CAMP LLC

Vehicle-to-Infrastructure (V2I-4) Consortium

Connected Intersection Program

Connected Signalized Intersection Verification – Field Test and Analysis Tools, Procedures and Preliminary Results

April 23, 2021

Executive Summary

This document describes the development of verification tools and test procedures to log the process and analyze the Signal Phase and Timing (SPaT) and intersection geometry (MAP) messages for Connected Intersections (CI) and test results from conducted field tests in Ann Arbor, Michigan.

As part of the implementation of safety and mobility applications based on connected traffic signal information, vehicle manufacturers need to be certain that the information provided by the traffic signal controller system via the Roadside Unit (RSU) is timely, accurate and nationally consistent as per the standards. The initial application focus is Red Light Violation Warning (RLVW).

The CI Program (CIP) is a collaborative effort with the Connected Vehicle Pooled Fund Study (CV PFS), in coordination with the University of Michigan Transportation Research Institute (UMTRI), to develop verification tools and test procedures that will enable Infrastructure Owner Operators (IOOs) to ensure proper implementation of connected signalized intersections. The Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I-4) Consortium for CIP, consisting of Ford, General Motors, Honda, Hyundai Motor Group, Nissan, and Toyota, provided the technical staff for this project.

To ensure over-the-air (OTA) broadcast of SPaT and MAP messages from connected signalized intersections, CAMP's technical team coordinated with the M-City CCI Project [1] team and established test procedures to verify SPaT and MAP message transmitted by the equipped intersections. The verification procedure was established at two levels as illustrated in Figure 1.

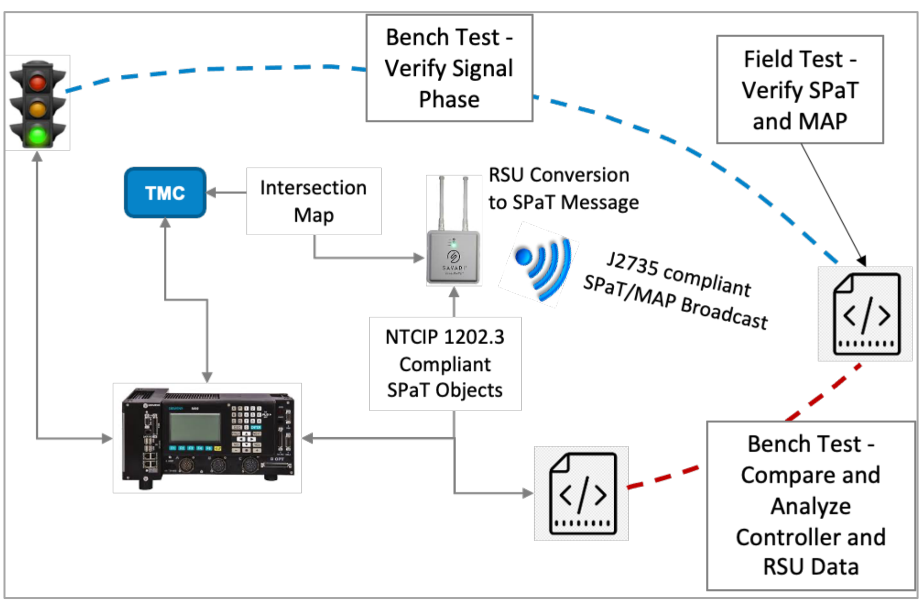

Figure 1: Test Procedure for Bench and Field Verification

1. Message-level test procedures for bench verification of an intersection control system for SPaT data from the signal controller that conforms to the SAE J2735 [2] specification from the RSU including verification of signal phase indication at the signal light and phase information in the SPaT message.
2. Application-level test procedures for field verification to:
   - Conform SPaT and MAP messages to the SAE J2735 standards specification
   - Conform all required data elements defined in the SPaT Challenge Verification Document [3] for RLVW application and additional input(s) from the USDOT/ ITE CI Project [4]
   - Verify data elements in the messages are within the proper limits as specified in J2735.

It is not feasible to anticipate and exercise all possible edge cases for any particular intersection control system in the field. The message-level verification of any particular intersection control system is expected to be performed in a laboratory setting.

Test Tool for Message Logging and Analysis

A portable tool to capture and log OTA SPaT and MAP messages for field verification and conformance consists of the following.

1. A portable Dedicated Short-range Communication (DSRC) based message receiver hardware to log broadcast messages in a format conformant with SAE J2735 using JavaScript Object Notation (JSON) Encoding Rule (JER)
2. A set of analysis and report generating software to process the logged messages as per the RLVW application requirement

Analysis Software Tool

A set of software applications was developed to process, analyze and visualize the logged messages. The analysis software requires input files for SPaT and MAP messages in a format described in Appendix A that contains message payload in JSON.

Step 1: Log SPaT and MAP messages for intersection under test.

- Log file contains both SPaT and MAP messages. It is quite likely that the file may contain messages associated with multiple intersections that are within the DSRC range.

Step 2: Separate messages for each intersection.

- In this step, logged message file is parsed and separate SPaT and MAP message files are generated for each intersection.

Step 3: Process SPaT message file.

- In this step, the SPaT message file in JSON is parsed and the associated data for the objects are extracted, analyzed and saved in a CSV formatted file for each logged message.

Step 4: Process MAP message file.

- In this step, the MAP message file in JSON is parsed and the associated data for the map objects are extracted, analyzed and saved in a CSV formatted file. In addition, a file containing data arrays to overlay the MAP message on Google Satellite view for visual verification is generated and used in step 5.
- Additionally in steps 3 and 4, a pass/fail summary report for the presence or absence of required SPaT and MAP data, as per the US Department of Transportation (USDOT) / Institute of Transportation Engineers (ITE) CI implementation and valid data limits as per SAE J2735, is generated.

Step 5: Visualize MAP message.

- In this step, a web-based application uses the generated data array file from MAP message processing in step 4 to overlay intersection map definition on Google satellite view on a web browser to visually verify the intersection definition.

Field Site Selection and Testing

The selection of intersections for field test verification was done in collaboration with the M-City CCI Project Team for connected intersections within the Ann Arbor Connected Environment. Six intersections were selected that provided varying characteristics of signal operations, intersection geometry, multiple lanes with turn pockets, three-way and four-way intersection and a traffic circle. Field tests were conducted in stationary conditions where it was safe to park the test vehicles close to the intersection in order to log broadcast messages. Intersections where traffic was heavy and unsafe to park near the intersection, messages were logged while driving through the intersection from different directions.

All intersections are equipped with Siemens M60 ATC signal controller and Lear Locomate Roadstar RSU.

Analysis of Field Tests

<u>SPaT Message:</u> Analysis of SPaT messages revealed the following.

- All intersections include required data elements for SPaT as defined in the SAE J2735 specification and the Cooperative Automated Transportation (CAT) Clarifications for Consistent Implementations (CCI) [5] Document. The need for additional data elements for CI implementation in the USDOT/ITE CI Project is listed in Appendix B.

- All intersections, except one, provided incorrect value of data the element that expresses the number of elapsed minutes of the current year in UTC time. The value was off by several hours from the time of test.
- The SPaT message analysis generates following time differences in milliseconds.
    - Time difference between consecutive messages received by the OBU from epoch timestamp - This time difference is expected to be maintained at approximately 100ms.
    - Time difference between consecutive messages generated by the RSU from message timestamp - This time difference is expected to be maintained at approximately 100ms.
    - Time difference between the message received time by the OBU and message generated time by the RSU - This time difference indicates the time taken by the RSU to the message, digitally sign and transmit.
- Analysis of time differences indicate the RSU is unable to consistently maintain SPaT message generation and transmission at 10Hz.
- For intersections that operate signals in actuated mode, when the green phase transitions into rest mode, the associated min end time indicates that the time to next phase is zero or below zero milliseconds. This is due to the processing time at the RSU for converting SPaT data to SPaT message, sign message with security certificate, place the message in queue for broadcast at the interval of 100ms and broadcast by the RSU.
- Two intersections did not broadcast SPaT messages. One of which is a non-signalized traffic circle. The other had expired security certificate for SPaT. As per the security system requirement, no message is broadcast for invalid or expired certificate.

<u>MAP Message:</u> Visualization of MAP messages for the tested intersections revealed the following.

- All intersections include required data elements in MAP message as defined in the SAE J2735 specification. The need for additional data elements for CI implementation in the USDOT/ITE CI Project is listed in Appendix B.
- Node points for egress lanes at one of the intersections are sequenced in reverse order. The first node point is not at the stop point. For egresses, the first node indicates where the outbound lane begins.
- One of the intersections has missing map definition of a right only turn lane.
- An outdated MAP message is being broadcast at one of the intersections. The lane definitions in the MAP message are not revised to reflect the reconfigured lanes.

These field test results are anticipated to provide technical input to multiple Standards Development Organizations (SDOs) developing guidelines for connected signalized intersections.

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List of Acronyms

ASN.1	Abstract Syntax Notation One
BSM	Basic Safety Message
CAMP	Crash Avoidance Metrics Partners LLC
CCI	Clarification for Consistent Implementation
CIP	Connected Intersection Program
CSIV	Connected Signalized Intersection Verification
CV PFS	Connected Vehicles Pooled Fund Study
CSV	Comma Separated Value
DSRC	Dedicated Short Range Communication
FHWA	Federal Highway Administration
GPS	Global Positioning System
IOO	Infrastructure Owner and Operator
MAP	Geometric Representation of an Intersection
OEM	Original Equipment Manufacturer
OTA	Over-the-Air
PCAP	Packet Capture
RLVW	Red Light Violation Warning
RSU	Road-side Unit
RTCM	Radio Technical Commission for Maritime Services
SDO	Standards Development Organizations
SPaT	Signal Phase and Timing
TMT	Technical Management Team
UPER	Unaligned Packed Encoding Rules
USB	Universal Serial Bus
USDOT	United States Department of Transportation
V2I	Vehicle-to-Infrastructure
V2I-4	Vehicle-to-Infrastructure 4 Consortium

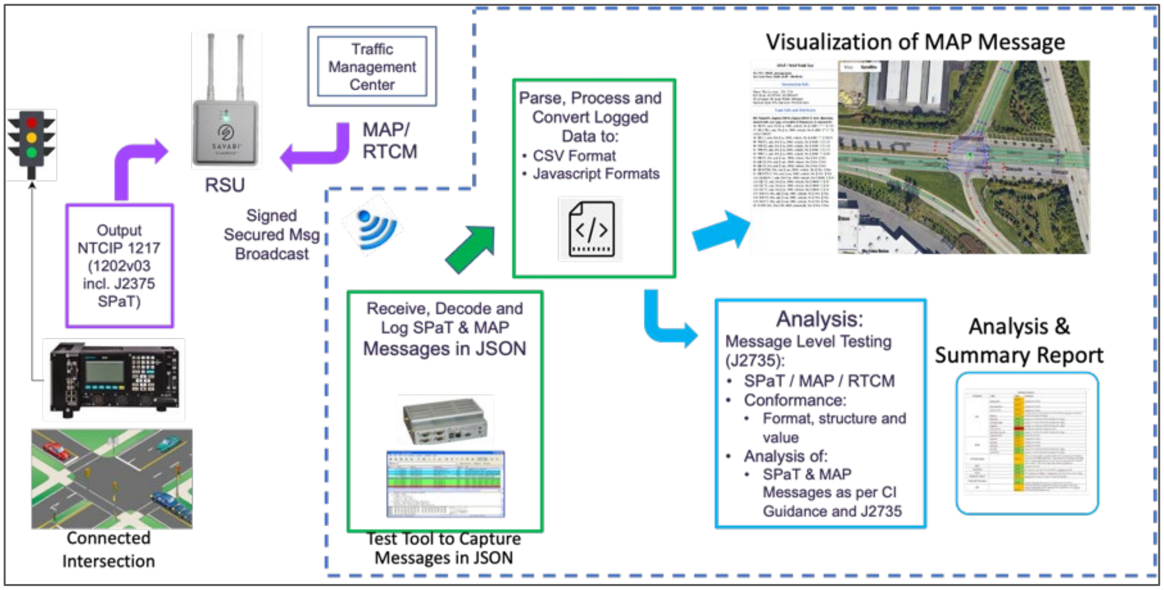
1 Introduction

For safety and mobility applications based on connected traffic signal information, vehicle manufacturers need to be certain that the information provided by the traffic signal controller system via the Roadside Unit (RSU) is timely, accurate and nationally consistent (includes J2735 and other relevant standards). Independent efforts are underway at M-City (CCI Project) to apply and verify the Clarifications for Consistent Implementations (CCI) Document developed by the Infrastructure Owners and Operators / Original Equipment Manufacturer (IOO/OEM) Forum at the Ann Arbor Connected Environment specifically for these connected intersections to support in-vehicle Red Light Violation Warning (RLVW) application. This effort is largely targeted at the infrastructure side of the over-the-air (OTA) interface. In order to have confidence in a deployed intersection's Signal Phase and Timing (SPaT), intersection geometry (MAP) and Global Positioning System (GPS) Radio Technical Commission for Maritime Services (RTCM) position correction broadcasts, verification tools and test procedures are needed to ensure proper implementation of each connected signalized intersection. Methods for ongoing state of health monitoring must also be established. Prior work by the Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium proposed initial verification procedures and test tools [6], but these require expansion and refinement to be utilized by IOOs for deployment verification of connected signalized intersections.

