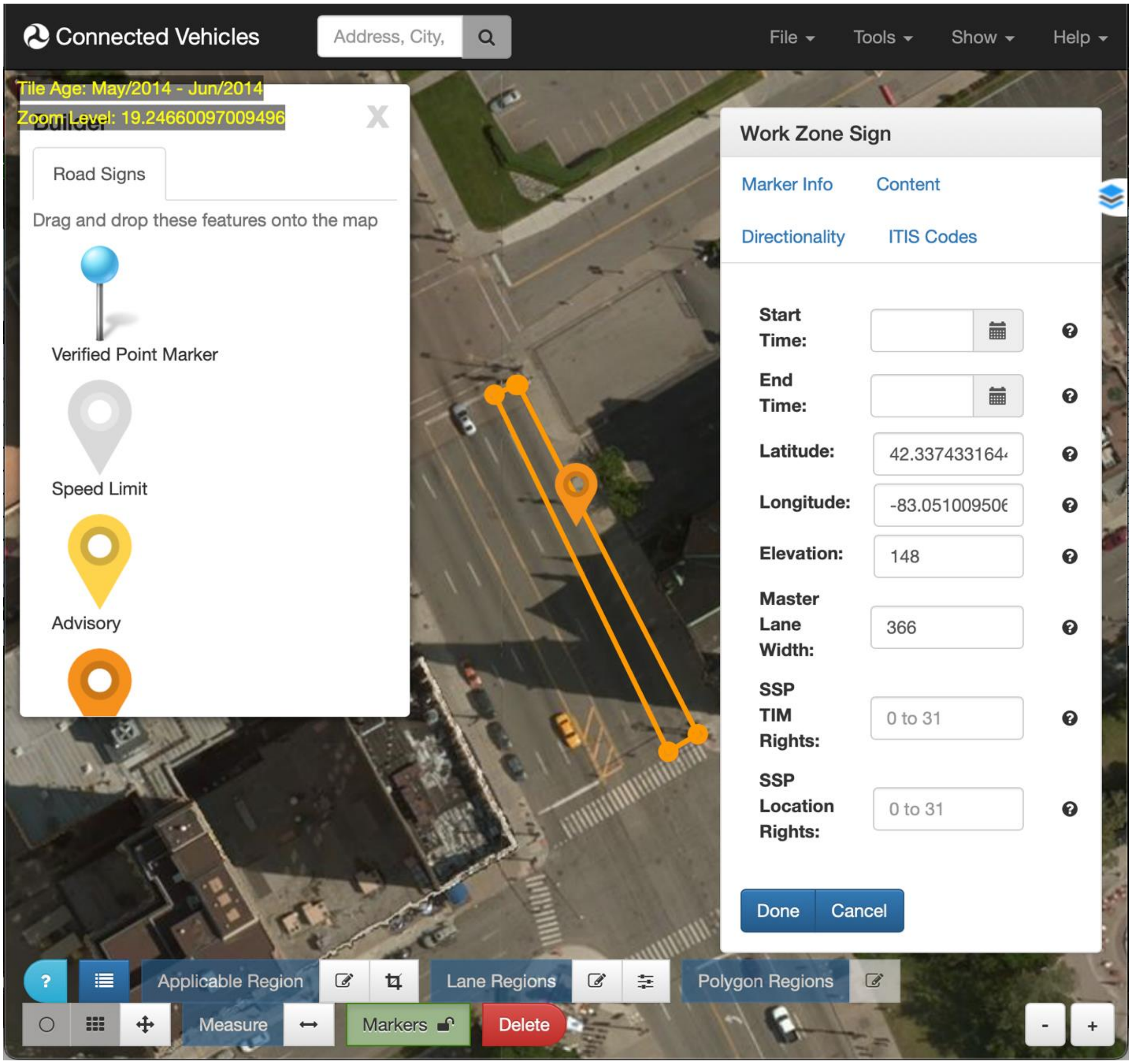


Figure 5-4 Interface of USDOT TIM Creator Tool

Figure 5-5 shows the interface of the MAP plugin in the V2X Hub. This interface was used to input and send the MAP messages from the V2X Hub when the V2X Hub was connected between the signal controller and the RSU.

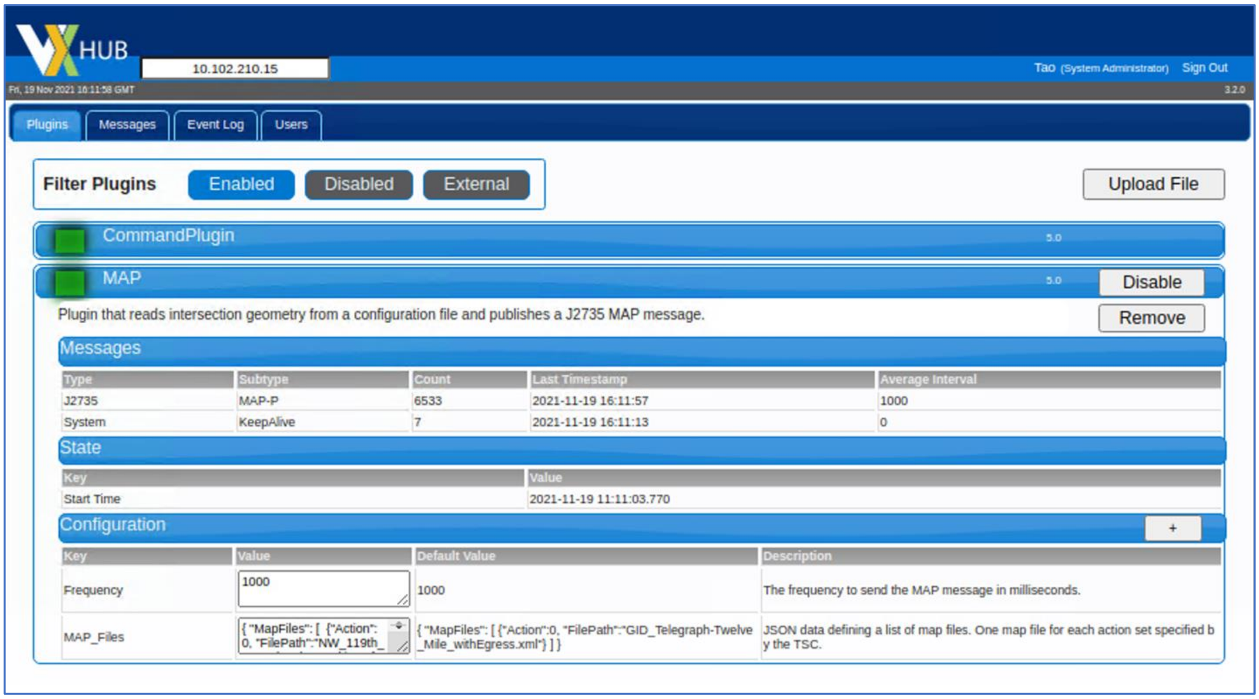


Figure 5-5 Interface of the V2X Hub Map Plugin

Figure 5-6 shows the interface of the message sender within the web app of the Siemens ESCoS RSU. It was used to send out the MAP and TIM messages from the RSU when the RSU was connected to the signal controller without using the V2X Hub in between. Figure 5-7 shows the interface of the log management within the web app of Siemens ESCoS RSU. The MAP and TIM messages sent out from the message sender as mentioned above were retrieved by exporting the logs from the log management for verification.

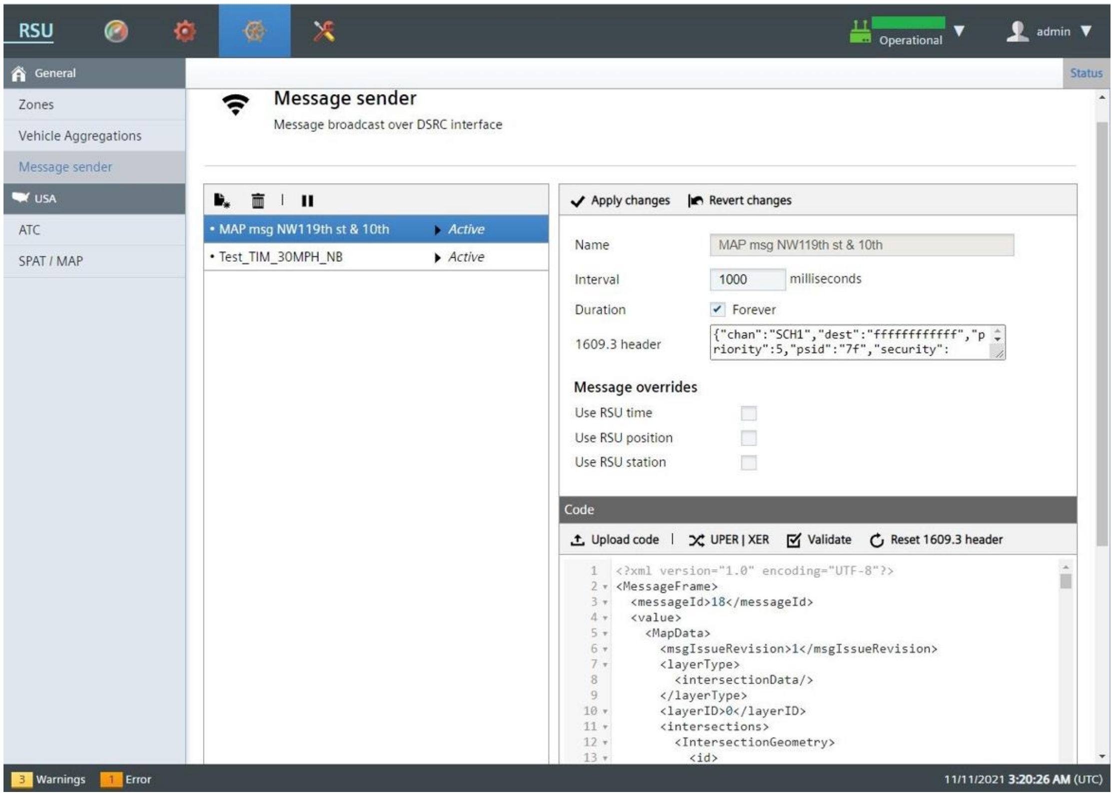


Figure 5-6 Interface of Message Sender within the Web App of Siemens ESCoS RSU

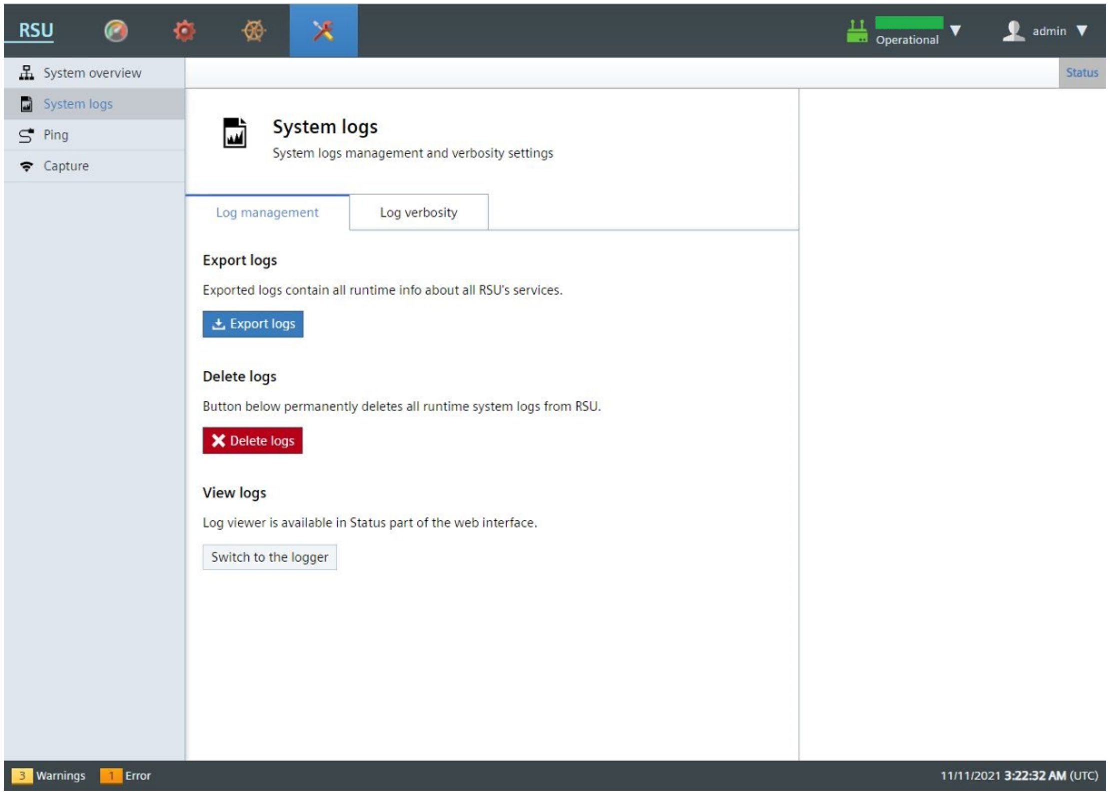


Figure 5-7 Interface of Log Management within the Web App of Siemens ESCoS RSU

Figure 5-8 shows the interface of Wireshark to capture the MAP or TIM messages in between the V2X Hub and the RSU. The interface also allows to capture the UDP stream to extract the payload of the UDP packets, which are encoded MAP or TIM messages, as shown inFigure 5-9.

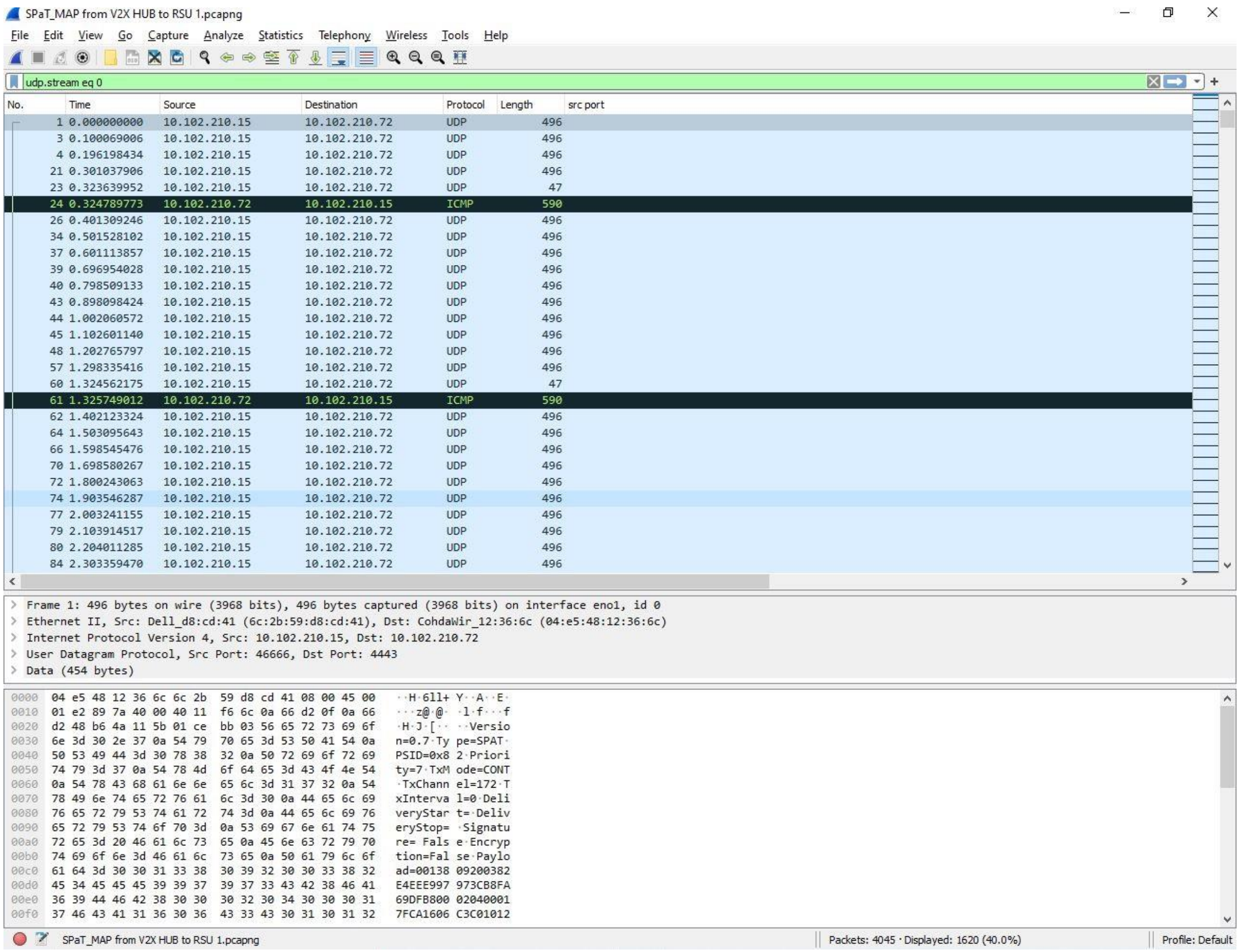


Figure 5-8 Interface of Wireshark for Message Capture

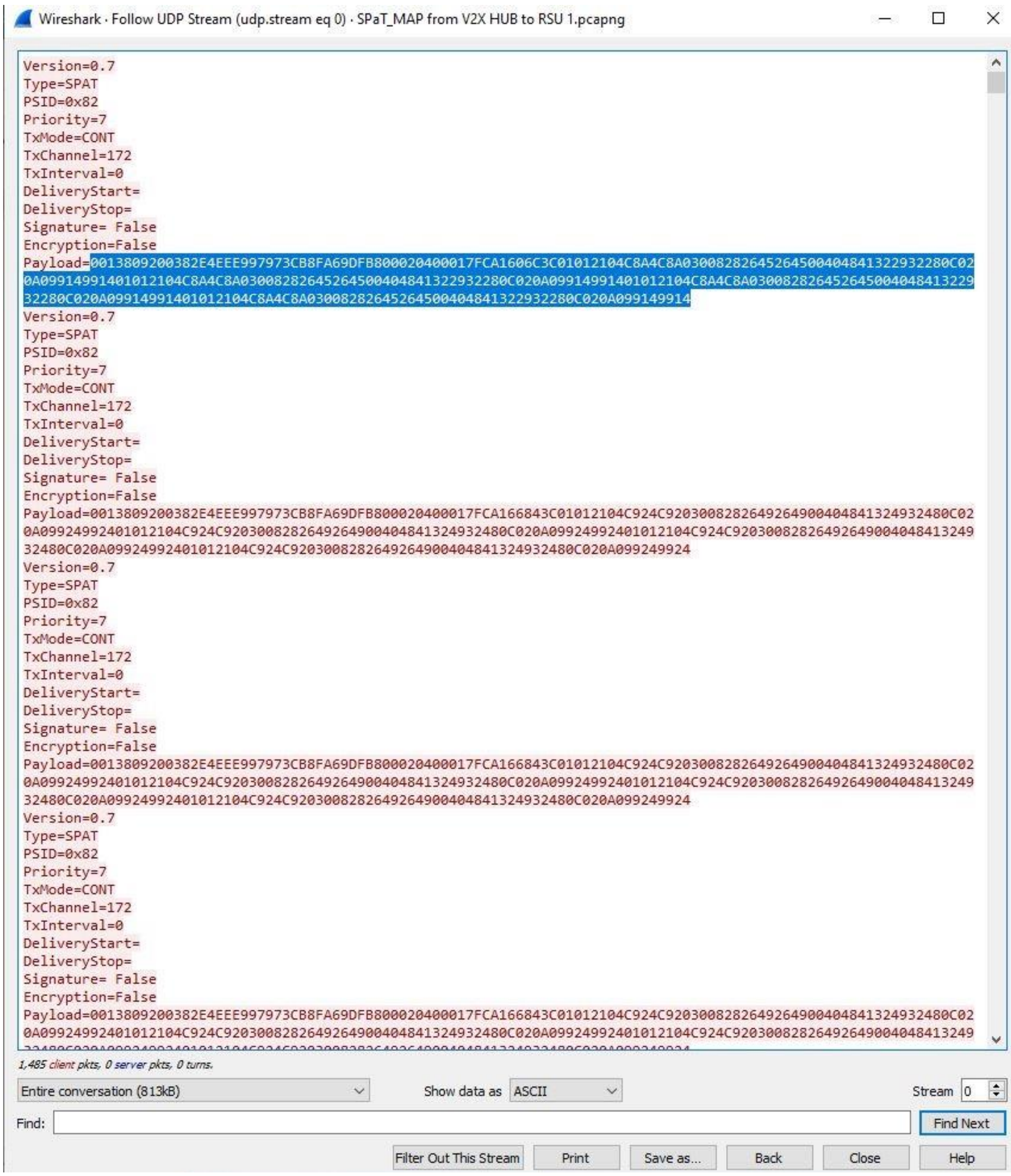


Figure 5-9 Interface of Wireshark for the UDP Stream

Once an encoded SPaT, MAP, or TIM message was extracted from the payload of the UDP packet captured via Wireshark, it was decoded from UPER Hex to human readable XML format by using a free online automotive ASN.1 message decoder tool provided by the official website of Marben, a company providing communication solutions for the telecommunication, transportation, and automotive markets. Figure 5-10 shows the interface of the web tool. The decoded output messages were compared with the input messages to verify the existence, completeness, and correctness of the required messages according to SAE J2735 standards.

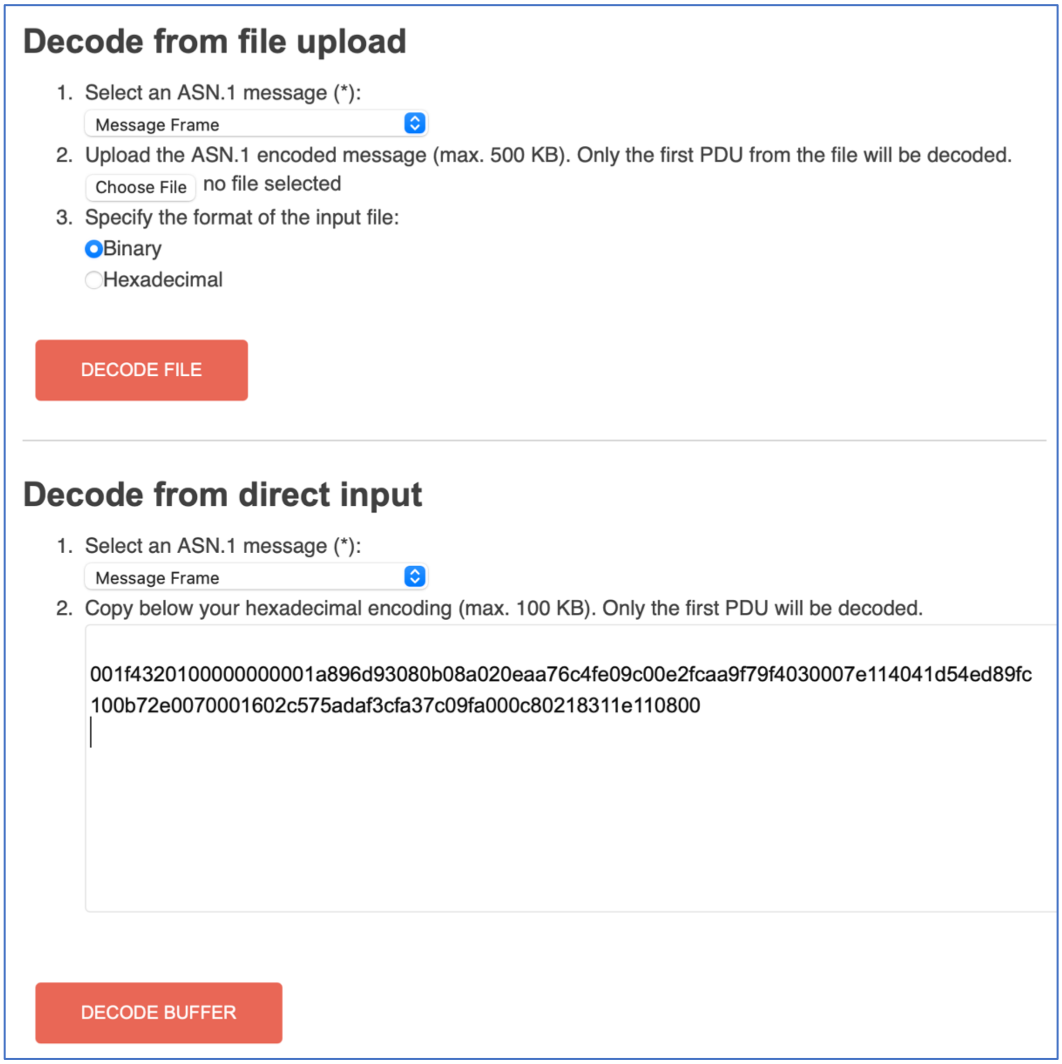


Figure 5-10 Interface of Free Online Automotive ASN.1 Message Decoder (Source: https://www.marben-products.com/decoder-asn1-automotive/)

5.5 TEST ENVIRONMENT SETUP

The Test Environment included the following devices:

- A power source appropriate to the DUT
- TrafficWare Commander ATC Signal Controller
- Siemens ESCoS Roadside Unit
- A Linux (Ubuntu) computer running the V2X Hub and the Wireshark software package to capture and save the encoded messages into .pcap files
- A Windows computer running the USDOT message creator tools for MAP and TIM messages and vehicle-to-everything (V2X) decoder to visualize and analyze the decoded messages

Figure 5-11 shows a photo of the test environment setup.