The CAMP V2I-4 Consortium, consisting of Ford, General Motors, Honda, Hyundai Motor Group, Nissan, and Toyota, assigned technical staff to the Technical Management Team (TMT) to this project. One of the tasks defined is to expand and refine the test / verification procedures and tools developed previously. By working interactively with the M-City CCI Project, the CAMP team evaluated and refined tools and procedures using laboratory evaluations and field testing within the Ann Arbor Connected Environment. The CAMP team also engaged with a steering group from the Connected Vehicles Pooled Fund Study (CV PFS), a program representing over half of the state IOOs in the United States and Canada, to directly communicate results from the Ann Arbor effort and provide a foundation for an expanded effort to ensure the refined tools and procedures will work appropriately in the range of infrastructure equipment and operating environments found in North America.

The CAMP TMT worked with the M-City CCI Project Team to establish test procedures to evaluate intersection performance at the lane level and timing patterns at both the message level and the application level. This includes establishing acceptable performance criteria and input gained through Connected Intersection (CI) Project under the Institute of Transportation Engineers (ITE) through US Department of Transportation (USDOT). The CI Implementation Guide defines the key capabilities and interfaces a connected signalized intersection must support to ensure interoperability with production vehicles for state and local infrastructure owner/operators (IOO). A CI is defined as an infrastructure system that broadcasts SPaT, mapping information (MAP), and position correction data to vehicles.

Figure 2 shows the scope of the field test using developed broadcast SPaT and MAP messages for test and verification for in-vehicle RLVW application.



Source: Imagery © 2021 Google, Imagery © 2021 Maxar Technologies Map Data ©2021. Overlaid data by CAMP Vehicle-to-Infrastructure (V2I-4) Consortium

Figure 2: Field Test Verification of SPaT and MAP Messages for In-Vehicle RLVW Application

As illustrated in the figure, focus of test and verification at message level is shown encapsulated inside the dashed lined box. Application-level verification needs to be performed in the field in order to assess reception of SPaT, MAP and possibly RTCM messages for the vehicle subsystem to locate itself on the proper approach lane under real-world operating conditions. However, due to resource and funding constraints, the RTCM position correction is not included in the test procedure and analysis as the deployed RSUs in the Ann Arbor Connected Environment do not support RTCM message broadcast.

1.1 Ann Arbor Connected Environment Bench Test

In addition to the field testing of selected intersections for RLVW, M-City and the Ann Arbor Connected Environment set up bench test environments to test scenarios and conditions to verify message content that are unsafe to test in field environment. As illustrated in Figure 3, the test is set up with the information flow for the bench test to exercise potential edge cases for any particular intersection control system that is not feasible to anticipate and exercise all possible edge cases in the field. In addition to SPaT/MAP messages from the RSU, the bench test includes a test of output from the signal controller illustrated as Test Point 1 for comparing against the SPaT messages from the RSU. Test setup, baseline and operational test cases are documented in separate reports [7][8][9].

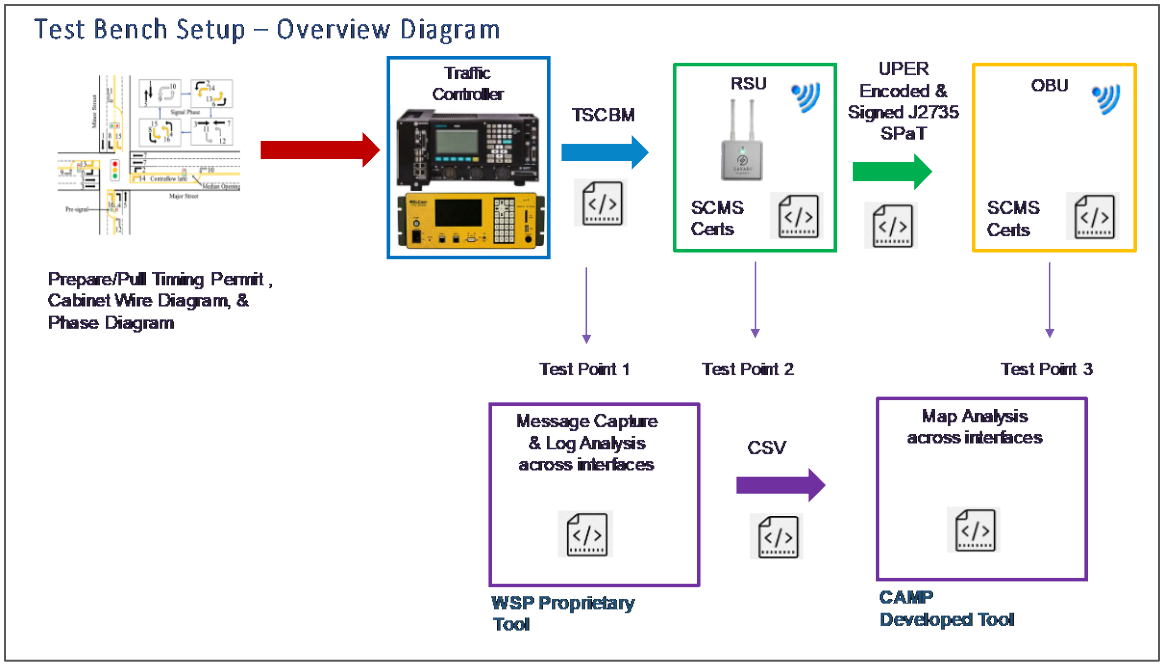


Figure 3: Bench Test Verification of SPaT from Controller and RSU for In-Vehicle RLVW Application

1.2 Organization of the Report

This report combines Subtasks 3.2 Test Procedure Definition and 3.4 Verification Tool Development under Task 3 Test Procedure and Tool Development. The report is organized in the following manner.

Section 2 describes the field tool to log broadcast messages, test setup and activation for message logging. Required message format for analysis software is also described in this section.

In Section 3, the text describes Subtask 3.4, verification tool development for message parsing and analysis including steps for generating reports in detail with examples.

Sections 4 and 5 describe Subtask 3.2, selection criteria and review of connected intersections in Ann Arbor Connected Environment for field tests and test procedures and test results, respectively.

Section 6 summarizes the test tool, field test and suggested future work.

Appendices provide detail about the SPaT and MAP message formats and test analysis report.

2 CI Field Test Tool for SPaT and MAP Message Logging and Verification

To ensure over-the-air (OTA) broadcast of SPaT and MAP messages from connected signalized intersections conform to the requirements of vehicle-based RLVW application is interoperable with deployed intersections, the CAMP technical team in coordination with the M-City CCI Project Team established test procedures to verify SPaT and MAP data transmitted by the equipped intersections. Two levels of the verification process were established as shown in Figure 4.

1. Message-level test procedures for bench verification of an intersection control system for SPaT data from the signal controller that conforms to the SAE J2735 messages from the RSU and verification of signal phase indication at the signal light and phase information in the SPaT message
2. Application-level test procedures for field verification to:
    - Conform SPaT and MAP messages to the SAE J2735 standards specification
    - Conform all required data elements defined in the SPaT Challenge Verification document for RLVW application and additional input(s) from the USDOT/ ITE CI Project
    - Verify data elements in the messages are within the proper limits as specified in J2735

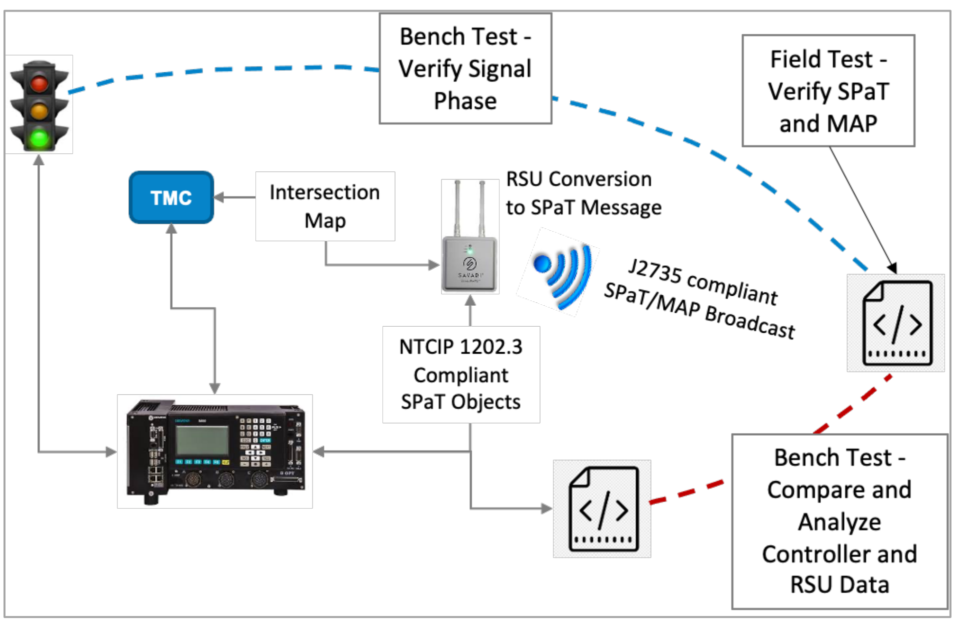


Figure 4: Test Procedure for Bench and Field Verification

A test tool for application-level field test to log and analyze OTA SPaT and MAP messages for verification and conformance was also developed. The tool consists of the following.

1. A portable Dedicated Short-range Communication (DSRC)-based message receiver hardware to receive SPaT and MAP messages and log them for processing and analysis. The receiver displays received messages on a hand-held device while logging.
2. A set of software applications to process, analyze and visualize the logged messages. The analysis application also generates reports of verification and conformance, as per the RLVW application requirements defined in CI implementation guide.

The hardware to log the messages and software to analyze them is described in the following sections.

2.1 Message Logging Tool

In 2017, CAMP contracted with a developer, eTrans Systems (now Kapsch TrafficCom), to develop a portable tool to receive and decode OTA SPaT and MAP messages and display the message content on a tablet or a hand-held device for visual verification of messages. For field testing in this project, enhancements to the tool were needed to log received messages for detail verification and analysis. CAMP engaged with the developer Kapsch TrafficCom to:

- Receive over the air transmitted SPaT, MAP and RTCM messages encoded as per the SAE J2735 201603 specification from an equipped signalized intersection.
- Decode digitally signed received messages with security certificate as per the standard.
- Log the decoded messages on a USB storage device in a file format conformant with SAE J2735 using JavaScript Object Notation (JSON) Encoding Rule (JER).
- Provide user interface to:
    a. Enter log file name or automatically generate unique file name
    b. Start/stop/pause data logging through connected hand-held device
    c. Display messages being logged on hand-held device

The DSRC-based test tool is built on an On-board Unit (OBU) to receive broadcast messages from the Road-side Unit (RSU). The messages are in Unaligned Packed Encoding Rules (UPER) encoded binary format. The message receiver decodes the messages and shows the intersection map and lane definitions from the MAP message and SPaT information on a tablet on a Google satellite view and logs the messages from intersection under test.

Figure 5 identifies the hardware components of the message logging tool. The communication interface with the OBU, the message receiver and logging device are displayed through a tablet over the Bluetooth wireless communication. The tablet also serves as a display device to view received messages in graphical form using software called "Kapsch Insight" for an Android tablet available from Google Play.

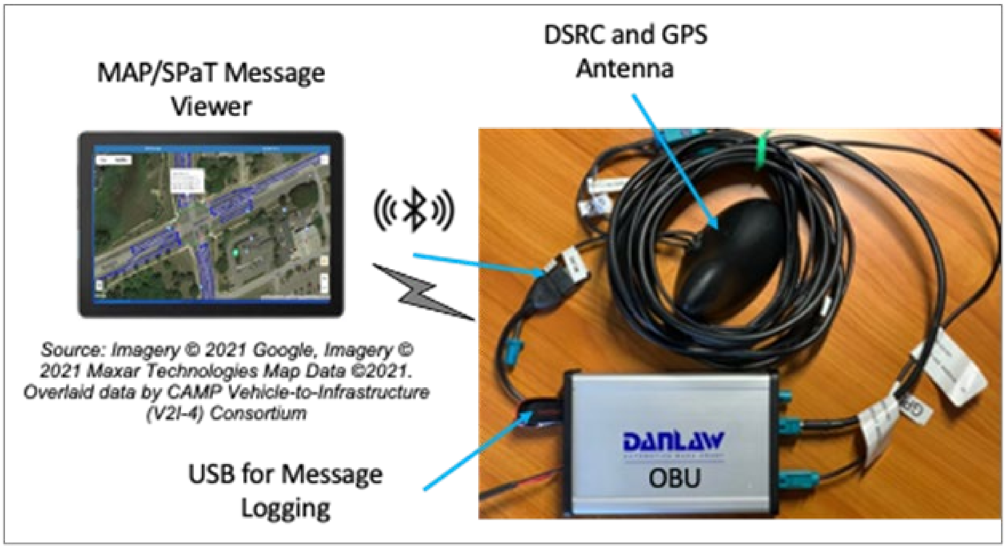


Figure 5: Field Test Tool for SPaT and MAP Message Logging

2.2 Setup and Activation for Message Logging

To view and log receive J2735 message broadcasts from an RSU, the tool is required to setup within the DSRC range. The following steps describe setting up and activating the tool.