Figure 5-11 Connected Vehicle-to Infrastructure Applications Testing Environment

In Section 4, four scenarios of test environment setup were identified for potential use in the testing.

- Scenario 1: Wireless Connection with V2X Hub (as shown in Figure 5-12)
- Scenario 2: Wireless Connection without V2X Hub (as shown in Figure 5-13)
- Scenario 3: Wired Connection (as shown in Figure 5-14)
- Scenario 4: Wireless Connection with OBU for Service Request Messages (SRM) (as shown in Figure 5-15)

As mentioned earlier, this section reports only on the wired connection scenario (Scenario 3). The results for the other scenarios will be presented in Section 8.

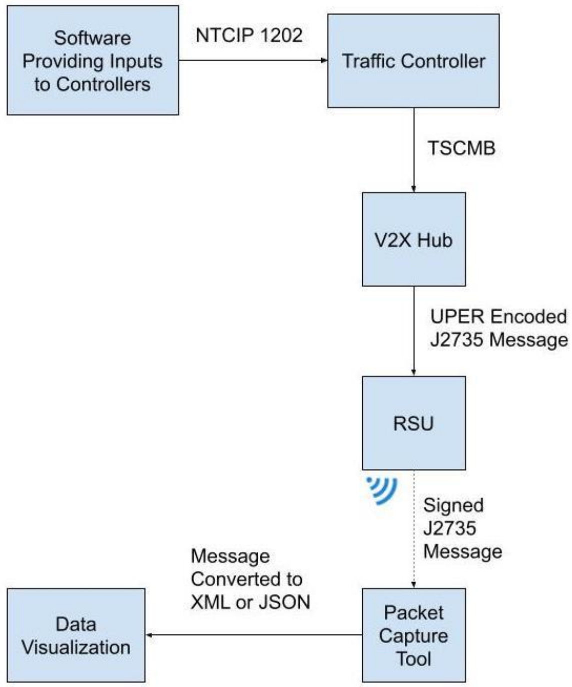


Figure 5-12 Test Environment Setup of Scenario 1

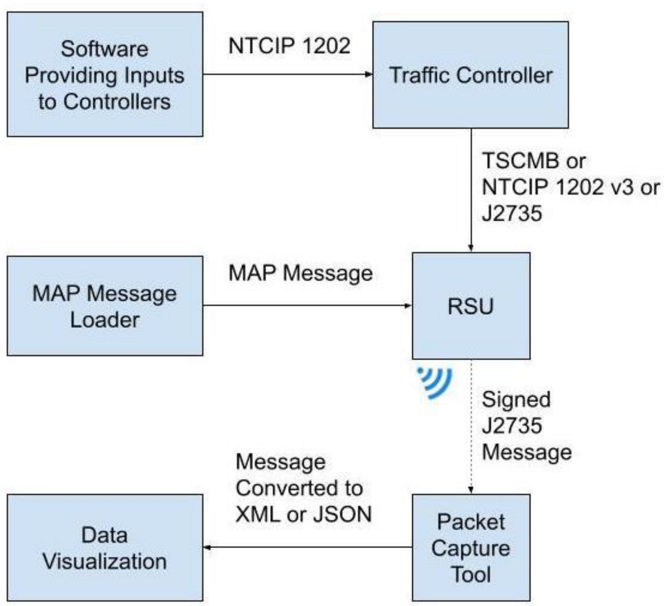


Figure 5-13 Test Environment Setup of Scenario 2

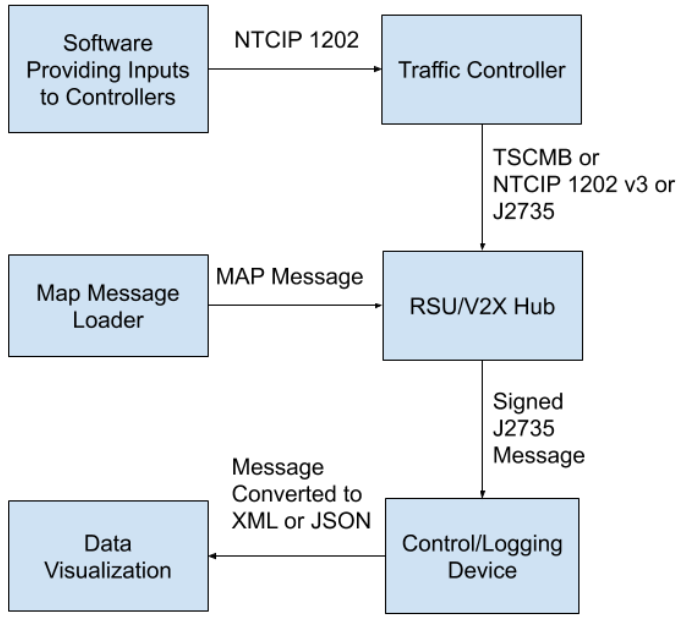


Figure 5-14 Test Environment Setup of Scenario 3

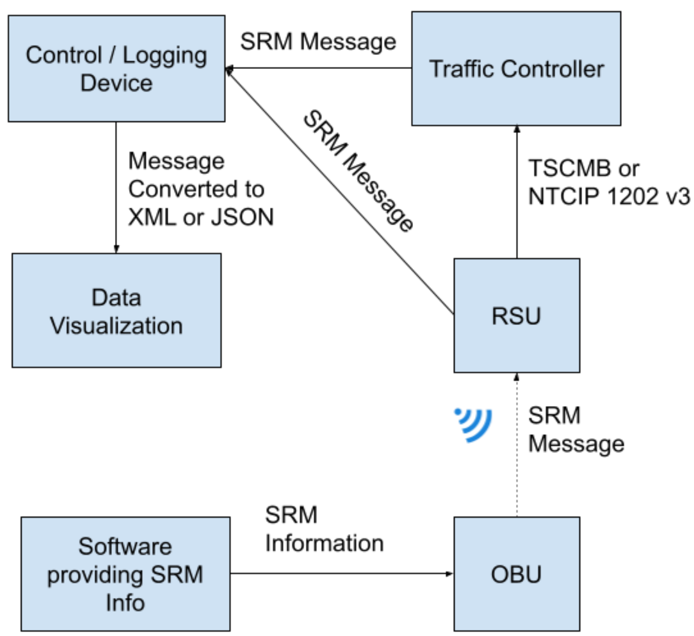


Figure 5-15 Test Environment Setup of Scenario 4 (for SRM only)

5.6 TEST RESULTS

This section presents the test results for each of the tested messages. The validation of the message includes two aspects. The first is to validate the existence of the fields (data elements / frames) of the tested message. The second is to validate the content and structure of the tested message. The validation is according to the definition of each tested message based on SAE J2735 (201603) standard.

The test results for each field of the tested messages are categorized as follows:

- **Pass**: The field in the message configured by input exists after transmission, matches with the input configuration, and complies with SAE J2735 (201603) standard.
- **Fail**: The field in the message is missing, not matching with the input, or not complying to J2735 (201603)
- **Unable to Test**: The field of the message is not tested because it cannot be produced as input to the V2X Hub or the RSU from the controller output, the MAP Creator tool, or the TIM Creator tool.

The test results for each tested message are presented in tables provided in the remainder of this section. The results are presented for the two test methods of this study (with and without the V2X Hub) the tables include the definition of each field according to SAE J2735 (201603) standards and its test result (Pass, Fail, or Not tested). In addition, there is a comment column that provides an explanation for the test result, if necessary.

5.6.1 SAE J2735 SPaT MESSAGES

The SPaT message is used to send the current state of each active phase of one or more signalized intersections in the system. Table 5-1 lists the test results of the SPaT messages when the V2X Hub was connected between the signal controller and the RSU. The Trafficware signal controller supports outputting the SPaT messages in both the NTCIP and SAE J2735 formats of messages. When it's configured to output the SPaT messages in the NTCIP format, the signal controller can be connected to the RSU directly or with V2X Hub in between the controller and the RSU. In this case, the messages will be converted to SAE J2735 format by the V2X Hub or the RSU prior to broadcasting the messages wirelessly by the RSU. When the controller is configured to output the SPaT messages in the SAE J2735 format, the signal controller can only be connected to the RSU directly since the current version of the V2X Hub does not accept the SPaT messages in the J2735 message format as an input.

However, the Siemens RSU firmware tested in this study was found to not being able to support SPaT messages export. This could be due to the limitation of the firmware version provided by the vendor to the team. Because of the above, with the current configuration available to the team the test retrieved the SPaT messages by capturing them either in between the V2X Hub and the RSU (when the signal controller is producing NTCIP messages) or in between the signal controller and the RSU (when the signal controller is producing J2735 messages). It was found that the SPaT messages captured in these two messages capturing methods are identical. Thus, the test results presented in this section represent what was obtained using the two methods. The decoded messages were compared with the inputs from the signal controller interface to verify the messages.

The results show that while all the tested fields of the SPaT messages passed the test, there were also some format differences for some fields between the input and output values. For example, a SPaT message includes the minEndTime and maxEndTime data elements, which are used to convey the earliest and latest time possible at which the phase could change, except when unpredictable events occur such as those related to a preemption or priority call that disrupts a currently active timing plan. When the values of these elements are configured from the signal control interface, they are represented by the human-readable value and format in seconds. However, in the output message captured between V2X Hub and the RSU, they are represented by time stamp (time mark) in units of 1/10th second from UTC (Coordinated Universal Time) time.

Table 5-1 SPaT Message Test Results

SAE J2735 (201603) SPaT Message		Test Result	Comment
• timeStamp MinuteOfTheYear	Optional	Unable to test*	
• name DescriptiveName	Optional	Unable to test	
• intersections IntersectionStateList (Sequence of IntersectionState)	Required	Pass	
○ IntersectionState		Pass	
▪ name DescriptiveName	Optional	Pass	
▪ id IntersectionReferenceID	Required	Pass	
♦ region RoadRegulatorID	Optional	Unable to test	
♦ id IntersectionID	Required	Pass	
▪ revision MsgCount	Required	Pass	
▪ status IntersectionStatusObject	Required	Pass	
▪ moy MinuteOfTheYear	Optional	Pass	
▪ timeStamp DSecond	Optional	Pass	
▪ states MovementList (Sequence of MovementState)	Required	Pass	
♦ MovementState	Required	Pass	
¤ movementName DescriptiveName	Optional	Unable to test	
¤ signalGroup SignalGroupID	Required	Pass	
¤ state-time-speed MovementEventList	Required	Pass	
+ MovementEvent	Required	Pass	
− eventState MovementPhaseState	Required	Pass	
− timing TimeChangeDetails	Optional	Pass	
› startTime TimeMark	Optional		
› minEndTime TimeMark	Optional	Pass	The input and output are different in format. For example, the input in the signal controller is in seconds. The output in the

SAE J2735 (201603) SPaT Message		Test Result	Comment
			SPaT message is a time mark. Input: 20 seconds Output: 29166
› maxEndTme TimeMark	Optional	Pass	The input and output are different in format. For example, the input in the signal controller is in seconds. The output in the SPaT message is a time mark. Input: 20 seconds Output: 29166
› likelyTime TimeMark	Optional	Unable to test	
› confidence TimeIntervalConfidence	Optional	Unable to test	
› nextTime TimeMark	Optional	Unable to test	
– speeds AdvisorySpeedList › AdvisorySpeed # type AdvisorySpeedType # speed SpeedAdvice # confidence SpeedConfidence # distance ZoneLength # class RestrictionClassID	Optional Required Required Optional Optional Optional Optional	Unable to test	
▪ maneuverAssistList ♦ ConnectionManeuverAssist	Optional Required	Unable to test	

SAE J2735 (201603) SPaT Message		Test Result	Comment
¤ connectionID LaneConnectionID ¤ queueLength ZoneLength ¤ availableStorageLength ZoneLength ¤ waitOnStop WaitOnStopline ¤ pedBicycleDetect PedestrianBicycleDetect	Required Optional Optional Optional Optional		

* Unable to test: the field could not be tested because it could not be produced as input to the V2X Hub from the signal controller output

5.6.2 SAE J2735 MAP MESSAGES

The MAP message is used to convey geographic road information of one or more signalized intersections in the system. The tests for the MAP messages were performed for both the V2X Hub and RSU scenarios, so the results are presented separately.

Table 5-2 provides the test results of MAP message when V2X Hub was used as a middleware to the RSU. The results show that while most of the tested fields of the MAP message passed the verification, there were also some “failed” fields, if the definition of Pass is to have the exact values between the input and output values. Very small differences were observed for example for the longitude value of the reference point of one intersection and the X and Y offset of the node points in a lane. However, the difference was so small that it may be ignorable. For example, the X and Y offset (relative to a reference point) of the node points in a lane had only several centimeters difference between the input and output values (e.g., 335 vs. 334 for X offset, and -1859 vs. -1865 for Y offset). Table 5-3 provides the test results of MAP message when the RSU was directly connected to the signal controller without V2X Hub. The results show that all the tested fields of the MAP message passed the verification.

Table 5-2 MAP Message Test Result (V2X Hub)

SAE J2735 (201603) MAP Message		Test Result	Memo
• timeStamp MinuteOfTheYear	Optional	Unable to test*	
• msgIssueRevision MsgCount	Required	Fail	Input is 1, and output is 0
• layerType	Optional	Pass	
• layerID	Optional	Fail	Missing in output
• intersections IntersectionGeometryList (Sequence of IntersectionGeometry)	Optional	Pass	
○ IntersectionGeometry	Required	Pass	
▪ name DescriptiveName	Optional	Pass	New added int output
▪ id IntersectionReferenceID	Required	Pass	
♦ region RoadRegulatorID	Optional	Unable to test	
♦ id IntersectionID	Required	Pass	
▪ revision MsgCount	Required	Pass	
▪ refPoint Position3D-2	Required	Pass	
♦ lat Latitude	Required	Pass	
♦ long Longitude	Required	Fail	Minor difference found. E.g., input: -802145942, output: -802146237
▪ laneWidth	Optional	Pass	
▪ LaneList (Sequence of GenericLane)	Required	Pass	
♦ GenericLane	Required	Pass	
¤ laneID	Required	Pass	
¤ name DescriptiveName	Optional	Pass	
¤ ingressApproach ApproachID	Optional	Pass	
¤ egressApproach ApproachID	Optional	Pass	
¤ laneAttributes	Required	Pass	
+ directionalUse LaneDirection	Required	Pass	
+ sharedWith LaneSharing	Required	Pass	
+ laneType LaneTypeAttributes	Required	Pass	
¤ maneuvers AllowedManeuvers	Optional	Pass	

SAE J2735 (201603) MAP Message		Test Result	Memo
¤ nodeList NodeListXY	Required	Pass	
+ nodes NodeSetXY	Choice	Pass	
− NodeXY	Required	Pass	
› delta NodeOffsetPointXY	Required	Fail	Minor difference found. E.g., Input: x is 335, y is -1859, Output: x is 334, y is -1865
› attributes NodeAttributeSetXY	Optional	Unable to test	
# localNode NodeAttributeXY List	Optional	Unable to test	
❖ NodeAttrib uteXY	Required	Unable to test	
# disabled SegmentAttribute XYList	Optional	Unable to test	
❖ SegmentAt tributeXY	Required	Unable to test	
# enabled SegmentAttribute XYList	Optional	Unable to test	
❖ SegmentAt tributeXY	Required	Unable to test	
# data LaneDataAttribute List	Optional	Unable to test	
❖ LaneDataA ttribute	Required	Unable to test	
# dWidth Offset-B10	Required	Unable to test	

SAE J2735 (201603) MAP Message		Test Result	Memo
# dElevation Offset-B10	Required	Unable to test	
+ computed ComputedLane	Choice	Unable to test	
– referenceLaneId LaneID	Required	Unable to test	
– offsetXaxis	Required	Unable to test	
– offsetYaxis	Required	Unable to test	
– rotateXY Angle	Optional	Unable to test	
– scaleXaxis Scale-B12	Optional	Unable to test	
– scaleYaxis Scale-B12	Optional	Unable to test	
¤ connectsTo ConnectsToList	Optional	Pass	
+ Connection		Pass	
– connectingLane	Required	Pass	
› lane LaneID	Required	Pass	
› maneuver AllowedManeuvers	Optional	Pass	
– remoteIntersection IntersectionReferenceID	Optional	Unable to test	
› region RoadRegulatorID	Optonal	Unable to test	
› id IntersectionID	Required	Unable to test	
– signalGroup SignalGroupID	Optional	Pass	
– userClass RestrictionClassID	Optional		
– connectionID LaneConnectionID	Optional	Pass	

SAE J2735 (201603) MAP Message		Test Result	Memo
¤ overlays OverlayLaneList	Optional	Unable to test	
+ LaneID	Required	Unable to test	
• roadSegments RoadSegmentList	Optional	Unable to test	
• dataParameters	Optional	Unable to test	
• restrictionList RestrictionClassList	Optional	Unable to test	

* Unable to test: the field could not be tested because it could not be produced as input to the V2X Hub from the USDOT MAP creator tool

Table 5-3 MAP Message Test Result (RSU)

SAE J2735 (201603) MAP Message		Test Result	Memo
• timeStamp MinuteOfTheYear	Optional	Unable to test*	
• msgIssueRevision MsgCount	Required	Pass	
• layerType	Optional	Pass	
• layerID	Optional	Pass	
• intersections IntersectionGeometryList (Sequence of IntersectionGeometry)	Optional	Pass	
○ IntersectionGeometry	Required	Pass	
▪ name DescriptiveName	Optional	Unable to test	
▪ id IntersectionReferenceID	Required	Pass	
♦ region RoadRegulatorID	Optional	Unable to test	
♦ id IntersectionID	Required	Pass	
▪ revision MsgCount	Required	Pass	
▪ refPoint Position3D-2	Required	Pass	
♦ lat Latitude	Required	Pass	
♦ long Longitude	Required	Pass	

SAE J2735 (201603) MAP Message		Test Result	Memo
▪ laneWidth	Optional	Pass	
▪ LaneList (Sequence of GenericLane)	Required	Pass	
♦ GenericLane	Required	Pass	
¤ laneID	Required	Pass	
¤ name DescriptiveName	Optional	Pass	
¤ ingressApproach ApproachID	Optional	Pass	
¤ egressApproach ApproachID	Optional	Pass	
¤ laneAttributes	Required	Pass	
+ directionalUse LaneDirection	Required	Pass	
+ sharedWith LaneSharing	Required	Pass	
+ laneType LaneTypeAttributes	Required	Pass	
¤ maneuvers AllowedManeuvers	Optional	Pass	
¤ nodeList NodeListXY	Required	Pass	
+ nodes NodeSetXY	Choice	Pass	
− NodeXY	Required	Pass	
› delta NodeOffsetPointXY	Required	Pass	
› attributes NodeAttributeSetXY	Optional	Unable to test	
# localNode NodeAttributeXY List	Optional	Unable to test	
❖ NodeAttrib uteXY	Required	Unable to test	
# disabled SegmentAttribute XYList	Optional	Unable to test	
❖ SegmentAt tributeXY	Required	Unable to test	

SAE J2735 (201603) MAP Message		Test Result	Memo
# enabled SegmentAttributeXYList	Optional	Unable to test	
❖ SegmentAttributeXY	Required	Unable to test	
# data LaneDataAttributeList	Optional	Unable to test	
❖ LaneDataAttribute	Required	Unable to test	
# dWidth Offset-B10	Required	Unable to test	
# dElevation Offset-B10	Required	Unable to test	
+ computed ComputedLane	Choice	Unable to test	
– referenceLaneId LaneID	Required	Unable to test	
– offsetXaxis	Required	Unable to test	
– offsetYaxis	Required	Unable to test	
– rotateXY Angle	Optional	Unable to test	
– scaleXaxis Scale-B12	Optional	Unable to test	
– scaleYaxis Scale-B12	Optional	Unable to test	
¤ connectsTo ConnectsToList	Optional	Pass	
+ Connection		Pass	
– connectingLane	Required	Pass	
› lane LaneID	Required	Pass	

SAE J2735 (201603) MAP Message		Test Result	Memo
› maneuver AllowedManeuvers	Optional	Pass	
– remoteIntersection IntersectionReferenceID	Optional	Unable to test	
› region RoadRegulatorID	Optonal	Unable to test	
› id IntersectionID	Required	Unable to test	
– signalGroup SignalGroupID	Optional	Pass	
– userClass RestrictionClassID	Optional	Unable to test	
– connectionID LaneConnectionID	Optional	Pass	
¤ overlays OverlayLaneList	Optional	Unable to test	
+ LaneID	Required	Unable to test	
• roadSegments RoadSegmentList	Optional	Unable to test	
• dataParameters	Optional	Unable to test	
• restrictionList RestrictionClassList	Optional	Unable to test	

* Unable to test: the field could not be tested because it could not be produced as input to the RSU from the USDOT MAP creator tool

5.6.3 SAE J2735 TIM MESSAGES

The TIM message is used to send various types of traffic condition information to the OBU of the equipped vehicles. Table 5-4 presents the test results of the TIM message when the RSU was directly connected to the signal controller without V2X Hub. The results show that all the tested fields of the TIM message passed the verification. The V2X Hub also has a TIM plugin to allow sending TIM messages to the RSU.

Table 5-4 TIM Message Test Result (RSU)

SAE J2735 (201603) TIM Message		Test Result	Memo
• msgCnt MsgCount	Required	Pass	
• timeStamp MinuteOfTheYear	Optional	Unable to test*	
• packetID UniqueMSGID	Optional	Pass	
• urlBURL URL-Base	Optional	Unable to test	
• dataFrames TravelerDataFrameList (Sequence of TravelerDataFrame)	Required	Pass	
○ TravelerDataFrame	Required	Pass	
▪ sspTimRights SSPindex	Required	Pass	
▪ frameType TravelerInfoType	Required	Pass	
▪ msgId	Required	Pass	
♦ furtherInfoID	Choice	Unable to test	
♦ roadSignID	Choice	Pass	
¤ position Position3D	Required	Pass	
+ lat Latitude	Required	Pass	
+ long Longitude	Required	Pass	
+ elevation	Optional		
¤ viewAngle HeadingSlice	Required	Pass	
¤ mutcdCode	Optional	Pass	
¤ crc MsgCRC	Optional	Unable to test	
▪ startYear DYear	Optional	Pass	
▪ startTime MinuteOfTheYear	Required	Pass	

SAE J2735 (201603) TIM Message		Test Result	Memo
▪ duratonTime MinutesDuration	Required	Pass	
▪ priority SignPrority	Required	Pass	
▪ sspLocationRights SSPindex	Required	Pass	
▪ regions GeographicalPathList (Sequence of GeographicalPath)	Required	Pass	
♦ GeographicalPath	Required	Pass	
¤ name DescriptiveName	Optional	Unable to test	
¤ id RoadSegmentReferenceID	Optional	Unable to test	
+ region RoadRegulatorID	Optional	Unable to test	
+ id RoadSegmentID	Required	Unable to test	
¤ anchor Position3D	Optional	Pass	
+ lat Latitude	Required	Pass	
+ long Longitude	Required	Pass	
+ elevation	Optional	Unable to test	
¤ laneWidth	Optional	Pass	
¤ directionality DirectionOfUse	Optional	Pass	
¤ closedPath BOOLEAN	Optional	Pass	
¤ direction HeadingSlice	Optional	Pass	
¤ description	Optional	Pass	
+ path OffsetSystem	Choice	Pass	
− scale Zoom	Optional	Unable to test	

SAE J2735 (201603) TIM Message		Test Result	Memo
– offset NodeListXY	Required	Pass	
› nodes NodeSetXY (Sequence of NodeXY)	Choice	Pass	
# NodeXY	Required	Pass	
❖ delta NodeOffsetPointXY	Required	Pass	
➢ node-XY1 Node-XY-20b	Choice	Unable to test	
✓ x Offset-B10	Required	Unable to test	
✓ y Offset-B10	Required	Unable to test	
➢ node-XY2 Node-XY-22b	Choice	Unable to test	
✓ x Offset-B11	Required	Pass	
✓ y Offset-B11	Required	Pass	
➢ node-XY3 Node-XY-24b	Choice	Pass	

SAE J2735 (201603) TIM Message		Test Result	Memo
✓ x Offset-B12	Required	Pass	
✓ y Offset-B12	Required	Pass	
➢ node-XY4 Node-XY-26b	Choice	Pass	
✓ x Offset-B13	Required	Pass	
✓ y Offset-B13	Required	Pass	
➢ node-XY5 Node-XY-28b	Choice	Pass	
✓ x Offset-B14	Required	Pass	
✓ y Offset-B14	Required	Pass	
➢ node-XY6 Node-XY-32b	Choice	Pass	

SAE J2735 (201603) TIM Message		Test Result	Memo
✓ x Offset-B16	Required	Pass	
✓ y Offset-B16	Required	Pass	
➢ node-LatLon Node-LLmD-64b	Choice	Pass	
✓ lon Longitude	Required	Pass	
✓ lat Latitude	Required	Pass	
❖ attributes NodeAttributeSetXY	Optional	Unable to test	
➢ localNode NodeAttributeXYList	Optional	Unable to test	
✓ NodeAttributeXY	Required	Unable to test	
➢ disabled SegmentAttributeXYList	Optional	Unable to test	

SAE J2735 (201603) TIM Message		Test Result	Memo
✓ SegmentAttributeXY	Required	Unable to test	
➢ enabled SegmentAttributeXYList	Optional	Unable to test	
✓ SegmentAttributeXY	Required	Unable to test	
➢ data LaneDataAttributeList	Optional	Unable to test	
✓ Lane Data Attribute	Required	Unable to test	
➢ dWidth Offset-B10	Optional	Unable to test	
➢ dElevation Offset-B10	Optional	Unable to test	
› computed ComputedLane	Choice	Unable to test	
# referenceLaneId LaneID	Required	Unable to test	
# offsetXaxis	Required	Unable to test	

SAE J2735 (201603) TIM Message		Test Result	Memo
❖ small DrivenLineOffsetSm	Choice	Unable to test	
❖ large DrivenLineOffsetLg	Choice	Unable to test	
# offsetYaxis	Required	Unable to test	
❖ small DrivenLineOffsetSm	Choice	Unable to test	
❖ large DrivenLineOffsetLg	Choice	Unable to test	
# rotateXY Angle	Optional	Unable to test	
# scaleXaxis Scale-B12	Optional	Unable to test	
# scaleYaxis Scale-B12	Optional	Unable to test	
+ geometry GeometricProjection	Choice	Unable to test	
+ oldRegion ValidRegion	Choice	Unable to test	

* Unable to test: the field could not be tested because it could not be produced as input to the RSU from the USDOT TIM creator tool

6 UTILIZATION OF HARDWARE-IN-THE-LOOP SIMULATION TO SUPPORT THE TESTING OF CV APPLICATIONS

This project utilized hardware-in-the-loop simulation to test CV technologies and applications. These applications promise the enhancement of safety and mobility while reducing the transportation environmental impacts. A fundamental prerequisite for CV applications to deliver the needed functionality at signalized intersections is the access to the SPaT information in the traffic signal controller. Modern actuated traffic signal controllers contain several features with which controllers can provide varying green intervals for actuated phases, skip phases, and terminate phases depending on the traffic demand fluctuation from cycle to cycle. Such features introduce additional challenges when testing and evaluating the CV applications that are mainly based on signal information such as the current phase termination time due to the uncertainty in this information. The uncertainty in the SPaT messages with the presence of an actuated traffic signal controller is one of the main challenges that signalized intersection CV-based applications encounter.

Actuated signals consist of variable phases that are called and extended in response to traffic demands. With actuated traffic signal operations, there is uncertainty in the end-of-green information provided to the vehicles using the SPaT message. The RLVW algorithm lacks the input information about when exactly the phase is going to be terminated since this depends on the conflicting movement actuation. In the case of congested conditions on all movements, all phases are expected to reach their maximum values (Max Out) allowing the provision of accurate SPaT messages. The underlying algorithm on the On-Board Equipment (OBE) can then use this information to perform the required calculations and send alerts and warnings to drivers based on the received SPaT information. In the case of Cooperative Driving Automation (CDA), connected automated vehicles can use this information in planning their trajectories. However, in the case of free-flow traffic operations, the signal phases are expected to terminate before the maximum green time is reached (Gap Out), which results in varying ends of the green time between cycles and affects the functionality and performance of the applications.

Research studies have evaluated the impacts of CV-based applications (*30–35*). However, there is a gap in the literature when it comes to assessing the benefits of CV-based applications at signalized intersections under actuated signal controller operations. The main goal of this study is to evaluate the performance of the Red-Light Violation Warning application (RLVW) as an example of CV-based applications under actuated signal controller and to assess a method to mitigate the uncertainty mentioned above.

A microscopic simulation environment is utilized as a primary tool for assessing the benefits of the RLVW application. The utilized simulation environment allows the interface of the simulation software and hardware elements in a hardware-in-the-loop simulation (HILS) platform. The platform integrates a physical actuated traffic signal controller for better evaluation of the performance of the RLVW application. The study uses the direct output files from the simulation to analyze the mobility benefits of the application. In addition, the study used the simulated vehicle trajectories to identify, classify, and evaluate the safety benefits of the application based on surrogate safety measures utilizing the Surrogate Safety Assessment Model (SSAM) developed by the Federal Highway Administration (FHWA) (*36*).

6.1 LITERATURE REVIEW

There are several parameters related to the CV-based control algorithm and the actual traffic signal controller that are difficult to be tested or evaluated using the microscopic simulation tool by itself. However, the recent advancement in simulation packages and the advanced signal controller Application Program Interfaces (APIs) provide researchers with a wide variety of options to test and evaluate the impacts of CV-based technologies in a realistic and risk-free environment. HILS is one of the available options that allow better replication of real-world operations in the modeling of CV applications. The review of literature in this section is divided into two main sections: a review of studies that utilized microscopic simulation in modeling RLVW applications and a review of studies that utilized HILS to model CV applications.

6.1.1 Red-Light Violation Warning Application

RLVW is a CV-based safety application that aims to reduce the number of red-light running events and improve safety at signalized intersections. RLVW is expected to reduce the uncertainty in the driver's behavior, particularly in the vicinity of the dilemma zone due to increasing drivers' awareness of the signal status as they approach a signalized intersection (*37*). A key element that pertains to the success of this application is the presence of roadside equipment (RSE) that transmits SPaT information from the traffic signal controller to the CV-equipped vehicles. The RLVW application on the OBE utilizes this information along with the vehicle approaching speed and distance to the intersection stop line to provide warnings to drivers, allowing them to make decisions to avoid running a red-light (*38*). The application can also work as part of cooperative driving automation with the utilization of the SPaT information by the vehicle automation software.

An ongoing effort (*39*) funded by the United States Department of Transportation (USDOT) ITS Joint Program Office (JPO), referred to as the Connected Intersection (CI) project, and has defined the concept of operations, functional requirements, system design details, and testing requirements for the CV-based RLVW applications (*39*). There are no official documents from this effort yet, but such documents are expected to be released in the near future. The above-mentioned USDOT effort identified the need for what it called an assured green period (AGP) to mitigate the issue with the uncertainty in the provision of the end of the green time in SPaT messages with actuated signal control. The AGP is an extension of the green for the phase that serves the approaching CV vehicles and is calculated based on the approach speed and distance from the stop line. When the AGP is combined with the yellow interval, it provides enough time for reducing the possibility that an equipped vehicle will violate the red-light and continue to be present in the intersection during a red signal state.

Yan et al., (*40*) examined a prototype concept of an RLVW system that sends audio alerts to drivers approaching a signalized intersection at the onset of yellow. The researchers analyzed the effect of RLVW on the number of red-light running violations using a driving simulator and showed a reduction in the red-light running violations by 84.3 percent. In addition, the researchers reported that the RLVW reduces the drivers' likelihood to make go decisions at the onset of yellow 86 times compared to unequipped vehicles. Banerjee et al. (*41*) analyzed the effect of RLVW on the braking behavior of drivers as reflected by the speed reduction time series at the onset of yellow using a driving simulator and eye-tracking. The results showed that participants react more quickly to the changes in traffic signals in the presence of RLVW.

Nassereddine et al., (*42*) conducted a driving simulator experiment to evaluate the benefits of a CV-based RLVW application that communicates in-vehicle alerts about the presence of a potential vehicle running the red-light. The experiments were conducted using three different scenarios where the RLVW system issued the alert at 50, 100, and 150 feet upstream of the stop line. The study results showed that the utilized warning system was more effective in sending violation warnings when activated at a distance of 50 feet or 100 feet upstream of the stop line.

Hussain et al., (*43*) assessed the changes in drivers' safe-stopping behavior and red-light running voice warning alternatives using a driving simulator experiment. The experiments evaluated five different alternatives that include providing the default traffic signal setting, flashing green, red LED ground lights (R-LED), yellow interval countdown sign, and red-light running detection camera warning (RW-gantry). The study showed that the R-LED and the RW-gantry were the most effective solutions in encouraging a consistent stopping behavior at the signalized intersection.

Mohammed et al. (*44*) tested the impact of providing in-vehicle advisory auditory RLVW. The researchers utilized a real-world testbed that is consisted of a physical traffic signal controller, roadside equipment, on-board equipment, and testing vehicle. The drivers' performance was tested in terms of the average speed, maximum speed, and acceleration/deceleration profiles. The researchers reported that the proposed application has promising impacts on improving safety and driver awareness at signalized intersections.

6.1.2 Hardware-in-the-Loop Simulation

HILS integrates traffic simulation software and a physical traffic signal controller. With the HILS, the simulation software generates virtual traffic and virtual detector data and sends the information to the signal controller, which generates signal states and sends them back to the simulation model. The HILS platforms set the signal controller to react to the virtual detector calls as if they were coming from real-world detectors. The communication between the traffic signal controller and the traffic simulation package can be done either using a middleware interface or a hardware interface. The middleware is an interface that acts as a bridge between the traffic signal controller and the simulation platform. This communication can be achieved using the National Transportation Communications for Intelligent Transportation System (ITS) Protocol (NTCIP) standards by developing programs that send and receive Simple Network Management Protocol (SNMP) requests (*35*). The hardware interface is referred to as Controller Interface Device (CID). CID is a device that connects the traffic signal controllers and the simulation software by transferring the discrete logic levels of the control pins of the traffic signal controller to the microscopic simulation model (*45*). The controller receives the virtual detector calls from the simulation, generates the signal status, and sends the signal state back to the simulation software through the CID.

Gelbal et al. (*46*) evaluated a combination of the RLVW and the Green Light Optimized Speed Advisory (GLOSA) applications using the HILS testing platform. The researchers integrated a roadside unit and a traffic cabinet in a simulation environment to allow the testing of different scenarios. The study results successfully showed the ability of the developed HIL platform in generating both an optimal speed advisory for passing at the green light and providing red-light violation warnings. However, the researchers assumed fixed green intervals with no uncertainty in the end-of-green time.

Ma et al. (*35*) developed a HILS proof-of-concept platform for use in testing the CV-based Cooperative Adaptive Cruise Control (CACC) application. The HILS system includes a physical connected automated vehicle (CAV), field test track, CV equipment, and a microscopic simulation tool. The platform was used to test and quantify the potential benefits of a CAV queue-aware signalized intersection approach and departure (Q-SIAD) application. The Q-SIAD algorithm combines the signal phase and timing (SPaT), downstream queue length, vehicle's acceleration/deceleration, and the status of other vehicles to generate recommended speed profiles. Szendrei et al. (*32*) developed a HILS platform for testing CV applications. The platform consists of an open-simulation software, which is the Simulation of Urban Mobility (SUMO) software; an orchestrator, which manages all elements of the HILS system components; and commercial CV devices. The researchers reported that the proposed HILS framework offered a cost-efficient tool for testing and evaluating CV-based applications in a laboratory environment.

Yun et al. (*47*) utilized a HILS testing platform for comparing various emergency vehicle preemption (EVP) strategies using a coordinated-actuated traffic signal controller. The testing platform consisted of VISSIM connected to four Type 170 signal controllers to examine the performance of different EVP strategies such as the short-way and dwell. The researchers implemented the platform to model four coordinated-actuated signalized intersections. The study results showed that the short-way strategy had the best performance in minimizing the impacts of EVP. Sunkari et al. (*48*) developed a HILS platform that enables controlled field testing of CV-based applications in an augmented testing environment. The HILS utilized a microscopic simulation tool to generate detector calls that are sent to the traffic signal controller to operate in an actuated mode and receiving SPaT from the controller. The results of the study showed that the developed HILS platform is capable of testing various CV-based applications in a cost-effective and risk-free manner.

6.2 METHODOLOGY

A basic four-leg signalized intersection is modeled with moderate traffic volumes. The study sets the parameters of the signal timing including the minimum green times, maximum green times, yellow intervals, all-red intervals, and passage times according to the Transportation Research Board Traffic Signal Timing Manual (*49*). The major street signals are set to continuously Rest-in-Green. The PTV's Verkehr in Städten SIMulationsmodell (VISSIM) Version 20 is used as the microscopic simulation tool to model a test network and to assess the impacts of the actuated signal control operation on the performance of the CV-based RLVW application in a HIL environment

(*50*). The demands for the through and left-turn movements on both the northbound and southbound approaches are set to be 192 vehicles per hour and 383 vehicles per hour, respectively. The demands for the through and left-turn movements on both the westbound and eastbound approaches are set to be 255 vehicles per hour and 510 vehicles per hour, respectively. Each of the eight movements has one exclusive lane. The RLVW was applied to the through movements for evaluation purposes.

The assessment is done based on mobility and safety performance measures. The mobility measures are the stopped delay, number of stops, and approach delay based on simulation model outputs. The average stop delay is defined in the utilized simulation tool as the aggregate sum of stopped time of all vehicles for a particular time interval divided by the total entering volume for that movement. The number of stops is the average number of vehicle-stops per vehicle due to signal control. The approach delay is the average delay of all vehicles obtained by subtracting the theoretical (ideal) travel time from the actual travel time (*50*). The safety measures involve collecting the total number of RLR events and surrogate measures related to the right-angle and the rear-end conflicts at the intersection approaches, which are the types of conflicts associated with RLR.

6.2.1 Actuated Signal Controller Support of RLVW

As mentioned in the review of literature, a potential design element for an actuated signal controller support of the RLVW is to dedicate an AGP to mitigate the uncertainty of the remaining green time due to the actuated signal operation. The parameters needed to estimate the AGP are the approach speed, the stopping distance, and the time required to clear the intersection, as shown inFigure 6-1. The utilized approach speed in the calculation of the AGP is the 85th percentile speed, as discussed in the Connected Intersection effort funded by the USDOT mentioned earlier (*39*). This speed is recognized as a reasonable speed to use in calculating the AGP since most drivers on the road consider it to be safe and reasonable under ideal conditions.

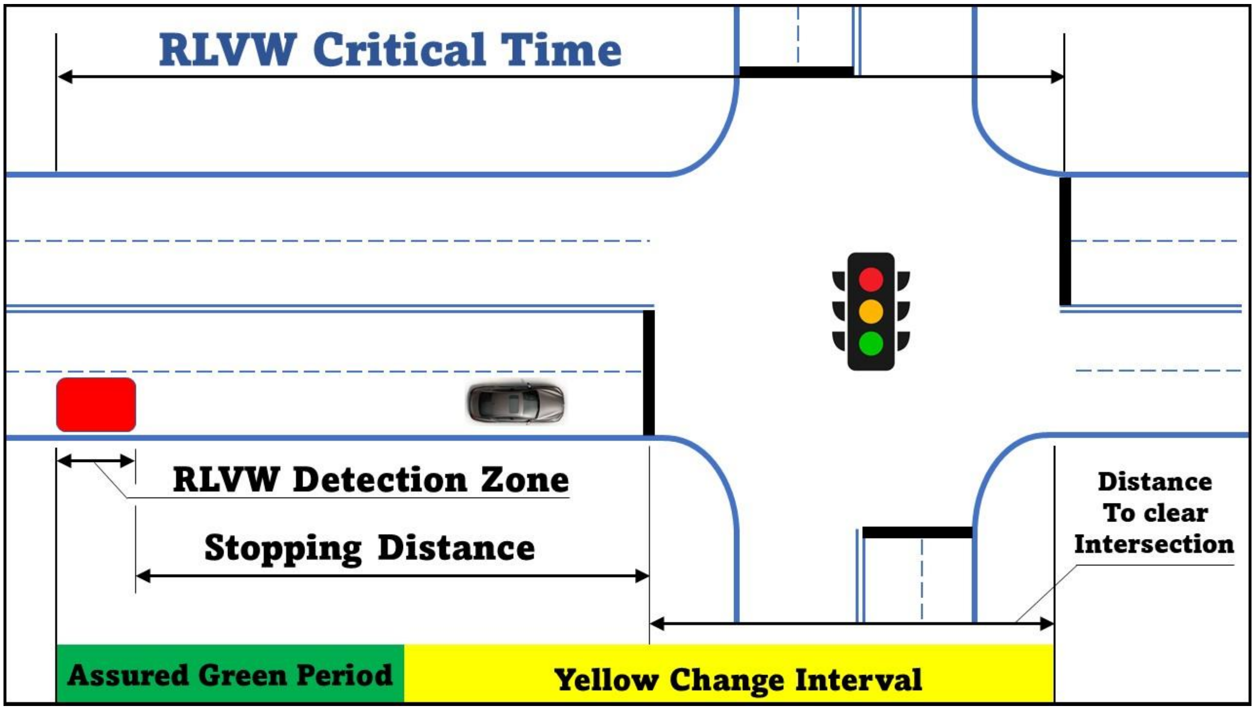


Figure 6-1 Case study signalized intersection for modeling RLVW application.

According to the discussion and the deliverable from the USDOT effort (*39*), a RLVW detection zone is an area on a through movement lane that the vehicle is to be detected by the RSE through vehicle-to-infrastructure communication to support the RLVW application. The detection zone location is set such that the distance from the stop line to the RLVW detection zone is equal to a full stopping distance. If the CI detects a vehicle in the RLVW detection zone, the associated movement is in green, and the signal controller is not terminating the movement, then the controller needs to set the minimum end time of the movement phase to the current time plus the AGP. If the CI determines that a movement currently in green is to terminate, the controller provides an assured green end time (AGET) that is equal to or greater than the minimum end time of the phase. The controller provision of the AGET allows the RLVW application on the OBE to receive accurate SPaT messages. Vehicles upstream of the detection zone will have enough time to stop before the stop line.

Figure 6-1 shows the distance required to bring a vehicle to a complete stop when detected in a RLVW detection zone and can be calculated from Equation (6-1).

$$S_d = V_{approach} t_{PR} + \frac{V_{stop}^2 - V_{approach}^2}{2 \times (a + 32.2 G_i)} \quad (6\text{-}1)$$

where,
S_d = stopping distance,
$V_{approach}$= approach speed (85th percentile speed),
V_{stop}= stopped vehicle speed or (zero miles per hour),
t_{PR}= perception reaction time,

a = deceleration rate of vehicles, and G_i = approach grade.

The time required to travel through the stopping distance and to clear the intersection can be calculated from Equations (6-2) and (6-3).

$$t_{sd} = \frac{S_d}{V_{approach}} \tag{6-2}$$

$$t_{clear} = \frac{S_{clear}}{V_{approach}} \tag{6-3}$$

where,
t_{sd} = time to traverse the stopping distance,
t_{clear} = time to clear the intersection,
S_{clear} = distance to clear the intersection.

The RLVW critical time required for the calculation of the AGP is the summation of time to traverse the stopping distance, time to clear the intersection, and the time required to traverse the detection zone as shown in Equation (6-4). Finally, the AGP can be calculated by subtracting the yellow interval from the RLVW critical time as shown in Equation (6-5).

$$t_{RLVW} = t_{sd} + t_{clear} + t_{RDZ} \tag{6-4}$$
$$\text{AGP} = t_{RLVW} - t_{yellow} \tag{6-5}$$

where,
t_{RLVW} = red-light violation warning critical time,
t_{RDZ} = time required to traverse the detection zone,
t_{yellow} = duration of the yellow interval,
AGP = assured green period.

6.2.2 Hardware-in-the-Loop Simulation Environment Setup

This section describes the methods used to build the simulation environment required for testing the CV-based RLVW algorithm in a HILS under actuated signal control operation. The physical traffic signal controller used in this study is Econolite Cobalt G-series with the EOS 140-1048-2CV firmware. The actuated controller model is based on the National Electrical Manufacturers Association (NEMA) standards for signal controllers (*51*). As previously mentioned, the communication between the traffic signal controller and the traffic simulation package can be done, either using a middleware interface or a hardware interface such as CID. In this study, middleware is used to eliminate some of the system hardware latencies reported in the literature as a result of using the CIDs (*45*). Figure 6-2 shows the system framework and data flow between different components of the utilized HILS platform.

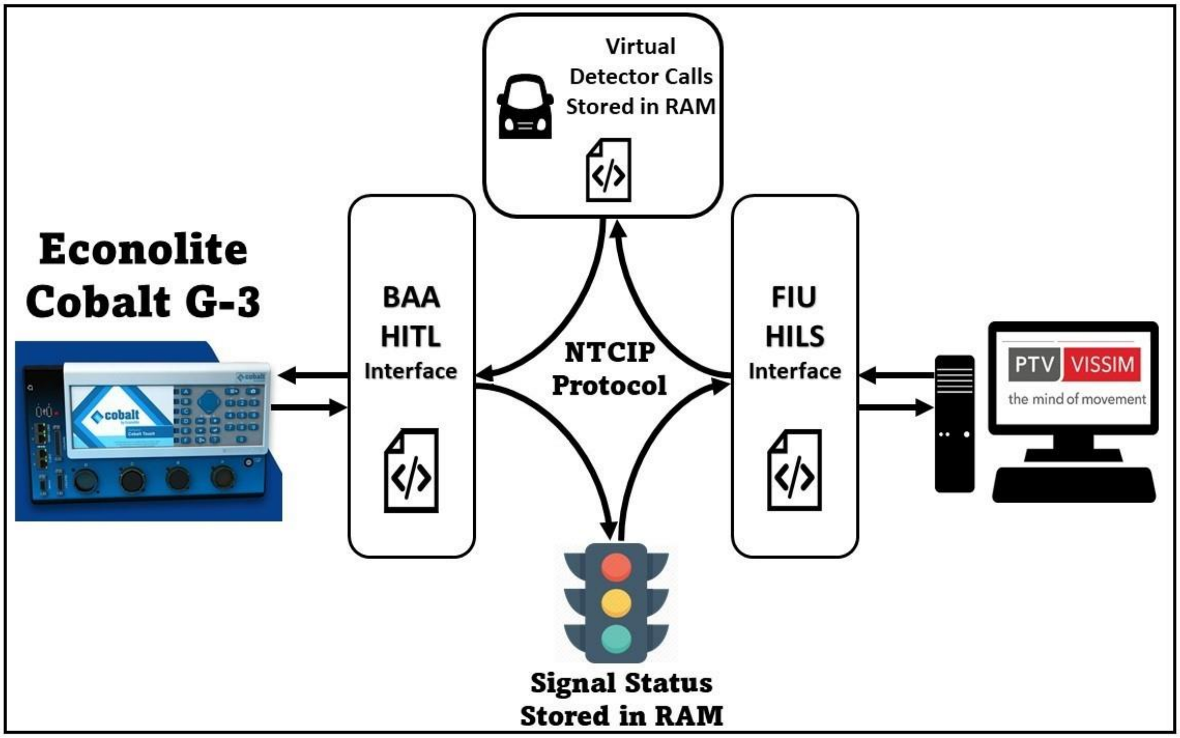


Figure 6-2 Data flow between the HILS hardware and software components

The developed middleware is based on the NTCIP communication standards and consists of two main programs. The first program is called BAA_HITL and was developed in a previous Federal Highway Administration (FHWA) project (*33*). The researchers in this study developed the second program, which is called FIU_HILS. This study integrated both programs in one compiled solution module using the C# programming language, as shown in Figure 6-2. The traffic signal controller is connected over the network with a fixed MAC address and IP address that are used to communicate with the BAA_HITL and FIU_HILS programs to receive detector calls from the simulation and to send signal phase states to the simulation.

VISSIM Version 20 is used in this system to generate virtual background traffic (*50*). An external signal controller module is developed using the signal controller Application Program Interface (SC-API) in the simulation tool. The simulation tool sends all detector data and virtual vehicle status data to the FIU_HILS interface, which then passes these data to the computer RAM. The BAA_HITL interface reads the detector calls from the RAM and sends these calls through SNMP commands (*52*) to the Econolite Cobalt G-series controller. Figure 6-3 shows the vehicle detector placement in the simulation model along with the full middleware interface and the log window of the system. Each detector is assigned a port number corresponding to a specific signal phase number that is called over the detector channel. The assignment gives odd numbers to the left-turn movements and even numbers to the through movements.

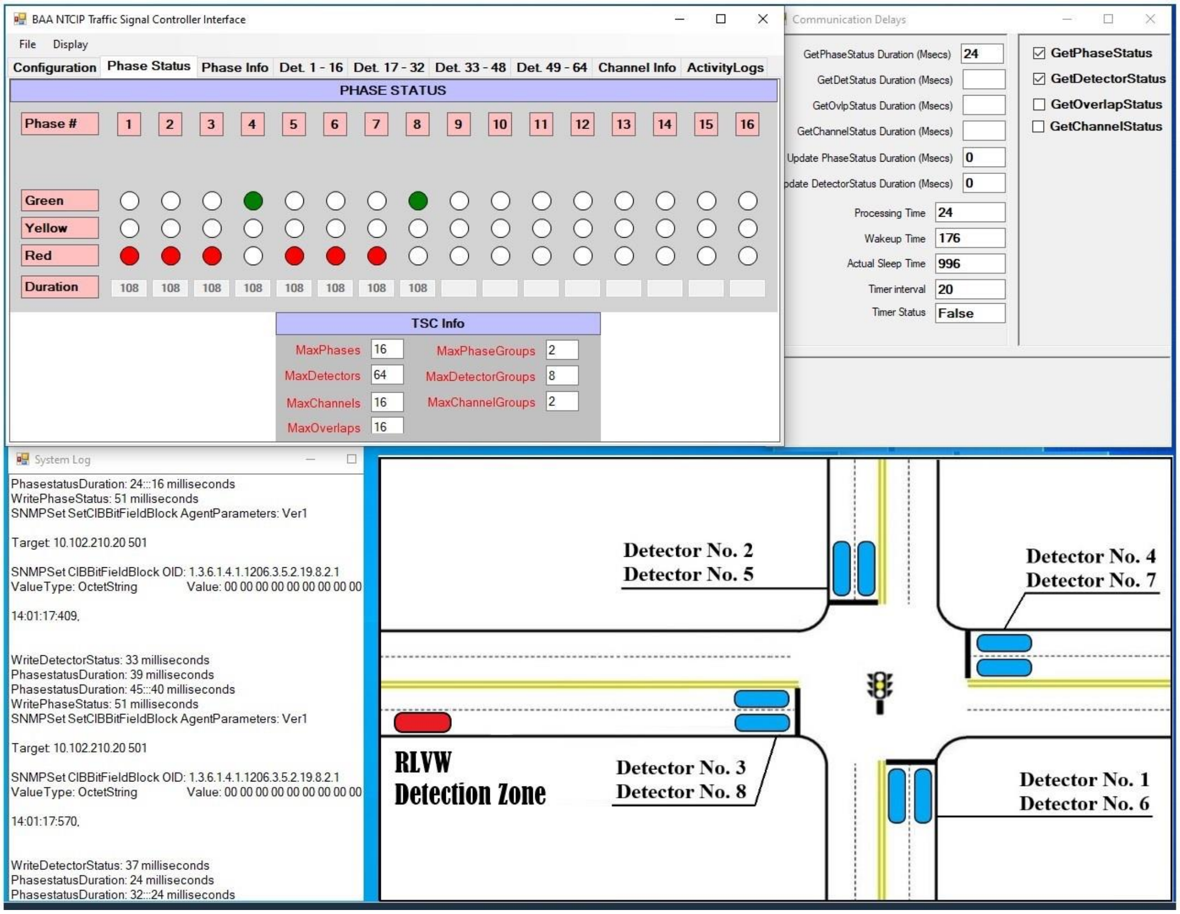


Figure 6-3 HILS middleware interface and detector setup

The actuated signal controller is programmed to rest-in-green on the major approach. This setup will force the green interval to serve the minor road only in the presence of a conflict call. It should be noted that at the time of writing this paper the EOS firmware 140-1048-2CV does not support the AGP. Thus, it was necessary to mimic the AGP in the simulation model in two main steps. First, a "dummy" detector is placed at the location of the RLVW detection zone as shown in Figure 6-3. The location of the RLVW detection zone is computed based on the 85th percentile speed of the subject approach. The dummy detector is responsible for detecting the approaching connected vehicles in the simulation and sending the information to the RSE to calculate the assured green extensions to the signal controller. This detector only detects the modeled CV vehicle class in the simulation model since conventional vehicles do not have access to the RLVW information and there is no need to provide the assured green period for these vehicles. When detecting a vehicle in the RLVW Detection Zone, the model used the "Vehicle Detector Extend Parameter" according to the NTCIP 1202 V03.26 standards to model the AGP. This parameter is the period a vehicle detector actuation is extended from the point of termination when the phase is Green.