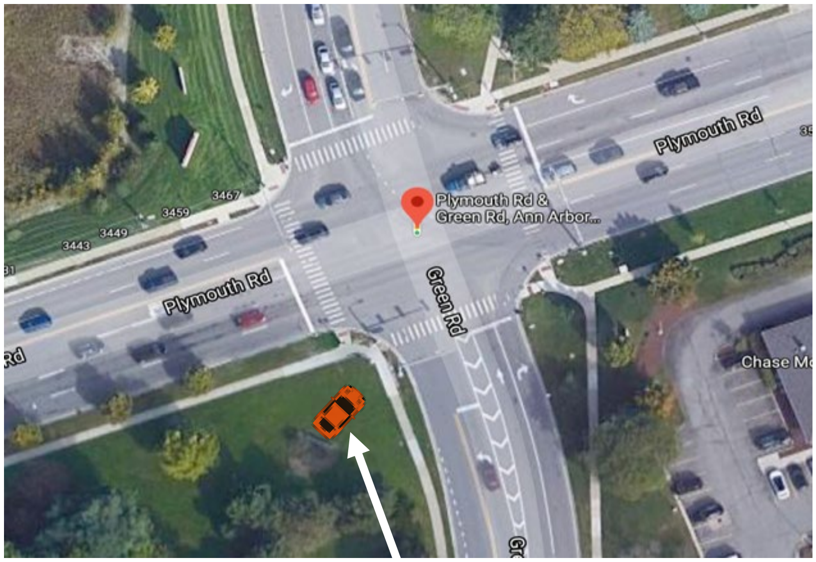
- To log the messages in JSON, the OBU is required to be updated with "obu_install-acv-3301-arm-multi-obs-1.2.6.ssx" software. This software was developed by Kapsch for this project.
- To configure message capture in JSON using an external USB drive, add following parameters to etrans.conf file in USB drive to activate message logging.

  vehicle_id = 0
  logging_json_enabled = true
- To log only the messages that are received and not transmitted by the OBU, add following parameter to the config file:

  logging_ignore_tx = true
- It is recommended to use USB 2.0 or higher version that provides sequential write speed of 3 to10 MB/s to avoid delay in data writing and data loss during logging.

The following steps describe test setup for logging messages for an intersection under test.

1. As shown in Figure 6, park the test vehicle within the DSRC range at a safe place near the intersection.



Source: Imagery © 2021 Google, Imagery © 2021 Maxar Technologies Map Data ©2021. Overlaid data by CAMP Vehicle-to-Infrastructure (V2I-4) Consortium

Figure 6: Test Vehicle for Capturing SPaT and MAP Messages at an Intersection

2. Plug in the Bluetooth transceiver to the OBU's USB port.
3. Plug in the USB mass storage containing etrans.conf file to OBU's USB port.
4. Connect the GPS and DSRC antenna to the GPS and DSRC1 connectors on the OBU.
5. Place the magnetic mount antenna on the roof of the vehicle. It is not necessary to place the antenna in the center of the vehicle.
6. Power on the tablet and launch the Kapsch Insight application.
7. Insert the USB drive and power on the OBU.
8. The OBU will boot and establish a Bluetooth connection with the tablet.
    a. The tablet requires internet connectivity to view received SPaT and MAP messages on Google Map.
9. The OBU will start logging the received SPaT/MAP data in the USB drive.

10. Select Live Map tab on the tablet to view intersection map overlaid with the received SPaT/MAP message data.

2.3 SPaT and MAP Message Log Format

The SPaT and MAP message broadcast by the RSU are in binary machine-readable packets encoded in UPER. This data format provides compact message size more suitable for transmission but for post processing, the messages are logged using JER, conformant with SAE J2735. The Figure 7 illustrates conceptual message logging using the tool.

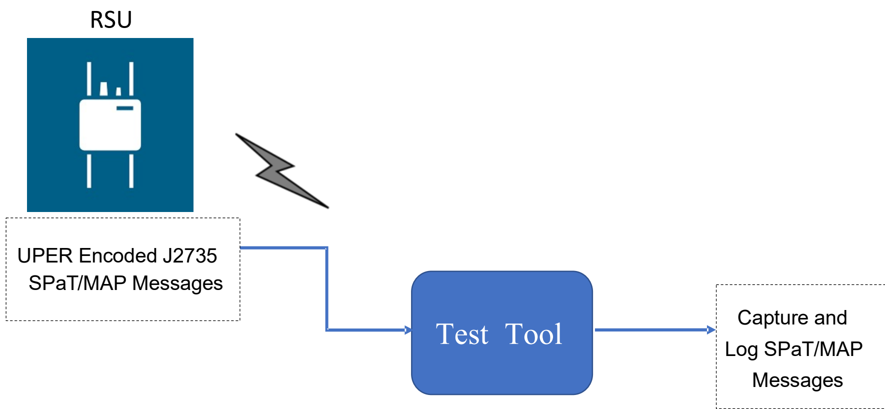


Figure 7: SPaT and MAP Message Logging Concept

The log file is a comma separated text file with each record containing four parts. Each record in the log file is separated (terminated) with a line feed. The parts of the log file are as follows:

A. TimeStamp: A 13-digit unix epoch timestamp in milliseconds since January 1, 1970 for message received by the OBU before being decoded.
B. MessageID: The J2735 MessageID to indicate message type: 18=MAP, 19=SPaT
C. Message Payload: A J2735 SPaT or MAP message payload in JSON Encoding Rules format.
D. SignedMessageIndicator: 0 represents unsigned message, 1 represents signed message but not verified.

An example of logged message for SPaT and MAP in JSON imported into Microsoft Excel is shown in Figure 8 and Figure 9, respectively.

A	B	C							D
1614109658855	19	'{"messageId":19	value:{"inter	revision:52	status:"0000	moy:78440	timeStamp:3	states:[{"sig	0
1614109658860	19	'{"messageId":19	value:{"inter	revision:53	status:"0000	moy:78440	timeStamp:3	states:[{"sig	0
1614109658865	19	'{"messageId":19	value:{"inter	revision:54	status:"0000	moy:78440	timeStamp:3	states:[{"sig	0
1614109658901	19	'{"messageId":19	value:{"inter	revision:55	status:"0000	moy:78440	timeStamp:3	states:[{"sig	0
1614109658905	19	'{"messageId":19	value:{"inter	revision:56	status:"0000	moy:78440	timeStamp:3	states:[{"sig	0
1614109658908	19	'{"messageId":19	value:{"inter	revision:57	status:"0000	moy:78440	timeStamp:3	states:[{"sig	0
1614109658912	19	'{"messageId":19	value:{"inter	revision:58	status:"0000	moy:78440	timeStamp:3	states:[{"sig	0
1614109658915	19	'{"messageId":19	value:{"inter	revision:59	status:"0000	moy:78440	timeStamp:3	states:[{"sig	0
1614109658919	19	'{"messageId":19	value:{"inter	revision:60	status:"0000	moy:78440	timeStamp:3	states:[{"sig	0
1614109658922	19	'{"messageId":19	value:{"inter	revision:61	status:"0000	moy:78440	timeStamp:3	states:[{"sig	0
1614109658926	19	'{"messageId":19	value:{"inter	revision:62	status:"0000	moy:78440	timeStamp:3	states:[{"sig	0
1614109658929	19	'{"messageId":19	value:{"inter	revision:63	status:"0000	moy:78440	timeStamp:3	states:[{"sig	0
1614109658933	19	'{"messageId":19	value:{"inter	revision:64	status:"0000	moy:78440	timeStamp:3	states:[{"sig	0

Figure 8: Example Logged SPaT Messages

A	B	C	D
1614106179682	18	{"messageId":18,"value":{"msgIssueRevision":0,"layerType":"intersecti	0

Figure 9: Example Logged MAP Message

The logged message payload in JSON is shown in column C as an example. The payload shown is a truncated message. The full message is a long string. Examples of full SPaT and MAP messages are provided in Appendix A. It is important to note that the logged messages must use the same names as specified in the ASN.1 description of J2735 SPaT and MAP message. For detail, refer to SAE J2735-201603 Final ASN specification [10].

A log file may contain SPaT and MAP messages from multiple intersections that are within the DSRC range of the test setup. It is necessary to separate the messages for individual intersection for processing. Software to process messages for analysis is described in Section 4.

2.4 SPaT / MAP Messages in JSON from Packet Capture

The test tool described in the previous section provides a built-in mechanism to receive and log UPER encoded SPaT and MAP messages in JSON as required by the message processing and analysis software. As an alternative to using the logging tool, data logs with JSON-encoded SPaT/MAP messages can be generated from Packet Capture (PCAP) formatted data files. PCAP is a standard data format used for capturing computer network traffic and is commonly used in the V2X industry for sharing data. CAMP developed a software tool which takes PCAP files as input and outputs a CSV file similar to what is described in the preceding section. The output file contains a message payload in same JSON encoding as the logging tool for parsing and analysis.

The software provides an easy to use user interface to select and convert PCAP file to JSON. Additionally, the software converts Basic Safety Message (BSM) in PCAP to JSON as well as shown as an example in Figure 10.

#	A	B	C	D	E	
1	1536932776951	'RX'	18	0	{"messageId": 18	"value": {"intersections": [{"id": {"id": 1066}
2	1536932776953	'RX'	19	0	{"messageId": 19	"value": {"intersections": [{"id": {"id": 1066
3	1536932777027	'RX'	20	0	{"messageId": 20	"value": {"coreData": {"accelSet": {"lat": 0

Figure 10: Example Logged SPaT / MAP / BSM Message

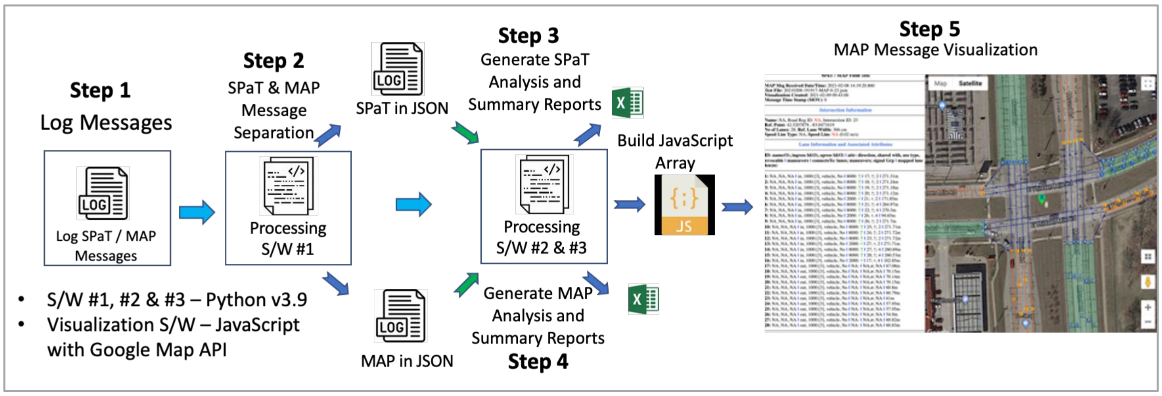
The output file format generated by the conversion software is slightly different from the logging tool. The conversion format is described below.

A. TimeStamp: A 13-digit unix epoch timestamp in milliseconds since January 1, 1970 for the received message.
B. Flag to indicate message reception (RX) or transmission (TX).
C. MessageID: The J2735 MessageID that indicates message type: 18 = MAP, 19 = SPaT, 20 = BSM .
D. SignedMessageIndicator: 0 = unsigned/unavailable, 1 = signed, 2 = signed and verified.
E. Message Payload: A J2735 SPaT, MAP or BSM message in JSON Encoding Rules format.

3 Message Processing and Analysis

One of the key elements of connected intersection verification is to process and analyze received OTA SPaT and MAP messages to ensure its conformance to defined requirements for data frames and elements as per the CI implementation guide for interoperable connected signalized intersections for the RLVW application.

As shown in Figure 11, the set software applications for processing and analysis consists of five steps.



Source: Imagery © 2021 Google, Imagery © 2021 Maxar Technologies Map Data ©2021. Overlaid data by CAMP Vehicle-to-Infrastructure (V2I-4) Consortium

Figure 11: Steps to Process and Analyze Logged Messages

3.1 Step 1: Log SPaT and MAP Messages

In Step 1, SPaT and MAP messages are logged using the tool described in Section 2. The tool is set up to log the J2735 broadcast of SPaT and MAP messages for processing and analysis. It is recommended to log messages for a sufficient amount of time to get at least three to five full cycles of SPaT messages for analysis. The logged file contains both SPaT and MAP messages, and it is quite likely that it may also contain messages associated with multiple intersections that are within the DSRC range.

The logging tool creates a unique file name for the logged data using current date and time as .csv file type. For example, file name 20210223-200715.csv indicates data collection began on February 23, 2021 at h:20, m:07, s:15 in Coordinated Universal Time (UTC).

3.2 Step 2: Separate SPaT and MAP Messages

In this step, the software application separates SPaT and MAP messages for each intersection and saves them in separate files. It is necessary to parse the log file and generate individual files for SPaT and MAP for each intersection for processing and analysis for individual intersection.