6.2.3 CV-based RLVW Modeling and Network Calibration

The first step for simulating the CV-based RLVW algorithm is to calibrate the simulated signalized intersection to account for the real-world stopping probability distribution and to ensure that it better simulates the driving behaviors as they approach the signal on the yellow interval. The authors of this study (*53*) developed a methodology to calibrate and fine-tune simulation model parameters to replicate the real-world stopping probability at signalized intersections. This study utilized the results from that work in fine-tuning simulation model parameters. Below is a short description of the model calibration and the detailed methodology can be found in Hadi et al. (*53*).

This study fine-tunes the parameters of a built-in distribution in the VISSIM software for modeling the drivers' decision-making behavior at the onset of the yellow interval (*50*). This distribution is based on a logistic regression function that represents the drivers' stop probability. The function uses three parameters: Alpha (α), Beta1 (β_1), and Beta2 (β_2). The reaction-to-yellow of the drivers in the model is a function of the values of these three parameters along with the vehicle speed (v) and the distance to the stop line at the initiation of the yellow interval (dx). Equation (6-6) below shows the utilized probability function (p) as follows:

$$p = \frac{1}{1+e^{-\alpha-\beta_1 v-\beta_2 dx}} \quad (6\text{-}6)$$

where,
p = probability that a vehicle will stop at an amber light,
α, β_1, and β_2 = first, second, and third logistic coefficients, respectively.

As described by Hadi et al., (*53*) the three parameters in Equation (6-6) significantly influence the probability of a driver making a Stop or a Go decision, and subsequently the likelihood of violating a red-light indication. The researchers utilized a nonlinear optimization process to identify the optimal combination of the three parameters that best replicate the real-world drivers' behavior during the yellow interval. They found that the combination of $\alpha = 1.600$, $\beta 1 = -0.190$, and $\beta 2 = 0.043$ was able to reduce the Sum Square Error (SSE) from 9.75 at the first random iteration prior to optimization to 0.003 for the final optimal solution.

6.2.4 Investigation of RLVW Impacts and Performance

This study used the simulation model, calibrated as described above, to analyze the performance of the CV-based RLVW under actuated signal control operation. The NTCIP "Vehicle Detector Extend Parameter" was used, as described earlier, to model the provision of the AGP to support accurate SPaT messages for the RLVW application. Given that the signal controller is programmed to rest-in-green on the major movement (the main street through movement), there are two possible scenarios for the CV-based RLVW operation. The first scenario is when the phase of the major movement is in green, and there is no conflict call on the cross street (i.e., the signal controller is not terminating the major street phase). In this case, there will be no action required from the RSE. The second scenario is when having a conflict call on the cross street and the major movement currently in green is about to be terminated. In this case, the controller will place an assured green extension for CV RLVW-equipped vehicles that are detected in the RLVW detection zone.

CVs that receive and utilize the SPaT messages were coded as an additional vehicle class in the simulation model. The simulation is done with a varying RLVW utilization rate that is defined as the multiplication of the CV market penetration rate and the percentage of positive response to the

RLVW alerts among the CV drivers (*53*). The RLVW application on the OBE receives and utilizes SPaT messages with the AGP calculated and implemented by the RSE. It should be noted that the AGP is modeled assuming that the market penetration rate is equal to the utilization rate, meaning that all vehicles are assumed to utilize the provided RLVW. This assumption can obviously be varied depending on the purpose of the study.

As the simulated CV vehicle approaches the signalized intersection, it continuously obtains the current traffic signal status through SPaT messages, if they are within the communication range. If the CVs are detected in the RLVW detection zone, the controller will place an assured extension for the green time. This green extension when added to the yellow interval allows the vehicle to clear the intersection safely and eliminate the potential of running a red light. A C# program was written to send SNMP packets carrying the Vehicle Detector Extend Parameter to the controller in a tenth of seconds using the corresponding NTCIP object identifier (OID). In addition, if the remaining green time is less than the AGP or the current signal is yellow and it is determined that these vehicles cannot clear the intersection safely within the assured extended green time, the vehicle will receive a warning message indicating the potential of a red-light violation. The on-board application notifies the drivers when they need to decelerate to come to a complete stop and avoid a red-light violation.

The study developed an algorithm to analyze the vehicle trajectories output from the simulation models to count the number of vehicles that violate the red-light in the simulation. The variables of interest obtained from each simulation for use in the investigation include vehicle speed, the distance to stop line, and the remaining time to the end of the current signal state, which indicates how many seconds have passed during the current signal phase.

The benefits of the RLVW are assessed under actuated signal control in terms of safety and mobility. The safety performance measures of the RLVW are quantified based on the SSAM tool developed by the FHWA using the extracted vehicle trajectories from the simulation. The SSAM is a tool that estimates the safety of traffic facilities by analyzing the traffic conflicts which is then converted to Surrogate Safety Measures (SSM). This study utilizes the Time-To-Collision (TTC) and Post-Encroachment Time (PET), which are two surrogate measures defining the conflict between two vehicles using the specified threshold values. The threshold values of the TTC and PET used in the analysis are 1.5 seconds and 5.0 seconds, respectively, which are the default values in the SSAM.

6.3 RESULTS AND DISCUSSION

This section discusses the results of the evaluation of the impacts of the RLVW application under actuated signal operation based on delay and safety performance measures. Each data point reported from the simulation was the average of the outputs from ten simulation model runs, each with different seed numbers, to account for the stochasticity of the microscopic simulation model. The simulation was carried for 70 minutes (10 minutes of warm-up and 1 hour of evaluation time). For the modeled case study intersection, the maximum communication range was assumed to be 1,000 ft, according to the 5.9 GHz dedicated short-range communication (DSRC) operational concept and technology requirements. The broadcast reception range for an On-board Unit is typically 1,100 ft at a standard roadside unit (*54*). Please, note that the application may be implemented using C-V2X communication technology and the communication range can be updated based on the utilized communication technology capability. The perception-reaction time is assumed to be 1.5 seconds according to the standards of the AASHTO to allow 1.0 second for perception time and 0.5 second for reaction time.

Based on Equations (6-1) to (6-3) and utilizing the 85th percentile vehicle speeds the distance required for bringing vehicles to complete stop is 393.75 feet and the time required to clear the modeled intersection is 2.0 seconds. In addition, the time to travel through the stopping distance is 5.25 seconds. According to Equation (6-4), the results show that the RLVW critical time is 7.75 seconds. By subtracting the yellow interval from the RLVW critical time, the AGP is calculated to be 2.95 seconds to provide sufficient time for vehicles to cross the intersection safely without violating the red-light interval.

6.3.1 Mobility Measures

The mobility measures used in the evaluation include stopped delay, the number of stops, and the approach delay. The results in Table 6-1 shows that with increasing the CV utilization rate from 0% to 100%, the average stopped delay per vehicle increased from 20.01 seconds with 0% CV to 26.04 seconds (an increase of 30.14%) with 100% CV. In addition, the average number of stops per vehicle increased from 0.67 stops per vehicle to 0.79 stops per vehicle (an increase of 17.91%). Moreover, the approach delay per vehicle increased from 28.27 seconds to 34.42 seconds (an increase of 21.75%). This increase in delay and stops is directly attributable to the provision of AGP, as calculated in this study, and the assignment of additional green to the RLVW detected vehicles on the through movements of the main street. Please, note that the changes in delay and stops due to the implementation of the AGP are expected to be functions of the demands of various main street and cross street movements. The utilized demands in the case study are presented earlier in this paper. However, the impacts of different demands on the results are not explored in this study and could be explored in a future study.

Table 6-1 Impacts of Vehicle Detector Extend Parameter on Network Delay Measures

CV Utilization Rate (%)	Stopped Delay (sec/veh)	Average Number of Stops per vehicle	Approach Delay (sec/veh)
0%	20.01	0.67	28.27
10%	22.32	0.71	29.89
20%	22.17	0.72	29.84
30%	24.73	0.74	32.56
40%	22.80	0.71	30.46
50%	22.74	0.71	30.50
60%	23.22	0.75	31.31
70%	22.33	0.73	30.27
80%	24.07	0.75	31.79
90%	23.65	0.75	32.40
100%	26.04	0.79	34.42

6.3.2 RLVW Safety Measures Assessment

The utilized safety performance measures are the total number of red-light running events and safety surrogate measures produced by the SSAM tool. The utilized SSAM measures are related to the right-angle and the rear-end conflicts, which are the types of conflicts associated with RLR. In this study, the RLVW application is only evaluated for the through-movement vehicles on the main street. Figure 6-4 shows the total number of red-light running events with and without applying the AGP with RLVW utilization rates ranging from 0% to 100%. The results show that without utilizing the AGP, the total number of RLR decreased from 8.0 to 5.8 events per hour when the RLVW utilization rate increased from 0% to 100% providing only a 27% improvement in safety. The decrease in the RLR with the utilization rate increase was not continuous and fluctuated as the rate increased, as shown in Figure 6-4. On the other hand, the results with applying the AGP in Figure 6-4 showed a clear decreasing trend in the number of RLR events. The total number of RLR decreased from 8.3 to 0.7 events per hour with increasing the CV utilization rate from 0% to 100%. It can be inferred from Figure 6-4 that the AGP is able to assist the RLVW application under actuated signal control and reduce the red-light running events by approximately 92%.

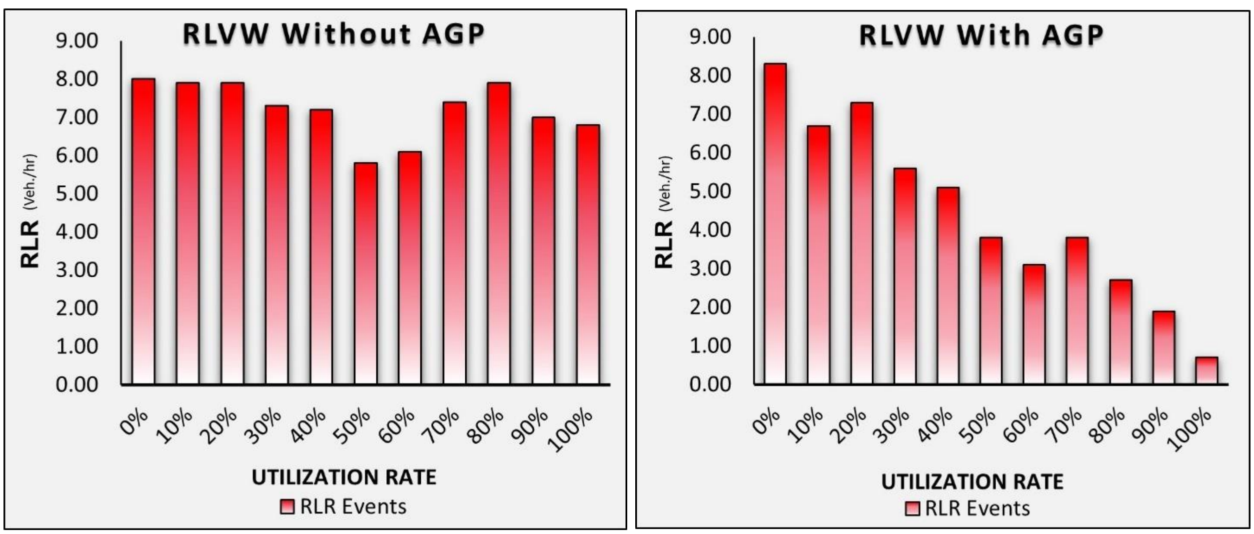


Figure 6-4 Impacts of the AGP on the number of Red-light running events

In terms of the surrogate safety measures obtained based on the SSAM assessment, Figure 6-5 shows the number of right-angle and rear-end conflicts with and without applying the AGP and with RLVW utilization rates ranging from 0% to 100%. The results show that without utilizing the AGP, the total number of right-angle conflicts fluctuates between 11.5 and 5.4 conflicts per hour when the RLVW utilization rate increased from 0% to 100%. However, with applying the AGP, there is a clear decreasing trend in the number of right-angle conflicts. The total number of right-angle conflicts decreased from 9.3 to 0.5 conflicts per hour with increasing the CV utilization rate from 0% to 100%.

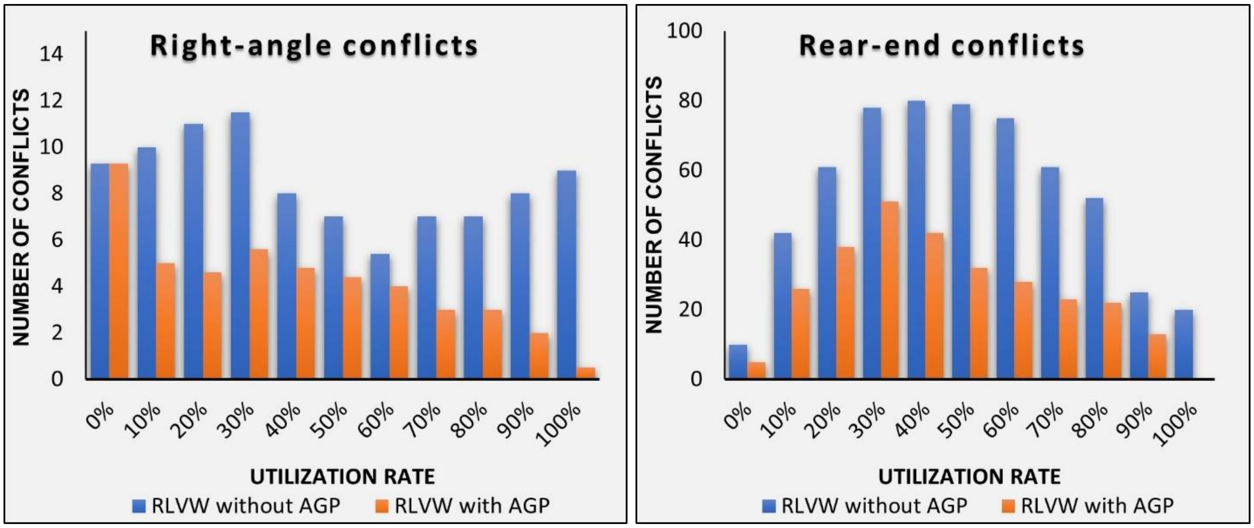


Figure 6-5 Surrogate safety assessment vs mobility benefits for the RLVW application

Regarding the rear-end conflicts, the results in Figure 6-5 showed that the number of conflicts increased with the increase in the RLVW utilization rate up to a utilization rate of 40%, reaching 80 conflicts per hour without utilizing the AGP and 42 conflicts per hour with utilizing the AGP. This is the result of the large probability of connected vehicles, being followed by conventional vehicles that do not have access to the RLVW information. At rates higher than 40%, there will be a higher chance of two or more connected vehicles following each other. Hence, the number of rear-end conflicts starts to decrease. As the utilization rate increases further, the rear-end conflicts continue to drop and decrease from 80 to 20 conflicts per hour with increasing the utilization rate of RLVW from 40% to 100%, without utilizing the AGP. While the rear-end conflicts decrease from 42 to zero conflicts per hour with increasing the utilization rate of RLVW from 40% to 100%, with utilizing the AGP.

6.4 CONCLUSIONS

This study investigated the use of CV-based RLVW in the presence of actuated traffic signal control operations. The main goal of this research is to quantify the safety and mobility impacts of CV-based RLVW, given the uncertainty in the end-of-green time under an actuated signal controller. The study investigated the provision of AGP, as a solution to mitigate this uncertainty.

By comparing the total number of RLR with and without applying the AGP for the case study intersection utilized in this paper, the results show that the total number of RLR fluctuates between 8.0 and 5.8 events per hour when increasing the RLVW utilization rate from 0% to 100% without AGP. On the other hand, the total number of RLR events decreased by approximately 92% when the RLVW utilization reaches 100% and with utilizing the AGP. The safety assessment based on surrogate safety measures shows that without utilizing the AGP, the total number of right-angle conflicts fluctuates between 11.5 and 5.4 conflicts per hour when increasing the RLVW utilization rate from 0% to 100%. However, with applying the AGP, there is a clear decreasing trend in the number of right-angle conflicts from 9.3 to 0.5 conflicts per hour with increasing the CV utilization rate from 0% to 100%. The rear-end conflicts decrease from 80 to 20 conflicts per hour with increasing the utilization rate of RLVW from 40% to 100%, without utilizing the AGP. The rear-end conflicts decrease from 42 to zero conflicts per hour with increasing the utilization rate of RLVW from 40% to 100%, with utilizing the AGP.

Based on the analysis in this study, it can be concluded that the AGP can improve the performance of the CV-based RLVW application. The combination of the CV-based RLVW application on the on-board equipment and the AGP on the actuated controller can reduce the overall intersection RLR by approximately 92% and improve the overall safety of the signalized intersection as measured by the RLR events, rear-end conflicts, and right-angle conflicts. However, the results showed that the application of the AGP, as applied and assessed in this paper, can increase stopped delay, number of stops, and approach delay. This issue will need to be further investigated to determine the optimal setting of the AGP considering both mobility and safety impacts.

7 INVESTIGATION OF ALTERNATIVE SIMULATION APPROACHES TO SUPPORT THE TESTING OF CV APPLICATIONS

Microscopic traffic simulation is widely used for simulating and testing emerging vehicle technologies in a risk-free controlled environment. Signal control and Connected Vehicle (CV) technologies and applications at signalized intersections can be simulated and tested using simulation platforms in three distinguishing approaches: Emulator-in-the-loop (EILS), Software-in-the-loop (SILS), and hardware-in-the-loop (HILS). Each of these approaches generates the traffic signal states in different mechanisms that might significantly impact the results from simulation models that rely heavily on the traffic signal controller operations.

EILS is the simplest method and the commonly used method for signal state generation both in practice and research. As an example, the simulation software packages such as PTV's Verkehr in Städten SIMulationsmodell (VISSIM) generates the signal state using the built-in Ring Barrier Controller (RBC) logic programmed (*50*). SILS represents the incorporation of the commercial traffic signal controller functionalities and parameters into a software that resides on the computer that hosts the simulation software, providing the same functionalities as a physical controller. HILS incorporates a physical traffic signal controller in the loop to be used for generating signal states during simulation.

In addition to the potential differences in traffic signal operations that can impact the results of the simulation model, the use of different approaches to emulate signal control can impact the assessment of CV-based applications at signalized intersections. HILS is ideal for testing Connected Vehicle-to-Infrastructure (V2I) safety and mobility applications at signalized intersections. This is because it provides the ability to test the interfaces between the traffic controllers and roadside unit (RSU) and between the RSU and the on-board unit (OBU) using interface standards such as the National Transportation Communications for Intelligent Transportation Systems Protocol (NTCIP) and the Society of Automotive Engineers (SAE) J2735 and J2945 standards. Such environment can also assist in examining the impacts of V2I applications and the parameters associated with these applications and the signal controller on traffic operation performance. For example, V2I traffic safety applications like red-light violation warning (RLVW) require the transmission of wireless messages from the RSU to the OBU that includes signal phase and timing (SPaT) information obtained through an interface between the RSU and the traffic signal controller. During the microscopic simulation of such applications, there is a potential for signal control differences that can affect the overall performance of the applications.

A previous effort examined the impact of using the EILS, SILS, and HILS approaches in the evaluation of traffic control (*45*). The researchers concluded that the HILS and the SILS were able to provide more consistent and realistic signal timings compared to the EILS, especially in the case of coordinated-actuated controller operations. However, for intersections with pre-timed signal control and isolated actuated control, the three methods provided similar results. In general, the SILS and the HILS were very similar when used in assessing the operational performance and results.

Researchers are using EILS, SILS, and HILS platforms to model CV applications and strategies (*30–33*, *55*), although most research and industry projects use EILS. It is still not clear to what extent the utilization of different approaches to emulate signal control can affect the assessment of the performance of CV applications using simulation. With this recognition, the main goal of this study is to perform a cross-evaluation between the use of the aforementioned approaches in simulating signal control to quantify the impacts on the results of the assessment of RLVW, as an example of CV-based applications under two different modes of signal control (i.e., pre-timed and actuated control). This evaluation will answer the question of whether the simulation of identical signalized intersections with identical signal timing plans and traffic flow would generate similar results when assessing the RLVW application algorithm with EILS, SILS, and HILS in terms of the number of red-light running and the overall safety of the intersection.

7.1 LITERATURE REVIEW

The review of literature in this section is divided into three subsections: a review of the state-of-the-art HILS models and platforms, studies related to testing and evaluation of SILS methods, and a review of studies that used or investigated combinations of EILS, SILS, and HILS platforms.

7.1.1 Hardware-in-the-Loop Simulation

HILS integrates traffic simulation software and a physical traffic signal controller. In this environment, the physical external signal controller replaces the EILS, which is the internal controller emulation in the simulation software. With the HILS, the simulation software generates virtual detector data and sends the information to the signal controller, which generates signal states and sends them back to the simulation model. The HILS platforms set the signal controller to react to the virtual detector calls as if they were coming from real-world detectors.

The communication between the traffic signal controller and the traffic simulation package can be done either using a middleware interface or a hardware interface. The middleware is an interface that acts as a bridge between the traffic signal controller and the simulation platform based on the NTCIP standards. This communication can be achieved by developing programs that send and receive Simple Network Management Protocol (SNMP) requests (*33*). The hardware interface is referred to as Controller Interface Device (CID). CID is a device that connects the traffic signal controllers and the simulation software by transferring the discrete logic levels of the control pins on the traffic signal controller to the microscopic simulation model (*56*). The controller receives the virtual detector calls from the simulation every simulation time step, generates the signal status, and sends the signal state back to the simulation software through the CID.

Ma et al. (*35*) developed a HILS proof-of-concept platform for use in testing the CV-based Cooperative Adaptive Cruise Control (CACC) application. The researchers proposed a HILS testing architecture for the CACC application. The HILS system includes a physical CAV, field test track, CV equipment, and microscopic simulation tool. The platform was used to test and quantify the potential benefits of a CAV queue-aware signalized intersection approach and departure (Q-SIAD) application. The Q-SIAD algorithm combines the signal phase and timing (SPaT), downstream queue length, vehicle's acceleration/deceleration, and the status of other vehicles to generate recommended speed profiles.

Szendrei et al. (*32*) developed a HILS platform for testing CV applications. The platform consists of an open-simulation software, which is the Simulation of Urban Mobility (SUMO) software; an orchestrator, which manages all elements of the HILS system components, and commercial CV devices. The researchers reported that the proposed HILS framework offered a cost-efficient tool for testing and evaluating CV-based applications in a laboratory environment.

7.1.2 Software-in-the-Loop Simulation

SILS represents the integration of traffic simulation with a commercial traffic signal controller's software. The SILS platforms support complex signal timing settings and advanced controller parameters available in real-world controllers that are not supported by EILS (*57*). For example, one of the commercially available SILS in the VISSIM simulation tool is the ASC/3 controller software developed by Econolite. The ASC/3 controller consists of a Data Manager, Traffic Control Kernel, Controller Front Panel Simulator, and Dynamic Link Library (DLL) interface. The controller software provided in this environment has a total of 200 logic commands that can be utilized in traffic signal operations in the simulation model (*58*). The Data Manager is a graphical interface that is used to input the controller data (e.g., timing plans, detectors data) and store this data in database files. The Traffic Control Kernel is the virtual controller core software that includes all the internal data inputs processing and guarantees consistency in signal control operation between the simulated SILS running in simulation and a physical signal controller. The Controller Front Panel Simulator is a Graphical User Interface (GUI) designed to replicate the controller physical display and keypad. The DLL interface enables the simulation model to receive the controller status information and pass the detector information to the simulated controllers (*57*).