The processing software examines each record in the logged file for intersection reference ID data elements consisting of road regulator ID and intersection ID for separating logged records for individual intersection. The processing software determines the SPaT or MAP message based on message ID for the intersection and saves them in separate files. For example, in cases where three intersections are within range of the tool, with road regulator 45 and intersection IDs 173, 116 and 155, a of total six files, two for each intersection are generated. The unique file naming is generated containing the date and time from the original log file appended with SPaT or MAP as appropriate and road regulator ID and intersection ID with .json file extension as:

- For SPaT message: 20210223-200715-SPaT-45-173.json
- For MAP message: 20210223-200715-MAP-45-173.json
- For SPaT message: 20210223-200715-SPaT-45-116.json
- For MAP message: 20210223-200715-MAP-45-116.json
- For SPaT message: 20210223-200715-SPaT-45-155.json
- For MAP message: 20210223-200715-MAP-45-155.json

For the SPaT message file, all received messages are saved. However, for the MAP message, only one message is saved as only one message is required to process the intersection definition since the message content does not change every second as it is transmitted by the RSU. This application software is developed in Python programming language.

3.3 Step 3: Process and Analyze SPaT Messages:

In this step, a previously generated SPaT message .json file is processed. The received message contains several levels of nested data frames and associated data elements. The processor parses and processes nested frames and extracts data elements for each message and saves them in CSV file format. Figure 12 shows example output of the processed file in CSV format. The information shown in the figure is truncated for illustration.

epoch_TS_ms	epoch_UTC	epoch_diff_	Msg_I	TS_MO	Intx_Nam	Intx_Reg_	Intx_I	Msg_Re	Intx_Status_(	Intx_MC	Intx_TS_m	Intx_Time
1614106178971	2021/02/23:18:49:38.971	0	19	NA	NA	NA	116	19	0	78382	38689	54d:10:22:38.
1614106179064	2021/02/23:18:49:39.064	93	19	NA	NA	NA	116	20	0	78382	38791	54d:10:22:38.
1614106179163	2021/02/23:18:49:39.163	99	19	NA	NA	NA	116	21	0	78382	38891	54d:10:22:38.
1614106179261	2021/02/23:18:49:39.261	98	19	NA	NA	NA	116	22	0	78382	38993	54d:10:22:38.
1614106179364	2021/02/23:18:49:39.364	103	19	NA	NA	NA	116	23	0	78382	39093	54d:10:22:39.
1614106179463	2021/02/23:18:49:39.463	99	19	NA	NA	NA	116	24	0	78382	39191	54d:10:22:39.
1614106179564	2021/02/23:18:49:39.564	101	19	NA	NA	NA	116	25	0	78382	39291	54d:10:22:39.

Figure 12: Example - Generated Output File for SPaT Messages in CSV

Table 1 shows all the data elements of a complete SPaT message in CSV format. In addition to the data in the message, additional columns are generated that provide computed time values from the data elements in the message for further analysis. This application software is developed in Python programming language.

Table 1: C0SV File Format of Processed SPaT Message

Column	Column Heading	Description
A	epoch_TS_ms	Epoch timestamp – Message received time in milliseconds since Jan. 1, 1970
B	epoch_UTC	Converted column A to show epoch in yyyy/mm/dd:hh:mm:ss.sss format
C	epoch_diff_ms	Computed time difference in milliseconds from the previous message received
D	Msg_ID	Message Id for SPaT message
E	TS_MOY	Message timestamp in Minute of the Year format
F	Intx_Name	Descriptive name of the intersection
G	Intx_Reg_ID	Intersection road regulator ID
H	Intx_ID	Intersection ID
I	Msg_Rev	Message revision count
J	Intx_Status_Obj	Intersection status object (hex)
K	Intx_MOY	Intersection time in Minute of The Year
L	Intx_TS_ms	Intersection timestamp in milliseconds within the minute
M	Intx_Time	Computed time in days:hh:mm:ss.sss from values in col. E or K & L
N	Msg_TS_Diff_ms	Computed time difference in milliseconds from the previous message in column L
O	RX_Time_Diff_ms	Computed time difference in milliseconds between message received epoch time and the computed time in column M (RSU message timestamp)
	Intersection States – Movement List	
P	Sig_Grp_#n	Signal group #n
Q	Event_State_#n	Current event state for signal group #n
R	Sig_Phase_#n	Current signal phase for signal group #n

Column	Column Heading	Description
	Timing Section	
S	Start_TM_#n	Time mark for startTime for signal group #n
T	Start_Time_#n	Start time in 0:mm:ss.sss
U	MinEnd_TM_#n	Time mark for minEndTime for signal group #n
V	MinEnd_Time_#n	Min end time in 0:mm:ss.sss
W	Min_ET_Remain_#n	Min end time remain for the current phase – computed from col. V & M
X	Min_ET_Remain_epoch_#n	Min end time remain for the current phase – computed from col. V & A
Y	MaxEnd_TM_#n	Time mark for maxEndTime for signal group n
Z	MaxEnd_Time_#n	Max end time in: 0:mm:ss.sss
AA	Max_ET_Remain_#n	Max end time remain for the current phase – computed from col. Z & M
AB	Max_ET_Remain_epoch_#n	Max end time remain for the current phase – computed from col. Z & A
AC	Next_TM_#n	Time mark for nextTime for signal group #n
AD	Next_Time_#n	Next time in 0:mm:ss.sss
	Columns P through AD are repeated for each signal group in Intersection States	

#n - indicates signal group number

3.3.1 SPaT Summary Report

In this step, in addition to processing SPaT messages and generating a detailed output file in CSV format, a pass/fail summary report is generated as shown in Figure 13. The summary report lists all required SPaT data frames and elements for CI as defined in the CI implementation guide for the RLVW application. Table 4 in Appendix B lists the SAE J2735 data frames and elements for SPaT. The summary report indicates pass/fail to indicate presence or absence of the required data as per the CI implementation and its value within limits as defined in SAE J2735 specification.

A	B	C	D	E	F	G	H	I	J	K	L	M	N
Test Name:													
SPaT File:						# of Msg:		Test Time:					
Date & Time:													
						SAE	Pass/Fail	CI Impl.	Pass/Fail	Invaid	Data Range	Data Range	Remark
		SPaT Data				J2735	J2735	for RLVW	CI RLVW	Data	Low	High	
messageId=DE_DSRC_MessageID=19 (SPaT UPER)						M	Pass	M	Pass		0	32767	
	timeStamp=DE_MinuteOfTheYear					O	--	M	Pass		0	5274040	
	name=DE_DescriptiveName (only for debug)					O	--	O	--				
	intersections=DF_IntersectionStateList					M	Pass	M	Pass				
		name=DE_DescriptiveName (only for debug)				O	--	O	--				
		id=DF_IntersectionReferenceID				M	Pass	M	Pass				
			region=DE_RoadRegulatorID			O	--	M	Pass		0	65535	
			id=DE_IntersectionID			M	Pass	M	Pass		0	65535	
		revision=DE_MsgCount				M	Pass	M	Pass		0	127	
		status=DE_IntersectionStatusObject				M	Pass	M	Pass		513	65532	
		moy=DE_MinuteOfTheYear				O	--	O	--		0	5274040	
		timeStamp=DE_Dsecond				O	--	M	Pass		0	65535	
		enabledLanes=DF_EnabledLaneList				O	--	C	Pass				C-When revocable lane is active
		states=DF_MovementList=1 to 255 x DF_MovementS				M	Pass	M	Pass				
			movementName=DE_DescriptiveName			O	--	O	--				
			signalGroup=DE_SignalGroupID			M	Pass	M	Pass		0	255	
			state-time-speed=DF_MovementEventl			M	Pass	M	Pass				
				eventState=DE_Movemen		M	Pass	M	Pass				
				timing=DF_TimeChangeD		O	--	M	Pass				
					startTime=D	O	--	C	--		0	36001	C-If available
					minEndTime	M	Pass	M	Pass		0	36001	
					maxEndTime	O	--	M	Pass		0	36001	
					likelyTime=D	O	--	--	--		0	36001	
					confidence=[	O	--	--	--		0	15	
					nextTime=DI	O	--	C	Pass		0	36001	C-If available
Notes:	Columns A through F: SPaT objects as defined in SAE J2735												
	Column G: M - Mandatory and O - optional objects for SPaT as defined in J2735 specification												
	Column H: Pass (present), Fail (absent) or NA (Not Applicable) for the objects in SPaT messages as per column G												
	Column I: M - Mandatory and O - optional objects for SPaT as defined in the CI Guidance for RLVW application												
	Column J: Pass (present), Fail (absent) or NA (Not Applicable) for the objects in SPaT messages as per column I												
	Column K: Incorrect data value for the object or the value is ouside the range as listed in columns L and M												
	Column L: Valid lowest numeric data value as defined in J2735. Blank indicates - data frame or alphanumeric object												
	Column M: Valid highest end of data value as defined in J2735. Blank indicates - data frame or alphanumeric object												

Figure 13: SPaT Summary Report in CSV

Table 2 describes SPaT data items and each column in a summary report.

Table 2: Description of Test Summary Report for SPaT Data

Item	Description
Test Name	Test name description
SPaT File	Logged SPaT message file name
Date & Time	Date and Time of the test
# of Msg	# of messages processed

Item	Description
Test Time	Total test time in hh:mm:ss.sss
Col A thru F, Rows 6 thru 30	List of required data frames/elements for SPaT as per the CI guidance document
Column G	SAE J2735 - Indicates M (mandatory) and O (Optional) for data object as defined in the SAE J2735
Column H	Pass/Fail J2735 – Indicates Pass (presence) or Fail (absence) for the mandatory data object in the message as defined in SAE J2735
Column I	CI Implementation for RLVW – Indicates M (mandatory) or O (optional) as defined in the CI guidance for RLVW application
Column J	Pass/Fail CI RLVW – Pass/Fail is assigned under following two situations: 1. To indicate Pass (presence) or Fail (absence) of the mandatory data object in the message as defined in the CI Implementation for RLVW application 2. To indicate either the data value in the message is outside the range as defined in column L and M or the derived data value is incorrect. For example, computed hour and minute from the MinuteOfTheYear in the message could be is incorrect when compared with hour and minute in UTC of the test time.
Column K	Invalid Data – Invalid or incorrect data value in the message that is either outside the rage defined in columns L and M or the data value is within the range but incorrect
Column L	Data Range Low – Valid lowest value for the data as defined in J2735 specification
Column M	Data Range High – Valid highest value for the data as defined in J2735 specification
Column N	Remark

3.4 Step 4 – Process MAP Message:

In this step, previously generated MAP message .json file is processed. The generated output file is in CSV format. The MAP message contains several levels of nested data frames and associated data elements. Figure 14 shows an example of a generated output file in CSV. The information shown in the figure is truncated for this illustration.

Message ID	18																			
Msg Timestamp (MOY)	0																			
Msg Revision	0																			
Layer Type & ID	intersectionD	1																		
Start of Intersection																				
Intersection Name, Road Reg & Ref II	NA	NA	116																	
Msg Count	3																			
Reference Point	42.2446391	-83.71461	27.6																	
Ref Lane Width, Type & Speed	306	NA	NA																	
*** Start of Lane Set ***																				
List of Lane ID	3	4	5	6	7	8	9	10	11	12	13	16	18	19	20	21	22	23	26	27
For Lane ID -->	3																			
Lane Info - id, name, ing & egr id	3	NA	2	NA																
Lane Attributes (dir, sharedWith, lane	in	1d80	vehicle	1																
Maneuvers	8000																			
*** Start of Node Set ***	3																			
NodeSet X Offset	-2347	-1200	-1485	-1215	-1213	-960	-1273	-4874	-1348	-1321	-1402	-1024	-1041	-1485	-1657	-1836	-1789	-1902	-2190	-4194
NodeSet Y Offset	-1376	-181	-238	-245	-308	-269	-391	-1684	-435	-375	-347	-255	-239	-239	-307	-218	-168	-124	-70	57
Node Latitude (computed from offset	42.2445153	42.244499	42.244478	42.244456	42.244428	42.244404	42.244368	42.244217	42.244178	42.244144	42.244113	42.24409	42.244068	42.244047	42.244019	42.244	42.243984	42.243973	42.243967	42.243972
Node Longitude (computed from offs	-83.7148904	-83.71504	-83.71522	-83.71536	-83.71551	-83.71563	-83.71578	-83.71637	-83.71653	-83.71669	-83.71686	-83.71699	-83.71711	-83.71729	-83.71749	-83.71772	-83.71793	-83.71816	-83.71843	-83.71894
Node Attr Local	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Node Attr Disabled	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Node Attr Enabled	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Node Attr Data type	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Node Attr Data Speed	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Node Attr Width	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Node Attr Elevation	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
*** End of Node Set ***	3																			
Computed Lane	NA	NA	NA	NA	NA	NA														
ConnectsTo Lanes	12																			
ConnectsTo Allowed Maneuver	8000																			
ConnectsTo Remote Int	NA	NA																		
ConnectsTo Signal Group	2																			
ConnectsTo User Class	NA																			
ConnectsTo Conn ID	NA																			

Figure 14: Example - Generated MAP Message Output File in CSV

Additionally in this step, a MAP_data_jsArray.js file is also generated for JavaScript application software used in Step 5 to generate visualization of the MAP message for the intersection. The visualization overlays the map definition on the Google satellite view. The application software to process and generate the CSV file for MAP message detail and the JavaScript array file are developed in Python programming language.

3.4.1 MAP Summary Report

In addition to processing the MAP message, in this step, a pass/fail summary report for the MAP message is also generated as shown in Figure 15. The summary report lists all required MAP message data frames and elements as defined for CI implementation for the RLVW application. Several data elements are defined as conditionally mandatory based on its usage. Figure 15 shows the MAP summary report in CSV format. The generated summary report indicates pass/fail for presence or absence of the required data and its value within range as defined in SAE J2735 specification.

A B C D E F	G	H	I	J	K	L	M	N
Test Name:								
MAP File:								
Date & Time:								
SAE J2735 MAP Data Frames and Elements	M/O/C in SAE J2735	Pass/Fail J2735	M/O/C in CI Impl - RLVW	Pass/Fail CI RLVW	Invaid Data	Data Range Low	Data Range High	Remark
messageId=DE_DSRCmsgID=18 (MAP UPER)	M	Pass	M	Pass		0	32767	
msgIssueRevision=DE_MsgCount	M	Pass	M	Pass		0	127	
intersections=DF_IntersectionGeometryList=1 to 32 X DF_IntersectionGeometry	O	--	M	Pass				
id=DF_IntersectionReferenceID	M	Pass	M	Pass				
region=DE_RoadRegulatorID	O	--	M	Pass		0	65535	
id=DE_IntersectionID	M	Pass	M	Pass		0	65535	
revision=DE_MsgCount	M	Pass	M	Pass		0	127	
refPoint=DF_Position3D	M	Pass	M	Pass				
lat=DE_Latitude	M	Pass	M	Pass		-900000000	900000001	
long=DE_Longitude	M	Pass	M	Pass		-900000000	900000001	
elevation=DE_Elevation	O	--	M	Pass		-4096	61439	
laneWidth=DE_LaneWidth	O	--	M	Pass		0	32767	
speedLimits=DF_SpeedLimitList=1 to 9 x DF_RegulatorySpeedLimit	O	--	M	Pass				
type=DE_SpeedLimitType	C (if Incl)	Pass	M	Pass				
speed=DE_Velocity	C (if Incl)	Pass	M	Pass		0	8191	
laneSet=DF_LaneList=1 to 255 X DF_GenericLane	M	Pass	M	Pass				
laneID=DE_LaneID	M	Pass	M	Pass		0	254	0=unknown, 255=future us
laneAttributes=DF_LaneAttributes	M	Pass	M	Pass				
directionalUse=DE_LaneDirection	M	Pass	M	Pass		0	1	
sharedWith=DE_LaneSharing	M	Pass	M	Pass				
laneType=DF_LaneTypeAttributes (revocable)	M	Pass	M	Pass				
maneuvers=DE_AllowedManeuvers	O	--	M	Pass		0	4096	12 bits
nodeList=DF_NodeListXY=Choice of DF_NodeSetXY OR DF_Comput	M	Pass	M	Pass				
nodes= DF_NodeSetXY=2 to 63 X DF_NodeXY	M	Pass	M	Pass				
delta=DF_NodeOffsetPointXY	M	Pass	M	Pass				
node-XY1=DF_Node_XY_20b	O.1 (1..*)	Pass	O.4 (1..*)	--				
x=DE_Offset_B10	C (if node-XY	Pass	C (if node-XY	--		-512	511	
y=DE_Offset_B10	C (if node-XY	Pass	C (if node-XY	--		-512	511	
node-XY2=DF_Node_XY_22b	O.1 (1..*)	Pass	O.4 (1..*)	--				
x=DE_Offset_B11	C (if node-XY	Pass	C (if node-XY	--		-1024	1023	
y=DE_Offset_B11	C (if node-XY	Pass	C (if node-XY	--		-1024	1023	
node-XY3=DF_Node_XY_24b	O.1 (1..*)	Pass	O.4 (1..*)	--				
x=DE_Offset_B12	C (if node-XY	Pass	C (if node-XY	--		-2048	2047	
y=DE_Offset_B12	C (if node-XY	Pass	C (if node-XY	--		-2048	2047	
node-XY4=DF_Node_XY_26b	O.1 (1..*)	Pass	O.4 (1..*)	--				
x=DE_Offset_B13	C (if node-XY	Pass	C (if node-XY	--		-4096	4095	
y=DE_Offset_B13	C (if node-XY	Pass	C (if node-XY	--		-4096	4095	
node-XY5=DF_Node_XY_28b	O.1 (1..*)	Pass	O.4 (1..*)	--				
x=DE_Offset_B14	C (if node-XY	Pass	C (if node-XY	--		-8192	8192	
y=DE_Offset_B14	C (if node-XY	Pass	C (if node-XY	--		-8192	8192	
node-XY6=DF_Node_XY_32b	O.1 (1..*)	Pass	O.4 (1..*)	--				
x=DE_Offset_B16	C (if node-XY	Pass	C (if node-XY	--		-32768	32767	
y=DE_Offset_B16	C (if node-XY	Pass	C (if node-XY	--				
attributes=DF_NodeAttributeSetXY	O	Pass	O	--				
data=DF_LaneDataAttributeList=1 to 8 x DF_LaneDataA	O	--	O	--				
DF_LaneDataAttribute=Choice	O	Pass	C (if data is in	--				
speedLimits=DF_SpeedLimitList=1 to 9 X DF_Regul	O	--	C (if data is in	--				
type=DE_SpeedLimitType	C (if speedLin	Pass	C (if data is in	--				
speed=DE_Velocity	C (if speedLin	--	C (if data is in	--				
dWidth=DE_Offset_B10	O	Pass	C (for differen	--				
dElevation=DE_Offset_B10	O	Pass	C (for differen	--				
computed=DF_Computed Lane	O	Pass	C (For compu	--				
referenceLaneId=DE_LaneID	C (if compute	Pass	C (For compu	--				
offsetXaxis=Choice	C (if compute	Pass	C (For compu	--				
small=DE_DrivenLineOffsetSmall	O.2 (1..*) (if c	Pass	O.7 (1) (For c	--				
large=DE_DrivenLineOffsetLarge	O.2 (1..*) (if c	Pass	O.7 (1) (For c	--				
offsetYaxis=Choice	C (if compute	Pass	C (For compu	--				
small=DE_DrivenLineOffsetSmall	O.3 (1..*) (if c	Pass	O.8 (1) (For c	--				
large=DE_DrivenLineOffsetLarge	O.3 (1..*) (if c	Pass	O.8 (1) (For c	--				
rotateXY=DE_Angle	O	Pass	O (For compu	--				
connectsTo=DF_ConnectsToList=1 to 16 X DF_Connection	O	Pass	M	Pass				
connectingLane=DF_ConnectingLane	C (if connects	Pass	M	Pass				
lane=DE_LaneID	C (if connects	Pass	M	Pass				
maneuvers=DE_AllowedManeuver	O	Pass	O	--				
signalGroup=DE_SignalGroupID	O	Pass	M	Pass				

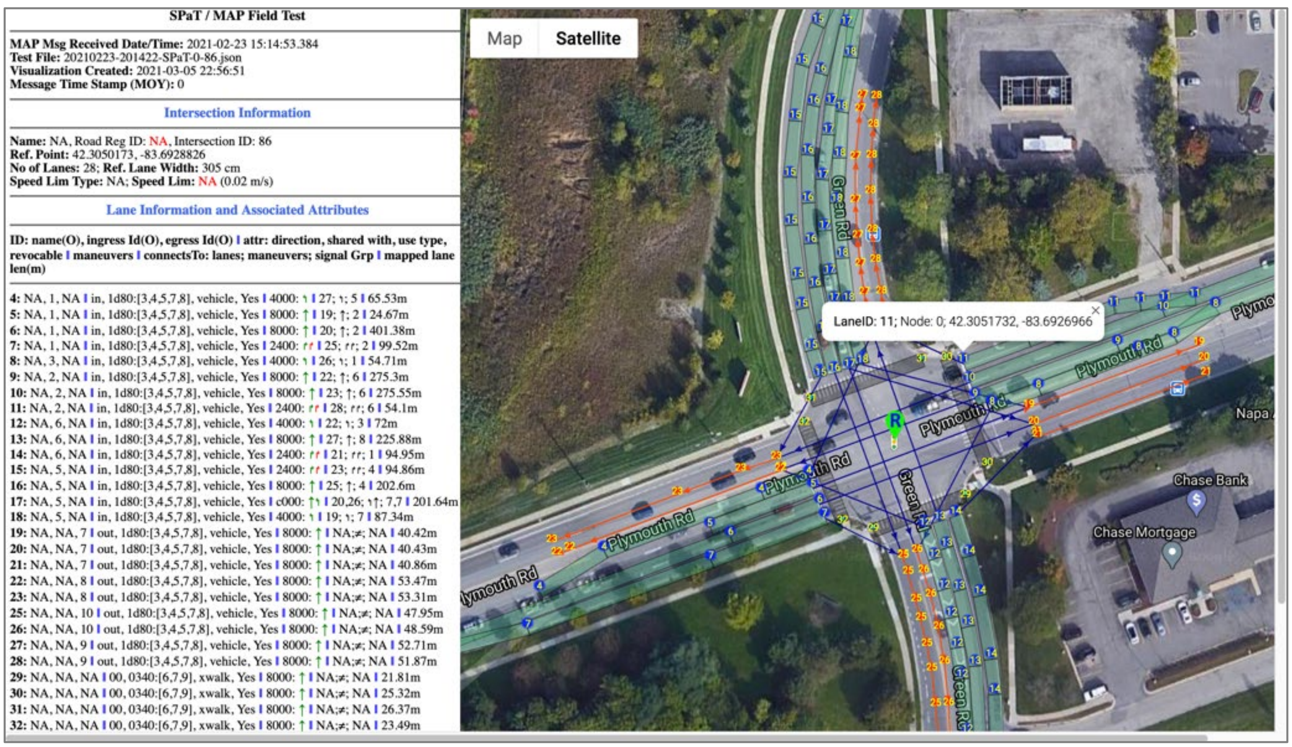
Notes:		
	Columns A-F	MAP objects as defined in SAE J2735
	Column G	M - Mandatory, O - Optional, or C - Conditional objects for MAP as defined in J2735 specification
	Column H	Pass (present), Fail (absent) or -- (Not Applicable) for the objects in MAP messages as per column G
	Column I	M - Mandatory, O - Optional or C - Conditional objects for MAP as defined in the CI Implementation Guide for RLVW application
	Column J	Pass (present), Fail (absent) or -- (Not Applicable) for the objects in MAP messages as per column I
	Column K	Invalid or incorrect data value for the object or the value is ouside the range as listed in columns L and M
	Column L	Valid lowest numeric data value as defined in J2735. Blank indicates - data frame or alphanumeric object
	Column M	Valid highest end of data value as defined in J2735. Blank indicates - data frame or alphanumeric object
	Column N	Remark

Figure 15: MAP Summary Report in CSV Format

3.5 Step 5 – MAP Message Visualization

In this step, generated MAP message data array for JavaScript is used to visualize the MAP message on a web browser. Visualization software is written in JavaScript that uses the Google satellite view to overlay the MAP message for visual verification. As shown in Figure 16, the left panel of the view provides complete detail of the intersection map that includes associated attributes for each lane in the message. The right side of the view shows overlaid lane geometry on the Google satellite view. This includes lane IDs, mapped node points, ingress lanes shaded in green, egress lanes in orange lines, and connections from ingress to egress lanes in blue. Position detail of any node can be displayed as a pop-up by moving the mouse pointer on displayed node point with lane ID.

It should be noted that the visualization is for the purpose of visual inspection and verification. The overlaid geometry of lane definitions may not exactly match the physical intersection on the Google satellite view. This could be due to combination of 1) Google map satellite view distortion due to elevation and/or 2) not precisely generated lane definition in the MAP message.



Source: Imagery © 2021 Google, Imagery © 2021 Maxar Technologies Map Data ©2021. Overlaid data by CAMP Vehicle-to-Infrastructure (V2I-4) Consortium

Figure 16: Visualization of MAP Message for Plymouth Road and Green Road Intersection, Ann Arbor, Michigan

The following table, Table 3, describes the displayed information about the intersection and the defined lanes in the MAP message.

Table 3: Description of Elements in MAP Message Visualization

Field Test Information	
• Received date and time of the MAP message	
• Test file name	
• Date and time of creation of visualization	
• Number of lanes, reference lane width (cm)	
• Speed limit type, speed limit (in units of 0.02m/s) – NA indicates not available	
Intersection Information	
• Intersection name, Road regulator ID and Intersection ID	
• Reference point location (Latitude, Longitude and Elevation)	
Lane List Information	
Lane Set Data	**Description**
Lane ID (M)	ID assigned to the lane
Name (O)	Descriptive name of the lane, NA indicates Not Available
Ingress ID (O)	Ingress approach ID, NA indicates Not Available
Egress ID (O)	Egress approach ID, NA indicates Not Available
Lane Attributes(M)	
Direction (M)	Indicates directional use, in = ingress, out = egress
Shared with (M)	Lane shared with - presence of other user types (travel modes). Hex value
Use Type	Lane usage type
Revocable	Revocable lane (Y/N)
Maneuvers (M)	
Maneuvers (M)	Allowed maneuvers (Hex value) followed by maneuver icon

Field Test Information	
List of connects to lanes (M)	
Lanes	Connecting lane ID
Maneuvers	Allowed maneuvers, indicated by maneuver icon
Signal Group	Signal group ID
Mapped Lane Length	Total length of mapped lane (M)

4 Selection of Intersections for Field Tests

The TMT collaborated with the M-City CCI Project Team to identify a corridor of connected intersections within the Ann Arbor Connected Environment that presents a broad range of operating conditions to support a robust evaluation of RLVW system performance. In this section, sites reviewed for potential site selection and the sites selected for the field tests are described.