Zlatkovic et al. (*59*) examined the operational implementation for transit signal priority (TSP) strategies using SILS. The authors compared the results from the simulation to the existing conditions and reported that the SILS is a powerful platform to analyze different aspects of TSP. He et al. (*60*) utilized the VISSIM ASC/3 Econolite SILS platform to evaluate the benefits of platoon-based multimodal signal control. The authors reported that the SILS can simulate the actual controller logic for actuated coordinated signals and TSP. Day and Bullock (*61*) investigated the impacts of fixed and floating force-off parameters in signal controller settings using a SILS platform. The authors reported that the SILS can produce controller logic that is close to real-world traffic signal operations.

7.1.3 Combined EILS, SILS, and HILS Evaluation

The major advantages of the EILS simulation platform include the ease in programming signal timing plans, higher simulation speed, and perfect synchronization between the traffic simulation model and the emulator (*45*). However, one of the major disadvantages is that the EILS platform lacks most of the advanced traffic signal controller parameters, especially in actuated control operation. Klanac (*62*) modeled six coordinated traffic signal controllers using a HILS environment integrated with the VISSIM simulation using CIDs for information exchange. Two testing scenarios were performed; the first scenario included twelve RBC-controlled intersections (which is the EILS in the VISSIM software), while the second scenario included a combination of six RBC-controlled intersections and 6 HILS intersections. The study conducted a comparative analysis between the coordination of signalized intersections controlled by the RBC virtual controller and the coordination of signalized intersections controlled using a HILS controller configuration. The study results showed a significant difference between the outcomes of the two modeling methods.

Chowdhury et al. (*56*) evaluated the performance of EILS, SILS, and HILS in modeling traffic signal operations in a basic actuated mode for an isolated signalized intersection in VISSIM. The authors extracted several sets of traffic and signal performance measures. The study concluded that there were significant differences in the results between the examined SILS and HILS platforms. The results showed that these differences are large enough to have a significant impact on the final model outcomes. The authors reported that these differences are caused by communication delays and the differences that exist in the internal controller logic. In addition, the authors reported that the inconsistent initialization of each signal controller in the simulation environment introduces some differences in the results.

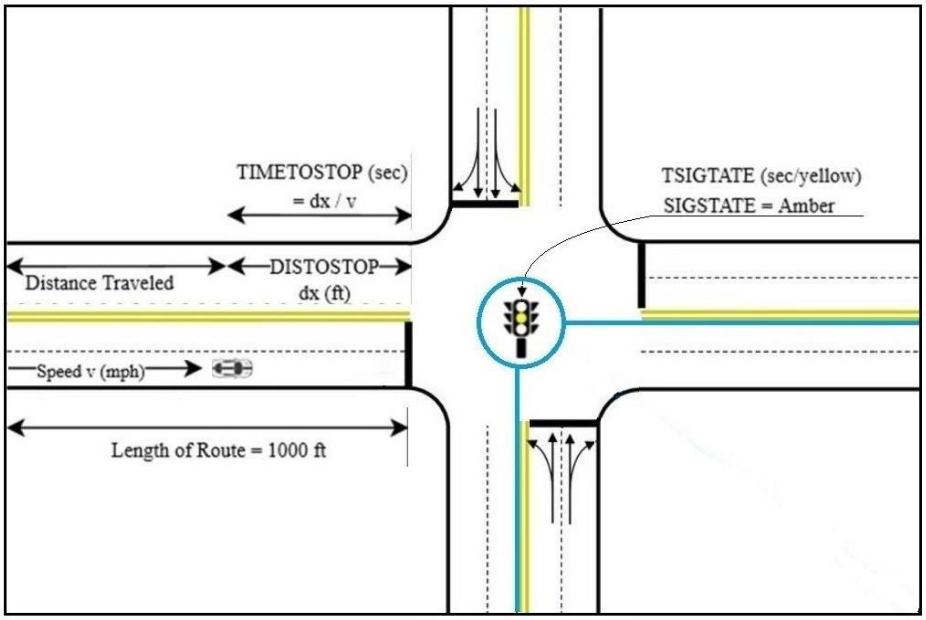
7.2 METHODOLOGY

This section describes the detailed methods used to build the simulation environment required for testing the CV-based RLVW algorithm in the EILS, SILS, and HILS. VISSIM Version 20 (*50*) is used as the microscopic simulation tool to model a test network and to assess the impacts of the simulation platform on the performance of the CV-based RLVW application.

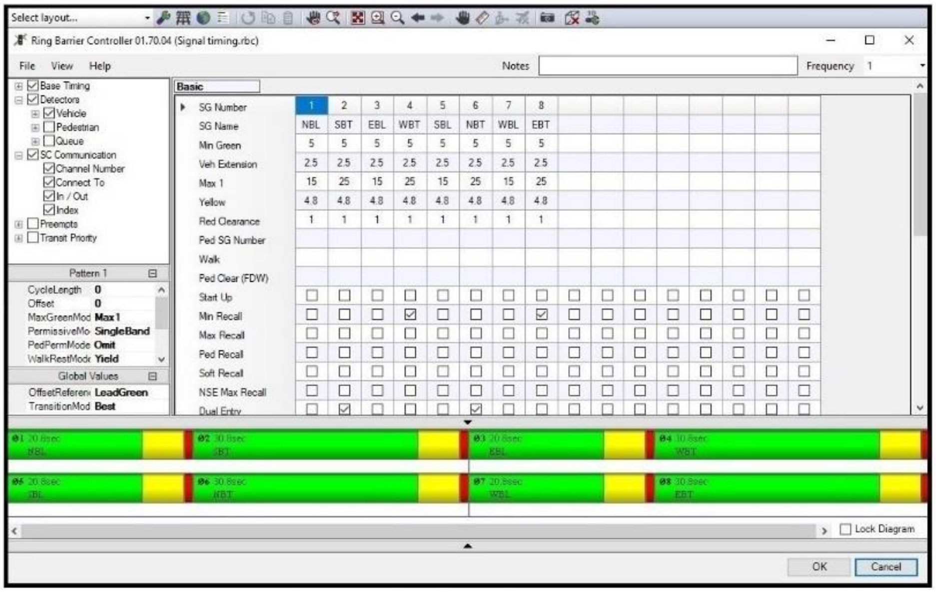
7.2.1 Case Study Network and Simulation Platforms

This study modeled the signalized intersection shown in Figure 7-1 and Figure 7-2 with the exact same conditions and signal controller parameters in the three tested simulation platforms (i.e., EILS, SILS, and HILS).

The signal controller parameters in the three platforms were identical including the phase regime (which is the NEMA 8-phase regime), phase sequence, phase minimum recall, dual entries, and signal timing plans. In addition, the geometry and traffic-related parameters in the utilized models were set at the same values including those for traffic volumes, desired speed distributions, headways, driving behavior, geometry, etc.

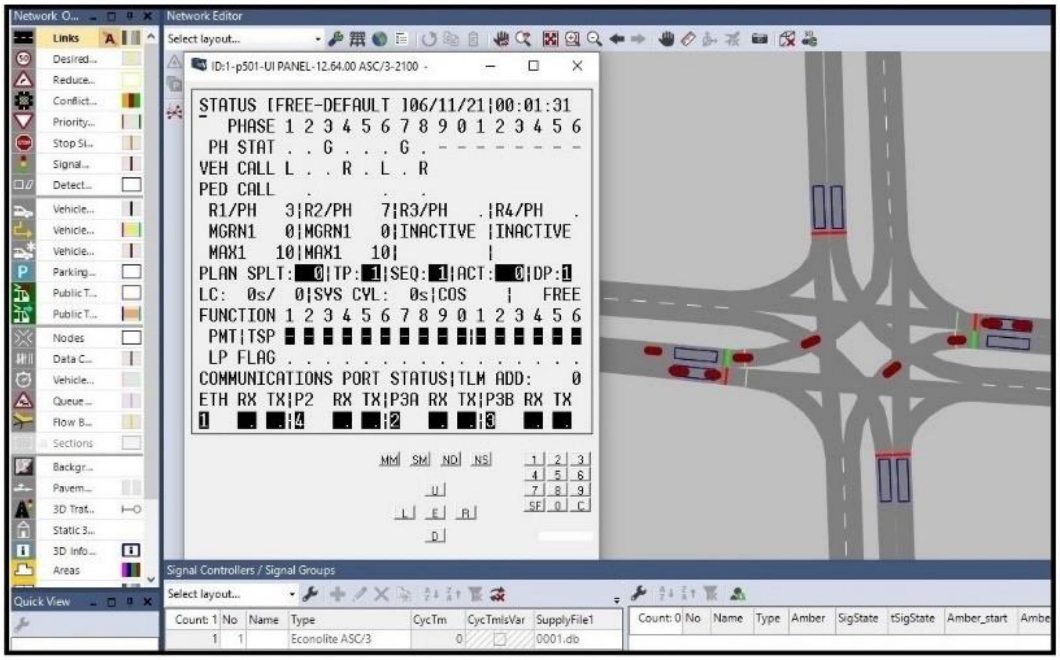


a) Modeled Signalized Intersection



b) Emulator-in-the-loop Simulation

Figure 7-1 (a-b) Case study network and major components of EILS Platform



a) Software-in-the-loop Simulation

b) Hardware-in-the-loop Simulation platform

Figure 7-2 (a-b) SILS and HILS platforms

Various sets of signal timing measures of effectiveness (MOEs) and RLVW safety performance measures are extracted from the output files produced by the simulation tool. The signal timing measures utilized in the comparison include the average green times and the total number of occurrences of each actuated phase. The RLVW safety performance measures include the number of red-light running (RLR), the number of right-angle conflicts, and the number of rear-end conflicts. In addition, the communication latencies between the signal controller and the detector actuations are quantified in the SILS and HILS platforms.

The actuated controller features such as minimum green time, maximum green time, yellow intervals, all-red intervals, and passage time are designed according to Transportation Research Board Traffic Signal Timing Manual (*49*). The minimum green is designed to provide enough time to clear all the vehicles that actuated the detector during yellow and all-red intervals.

7.2.2 EILS and SILS Platforms Setup

As stated earlier, the utilized simulation tool has a built-in RBC logic that is capable of replicating the NEMA standards for actuated traffic signal controllers (*50*). For each simulation time step, the traffic simulator sends the virtual detector calls to the internal emulator which returns the signal state for the next time step. In this study, the RBC editor Graphical User Interface (GUI) is used to input the signal timing plans according to a NEMA eight-phase setting and to set up the detector's assignment for each signal group.

The SILS platform used in this study consists of a traffic simulator model, an Econolite ASC/3 virtual controller supported by the utilized simulation tool, and a graphical interface that allows for exchanging the information and data entries between the traffic simulation model and the ASC/3 controller. In each time step, the traffic simulation model constantly updates the location of the vehicles in the network and the status of the detectors (i.e., ON/OFF), according to the vehicle actuation/presence. Accordingly, the vehicle detector calls are transferred to the ASC/3 virtual controller logic, which sends back the signal state to the modeled signal heads based on the predefined actuated signal timing parameters.

7.2.3 HILS Platform Setup

The physical traffic signal controller used in this study is Econolite Cobalt G-series supporting the EOS firmware 140-1048-2CV as shown in Figure 7-3. As previously mentioned, the communication between the traffic signal controller and the traffic simulation package can be done, either using a middleware interface or a hardware interface such as CID. In this study, middleware is used to eliminate some of the system hardware latencies reported in the literature as a result of using CIDs (*45*).

The CID introduces different types of delays associated with signal conversion, CID interface software, signal propagation, and signal transmission. The propagation delay is defined as the data packet travel time required between one point and another via the CID USB cable to the traffic controller. The transmission delay is defined as the delay attributed to the size of the data packet. The CID signal processing delay is the time required by the CID to convert data from analog to digital or vice versa (*45*). The utilized middleware in this study eliminates the propagation delay of CIDs because it uses the computer Random Access Memory (RAM) in transferring the data. Cunningham (*63*) reported that transferring internal data over the RAM is 10 times faster than using USB ports. For example, modern DDR4 RAM provides peak data transfer rate of around 25,600 megabytes per second MB/s (25.6 gigabytes GB/s) while the USB ports provide a maximum data transfer rate of 2,500 MB/s (2.5 GB/s) (*63*). The communication is done over stable Ethernet cables and network adapters, which reduce the data transfer limitations of the USB port in a CID.

The utilized middleware uses the NTCIP communication standards and consists of two main programs. The first program is called BAA_HITL and was developed in a previous Federal Highway Administration (FHWA) project (*35*). The researchers in this study developed the second program, which is called FIU_HILS. This study integrated both programs in one compiled solution module using the C# programming language as shown in Figure 7-3. The traffic signal controller is connected over the network with a MAC address and static IP address. The IP address is used to communicate with the BAA_HITL and FIU_HILS programs to receive detector calls from the simulation and to send signal control commands to the simulation.

Figure 7-3 shows the system framework and data flow between different components of the utilized HILS platform. The microscopic simulation model is used to generate virtual background traffic. An external signal controller module is written using the signal controller Application Program Interface (SC-API) in the simulation tool. The simulation tool sends all detector data and virtual vehicle status data to the FIU_HILS interface, which then passes these data to the computer RAM. The BAA_HITL interface reads the detector calls from the RAM and sends these calls through SNMP commands to the Econolite Cobalt G-series controller.

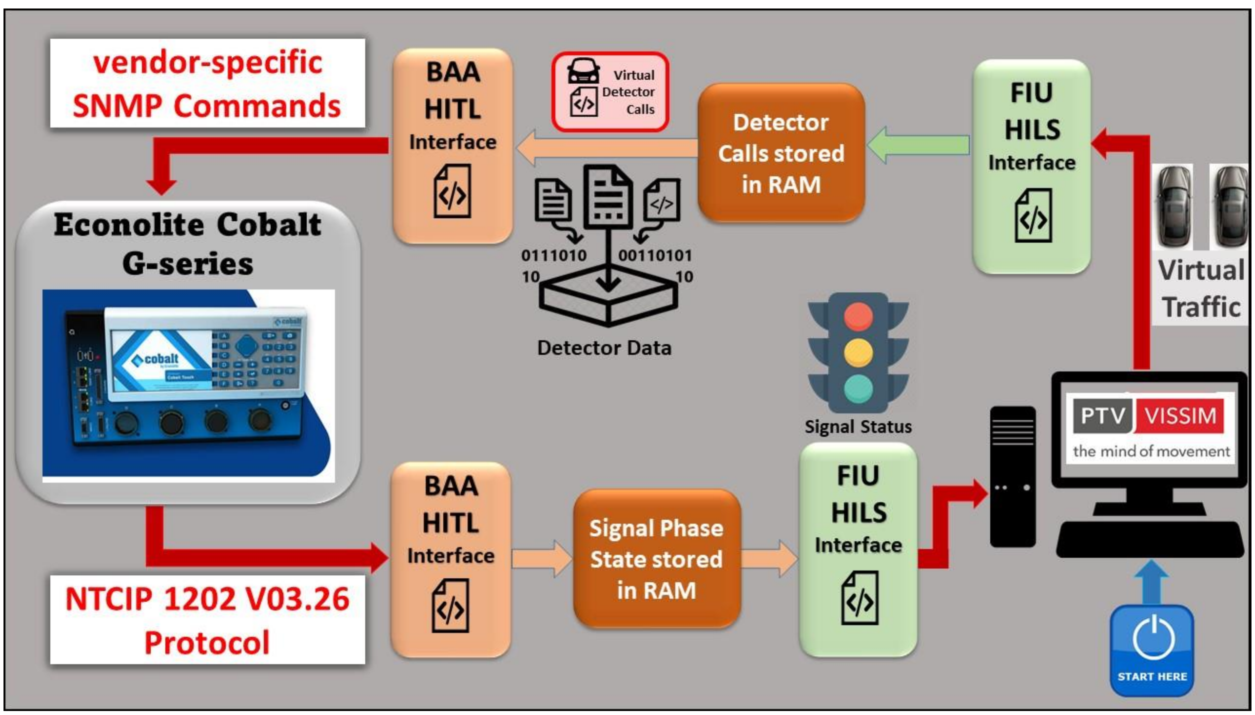


Figure 7-3 Data flow between the HILS hardware and software components

It should be noted that at the time of writing this paper the Cobalt controller does not support the extended vehicle detector object identifiers (OIDs) in the NTCIP 1202 version V03.26 standards.

In order to overcome this challenge, this study implemented a set of vendor-specific SNMP commands provided by Econolite to support the vehicle detector actuations. Accordingly, the physical controller generates the corresponding phase status based on the received detector calls and sends the phase status back to the RAM through the BAA_HITL interface. Then, the FIU_HILS interface uses the Component Object Model (COM) to enable the virtual signal heads in the simulation tool to be synchronized with the phase status of the physical traffic signal controllers in real-time. Figure 7-4 shows the vehicle detector placement in the simulation model along with the middleware interface and the log window of the communication delay.

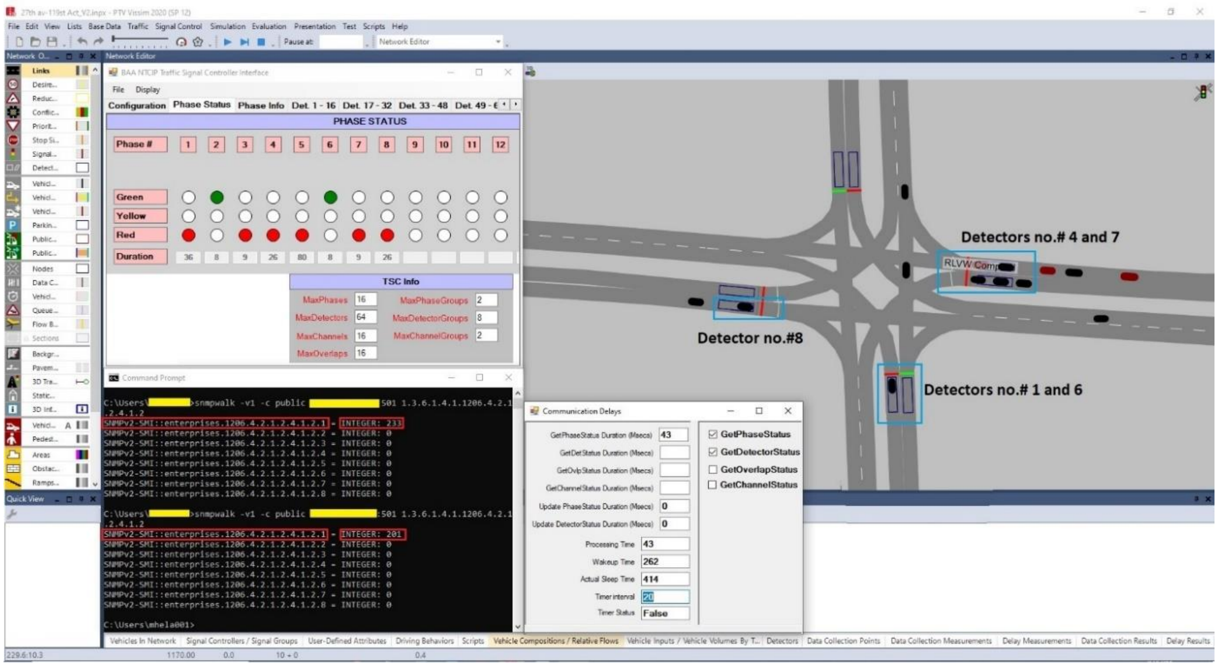


Figure 7-4 HILS middleware and SNMPWALK queries

7.2.4 CV-based RLVW Modeling and Network Calibration

The first step for simulating the CV-based RLVW algorithm is to calibrate the simulated signalized intersection to account for the real-world stopping probability distribution and to ensure that it better replicates the behaviors of drivers as they approach the signal on the yellow interval. The authors of this study developed a methodology to calibrate and fine-tune the simulation model parameters to replicate the real-world stopping probability at signalized intersections (*53*). This study utilized the results from that work in fine-tuning the simulation model parameters. Below is a short summary of the model calibration and the detailed methodology can be found in Hadi et al. (*53*).

This study fine-tuned the parameters of a built-in distribution in the VISSIM software for modeling the drivers' decision-making behavior at the onset of the yellow interval (*50*). This distribution is based on a logistic regression function that represents the drivers' stop probability. The function uses three parameters: Alpha (α), Beta1 (β_1), and Beta2 (β_2). The reaction-to-yellow of the drivers in the model is a function of these three parameters along with the vehicle speed (v) and the distance to the stop line at the initiation of the yellow interval (dx). Equation 7-1 below shows the utilized probability function (p) as follows:

$$p = \frac{1}{1+e^{-\alpha-\beta_1 v-\beta_2 dx}} \quad (7\text{-}1)$$

where,
p = probability that a vehicle will stop at a yellow light,
α, β_1, and β_2 = first, second, and third logistic coefficients, respectively.

As described by Hadi et al., (*53*)the three parameters in Equation 7-1 significantly influence the probability of a driver making a Stop or a Go decision, and subsequently the likelihood of violating a red-light indication. The researchers utilized a nonlinear optimization process to identify the optimal combination of the three parameters that best replicate the real-world drivers' behavior during the yellow interval. They found that the combination of α = 1.600, β1 = -0.190, and β2 = 0.043 was able to reduce the Sum Square Error (SSE) from 9.75 at the first random iteration to 0.003 at the optimal iteration.

7.2.5 Investigation of RLVW Impacts and Performance

This study used the simulation model, calibrated as described above, to analyze the impact of the three investigated platforms (i.e., EILS, SILS, and HILS) on the performance of the CV-based RLVW. The simulation is done with a varying RLVW utilization rate. The utilization rate is defined as the multiplication of the CV market penetration rate and the percentage of positive responses to the RLVW alerts among the CV drivers (*20*).

This study utilized the RLVW application algorithm adopted from Hadi et al. (*53*) and incorporated the algorithm in VISSIM using the COM Interface with Python computer programming. As the simulated CV approaches the signalized intersection, it continuously obtains the current traffic signal status through SPaT messages, if they are within the communication range. If the remaining green time is less than 5 seconds or the current signal is yellow, the algorithm checks whether the vehicle is within the pre-defined communication range. If so, the distance and time interval to reach the stop bar and the speed of the vehicle are measured. If the approaching vehicle is caught in the dilemma zone, and the vehicle is expected to run the red-light based on the current vehicle data, the vehicle receives a warning message indicating the potential of a red-light violation. The drivers' reaction time to the warning message is assumed to be about the same as the reaction of the driver to yellow indications at signalized intersections, which is estimated as 1-second on average. The algorithm then continues obtaining, refreshing, and using SPaT data continuously with a frequency of 10 times per second. The detailed flowchart of the RLVW algorithm sequence can be found in Hadi et al., (*53*).

The study developed an algorithm to analyze the vehicle trajectories output from the simulation models to count the number of vehicles that violated the red-light in the simulation. The variables of interest obtained from each simulation for use in the investigation include vehicle speed, distance to stop line, time of signal state, and current signal phase. The time to signal state indicates how many seconds have passed during the current signal phase.

The implications of the utilized simulation platform on the performance of the RLVW were assessed in terms of the impact on the results of the safety evaluation of the modeled signalized intersection. The impact of RLVW on safety was assessed using the Surrogate Safety Assessment Model (SSAM) developed by the FHWA based on the extracted vehicle trajectories from the simulation (*36*). The SSAM is a tool that estimates the safety of traffic facilities by analyzing the traffic conflicts which is then converted to Surrogate Safety Measures (SSM). This study utilizes the Time-To-Collision (TTC) and Post-Encroachment Time (PET), which are two surrogate measures defining the conflict between two vehicles using assigned threshold values. The threshold values of the TTC and PET used in the analysis are 1.5 seconds and 5.0 seconds, respectively, which are the default values in the SSAM tool to estimate the number of conflicts with CV-based RLVW in the simulation model.

7.3 RESULTS AND DISCUSSION

A four-legged intersection with eight movements and moderate traffic demand is modeled as shown in Figure 7-4. All the simulation runs were executed with 10 different random seed numbers to account for the simulation model stochasticity. The simulation resolution was 10 steps/second (100-millisecond). The simulation period was set at 70 minutes (10 minutes of warm-up and 1 hour of evaluation time). This section describes the results of the assessment of the RLVW to test the consistency of the EILS, SILS, and HILS environments and the implications on the assessment of the modeled CV-based RLVW application. The assessment is done based on communication delay, signal timing measures, and safety performance measures.

7.3.1 Communication Delay and Latencies

The results obtained for the case study of this paper reveal some of the operational differences due to using different signal controller methods in the simulation. For the EILS platform, at each simulation time step, the traffic simulator sends the virtual detector calls to the internal emulator, which returns the signal state for the next time step, almost in the same moment. Meaning, there is no communication latency between the RBC emulator and the traffic simulator. On the other hand, the SILS and HILS simulation platforms involve additional latency for transferring the information. The SILS includes a virtual Traffic Control Kernel along with the Dynamic Link Library that is responsible for sending the detector calls to the simulated ASC/3 controllers and receiving back the signal status information. The HILS integrates a physical traffic signal controller that receives the virtual detector calls from the simulation and sends back the signal states through the utilized middleware. The communication mechanism between the controller and the simulator in both the SILS and the HILS platforms introduces delay and latency in transferring the information.