4.1.1 Selection Criteria

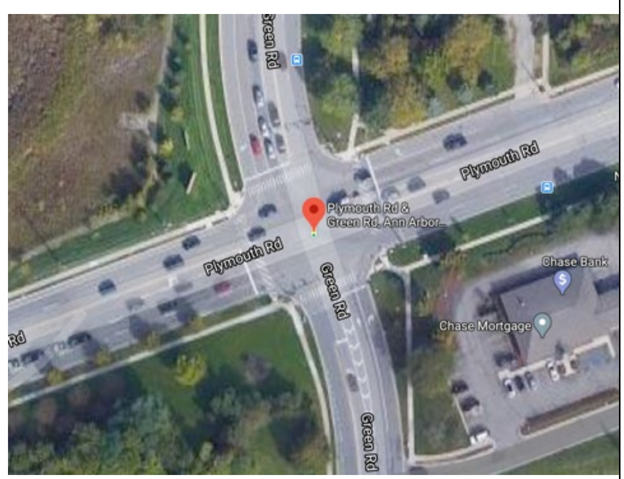
In this project, three connected signalized intersections were selected that vary in complexity as simple, moderately complex, and/or complex for field test. A simple intersection type may include 2 or 3 lanes with straight and turn movements. A moderately complex intersection type may include 3 or 4 lanes with straight, turn movements and turn pockets. A Complex intersection type may be a combination of protected and permissive movements, leading and lagging phase, etc., on top of the moderately complex intersection type.

Additionally, the intersection topology may include at least one intersection with curvature (moderately complex or complex). SPaT and MAP messages should be available and broadcast in the selected intersections. The selection of intersections may depend on the survey of SPaT and MAP, such as fixed or actuated SPaT signal operation for different times of day, node point accuracy in the MAP information, and data resources that were used to generate the MAP messages.

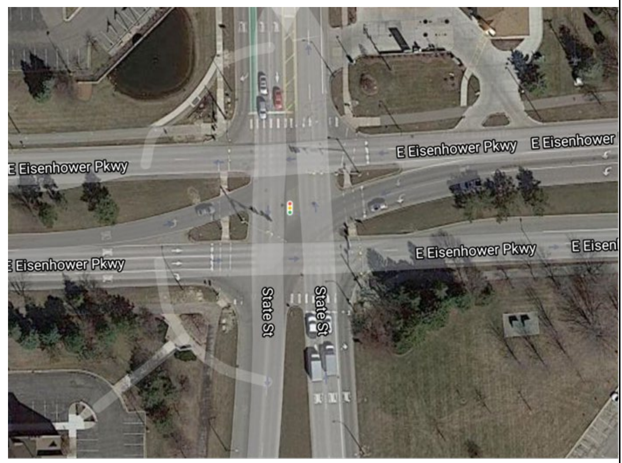
4.1.2 Review of Test Sites

The CAMP technical team reviewed sites listed in Table 4 as potential candidate field test sites in Ann Arbor, Michigan based on the selection criteria. The list of these sites was developed in coordination with M-City Ann Arbor Connected Environment Project. These intersections provide varying configurations of signal operations for SPaT and geometries for MAP verifications and are equipped with Siemens M60 ATC Signal Controller and Lear Locomote Roadstar RSUs.

Table 4: Review of Test Sites for Field Test

#	Site Locations - Ann Arbor, Michigan	Intersection – Google Map View
1	• Location: Murfin Ave. & Plymouth Rd. • Attributes: 1. Horizontal curvature and vertical slope 2. Curvature on all approaches 3. Includes turn lanes, no turn pockets	
2	• Site Identification #116 • Location: E. Eisenhower Pkwy. and Packard St. • Attributes: 1. Curvature on all approaches 2. Multiple intersecting lanes 3. No turn pockets 4. Semi complex MAP message due to lane layout and associated SPaT	
3	• Site Identification #86 • Location: Plymouth Rd. and Green Rd. • Attributes: 1. Mild curvature from Green Rd. approach 2. Varying number of approach lanes 3. Turn pockets for left and right turns 4. Leading and lagging protected and permissive turns 5. Restriped lanes	

#	Site Locations - Ann Arbor, Michigan	Intersection – Google Map View
4	• Site Identification #37 • Location: Ellsworth Rd. and State St. • Attributes: 1. Traffic Circle – non-traditional intersection 2. Approach for ingress and egress lanes for the circle 3. No turn pockets, ingress provides turning 4. Non signalized – No broadcast of SPaT message 5. Broadcast of MAP message	
5	• Site Identification #155 • Location: Plymouth Rd. and North US-23 Exit • Attributes: 1. “T” Intersection 2. Right turn pockets 3. Entrance and Exit Ramps	
6	• Site Identification #173 • Location: Fuller Rd. and Fuller Ct. • Attributes: 1. “T” Intersection 2. Turn pockets 3. Actuated signal operation ▪ 3-Phase intersection movements ▪ Dual Pedestrian movements	

#	Site Locations - Ann Arbor, Michigan	Intersection – Google Map View
7	• Site Identification #167 • Location: Ellsworth Rd. and Stone School Rd. • Conventional intersection with dedicated turn lanes	
8	• Site Identification #107 • Location: E Eisenhower Pkwy. & State St. • Major complex intersection with non-traditional lane configurations • Michigan left / U-Turn	

Source of all images in this table: Imagery © 2021 Google, Imagery © 2021 Maxar Technologies Map Data ©2021.

CAMP TMT selected the following six intersections and conducted the field tests.

Site ID #173 - Fuller Rd. and Fuller Ct.

Site ID #116 – E. Eisenhower Pkwy. and Packard St.

Site ID #86 - Plymouth Rd. and Green Rd.

Site ID #155 - Plymouth Rd. and North US-23 Exit

Site ID #107 – E. Eisenhower Pkwy. and State St.

Site ID #37 - Ellsworth Rd. and State St.

5 Field Test Results and Summary

The CAMP team conducted field tests during the afternoon peak time between 1 p.m. and 4 p.m. on two different days. SPaT/MAP broadcast messages were collected from the six intersections. For three intersections, tests were conducted and logged messages in stationary condition. For the other three intersections, due to heavy traffic and lack of safe parking within DSRC range, the CAMP team logged the messages by driving through the intersections. The following subsections describe analysis and observations of SPaT/MAP messages.

All intersections in the Ann Arbor Connected Environment are equipped with Siemens M60 ATC Signal Controllers generating SPaT and Lear Locomate Roadstar RSUs for SPaT and MAP message broadcast. All broadcast messages are digitally signed with a security appropriate certificate.

5.1 Test Analysis and Observations:

Appendix B, Table 7 and Appendix C, Table 8 lists the mandatory data for SPaT and MAP messages for CI implementation [ref] for RLVW application. The guidance defines several elements that are mandatory or conditionally mandatory for SPaT in addition to the J2735 specification.

The Ann Arbor Connected Environment Project has deployed close to 70 connected intersections based on the SAE J2735 201603 version of the specification. Additional data elements defined in the ITE/CI Project (Appendix C, Table 8) for RLVW application were not supported at the time tests were conducted.

Following subsections detail results/observations for each test site.

5.1.1 Intersection ID# 173:

Intersection Description:	Fuller Rd. & Fuller Ct., Ann Arbor, Michigan
Test Date and Start of Time (UTC):	2021/01/13 - 16:57:50.717
Number of SPaT Messages:	3430
Total Test Time:	5 min, 43 seconds

5.1.1.1 Invalid Data:

- status=DE_IntersectionStatusObject: value in message = 0, outside range (513 to 65532)
- moy=DE_MinuteOfTheYear:
    - Computed hour and minutes from moy is 08h:30m (UTC) does not match with the epoch time of 16h:57m (UTC) for message received.

5.1.1.2 Observation - SPaT Messages:

- state-time-speed=DF_MovementEventList

- MovementPhaseState
  - Protected-Movement-Allowed often called as “protected green” – for the movement phase for signal group #2, the associated minEndTime indicates negative value (~0.084ms) for approximately 13.6 s as shown in Figure 17.

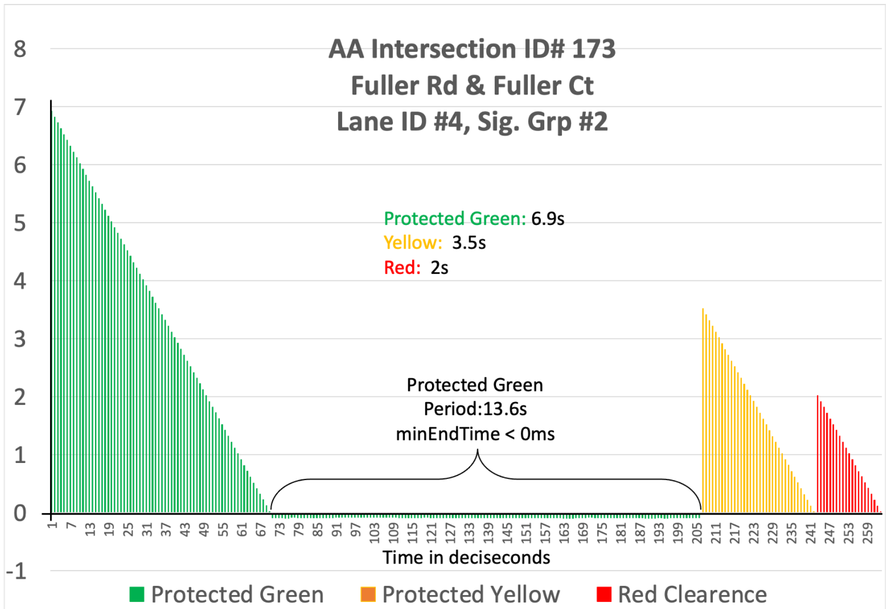


Figure 17: Protected Green minEndTime < 0s in SPaT

5.1.1.3 Observation - MAP Message:

The MAP message contains:

- Mapped lanes: 9
- Ingress lanes: 5
- Egress lanes: 3
- Crosswalk lane: 1

Figure 18 shows visualization of the MAP message for the intersection. As described in Section 4.5, the left side of the view provides complete detail for each lane and the right side provides overlaid lane definition on the Google satellite view.

At this intersection, no anomalies were observed.

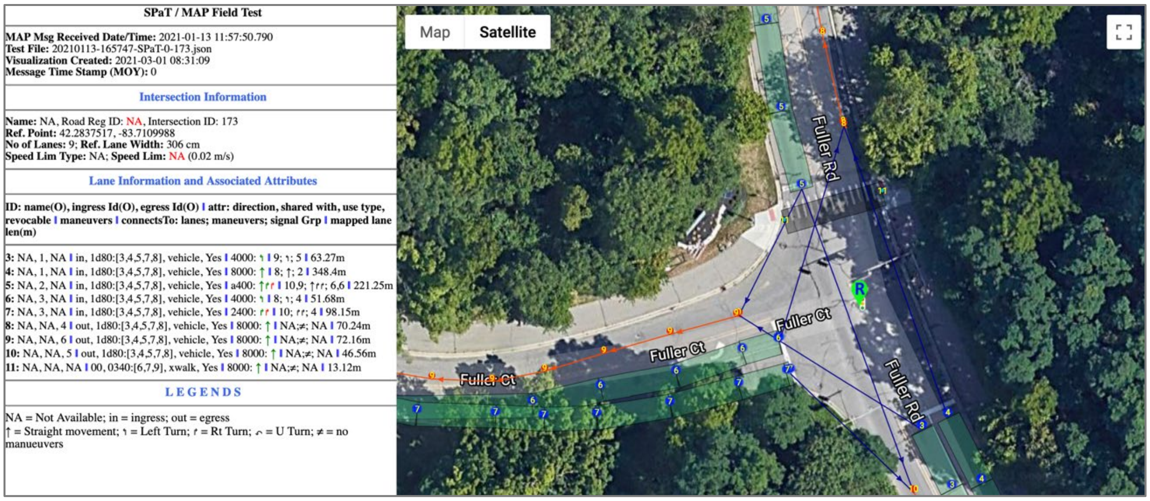


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Figure 18: Intersection MAP for Site ID# 173 - Fuller Rd. and Fuller Ct.

5.1.2 Intersection ID# 116:

Intersection Description: E. Eisenhower Pkwy. & Packard St., Ann Arbor, Michigan

Test Date and Start of Time (UTC): 2021/02/23 - 18:49:38.971

Number of SPaT Messages: 6530

Total Test Time: 10 min, 53 seconds

5.1.2.1 Invalid Data:

- status=DE_IntersectionStatusObject: value in message = 0, outside range (513 to 65532)
- moy=DE_MinuteOfTheYear:
  - Computed hour and minutes from moy data is 10h:22m (UTC) that does not match with the epoch time of 18h:49m (UTC) for the message received.

5.1.2.2 Observation - SPaT Messages:

Figure 19 shows graph of time difference between the reception of consecutive SPaT messages. The time difference is computed from logged epoch time in milliseconds at which the messages received by the test tool (OBU). In general, the time difference is close to 100 ms indicating messages are received at 10Hz. However, periodically, the time difference goes as high as 200 ms and lower than 50 ms at an approximately1500 ms interval. The SPaT messages for this intersection were logged while driving through the intersection. The periodic occurrence in the message receive time needs further investigation.

For the same intersection site ID #116, Figure 20 shows the graph of time difference between the message received and the message generation timestamp by the RSU, also in milliseconds.

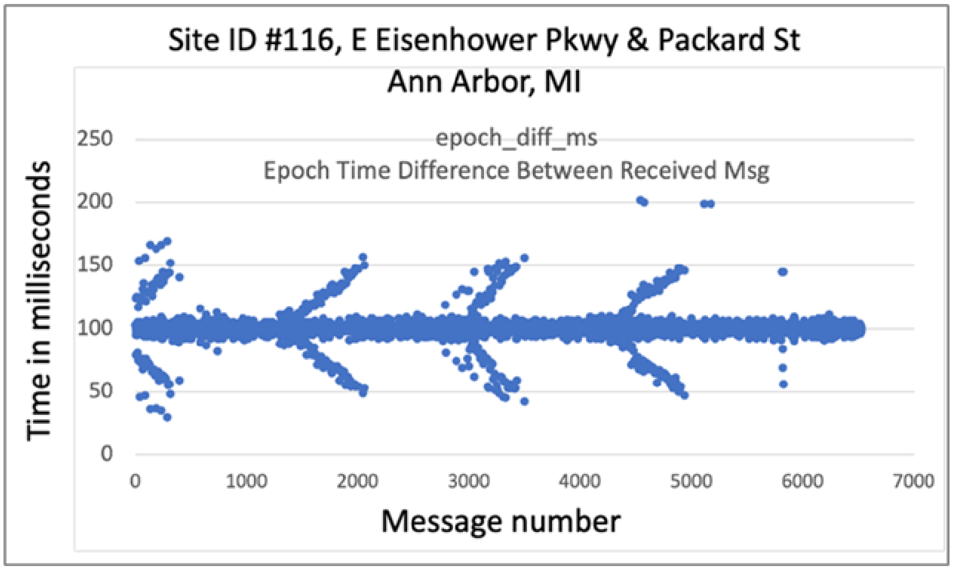


Figure 19: Time Difference Between the Consecutive Messages Received

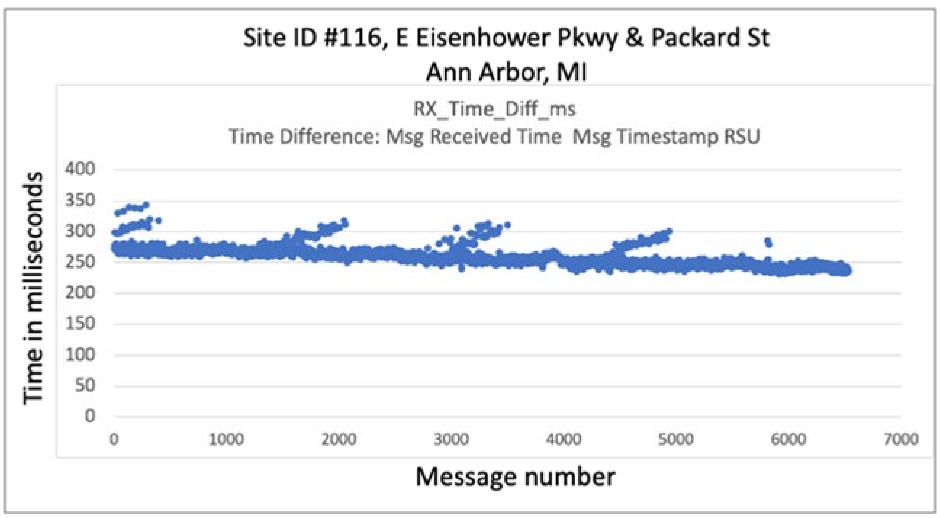


Figure 20: Time Difference Between the Message Received by the OBU and Message Generated by the RSU

As shown, the average time difference is 270 ms. In some cases, the difference is well above 300 ms at approximately the same interval of 1500 ms as shown in Figure 19 for message received time difference. This variation could be an indication that the RSU clock is not in synch with the OBU clock as they are on different time sources and the received time difference reflects a delay in transmission by the RSU. Further investigation is needed to answer the observed behavior.

5.1.2.3 Observation - MAP Message:

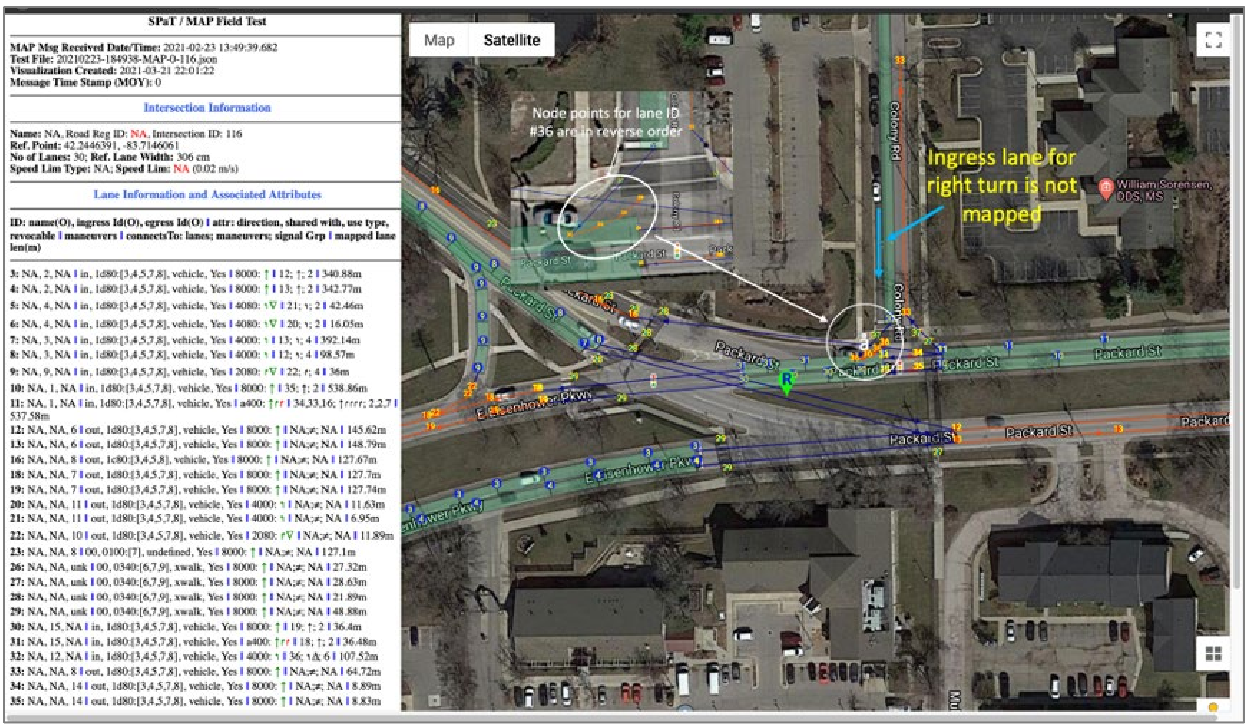
The MAP message contains:

- Mapped lanes: 30
- Ingress lanes: 12
- Egress lanes: 12
- Crosswalk lanes: 5
- Undefined lane type: 1

Figure 21 shows visualization of the MAP message for this intersection. As shown in inset, the mapped lane contains four node points for lane ID #36 that are sequenced in reverse order. The last node point is at the stop point and not the first node point.

The westbound roadway at the intersection has converging lanes creating a small section of roadway between two intersections where ingress lane connects to another section of ingress as storage area for traffic.

In the MAP message, map of the right most south bound lane of the Colony Rd. is not provided as indicated in the Figure 21.



Source: Imagery © 2021 Google, Imagery © 2021 Maxar Technologies Map Data ©2021. Overlaid data by CAMP Vehicle-to-Infrastructure (V2I-4) Consortium

Figure 21: Intersection MAP for Site ID# 116 – E. Eisenhower Pkwy. & Packard St.

5.1.3 Intersection ID# 86:

Intersection Description: Plymouth Rd. & Green Rd., Ann Arbor, Michigan

Test Date and Start of Time (UTC): 2021/02/23 - 20:15:05.956

Number of SPaT Messages: 8457

Total Test Time: 14 min, 7.5 seconds

5.1.3.1 Invalid Data:

- status=DE_IntersectionStatusObject: value in message = 0, outside range (513 to 65532)

5.1.3.2 Observation - SPaT Messages:

Unlike other intersection sites that were tested for moy=DE_MinuteOfTheYear, the computed minutes from moy data 20h:15m (UTC) did match with the epoch time for the received messages.

Figure 22 shows a graph of time difference between the consecutive SPaT messages received by the tool (OBU) in milliseconds. In general, the time difference between consecutive message received is approximately 100 ms indicating messages are received at 10Hz. However, as the graph shows, it did not remain consistent and periodically jumps to 200 ms and above or as low as 50 ms or lower. The observed variation in time difference needs further investigation.

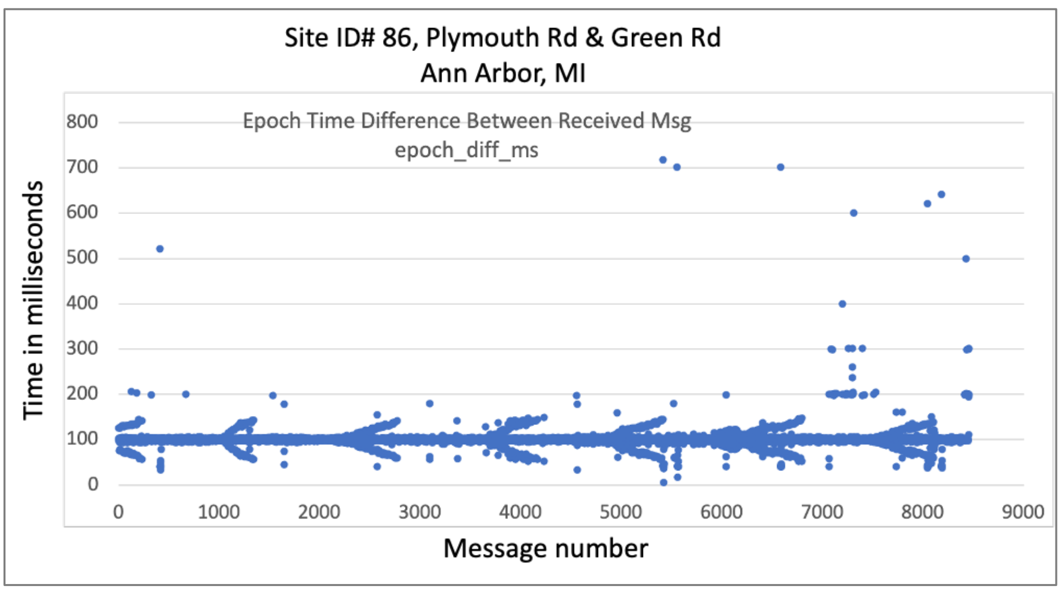


Figure 22: Site ID# 86 - Time Difference Between Consecutive Messages Received

Figure 23 shows combined graph of time difference between the consecutive SPaT messages received by the tool (OBU) in milliseconds and time difference between the message received and the message generation timestamp by the RSU.

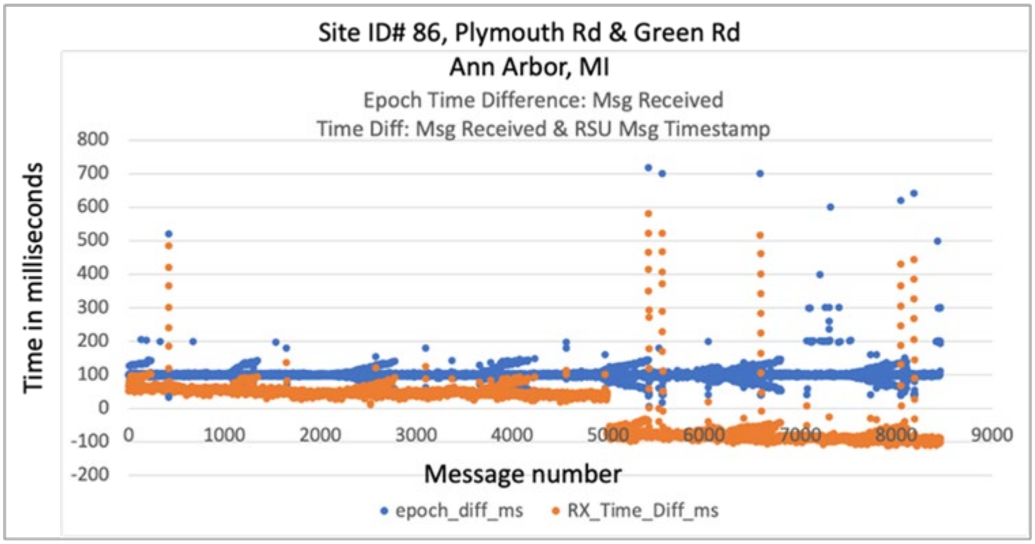


Figure 23: Site ID# 86 - Time Difference: 1) Received Messages and 2) Message Received and Message Generated

Since the RSU timestamps the message before broadcast and is later received by the OBU (both times are in UTC), it is expected that the message received timestamp is later than the message generation timestamp. As shown in the graph at the 4986th message, the time difference between the received time and the message generation time is negative. As shown in some instances, the time differences are as high as 700 ms for received message and 650 ms for received vs. generated time. Table 5 shows an anomaly in a segment of ten messages where received time is earlier than the generation time.