To further confirm, the communication delay is measured in milliseconds (Msec) and quantified for both SILS and HILS platforms using two measures: "Get Phase Status Duration" and "Processing Time". The Get Phase Status Duration is defined as the time required by the middleware to read the signal state from the traffic signal controller. The Processing Time is defined as the time required by the middleware for processing the signal state and the detector status (i.e., GET/SET and update). Both measures are quantified in the HILS platform using the communication delay log files generated by the middleware. Another C# program is written to collect the same information and measure the latency in the ASC/3 controller in the SILS platform.

For analysis purposes, a total of 1050 events of Get Phase Status Durations and Processing Times are collected for the SILS and HILS platforms to compare the latencies introduced in these two platforms. The results show that the average time intervals that are required to read the signal state from the ASC/3 controller in the SILS platform and from the Cobalt G-series controller are 30 milliseconds and 29.11 milliseconds, respectively. In addition, the average time intervals that are required for processing the detector information to the ASC/3 controller and to the Cobalt G-series controller are 506.64 milliseconds and 516.49 milliseconds, respectively. The average communication delays and latencies in transferring the information between the signal controller and the detector actuations in the SILS and HILS platforms are quite similar on average.

7.3.2 Signal Timing Measures of Effectiveness

The signal timing measures are the second category of measures investigated in this paper to test the consistency of the phase calls/actuations across the EILS, SILS, and HILS platforms. Figure 7-5 indicates that the EILS provides different results compared to the SILS and the HILS, but the SILS and HILS provide similar results. The average green times for all signal groups in the EILS are higher than those in the SILS and HILS. In addition, the average numbers of occurrences of the phases for all signal groups in the EILS are lower than those in the SILS and HILS. These two observations are related in that the provision of more green time per phase in the EILS increases the probability of skipping phases thus reducing the number of phase occurrences. The lower latency in detecting the vehicles by the control system in the ELIS increases the probability of extending the green for a detected vehicle compared to the SILS and HLIS.

The almost immediate controller/simulator communication in the EILS platform allows a higher number of vehicles to place and extend the detector calls in a phase, resulting in longer green intervals and fewer phase repetitions. On the other hand, the communication delays introduced in the SILS, and HILS may result in more vehicles not being served in the same phase as they arrive. This latency leads to shorter green intervals and a higher number of phase occurrences.

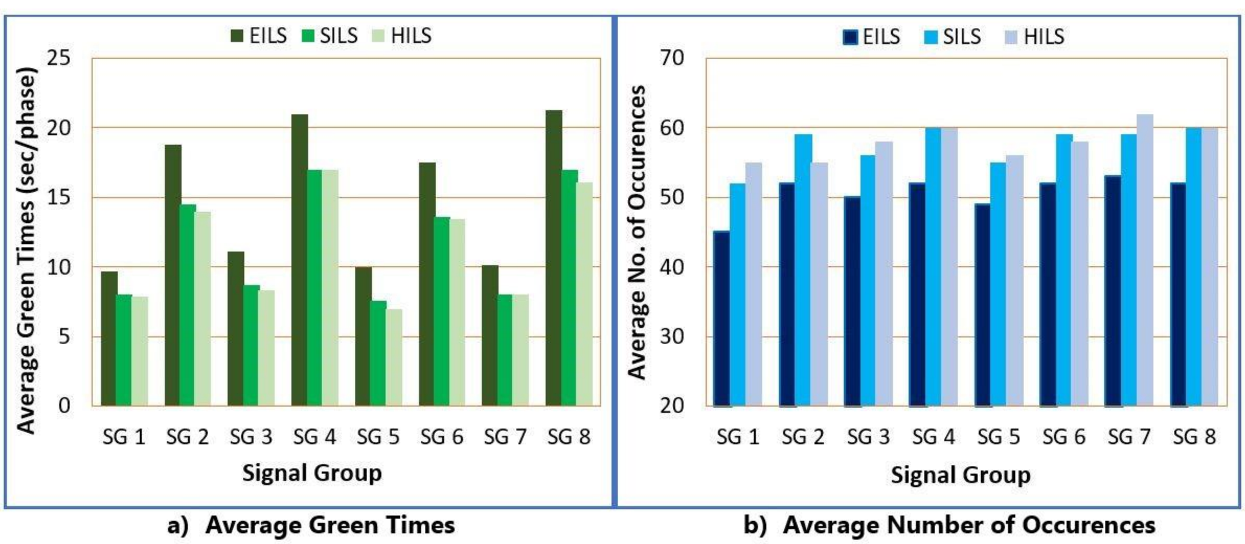


Figure 7-5 Signal timing MOEs results

7.3.3 Safety Enhancement Assessment

This study evaluated the impact of using the three different simulation platforms and methods of modeling traffic signal control on the assessed safety enhancement due to the RLVW application. The utilized SSAM measures in the assessment are related to the right-angle conflicts and rear-end conflicts, which are the main types of conflicts associated with RLR. This evaluation was done only for the through-movements on the main street. The evaluation of the safety benefits of the RLVW application uses the average of the outputs from ten simulation model runs, each with different seed numbers, to account for the stochasticity of the microscopic simulation model. The CV-based RLVW application was tested under pre-timed signal control operation and actuated signal control operation. Table 7-1 shows the impacts of the examined simulation platform on the safety performance of the RLVW application in the case of pre-timed signal control in terms of the number of red-light running and the total number of conflicts. The results show that for pre-timed signal operation, the utilized simulation platform does not have a significant impact on the modeled CV-based RLVW application. For example, the differences between the maximum and minimum numbers of RLR ranged from 0.3 to 1.7 RLR per hour. In addition, the differences between the maximum and minimum values for the right-angle conflicts ranged from 0.6 to 1.8 conflicts per hour. Moreover, the differences between the maximum and minimum values for the rear-end conflicts ranged from 2 to 7 conflicts per hour. In general, at utilization rates below 30%, the results showed that the number of conflicts increases as the RLVW utilization rate increases with pre-timed control. This is the result of the large probability of connected vehicles, being followed by conventional vehicles that do not have access to the RLVW information. At rates higher than 30%, there will be a higher chance of two or more connected vehicles following each other and the number of conflicts starts to decrease further to reach one conflict per hour for the EILS and HILS, and three conflicts per hour for the SILS at 100% utilization. The inconsistent initialization of the signal controller in the three platforms, as previously reported in the review of literature, might be the reason for introducing the minor differences in the results mentioned above.

Table 7-1 Impacts of Simulation Platform on RLVW Under Pre-timed Signal Control.

Pre-timed Signal Control									
UR	**EILS**			**SILS**			**HILS**		
	RLR	**SSAM Conflicts**		**RLR**	**SSAM Conflicts**		**RLR**	**SSAM Conflicts**	
		Right angle	Rear-end		Right angle	Rear-end		Right angle	Rear-end
0%	6.7	5.1	10	7.0	4.4	8	6.0	3.8	8
10%	7.1	5.4	40	6.7	5.0	38	5.0	6.0	39
20%	6.3	5.3	60	6.0	4.6	68	6.0	5.0	54
30%	5.6	6.8	64	5.6	5.6	68	5.0	4.5	65
40%	4.3	6.0	61	3.5	4.8	60	3.0	4.5	62
50%	3.6	4.8	60	2.6	4.4	60	2.0	4.0	65
60%	3.2	5.3	59	2.8	4.4	58	2.0	4.0	65
70%	3.9	4.7	45	3.2	4.0	43	3.0	4.0	44
80%	3.4	3.7	33	3.1	3.6	37	3.0	3.0	35
90%	2.3	3.5	18	1.9	3.4	20	1.0	2.5	23
100%	0.9	2.8	1	1.0	2.8	3	0.8	1.0	1

Table 7-2 shows the impacts of the examined simulation platform on the safety performance of the RLVW application in the case of actuated signal control operation. In general, the SILS and HILS platforms provided a higher number of red-light running events, right-angle conflicts, and rear-end conflicts compared to the EILS and this is because the number of phase occurrences in the SILS and the HILS is higher than the EILS which increase the probability of having higher numbers of RLR violations.

In comparing the differences between the three platforms under actuated signal control operation, the results show that the differences are higher compared to the differences with pre-timed signal control. For example, the differences between the maximum and minimum numbers of RLR ranged between 1.8 and 3 RLR per hour. In addition, the differences between the maximum and minimum values for the right-angle conflicts ranged between 2.0 to 5.7 conflicts per hour. Moreover, the differences between the maximum and minimum values for the rear-end conflicts ranged between 17 and 30 conflicts per hour.

Table 7-2 Impacts of Simulation Platform on RLVW Under Actuated Signal Control.

Actuated Signal Control									
UR	EILS			SILS			HILS		
	RLR	SSAM Conflicts		RLR	SSAM Conflicts		RLR	SSAM Conflicts	
		Right angle	Rear-end		Right angle	Rear-end		Right angle	Rear-end
0%	7.1	6.4	13	8.0	8.0	9	8.0	9.3	10
10%	6.9	4.3	25	7.9	8.5	37	8.0	10.0	42
20%	6.8	5.3	45	7.9	9.0	54	8.0	11.0	61
30%	6.8	5.3	50	7.3	9.5	65	7.0	11.5	78
40%	7.3	4.7	50	7.2	4.5	77	8.0	5.3	80
50%	6.5	3.0	58	5.8	6.0	76	6.0	5.5	79
60%	6.3	4.7	54	6.1	7.0	72	6.0	5.4	75
70%	6.9	5.7	43	7.4	5.0	54	7.0	7.0	61
80%	6.8	5.0	27	7.9	8.0	44	8.0	7.0	52
90%	6.2	3.0	20	7.0	7.0	21	7.0	8.0	25
100%	4.0	5.7	2	6.8	9.0	2	7.0	9.0	3

It is interesting from comparing the results in Table 7-1 and Table 7-2 that the number of red-light running events is clearly higher under actuated signal control compared to those with pre-timed signal control operation. For example, the differences between the pre-timed signal control and actuated signal control in terms of the number of red-light running ranged from 6% to 60% (0.2 to 3 RLR per hour) in the case of EILS and ranged from 13% to 82% (1.0 to 5.6 RLR per hour) in the case of SILS. In addition, the differences ranged from 25% to 86% (2.0 to 6.0 RLR per hour) in the case of HILS. The reason for these differences is because the end-of-green intervals for the main street through movements depends on the actuation of the minor movements. Thus, with an actuated traffic signal operation, the CV-based RLVW algorithm lacks the input information about when exactly the green interval is going to be terminated to the next phase.

In summary, the RLVW algorithm was able to successfully eliminate the RLR events by approximately 90% with increasing the CV utilization rate from 0% to 100% in the case of pre-timed signal control. However, in the case of actuated signal control, the RLVW algorithm was able to reduce the RLR events by only 26.7% according to the EILS, 15% according to the SILS, and 12.5% according to the HILS with increasing the CV utilization rate from 0% to 100%. The solution for this challenge is outside the scope of this paper and can be addressed in future research.

7.4 CONCLUSIONS

This study investigated the use of EILS, SILS, and HILS and methods of modeling traffic signal control operations as part of the simulation of CV-based RLVW application in a microsimulation environment. The main goal of this research is to compare the results obtained with the use of these three simulation platforms and how the use of the platforms impacts the assessed performance of the modeled CV application.

The study results showed that in the case of pre-timed signal control, there are small differences in the assessed performance when using the three simulation platforms. In the case of actuated control, the study results showed significantly higher differences in the assessed performance when using the EILS compared to the use of the other two platforms. The SILS and the HILS produced similar results. The differences can be attributed to the variations in the communication latencies between the EILS and the other two simulation platforms.

In comparing the impact of the pre-timed signal control and the actuated signal control on the assessed RLVW operation, the results showed that the number of RLRs was significantly higher in the case of actuated control compared to the number of RLRs under pre-timed signal control. The RLVW algorithm was able to successfully eliminate the RLR events by 90% with increasing the CV utilization rate from 0% to 100% in the case of pre-timed signal control. However, in the case of actuated signal control, the RLVW algorithm was able to reduce the RLR events by only 26.7% according to the EILS, 15% according to the SILS, and 12.5% according to the HILS with increasing the CV utilization rate from 0% to 100%. The reason for the deterioration in the performance of the RLVW with actuated control is the uncertainty in the end-of-green intervals provided to the vehicles using the SPaT messages since the end-of-green depends on the actuation of the minor movements. Future research is needed to evaluate methods to address this uncertainty and to improve the performance of RLVW application under actuated signal control.

8 DEMONSTRATION OF OPEN SKY TESTING OF THE MESSAGE-LEVEL TSETS

As stated earlier, Section 5 of this document included only a laboratory environment testing results using wired connection scenarios. Meaning, the CV messages were captured using an Ethernet interface and listening to a particular port on a wired network switch. Another testing alternative is to capture and analyze the messages wirelessly by listening to the wireless communication of the commercial device under test (i.e., RSU and OBU). This wireless capture needs to be tested because it replicates real-world communication scenarios and will be discussed in this section.

This section reports on the demonstration of the applications elements of the message-level test plan presented in Section 4 of this report that involves open sky testing of the message sets using wireless communications. The remaining of this section is structured in seven sections. Section 8.1 presents the test objective and scope. Section 8.2 describes the items under test. Section 8.3 presents the features tested. Section 8.4 presents the overview of the test design. Section 8.5 presents the test environment and its setup. Section 8.6 presents the test results.

8.1 TEST OBJECTIVE AND SCOPE

The objective of this document is to present the results from demonstrating the open-air testing of the connected vehicle-based applications to ensure that the messages conform to the requirements of the applications reported earlier and the applicable standards. This objective is similar to the objective of Section 5; however, the new testing goal is to verify the format, structure, values, and completeness of the wireless messages generated by the RSU and OBU over dedicated short-range communications (DSRC) radios rather than using wired connections as reported in Section 5. The scope of testing includes various messages and associate data elements to fulfill parts of the testing plan presented in Section 4. As such, the testing scope includes:

- verification that the messages received by the RSU are broadcasted correctly over the wireless DSRC radio,
- verification that the messages generated by the RSU are received wirelessly and correctly by the OBU,
- verification of the completeness of the data produced by the RSU according to Society of Automotive Engineers (SAE) J2735 message format for the messages and data elements, and
- the message-level verification for the Signal Request Messages (SRM) for signal priority and/or preemption applications.

8.2 ITEMS TESTED

In the demonstration conducted to meet the objectives of this task, the project team used CV devices under test along with the associated CV software applications obtained from Kapsch TrafficCom, commercial vendor.

Two CV devices were purchased, the first device under test is the Kapsch RIS-9260 Roadside

Unit, a RSU platform that meets the latest FDOT and the United States Department of Transportation (USDOT) RSU standards and supports reliable data exchange according to DSRC or C-V2X industry standards (IEEE WAVE/DSRC, ETSI ITS G5, or 3GPP C-V2X / LTE V2X) with compliant OBUs.

The second device under test is the Kapsch ACV-330 OBU, a physical CV device responsible for sending and receiving wireless SAE J2735 messages for CV-based applications support. The OBU can support providing infrastructure-to-vehicle (I2V) alerts and warnings to drivers such as those associated with speed zones, work zones, and red/yellow light warnings.

In addition, the research team used the Kapsch Assist and Kapsch Insight, which are two supplementary Kapsch mobile applications that provide visualization of the operation of the Kapsch DSRC OBUs during lab testing or on-road testing. These applications are installed on an Android mobile device such as a tablet to support the testing. This document discusses the system overview and methods of installation, configuration, and demonstration for the message level testing between the following items:

- Testing of commercially available Kapsch RIS-9260 RSU to ensure reliable wireless data exchange with the OBUs
- Testing of commercially available Kapsch ACV-330 OBU along with the aforementioned mobile applications that support the testing functionality.

Error! Reference source not found. shows the test environment that includes a traffic signal controller (Trafficware Commander), Kapsch RSU and Kapsch OBU.

Figure 8-1 Devices Under Test and Software Applications

As shown in Figure 8-1, the Kapsch RIS-9260 RSU receives the Signal Phase and Timing (SPaT) information from Trafficware Commander signal controller and receives the MAP information through scripts sending Simple Network Management Protocol (SNMP) commands. It then, broadcasts intersection signal phase and timing data and geometric description data to Kapsch OBU-equipped vehicles within the communication range of the intersection in accordance with SAE J2735 SPaT and MAP standards. Accordingly, the Kapsch Insight and Kapsch Assist applications on-board the vehicles, allowing the user to verify the values of the data elements if the messages received from the RSU, verify counts of received messages by type, and view system logs. The detailed description of the devices will be presented in the following sub-sections.

8.2.1 Kapsch RIS-9260 RSU

The RIS-9260 RSU uses a Debian based Linux operating system (OS). The RSU provides two separate operating systems, Live OS image and Rescue OS image to fix any accidental modification of the OS images. This section describes the key features and capabilities of the selected Kapsch RIS-9260 RSU, shown in Figure 8-2.

Figure 8-2 Kapsch RIS-9260 Roadside Unit

According to the brochure of the device, Kapsch RIS-9260 has the following key features:

- Meets the requirements of the US DOT RSU Specification V4.1
- Gigabyte (GB) Ethernet based system interface
- Power over Ethernet (PoE) supply of the device
- Internally protected against surges on data and power lines
- Two Global navigation satellite system (GNSS) antenna interface for positioning and time synchronization
- Two Omni-directional 5.9 GHz antenna interfaces (for DSRC or ITS G5)
- Two Omni-directional 5.9 GHz antenna interfaces (for C-V2X / LTE-V2X)
- Light-emitting diode (LED) status indication
- Internal mSATA solid-state drive (SSD) for memory extension, which is SSD that conforms to the mSATA interface specification developed by the Serial ATA (SATA) International Organization.

- Internal μSD memory card for memory extension
- Extended size of DDR3 RAM 2 GB and eMMC Flash 8GB.
- Wireless wide area network (WWAN) interface
- Antennas and mounting accessories

Kapsch RIS-9260 RSU transmits messages formatted in accordance with the SAE J2735 standards using one of the following two mechanisms:

- Store and Repeat
- Immediate Forward

The Store and Repeat mechanism is used to store the messages in the specified SNMPv3 Object Identifier (OID) of the RSU and send and repeat the CV-based messages as needed. Each message is accompanied by several instructions that define the message transmission rate, the start/end time for transmission, the broadcasting channel, the Provider Service Identifier (PSID), and whether the message should be signed and/or encrypted. These transmission instructions should be extracted from the received SNMPv3 message and written to the specified Object OID. For example, this mechanism was used in our study to upload and send an encoded MAP message every 1000 milli-second.

The Immediate Forward mechanism is used to send messages immediately, as they are received by the RSU from a back-office service. Similar to the Store and Repeat mechanism, each message is accompanied by several instructions that define the channel that should be used for the transmission, the PSID the message is associated with, and whether the message should be signed and/or encrypted.

The RSU can also receive messages broadcast by a DSRC-equipped mobile device and forward them to a remote host. Messages are forwarded based on the PSID. The PSID of the message to be forwarded, the IP address and port number of the remote host, the transport protocol to use, the receive signal strength, the interval at which to forward, and the period to forward messages are all configurable.

8.2.2 Kapsch ACV-330 OBU

The Kapsch ACV-330 OBU provides functionality for receiving and transmitting industry standard DSRC messages. Kapsch Insight and Kapsch Assist applications are two mobile software for CV-based applications and used to display any CV warning messages that have been created. The Insight application is a debugging tool for DSRC setup and a messaging tool for Kapsch OBUs. The application connects to an OBU over Bluetooth or Wi-Fi. It displays the vehicle information on a Google map and show the current CV-based messages received and broadcasted by the OBU over DSRC. The Assist application provides an end-user-like interface to display vehicle warnings and notifications. This section describes the key features and capabilities of the selected Kapsch ACV-330 OBU. Figure 8-3 shows the selected Kapsch ACV-330 OBU. According to the brochure of the device, it has the following key features.

Figure 8-3 Kapsch ACV-330 On-board Unit

- Meets the requirements of the US DOT RSU Specification V4.1
- GNSS that delivers lane-level accuracy
- Dual IEEE 802.11p radio
- Bluetooth connections support
- Wi-Fi connections support
- Powerful processor
- Integrated security
- Dedicated Short Range Communications (DSRC) support
- Ethernet interface
- Alternate Configurations Using a USB Drive

The Insight and Assist applications are installed on an Android mobile device that is connected to the OBU using Bluetooth. The research team purchased Samsung tablet A-8 10.5” to run the Kapsch software applications (i.e., Insight and Assist). Any mobile device can connect to the Kapsch OBU either using Bluetooth or by using a Wi-Fi network if the mobile device and OBU are on the same network.

The Kapsch Insight application allows the display of a live map that shows the location of the current vehicle that the user is connected to and any DSRC objects that are within range. The application also displays the signal status (i.e., red, green, or yellow) based on the received phasing information in the SPaT message. In addition, the application shows the lanes and approaches for the signalized intersections or other geographical areas based on the encoded data in the received MAP messages.

The Insight application allows the user to see Basic Safety Messages (BSM) data for connected vehicles, any warning messages that have been created, and overall counts of messages received.

It then presents a summary of the BSM traffic with the critical pieces (i.e., not all data elements) of information relating to the position, speed, and identity of the vehicle. Moreover, the Insight application shows counts for messages that have been received by the unit. There are separate counts for BSM, MAP, and SPaT messages. Any other known messages received (vehicle warnings, etc.) are collected in a separate category.

The Kapsch Assist application is designed to inform drivers about any warning conditions that are generated as a result of CV-based DSRC communication. Kapsch Assist shows the speed of the vehicle and the number of vehicles and intersections that are being tracked over the wireless communications. In addition, the application shows the phase and timing of the traffic signal (if known). The displayed CV-based warnings include speed zones, construction zones, and red/yellow light warnings. A couple of example screens are shown below in Figure 8-4.

Figure 8-4 Kapsch Assist CV-based Vehicle-to-Infrastructure V2I warnings (Source: Kapsch OBU User Manual)

8.3 FEATURES TESTED

This testing demonstration addresses the wireless message level testing of SPaT, MAP, and SRM messages. It should be noted that the results of testing the SPaT and MAP messages in this section was found to be exactly matching the results reported in Section 5. As such, the results of the testing are not presented in this section because they are redundant. The only testing results presented in this document are those for the Signal Request Message (SRM) testing since the test of these messages was not reported on in Section 5.

The test verifies the following:

a) Verification against the SAE J2735 data dictionary message structure

b) Verification against the limits of the data elements as specified in the SAE J2735 data dictionary message (e.g., value ranges, string lengths, enumerated list values)

A functional inspection and testing are carried out to ensure the following:

a) Verification that the GNSS antenna is receiving signals with true positioning and time
b) Verification that both 5.9 GHz antennas are properly mounted and ready for broadcasting
c) Verification of proper voltage and grounding of PoE injector or the presence of PoE enabled Ethernet wall ports
d) Verify that either a Dynamic Host Configuration Protocol (DHCP) is operational or static Internet Protocol (IP) address can be used to prevent IP conflicts.
e) Verify that the tested RSU and OBU are set to an operational mode

8.4 TEST DESIGN OVERVIEW

This section provides an overview of the message-level testing of CV-based applications utilizing the SPaT, MAP, and SRM messages including the activities performed and the types of tools utilized in the testing. It is assumed that the reader has a basic knowledge of DSRC communications, Unix and Linux commands, Secure Shell, SNMP commands as well as basic IP network communication.

The difference between the test design in this section and what was previously reported in Section 5 is that the testing was done without the V2X Hub developed by the USDOT. Therefore, a CV-processor-enabled traffic signal controller was directly connected to the Kapsch RIS-9260 through an Ethernet connection. Meaning, the traffic signal controller is able to communicate SPaT messages in an SAE J2735 data format.

The signal controller and the RSU were connected and configured on the same subnetwork to allow them to communicate with one another. The SPaT messages were received from the signal controller. The MAP messages were generated using the USDOT web tools and uploaded to the RSU by using scripts sending SNMP commands. Wireshark, a free and open-sourced packet analyzer software, was used to capture the wireless messages broadcasted over the RSU DSRC radio.

8.4.1 SAE J2735 SPaT MESSAGES CONFIGURATION

As previously reported in Section 5, Trafficware Commander ATC controller was used in this study and the controller interface was used to input the signal timing plan. The SPaT messages were changed by adjusting the different values and settings of the signal control parameters. The input changes were compared with the decoded output messages that are captured wirelessly from the RSU DSRC radios. Figure 8-5 shows the setup for the Trafficware commander screen to enable broadcasting SPaT messages with the SAE J2735 format.

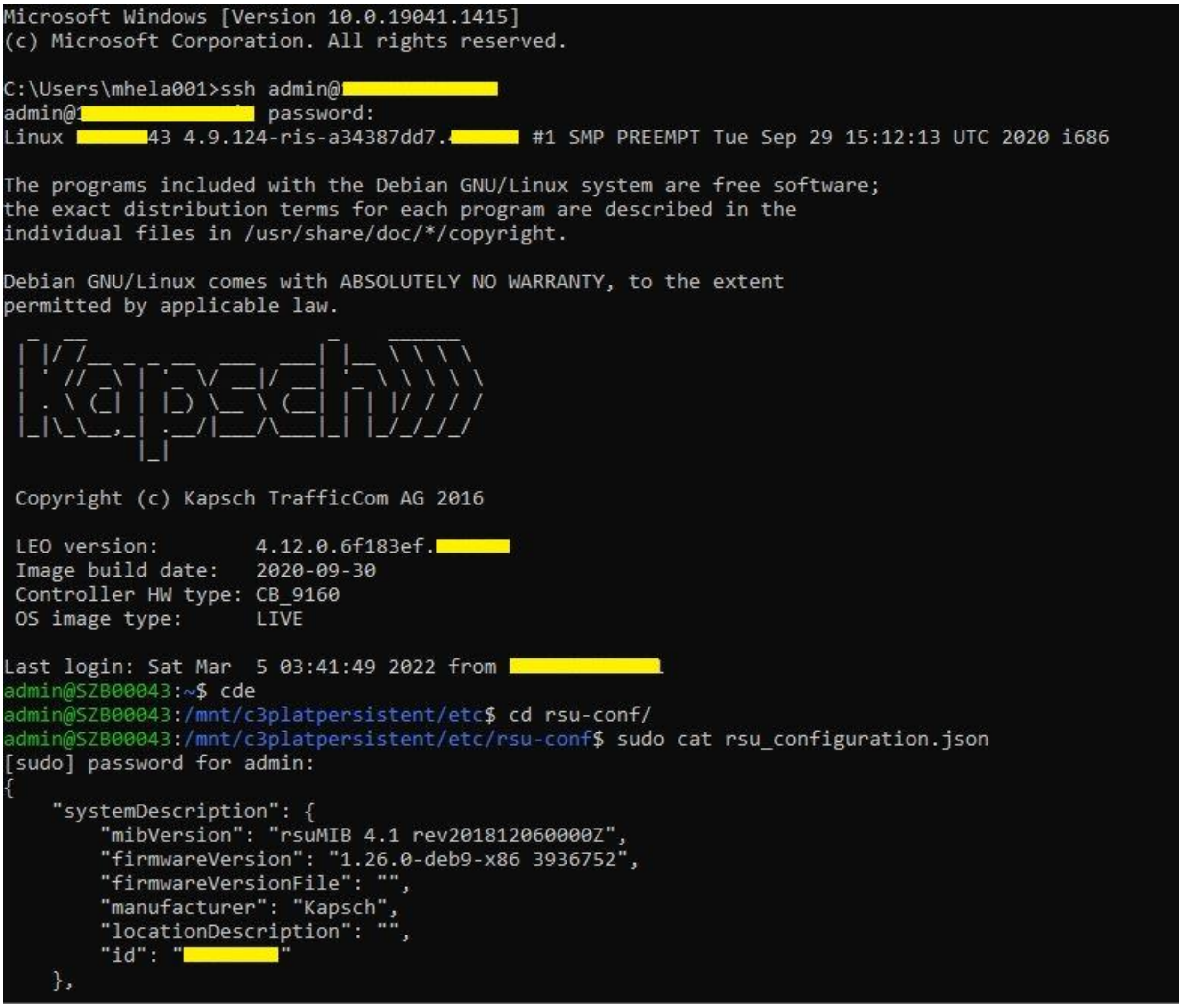
Figure 8-5 J2735 SPaT Configuration of TrafficWare Commander ATC Controller

As shown in Figure 8-5, the differences between the controller DSRC setup in the test reported in Section 5 and this section (Section 8) are first; the message format attribute "MsgFrmt" is changed from "Trafficware" NTCIP compliant standard to "SAE J2735" to allow the controller to communicate SPaT messages with SAE J2735 without the need for the V2X Hub in the middle. Second, the attribute "Mode" is changed from "INT" to "CONT" to allow the continuous broadcasting of the messages. Third, the channel number is set to "172" to match the SPaT message configuration on the RSU interface. The rest of the controller DSRC setup attributes are the same, as was used in Section 5.

8.4.2 SAE J2735 MAP MESSAGES CONFIGURATION

The USDOT MAP creator tool was used to generate and encode the MAP messages. This tool allows a user to define the approaches and lanes of an intersection using a graphical interface. The authors previously presented more details regarding the USDOT MAP creator tool interface in Section 5. The tool encoder is used to encode the MAP messages as UPER HEX using a FRAME plus MAP message type and explicit (64) bit node offsets.

As shown in Figure 8-6, the tested RSU was accessed using the Secure Shell Protocol (SSH). The SSH is a cryptographic network protocol for operating network services securely based on a client–server architecture using either remote login or command-line execution. The MAP messages were uploaded to the RSU by using scripts sending SNMP commands.



```
Microsoft Windows [Version 10.0.19041.1415]
(c) Microsoft Corporation. All rights reserved.

C:\Users\mhela001>ssh admin@[redacted]
admin@[redacted] password:
Linux [redacted]43 4.9.124-ris-a34387dd7.[redacted] #1 SMP PREEMPT Tue Sep 29 15:12:13 UTC 2020 i686

The programs included with the Debian GNU/Linux system are free software;
the exact distribution terms for each program are described in the
individual files in /usr/share/doc/*/copyright.

Debian GNU/Linux comes with ABSOLUTELY NO WARRANTY, to the extent
permitted by applicable law.

 Copyright (c) Kapsch TrafficCom AG 2016

 LEO version:         4.12.0.6f183ef.[redacted]
 Image build date:    2020-09-30
 Controller HW type:  CB_9160
 OS image type:       LIVE

Last login: Sat Mar  5 03:41:49 2022 from [redacted]
admin@SZB00043:~$ cde
admin@SZB00043:/mnt/c3platpersistent/etc$ cd rsu-conf/
admin@SZB00043:/mnt/c3platpersistent/etc/rsu-conf$ sudo cat rsu_configuration.json
[sudo] password for admin:
{
    "systemDescription": {
        "mibVersion": "rsuMIB 4.1 rev201812060000Z",
        "firmwareVersion": "1.26.0-deb9-x86 3936752",
        "firmwareVersionFile": "",
        "manufacturer": "Kapsch",
        "locationDescription": "",
        "id": "[redacted]"
    },
```

Figure 8-6 Logging into Kapsch RIS-9260 RSU using Secure Shell command line

The commands below show an example to set up an SAE J2735 MAP message using the SNMP interface.

- RSU-MIB:rsuSRMDsrcMsgId.1 i 18 \ (DSRC message ID)
- RSU-MIB:rsuSRMTxMode.1 i 1 \ (Transmission Channel Mode)
- RSU-MIB:rsuSRMTxChannel.1 i 172 \ (Transmission Channel)
- RSU-MIB:rsuSRMTxInterval.1 i 1000 \ (Transmission Interval)
- RSU-MIB:rsuSRMDeliveryStart.1 x 07e40b071610 \ (Start Time)
- RSU-MIB:rsuSRMDeliveryStop.1 x 0 \ (Stop Time)
- RSU-MIB:rsuSRMPayload.1 x 00128…7758\ (Message Payload)
- RSU-MIB:rsuSRMEnable.1 i 1 \ (Enable Broadcasting)
- RSU-MIB:rsuSRMStatus.1 i 4 (Current Status)

The key point to note is that the DSRC message ID (rsuSRMDsrcMsgId in the SNMP interface above) should match the content of the message. This can usually be checked by ensuring the first 2 bytes in the payload match the message type. For example, here 18 = 0x0012. The

MIB:rsuSRMPayload will be responsible for the full MAP message payload.

If the user wants to update any field in the message, the RSU will need to be set in a standby mode to allow the modification of the required fields.

As previously mentioned, the RSU will transmit DSRC messages based on SNMP OIDs. Each OID entry and related SNMP message contain the transmission instructions and encoded payload for one DSRC message. The RSU begins transmitting the payload of an OID Store and Repeat entry over a DSRC radio on or after the start time specified in rsuSRMDeliveryStart.

Figure 8-7 shows the user interface of the Kapsch Insight application. It shows the location of the current connected vehicle and any DSRC objects that are within the communication range. The OBU or the connected vehicle is shown using a green vehicle icon under normal operations. The vehicle will change shades between yellow and red when warnings are raised for that vehicle. By default, the application is set with the Map Centering mode to “On” so that the user’s vehicle is always centered on the map.

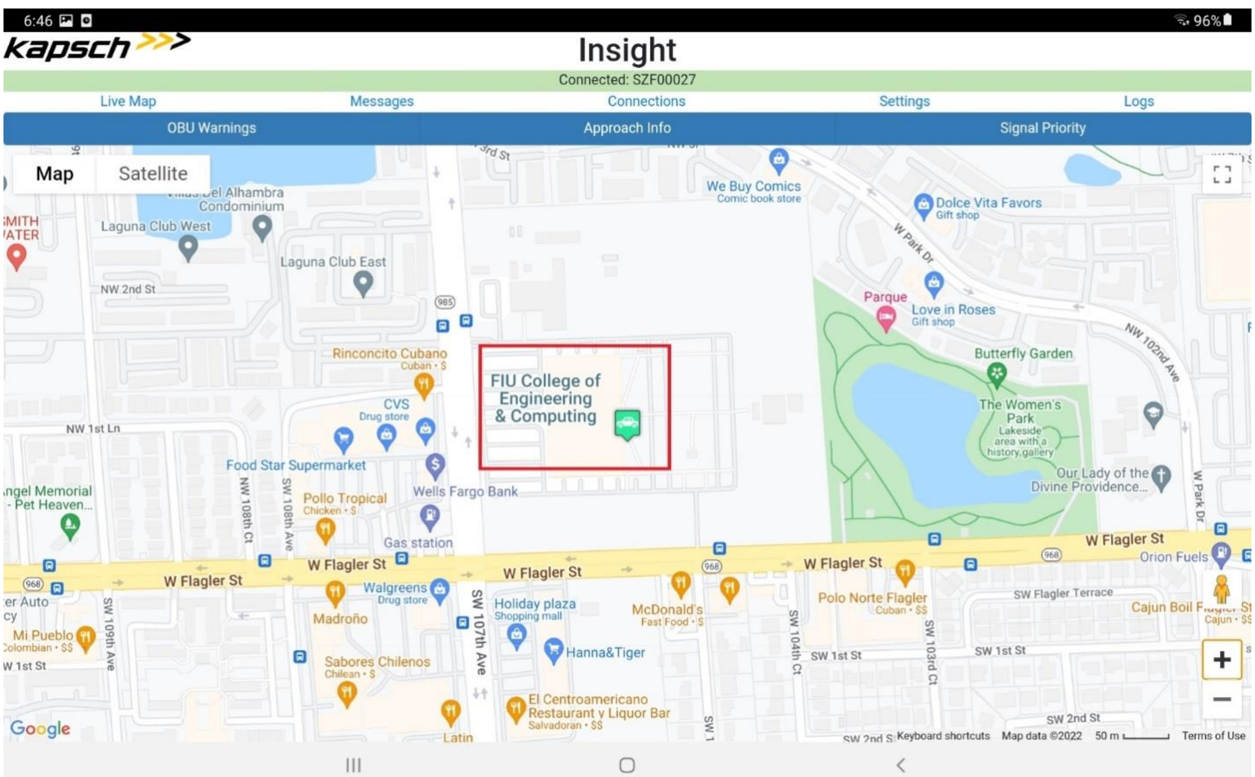


Figure 8-7 Kapsch Insight Application on the Samsung A-8 Tablet

Figure 8-8 shows the interface of Wireshark to capture the wireless SPaT, MAP and SRM messages in between the RSU and the OBU. The difference between the Wireshark setup in this Section and what was previously reported in Section 5, is that the listening mode is set to wireless capturing. It can be inferred from the figure that the “Source” column (highlighted in red) contains the source of the data packets sent from the RSU with its corresponding MAC address. The messages are broadcasted wirelessly as shown in the "Destination" column. This process was done through IEEE P1609.3 Wave Short Message Protocol (WSMP), which is a networking protocol specifically designed for V2X communications. The messages used by WSMP are known as WAVE Short Messages (WSM). For capturing the messages, the .pcap files were extracted from the DSRC radios interface supported by the RSU. The research team transferred the .pcap files from the DSRC interface to a computer hosting the Wireshark software by using WinSCP which is an open-source SSH File Transfer Protocol (SFTP).

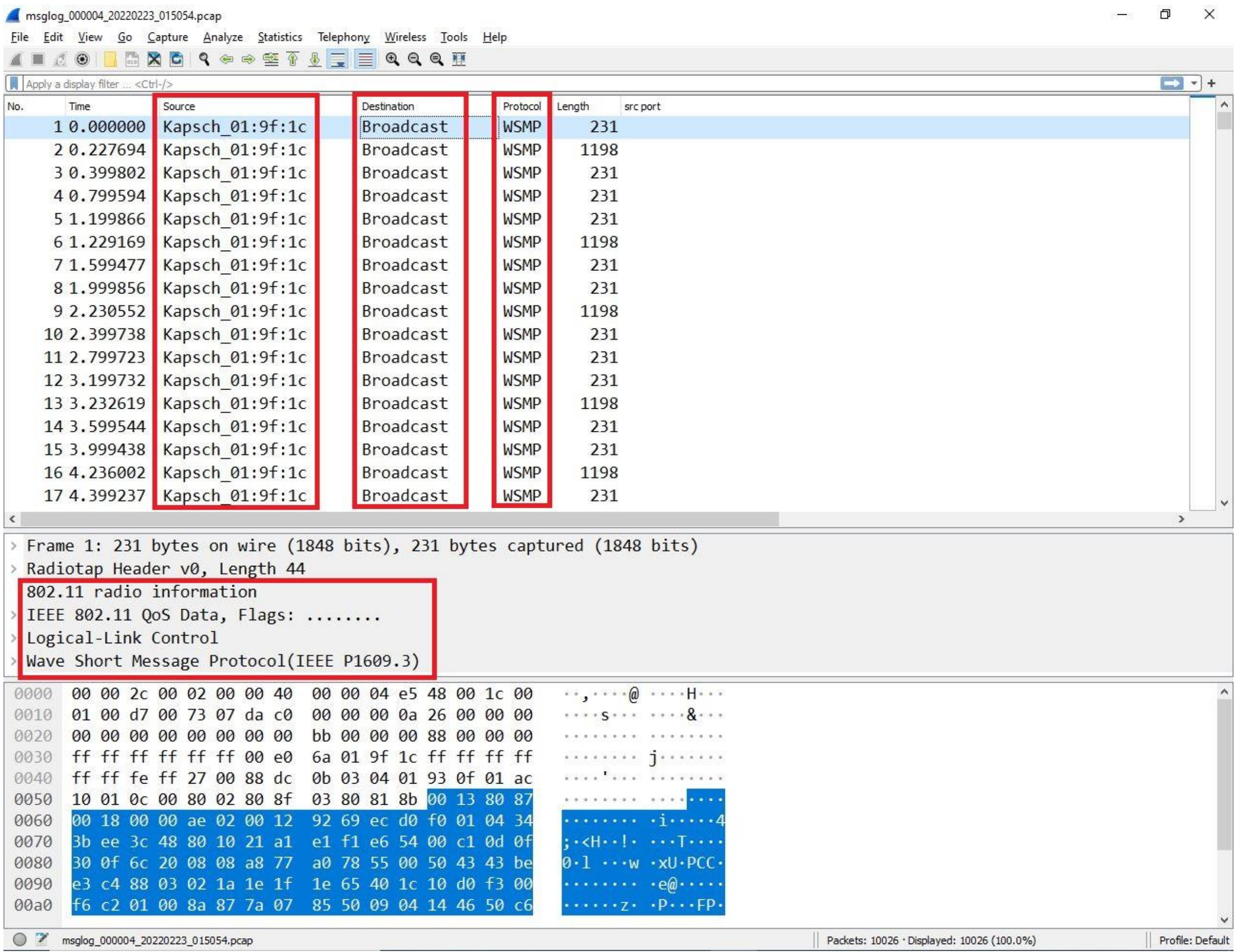


Figure 8-8 Interface of Wireshark for Wireless Message Capture

The packets were copied from Wireshark as a "Hex Stream" or "Hex Dump" and decoded from UPER Hex to human readable XML format by using the same online automotive ASN.1 message decoder tool that was reported in Section 5. The only difference between this Section and this section in this aspect is that the PSID resides in the header of WSM messages transported by WSMP. Accordingly, it was necessary to manually delete the header of the WSM messages before pasting the payload to the decoder.

8.4.3 SAE J2735 SRM MESSAGES CONFIGURATION

As previously mentioned in the test objective and scope, this section presents the wireless message-level verification for the SRM for signal priority and/or preemption applications. The SRM testing was not reported in Section 5. According to the Kapsch OBU User Manual, the typical flow for signal priority/preemption applications are as follows:

- An RSU broadcasts a Wave Service Announcement (WSA) advertising the PSID for signal request messages.
- The OBU responds to the WSA and sets up its alternating radio for the correct channel.
- Once the vehicle enters a lane in the intersection, it is ready to start sending signal request messages.
- If the flag is set where the priority request requires user input, a message is sent to the Insight application to get feedback from the driver to start the process.
- The signal request messages are sent with the information for the lane that the vehicle is travelling in.
- The vehicle listens for the signal status messages to check if the request is accepted.
- Once the vehicle exits the lane, it stops sending the signal request messages.

The above description for the SRM message flow is normally applied during real-world operations (i.e., actual field testing). Meaning, the OBU should be assigned to an ingress lane at a signalized intersection in real-time based on the information from the MAP data. However, this section is based on laboratory testing, so it was necessary to simulate the SRM message on the RSU and the OBU using JSON scripts. The laboratory simulation of the SRM messages is done as follows:

- The RSU broadcasts a WSA advertising the PSID for signal request messages.
- The OBU responds to the WSA and sets up its alternating radio for the correct channel.
- A .CSV file is uploaded to the OBU directory containing a simulation of emergency vehicle GPS data stream.
- A configuration file is uploaded to the OBU containing a simulation of the PSID service used, emergency vehicle ID, and the enabled vehicle signal request processing.
- A new RSU configuration file is uploaded to the RSU directory containing a simulation of traffic lights, intersection ID, signal groups, priority plan, and preemption plan.
- The signal request messages are sent with the information for the lane that the vehicle is traveling in.
- The vehicle listens for the signal status messages to check if the request is accepted.
- Once the vehicle exits the lane it stops sending the signal request messages.

Figure 8-9 shows a successful simulation of sending signal request message with a referenced time stamp from a simulated emergency vehicle.

```
admin@SZF00027: ~
admin@SZF00027:~$ trl
03/23 17:43:20.135 [2826894144] INFO  vehicle.signalrequest - Sending Signal request message: Signal Request Message:  Time Stamp: Wed Mar 23 17:43:19 2022 Sec Mark
: 19137 Seq #: 0 Requested Time Start: Wed Mar 23 17:43:36 2022 Requested Duration: 20 Requesting Vehicle/Station: 99/0 RequestorType: role: ambulance  Intersection
 Id: 1 Request Id: 1 Request Type: 1 Preemption Request: 0 Inbound Access Point: Lane: 1 Outbound Access Point:  Identifier: 00000063:1
03/23 17:43:20.221 [2843679552] INFO  vehicle.signalrequest - Received Signal Status Message: Signal Status Message:  Time Stamp: Wed Mar 23 17:43:00 2022 Sec Mark:
 25441 Seq #: 1  Status: {Sequence #: 1 Intersection Id: 1  Status Package: {Requesting Vehicle/Station: 99/0 Request Id: 1 Status: 4 Sequence Number: 0 Inbound: La
ne: 1 }}
03/23 17:43:20.310 [2843679552] INFO  vehicle.signalrequest - Received Signal Status Message: Signal Status Message:  Time Stamp: Wed Mar 23 17:43:00 2022 Sec Mark:
 25441 Seq #: 1  Status: {Sequence #: 1 Intersection Id: 1  Status Package: {Requesting Vehicle/Station: 99/0 Request Id: 1 Status: 4 Sequence Number: 0 Inbound: La
ne: 1 }}
03/23 17:43:20.562 [2843679552] INFO  vehicle.signalrequest - Received Signal Status Message: Signal Status Message:  Time Stamp: Wed Mar 23 17:43:00 2022 Sec Mark:
 25441 Seq #: 1  Status: {Sequence #: 1 Intersection Id: 1  Status Package: {Requesting Vehicle/Station: 99/0 Request Id: 1 Status: 4 Sequence Number: 0 Inbound: La
ne: 1 }}
03/23 17:43:20.664 [2843679552] INFO  vehicle.signalrequest - Received Signal Status Message: Signal Status Message:  Time Stamp: Wed Mar 23 17:43:00 2022 Sec Mark:
 25441 Seq #: 1  Status: {Sequence #: 1 Intersection Id: 1  Status Package: {Requesting Vehicle/Station: 99/0 Request Id: 1 Status: 4 Sequence Number: 0 Inbound: La
ne: 1 }}
03/23 17:43:20.770 [2843679552] INFO  vehicle.signalrequest - Received Signal Status Message: Signal Status Message:  Time Stamp: Wed Mar 23 17:43:00 2022 Sec Mark:
 25441 Seq #: 1  Status: {Sequence #: 1 Intersection Id: 1  Status Package: {Requesting Vehicle/Station: 99/0 Request Id: 1 Status: 4 Sequence Number: 0 Inbound: La
ne: 1 }}
03/23 17:43:20.860 [2835286848] INFO  vehicle.signalrequest - Received Signal Status Message: Signal Status Message:  Time Stamp: Wed Mar 23 17:43:00 2022 Sec Mark:
 25441 Seq #: 1  Status: {Sequence #: 1 Intersection Id: 1  Status Package: {Requesting Vehicle/Station: 99/0 Request Id: 1 Status: 4 Sequence Number: 0 Inbound: La
ne: 1 }}
03/23 17:43:20.967 [2843679552] INFO  vehicle.signalrequest - Received Signal Status Message: Signal Status Message:  Time Stamp: Wed Mar 23 17:43:00 2022 Sec Mark:
 25441 Seq #: 1  Status: {Sequence #: 1 Intersection Id: 1  Status Package: {Requesting Vehicle/Station: 99/0 Request Id: 1 Status: 4 Sequence Number: 0 Inbound: La
ne: 1 }}
03/23 17:43:21.067 [2835286848] INFO  vehicle.signalrequest - Received Signal Status Message: Signal Status Message:  Time Stamp: Wed Mar 23 17:43:00 2022 Sec Mark:
 25441 Seq #: 1  Status: {Sequence #: 1 Intersection Id: 1  Status Package: {Requesting Vehicle/Station: 99/0 Request Id: 1 Status: 4 Sequence Number: 0 Inbound: La
ne: 1 }}
03/23 17:43:21.087 [2826894144] INFO  vehicle.signalrequest - Sending Signal request message: Signal Request Message:  Time Stamp: Wed Mar 23 17:43:20 2022 Sec Mark
: 20135 Seq #: 0 Requested Time Start: Wed Mar 23 17:43:36 2022 Requested Duration: 20 Requesting Vehicle/Station: 99/0 RequestorType: role: ambulance  Intersection
 Id: 1 Request Id: 1 Request Type: 1 Preemption Request: 0 Inbound Access Point: Lane: 1 Outbound Access Point:  Identifier: 00000063:1
03/23 17:43:21.166 [2843679552] INFO  vehicle.signalrequest - Received Signal Status Message: Signal Status Message:  Time Stamp: Wed Mar 23 17:43:00 2022 Sec Mark:
 25441 Seq #: 1  Status: {Sequence #: 1 Intersection Id: 1  Status Package: {Requesting Vehicle/Station: 99/0 Request Id: 1 Status: 4 Sequence Number: 0 Inbound: La
ne: 1 }}
03/23 17:43:21.259 [2835286848] INFO  vehicle.signalrequest - Received Signal Status Message: Signal Status Message:  Time Stamp: Wed Mar 23 17:43:00 2022 Sec Mark:
 25441 Seq #: 1  Status: {Sequence #: 1 Intersection Id: 1  Status Package: {Requesting Vehicle/Station: 99/0 Request Id: 1 Status: 4 Sequence Number: 0 Inbound: La
ne: 1 }}
03/23 17:43:21.360 [2843679552] INFO  vehicle.signalrequest - Received Signal Status Message: Signal Status Message:  Time Stamp: Wed Mar 23 17:43:00 2022 Sec Mark:
 25441 Seq #: 1  Status: {Sequence #: 1 Intersection Id: 1  Status Package: {Requesting Vehicle/Station: 99/0 Request Id: 1 Status: 4 Sequence Number: 0 Inbound: La
ne: 1 }}
03/23 17:43:21.462 [2843679552] INFO  vehicle.signalrequest - Received Signal Status Message: Signal Status Message:  Time Stamp: Wed Mar 23 17:43:00 2022 Sec Mark:
 25441 Seq #: 1  Status: {Sequence #: 1 Intersection Id: 1  Status Package: {Requesting Vehicle/Station: 99/0 Request Id: 1 Status: 4 Sequence Number: 0 Inbound: La
ne: 1 }}
03/23 17:43:21.559 [2843679552] INFO  vehicle.signalrequest - Received Signal Status Message: Signal Status Message:  Time Stamp: Wed Mar 23 17:43:00 2022 Sec Mark:
 25441 Seq #: 1  Status: {Sequence #: 1 Intersection Id: 1  Status Package: {Requesting Vehicle/Station: 99/0 Request Id: 1 Status: 4 Sequence Number: 0 Inbound: La
ne: 1 }}
03/23 17:43:21.669 [2835286848] INFO  vehicle.signalrequest - Received Signal Status Message: Signal Status Message:  Time Stamp: Wed Mar 23 17:43:00 2022 Sec Mark:
 25441 Seq #: 1  Status: {Sequence #: 1 Intersection Id: 1  Status Package: {Requesting Vehicle/Station: 99/0 Request Id: 1 Status: 4 Sequence Number: 0 Inbound: La
ne: 1 }}
03/23 17:43:21.764 [2843679552] INFO  vehicle.signalrequest - Received Signal Status Message: Signal Status Message:  Time Stamp: Wed Mar 23 17:43:00 2022 Sec Mark:
 25441 Seq #: 1  Status: {Sequence #: 1 Intersection Id: 1  Status Package: {Requesting Vehicle/Station: 99/0 Request Id: 1 Status: 4 Sequence Number: 0 Inbound: La
```

Figure 8-9 Kapsch ACV-330 OBU SRM Logs

8.5 TEST ENVIRONMENT SETUP

The Test Environment included the following hardware and software:

- A power source appropriate for the Devices Under Test
- TrafficWare Commander ATC Signal Controller
- Kapsch RIS-9260 Roadside Unit
- Kapsch ACV-330 On-board Unit
- Samsung Android Tablet A-8 10.5 inch
- A Windows computer running the WinSCP, Secure Shell and the Wireshark software package to capture, transfer, and decode the .pcap files
- A vehicle-to-everything (V2X) decoder to visualize and analyze the decoded messages
- Kapsch Insight and Kapsch Assist applications

To ensure that the SRM, MAP, and SPaT messages are being transmitted, the RSU should be placed in an open-sky environment to receive a valid GPS signal. To check for proper GPS signal, the user can run the “date” command which is expected to return the current date, time and valid GPS positioning. If the date is not correct, the RSU should be moved to an area with better reception. Figure 8-10 shows a photo of the open sky test environment setup.

During laboratory testing, there is always a possibility that radio communication interference or crash occurs. This interference can be corrected by one or more of the following measures:

- Reorient or relocate the receiving antenna
- Increase the separation between the equipment and receiver
- Connect the equipment into an outlet on a circuit different from that to which the receiver is connected

Since the wireless communication range between the devices is not meant to be very close in the real world as is the case in the laboratory environment, the research team unscrewed two of the DSRC antennas to reduce the DSRC waves in order to prevent wireless wave crashes.

Figure 8-10 Open Sky CV-based Applications Testing Environment

8.6 TEST RESULTS

This section presents the test results for each of the tested messages. The validation of the message includes two aspects. The first is to validate the existence of the fields (data elements / frames) of the tested message. The second is to validate the content and structure of the tested message. The validation is according to the definition of each tested message based on SAE J2735 (201603) standard.

The test results for each field of the tested messages are categorized as follows:

- **Pass**: The field in the message configured by input exists after transmission, matches with the input configuration, and complies with SAE J2735 (201603) standard.
- **Fail**: The field in the message is missing, not matching with the input, or not complying with SAE J2735 (201603)
- **Unable to Test**: The field of the message is not tested because it cannot be produced as input to the RSU from the controller output, the MAP creator tool, or the TIM creator tool.

The test results for each tested message are presented in tables provided in the remainder of this section. In addition, there is a comment column that provides an explanation for the test result, if necessary.

8.6.1 SAE J2735 SPaT MESSAGES

The SPaT message is used to send the current state of each active phase of one or more signalized intersections in the system. It was found that the results of testing the SPaT messages in this section (wireless communication testing) match exactly the results from testing using wired communications, previously reported in Section 5. Please refer to Section 5 for the test results of the SPaT messages. The decoded messages were compared with the inputs from the signal controller interface to verify the messages.

8.6.2 SAE J2735 MAP MESSAGES

The MAP message is used to convey geographic road information of one or more signalized intersections in the system. The tests for the MAP messages were performed in Section 5 for both the V2X Hub and RSU scenarios and the results were presented separately It was found that the results of testing the SPaT messages in this section (wireless communication testing) match exactly the results from testing using wired communications, previously reported in Section 5. Since the Kapsch RIS-9260 was connected directly to the Trafficware Commander, please refer to Section 5 for the test results of MAP message when the RSU was directly connected to the signal controller without V2X Hub.

8.6.3 SAE J2735 SRM MESSAGES

The SRM message is used for either a priority signal request or a preemption signal request. Different from other tested messages included in this document, a SRM message is initiated by the OBU equipped in a vehicle and received by the RSU. The messages are then forwarded to the signalized intersection controller. Table 8-1 provides a list of data elements/frames for transmitting SRM messages. Since the application for the SRM was done using a simulated messages approach, it was not possible to include some of the message elements in the simulated message. Thus, the test results for these fields were marked “Unable to test.”

Table 8-1 SRM Message Test Result

SRM Message	SAE J2735 (201603)	Test Result	Memo
• timeStamp MinuteOfTheYear	Optional	Pass	
• second DSecond	Required		
• sequenceNumber MsgCount	Optional	Pass	
• requests SignalRequestList (Sequence of SignalRequestPackage)	Optional		
– ○ SignalRequestPackage	Required	Pass	
– – ▪ request SignalRequest	Required	Pass	
– – – ♦ id id IntersectionID	Required	Pass	
– – – ♦ requestID RequestID	Required	Pass	
– – – ♦ requestType PriorityRequestType	Required	Pass	
– – – ♦ inBoundLane IntersectionAccessPoint	Optional		
– – – ♦ outBoundLane IntersectionAccessPoint	Optional		
– – ▪ minute MinuteOfTheYear	Optional		
– – ▪ second DSecond	Optional		
– – ▪ duration DSecond	Optional		
• requestor RequestorDescription	Required	Unable	
– – ▪ id VehicleID	Required	Unable	
– – – ♦ entityID TemporaryID	Choice		
– – – ♦ stationID StationID	Choice		
– – ▪ type RequestorType	Optional		
– – – ♦ role BasicVehicleRole	Required	Unable	
– – – ♦ subrole RequestSubRole	Optional		
– – – ♦ request RequestImportanceLevel	Optional		
– – – ♦ iso3883 Iso3833VehicleType	Optional		
– – – ♦ hpmsType VehicleType	Optional		
– – ▪ position RequestorPositionVector	Optional		
– – – ♦ position Position3D	Required	Pass	
– – – – ¤ lat Latitude	Required	Pass	
– – – – ¤ long Longitude	Required	Pass	

SRM Message	**SAE J2735 (201603)**	**Test Result**	**Memo**
¤ elevation Elevation	Optional		
♦ heading Angle	Optional		
♦ speed TransmissionAndSpeed	Optional		
¤ transmisson TransmissionState	Required	Unable	
¤ speed Velocity	Required	Unable	
▪ name DescriptiveName	Optional	Unable	
▪ routeName DescriptiveName	Optional		
▪ transitStatus TransitVehicleStatus	Optional		
▪ transitOccupancy TransitVehicleOccupancy	Optional		
▪ transitSchedule DeltaTime	Optional		

8.7 TESTING AT THE FDOT TRAFFIC ENGINEERING RESEARCH LABORATORY (TERL)

The research team of this project coordinated with the FDOT project manager on demonstrating the testing procedures developed in this project, as discussed in this section and Section 5 at the FDOT Traffic Engineering Research Laboratory (TERL). Two members of the research team including the principal investigator (PI) traveled to Tallahassee, FL to demonstrate the testing on April 20th, 2022. The research team showcased and demonstrated the following:

- Describing building a laboratory environment for message level testing of CV applications that includes Kapsch RIS-9260 Roadside Unit, the Kapsch ACV-330 OBU, Trafficware COMMANDER, and V2X Hub.
- Describing the system overview; data flow; and methods of installation, configuration, and demonstration of the CV environment.
- Demonstrating the successful communication between the CV devices using the Kapsch Assist and Kapsch Insight applications installed on the Android tablet.
- Presenting testing scenarios using wired and wireless communication with and without utilizing the V2X Hub.
- Demonstrating methods that were applied in this project for encoding, capturing, and decoding the SPaT, MAP, and SRM messages.

All devices purchased as part of the project were transported with the team for use in the demonstration. These devices include the following:

- Trafficware COMMANDER DSRC enabled and Power A chord.
- Kapsch RIS-9260 RSU – 4 DSRC antennas – 2 GPS antennas.
- Two Kapsch Power over Ethernet (PoE) devices.
- Kapsch ACV-330 OBU – GPS antenna – Bluetooth antenna
- AC/DC converter to power the OBU
- Samsung Tablet A8 10.5" (Kapsch installed applications) + Screen protector + 1 Cover and 1 Charger. Other items provided by the FDOT project manager for use by the research team in project tasks that include
    - Three Trafficware Controller Interface Devices (CIDs) – 3 cables – 3 adapters.
    - SIEMENS RSU – 4 DSRC antennas – 2 GPS antennas (note: the research team updated the SIEMENS RSU software, enabled SAE J2735 and GUI)
    - One SIEMENS Power over Ethernet (PoE) device.

The research team successfully demonstrated the message level testing using the devices and communicated to the TERL staff the different steps to setup and conduct the testing. All the devices mentioned above were left at TERL for use by the TERL staff to apply the methodology developed in this project for testing CV applications.

REFERENCES

1. U.S. DOT ITS Joint Program Office. ITS Standards Training. *ITS Professional Capacity Building*. https://www.pcb.its.dot.gov/StandardsTraining/Modules.aspx?ModuleID=68#mod68. Accessed Sep. 21, 2022.
2. USDOT. Architecture Reference for Cooperative and Intelligent Transportation. *Service Packages*. https://www.arc-it.net/html/servicepackages/servicepackages-areaspsort.html. Accessed Sep. 21, 2022.
3. USDOT. Connected Vehicle Pilot Deployment Program. *U.S. Department of Transportation*. https://www.its.dot.gov/pilots/success.htm. Accessed Jun. 20, 2022.
4. CAMP LLC. *SPaT Challenge Verification Document*. CAMP – Vehicle-to-Infrastructure Consortium, Farmington Hills, MI, 2017.
5. FDOT. *Connected Vehicle Road Side Unit*. Florida Department of Transportation, Tallahassee, FL, USA, 2020.
6. Metric Engineering. *I-75 Florida's Regional Advanced Mobility Elements Roadside & Onboard Units Testing*. Florida Department of Transportation, Tallahassee, FL, USA, 2018.
7. Tampa Hillsborough Expressway Authority. *Connected Vehicle Pilot Deployment Program Phase 2, Operational Readiness Plan (ORP) –Tampa (THEA) (Report No.: FHWA-JPO-17-464)*. U.S. Department of Transportation, Tampa, FL, USA, 2019.
8. Stephens, D., T. English, N. U. Serulle, D. Gopalakrishna, and V. Garcia. *Connected Vehicle Pilot Deployment Program Phase 2, Operational Readiness Plan-WYDOT CV Pilot (Report No.: FHWA-JPO-17-472)*. U.S. Department of Transportation, Washington, DC, USA, 2018.
9. Huang, Z., E. Leslie, and A. Balse. *Infrastructure Connectivity Certification Test Procedures for Infrastructure-Based CAV Components, Test Procedures, Signal Phase and Timing – NTCIP 1202 V03 (Report No.: FHWA-JPO-20-802)*. U.S. Department of Transportation, McLean, VA, 2019.
10. Balse, A., Z. Huang, and E. Leslie. *Infrastructure Connectivity Certification Test Procedures for Infrastructure Based CAV Components, Signal Phase and Timing — SAE J2735 (Report No.: FHWA-JPO-20-801)*. U.S. Department of Transportation, Reston, VA, 2019.
11. Balse, A., Z. Huang, and E. Leslie. *Infrastructure Connectivity Certification Test Procedures for Infrastructure-Based Connected Automated Vehicle Components: Test Procedures, MAP – SAE J2735 (Report No.: FHWA-JPO-20-803)*. U.S. Department of Transportation, Reston, VA, 2019.
12. OmniAir Consortium. *Conformance Test Specifications for SAE J2945 / 1 - On-Board System Requirements for V2V Safety Communications Test Suite Structure and Test Purposes (TSS & TP)*. OmniAir Consortium, Inc., Washington, DC, USA, 2017.
13. Hailemariam, M., J. D. Schneeberger, J. S. Anderson, J. Chang, and A. O'Hara. *Connected Vehicle Pilots Phase 2 Interoperability Test-Test Report (Report No.: FHWA-JPO-18-707)*. U.S. Department of Transportation, Washington, DC, USA, 2018.
14. Anderson, J., J. D. Schneeberger, J. Chang, A. Jacobi, and M. Hailemariam. *Connected Vehicle Pilots Phase 2 Interoperability Test: Test Plan (Report No.: FHWA-JPO-18-691)*. U.S. Department of Transportation, Washington, DC, USA, 2018.
15. Thompson, C. *New Hampshire's Response to AASHTO's SPaT Challenge*. Sebago

Technics Inc., 2019.
16. Fehr, W., T. Lusco, F. Perry, J. Marousek, B. A. Hamilton, G. Krueger, and D. McNamara. Southeast Michigan 2014 Test Bed Project Architecture: Implementing the USDOT's Connected Vehicle Reference Implementation Architecture. 2013.
17. Rajbhandari, R., H. Charara, B. Brydia, and C. S. Dobrovolny. *Connected Vehicle Test Bed at the Riverside Campus*. Texas A&M Transportation Institute, College Station, TX, USA, 2014.
18. Perry, F., K. Raboy, E. Leslie, Z. Huang, and D. Van Duren. *Dedicated Short-Range Communications Roadside Unit Specifications*. U.S. Department of Transportation, McLean, VA, 2017.
19. NEMA. *NEMA Standards Publication TS 10-2019 Connected Vehicle Infrastructure – Roadside Equipment*. National Electrical Manufacturers Association, Rosslyn, VA, USA, 2019.
20. IEEE-SA Standards Board. IEEE Guide for Developing System Requirements Specifications. In *IEEE Std 1233*, IEEE, New York, NY, USA, pp. 1–36.
21. SAE-International. *Dedicated Short Range Communications (DSRC) Message Set Dictionary J2735_201603*. Society of Automotive Engineers, Troy, Michigan, USA, 2016.
22. SPaT Challenge Resource Team. *SPaT Challenge SPaT Infrastructure System Model Functional Requirements*. Vehicle to Infrastructure Deployment Coalition, Washington, DC, USA, 2018.
23. Head, L. *Multi-Modal Intelligent Traffic Signal System*. Transportation Research Institute, University of Arizona, 2012.
24. Novosad, S., S. Johnson, V. Blue, D. Miller, J. Waggoner, and B. Frey. *Connected Vehicle Pilot Deployment Program Phase 1 , System Requirements Specification (SyRS) - Tampa (THEA)*. Tampa Hillsborough Expressway Authority, Tampa, FL, USA, 2016.
25. Galgano, S., M. Talas, D. Benevelli, R. Rausch, S. Sim, K. Opie, M. Jensen, C. Stanley, D. Stephens, and D. Pape. *Connected Vehicle Pilot Deployment Program Phase 1, System Requirements Specification (SyRS) – New York City (Report No.: FHWA-JPO-16-303)*. U.S. Department of Transportation, Washington, DC, USA, 2021.
26. Gopalakrishna, D., V. Garcia, A. Ragan, T. English, S. Zumpf, R. Young, M. Ahmed, F. Kitchener, N. U. Serulle, and E. Hsu. *Connected Vehicle Pilot Deployment Concept Phase 1, System Requirements Specification (SyRS) – WYDOT (Report No.: FHWA-JPO-16-291)*. U.S. Department of Transportation, Washington, DC, USA, 2020.
27. Timcho, T. J., E. L. Young, R. A. Klein, J. L. Schroeder, and D. R. Stephens. *Vehicle-to-Infrastructure (V2I) Safety Applications: System Requirements (No.: FHWA-JPO-13-061)*. U.S. Department of Transportation, McLean, VA, 2013.
28. CAMP LLC. *Vehicle-to-Infrastructure Program V2I Safety Applications Connected Work Zone Warning Application Deployment Guideline*. CAMP – Vehicle-to-Infrastructure Consortium, Farmington Hills, MI, 2019.
29. Starr, R. *SPaT V2I Interface for Red Light Violation Warning System Requirements Specification*. Cooperative Automated Transportation (CAT) Coalition - IOO/OEM Forum, 2020.
30. Arafat, M., M. Hadi, T. Hunsanon, and K. Amine. Stop Sign Gap Assist Application in a Connected Vehicle Simulation Environment. *Transportation Research Record*, Vol. 2675, No. 9, 2021, pp. 1127–1135. https://doi.org/10.1177/03611981211006111.
31. Zulkefli, M. A. M., P. Mukherjee, Z. Sun, J. Zheng, H. X. Liu, and P. Huang. Hardware-in-

the-Loop Testbed for Evaluating Connected Vehicle Applications. *Transportation Research Part C: Emerging Technologies*, Vol. 78, 2017, pp. 50–62. https://doi.org/10.1016/j.trc.2017.02.019.

32. Szendrei, Z., N. Varga, and L. Bokor. A SUMO-Based Hardware-in-the-Loop V2X Simulation Framework for Testing and Rapid Prototyping of Cooperative Vehicular Applications. In *Vehicle and Automotive Engineering*, Springer, Cham, pp. 426–440.
33. Ma, J., F. Zhou, Z. Huang, C. L. Melson, R. James, and X. Zhang. Hardware-in-the-Loop Testing of Connected and Automated Vehicle Applications: A Use Case for Queue- Aware Signalized Intersection Approach and Departure. *Transportation Research Record*, Vol. 2672, No. 22, 2018, pp. 36–46. https://doi.org/10.1177/0361198118793001.
34. Arafat, M., M. Hadi, M. A. Raihan, M. S. Iqbal, and M. T. Tariq. Benefits of Connected Vehicle Signalized Left-Turn Assist: Simulation-Based Study. *Transportation Engineering*, Vol. 4, 2021, p. 100065. https://doi.org/10.1016/j.treng.2021.100065.
35. Ma, J., F. Zhou, Z. Huang, and R. James. Hardware-In-The-Loop Testing of Connected and Automated Vehicle Applications: A Use Case for Cooperative Adaptive Cruise Control. *IEEE Conference on Intelligent Transportation Systems, Proceedings, ITSC*, Vol. 2018-Novem, 2018, pp. 2878–2883. https://doi.org/10.1109/ITSC.2018.8569753.
36. Pu, L., and R. Joshi. *Surrogate Safety Assessment Model (SSAM): Software User Manual (Report No.: FHWA-HRT-08-050)*. U.S. Department of Transportation, McLean, VA, 2008.
37. Stephens, D., J. Schroeder, and R. Klein. *Vehicle-to-Infrastructure (V2I) Safety Applications Performance Requirements, Vol. 3, Red Light Violation Warning (RLVW) (No.: FHWA-JPO-16-250)*. U.S. Department of Transportation, McLean, VA, 2015.
38. Stephens, D. R., T. J. Timcho, R. A. Klein, and J. L. Schroeder. *Accelerated Vehicle-to-Infrastructure (V2I) Safety Applications: Concept of Operations Document (No.: FHWA-JPO-13-058)*. U.S. Federal Highway Administration Office of Safety Research and Development, McLean, VA, 2013.
39. ITE. *System Design Details (SDD) for the Connected Intersections (CI) Implementation Guide*. Institute of Transportation Engineers Connected Intersections (CI) Committee, 2021.
40. Yan, X., Y. Liu, and Y. Xu. Effect of Audio In-Vehicle Red Light–Running Warning Message on Driving Behavior Based on a Driving Simulator Experiment. *Traffic Injury Prevention*, Vol. 16, No. 1, 2015, pp. 48–54. https://doi.org/10.1080/15389588.2014.906038.
41. Banerjee, S., M. Jeihani, N. K. Khadem, and M. M. Kabir. Influence of Red-Light Violation Warning Systems on Driver Behavior–a Driving Simulator Study. *Traffic Injury Prevention*, Vol. 21, No. 4, 2020, pp. 265–271. https://doi.org/10.1080/15389588.2020.1744135.
42. Nassereddine, H., K. R. Santiago-Chaparro, J. Riehl, and D. A. Noyce. Evaluation of a Warning System Communicating Non-Connected Red-Light-Running Vehicles to Connected Vehicles Using a Driving Simulator. *International Conference on Transportation and Development 2021: Transportation Operations, Technologies, and Safety - Selected Papers from the International Conference on Transportation and Development 2021*, 2021, pp. 156–167. https://doi.org/10.1061/9780784483534.014.
43. Hussain, Q., W. K. M. Alhajyaseen, K. Brijs, A. Pirdavani, and T. Brijs. Innovative Countermeasures for Red Light Running Prevention at Signalized Intersections: A Driving Simulator Study. *Accident Analysis & Prevention*, Vol. 134, 2020, p. 105349.

https://doi.org/10.1016/j.aap.2019.105349.
44. Mohammed, M., Y. Ke, J. Gao, H. Zhang, K. El-Basyouny, and T. Z. Qiu. Connected Vehicle V2I Communication Application to Enhance Driver Awareness at Signalized Intersections. No. 4, 2016, pp. 3054–3064.
45. Stevanovic, A., A. Abdel-Rahim, M. Zlatkovic, and E. Amin. Microscopic Modeling of Traffic Signal Operations: Comparative Evaluation of Hardware-in-the-Loop and Software-in-the-Loop Simulations. *Transportation Research Record*, Vol. 2128, No. 1, 2009, pp. 143–151. https://doi.org/10.3141/2128-15.
46. Gelbal, S. Y., M. R. Cantas, B. Aksun Guvenc, L. Guvenc, G. Surnilla, H. Zhang, M. Shulman, A. Katriniok, and J. Parikh. Hardware-in-the-Loop and Road Testing of RLVW and GLOSA Connected Vehicle Applications. No. 2020-April, 2020.
47. Yun, I., B. B. Park, C. K. Lee, and Y. T. Oh. Comparison of Emergency Vehicle Preemption Methods Using a Hardware-In-The-Loop Simulation. *KSCE Journal of Civil Engineering*, Vol. 16, No. 6, 2012, pp. 1057–1063. https://doi.org/10.1007/s12205-012-1447-2.
48. Sunkari, S., H. Charara, A. Bibeka, K. Balke, and P. Songchitruksa. A Platform to Evaluate Connected Vehicle Applications Using Hardware-in-the-Loop Simulation. 2018.
49. Urbanik, T., A. Tanaka, B. Lozner, E. Lindstrom, K. Lee, S. Quayle, S. Beaird, S. Tsoi, P. Ryus, D. Gettman, S. Sunkari, K. Balke, and D. Bullock. *Signal Timing Manual - Second Edition*. The National Academies Press, Washington, DC, USA, 2015.
50. PTV AG. *PTV Vissim 2020 User Manual*. PTV Group, Karlsruhe, Germany, 2020.
51. NEMA. *Traffic Controller Assemblies with NTCIP Requirements NEMA TS 2*. National Electrical Manufacturers Association, Rosslyn, VA, USA, 2021.
52. Case, J. D., M. Fedor, M. L. Schoffstall, and J. Davin. *Simple Network Management Protocol (SNMP)*. 1989.
53. Hadi, M., K. Amine, T. Hunsanon, and M. Arafat. Evaluating the Benefits of Red-Light Violation Warning System in a Connected Vehicle Simulation Environment. *Transportation Research Record: Journal of the Transportation Research Board*, Vol. 2675, No. 11, 2021, pp. 1372–1381. https://doi.org/10.1177/03611981211026662.
54. Cash, B. North American 5.9GHz DSRC Operational Concept/Band Plan (Doc No.: IEEE 802.11-03/0750r0). *IEEE*. 31. https://mentor.ieee.org/802.11/dcn/03/11-03-0750-00-dsrc-dsrc-concept-and-band-plan-ppt.ppt. Accessed Jul. 14, 2021.
55. Bachuwar, S., A. Bulsara, H. Dossaji, A. Gopinath, C. Paredis, S. Pilla, and Y. Jia. Integration of Autonomous Vehicle Frameworks for Software-in-the-Loop Testing. *SAE International Journal of Advances and Current Practices in Mobility*, Vol. 2, No. 5, 2020, pp. 2617–2622. https://doi.org/10.4271/2020-01-0709.
56. Chowdhury, S. E. S., A. Stevanovic, and N. Mitrovic. Evaluation of Multiple Hardware and Software in the Loop Signal Controllers in Simulation Environment. *Transportation Research Record*, Vol. 2672, No. 18, 2018, pp. 93–106. https://doi.org/10.1177/0361198118784168.
57. He, Q., P. "Taylor" Li, A. Stevanovic, C. Day, J. Won, Q. Wang, T. Zhou, Y. Feng, G. Wu, M. Zlatkovic, and D. Jolovic. *Traffic Signal Simulation Cookbook Version*. Signal Simulation Subcommittee of TRB Traffic Signal Systems Committee (ACP25-3), Washington, DC, USA, 2022.
58. Econolite. ASC/3 2070 Traffic Controllers for Traffic Operations. *Econolite Controllers*. www.econolite.com/wp-content/uploads/sites/9/2016/10/controllers-asc32070software-datasheet-2018.pdf. Accessed Jun. 9, 2021.

59. Zlatkovic, M., P. T. Martin, and A. Stevanovic. Predictive Priority for Light Rail Transit. *Transportation Research Record: Journal of the Transportation Research Board*, Vol. 2259, No. 1, 2011, pp. 168–178. https://doi.org/10.3141/2259-16.
60. He, Q., K. L. Head, and J. Ding. PAMSCOD: Platoon-Based Arterial Multi-Modal Signal Control with Online Data. *Transportation Research Part C: Emerging Technologies*, Vol. 20, No. 1, 2012, pp. 164–184. https://doi.org/10.1016/j.trc.2011.05.007.
61. Day, C. M., and D. M. Bullock. Design Guidelines and Conditions That Warrant Deployment of Fully Actuated Coordination. *Transportation Research Record*, Vol. 2439, No. 1, 2014, pp. 1–11. https://doi.org/10.3141/2439-01.
62. Klanac, I. *Configuration and Assessment of Hardware-in-the-Loop-Simulation with High Resolution Data to Coordinate Traffic Signals*. Florida Atlantic University, 2016.
63. Cunningham, C. Data Transfer Rates Compared (RAM vs PCIe vs SATA vs USB vs More!). *Logical Increments blog*. http://blog.logicalincrements.com/2018/08/data-transfer-rates-bandwidth-cpu-ram-pcie-m-2-sata-usb-hdmi. Accessed Jun. 17, 2021.