Table 5: Site ID# 86 - Time Difference Between Message Received and Message Generated

#	A	B	C	D	E	F	G	H	I
4981	1614111804425	2021/02/23 - 0:23:24.425	98	2	77543	24387	53d: 20:23:24.387	38	100
4982	1614111804525	2021/02/23 - 0:23:24.525	100	3	77543	24487	53d: 20:23:24.487	38	100
4983	1614111804630	2021/02/23 - 0:23:24.630	105	4	77543	24587	53d: 20:23:24.587	43	100
4984	1614111804736	2021/02/23 - 20:23:24.736	106	5	77543	24687	53d: 20:23:24.687	49	100
4985	1614111804825	2021/02/23 - 20:23:24.825	89	6	77543	24787	53d: 20:23:24.787	38	100
4986	1614111804924	2021/02/23 - 20:23:24.924	99	7	77543	25000	53d: 20:23:25.000	-76	213
4987	1614111805028	2021/02/23 - 20:23:25.028	104	8	77543	25100	53d: 20:23:25.100	-72	100
4988	1614111805125	2021/02/23 - 20:23:25.125	97	9	77543	25202	53d: 20:23:25.202	-77	102

#	A	B	C	D	E	F	G	H	I
4989	1614111805226	2021/02/23 - 20:23:25.226	101	10	77543	25302	53d: 20:23:25.302	-76	100
4990	1614111805324	2021/02/23 - 20:23:25.324	98	11	77543	25402	53d: 20:23:25.402	-78	100

Where:

- Column #: SPaT message number
- Column A: Epoch timestamp in milliseconds
- Column B: Current UTC date and time of the received message
- Column C: Received message time difference from the previous message in milliseconds
- Column D: Message revision count
- Column E: Message generation timestamp in MinuteOfTheYear as defined in SAE J2735
- Column F: Message generation timestamp in DSecond as defined in SAE J2735 within the current minute
- Column G: Current day of the current year and time of message generation by the RSU. Computed from Columns E and F
- Column H: Time difference in millisecond within current minute from message received time Column B and message generation time in Column G
- Column I: Time difference in milliseconds (DSecond) from the previous message generation time in Column F

As shown in highlighted SPaT message, the message received time is earlier than the generation time. Also, the message generation time is doubled from the previous message indicating timestamp anomaly at the RSU.

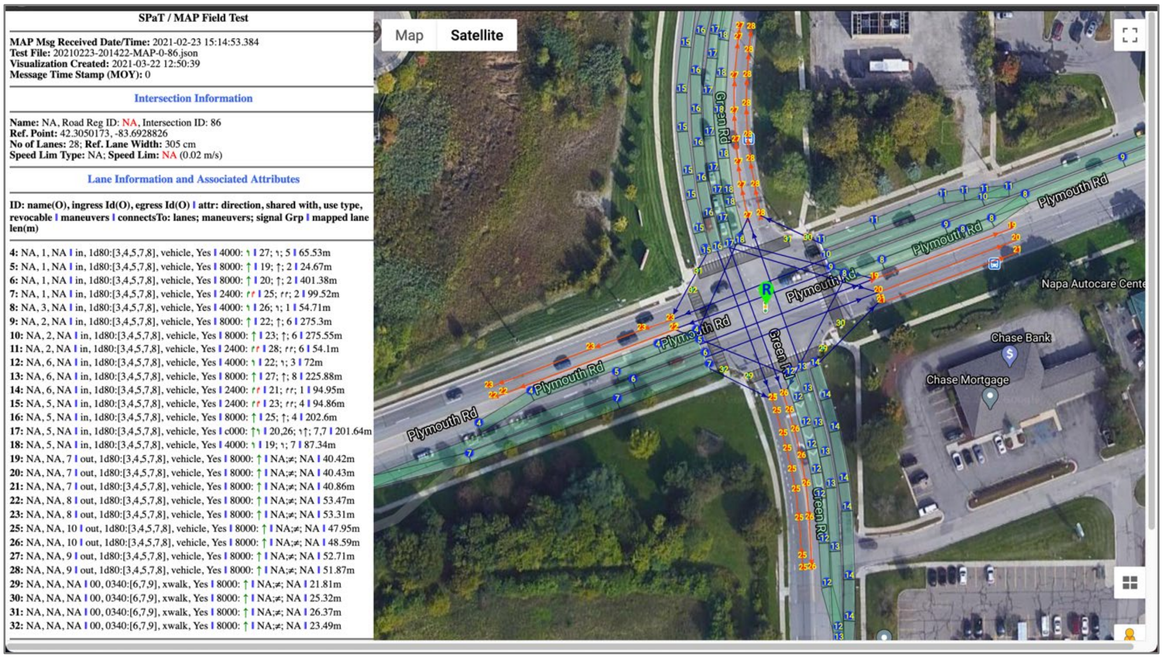
5.1.3.3 Observation - MAP Message:

The MAP message contains:

- Mapped lanes: 28
- Ingress lanes: 15
- Egress lanes: 9
- Crosswalk lanes: 4

Figure 24 shows visualization of the MAP message for this intersection. Since the geographic map of the intersection was developed for MAP message, the road has been resurfaced and the driving lanes are reconfigured. The left turn lane from northbound

Green Rd. to westbound Plymouth Rd. is reconfigured. However, the broadcast MAP message is not updated to reflect the change.



Source: Imagery © 2021 Google, Imagery © 2021 Maxar Technologies Map Data ©2021. Overlaid data by CAMP Vehicle-to-Infrastructure (V2I-4) Consortium

Figure 24: Intersection MAP for Site ID# 86 - Plymouth Rd. & Green Rd.

5.1.4 Intersection ID# 155:

Intersection Description:	Plymouth Rd. and North US-23 Exit
Test Date and Start of Time (UTC):	2021/02/23 - 20:14:27.456 (UTC)
Number of SPaT Messages:	2123
Total Test Time:	15 min, 9.058 seconds

5.1.4.1 Invalid Data:

- status=DE_IntersectionStatusObject: value in message = 0, outside range (513 to 65532)
- moy=DE_MinuteOfTheYear:
  - Computed hour and minutes from moy data is 10h:22m (UTC) which does not match with the epoch time of 18h:49m (UTC) for the message received.

5.1.4.2 Observation - SPaT Messages

Figure 25 shows time difference between the message received time at the OBU and the message generation by the RSU. Closer review of the logged timestamps indicates inconsistent time interval between the messages generated at the RSU.

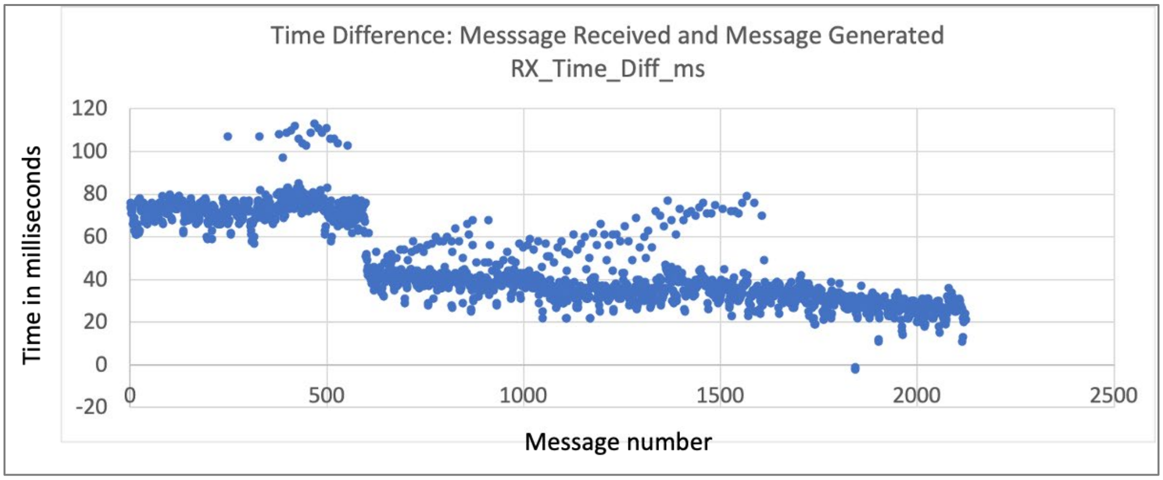


Figure 25: Site ID# 155 - Time Difference Between Message Received and Message Generated

Further analysis of the time difference between consecutive messages received is shown in the upper graph and messages generated in the lower graph in Figure 26. The upper graph of the message received time at OBU reflects the variation shown in the lower graph of message generation time at the RSU.

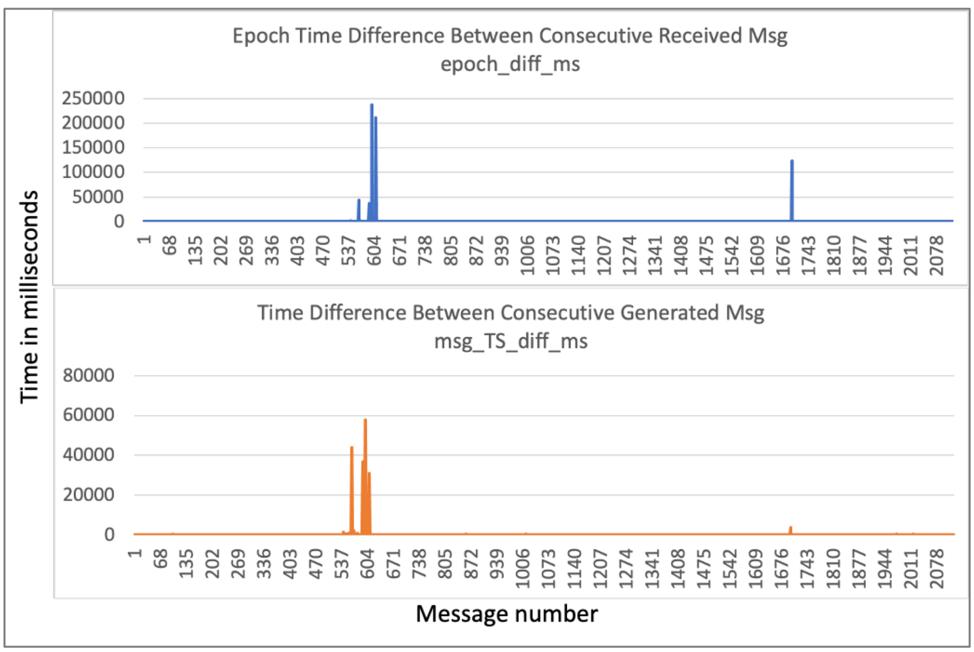


Figure 26: Time Difference: Upper Graph - Received Messages, Lower Graph - Generated Messages

Table 6 shows a segment of ten SPaT messages for the intersection with highly fluctuating timestamp for the generated messages.

Table 6: Site ID# 155 - Time Difference Between Message Received and Message Generated

#	A	B	C	D	E	F	G	H	I
591	1614111386653	2021/02/23 - 20:16:26.653	101	87	78469	26578	54d - 11:49:26.578	75	99
592	1614111423252	2021/02/23 - 20:17:03.252	36599	72	78469	3182	54d - 11:49:03.182	70	36604
593	1614111423345	2021/02/23 - 20:17:03.345	93	73	78469	3282	54d - 11:49:03.282	63	100
594	1614111424850	2021/02/23 - 20:17:04.850	1505	88	78469	4775	54d - 11:49:04.775	75	1493
595	1614111425048	2021/02/23 - 20:17:05.048	198	90	78469	4979	54d - 11:49:04.979	69	204
596	1614111428749	2021/02/23 - 20:17:08.749	3701	127	78470	8687	54d - 11:50:08.687	62	3708
597	1614111429851	2021/02/23 - 20:17:09.851	1102	11	78470	9784	54d - 11:50:09.784	67	1097
598	1614111447149	2021/02/23 - 20:17:27.149	17298	57	78470	27073	54d - 11:50:27.073	76	17289
599	1614111684836	2021/02/23 - 20:21:24.836	237687	21	78474	24785	54d - 11:54:24.785	51	57712
600	1614111684937	2021/02/23 - 20:21:24.937	101	22	78474	24885	54d - 11:54:24.885	52	100

Where:

- Column #: SPaT message number
- Column A: Epoch timestamp in milliseconds
- Column B: Current UTC date and time of the received message
- Column C: Received message time difference from the previous message in milliseconds
- Column D: Message revision count
- Column E: Message generation timestamp in MinuteOfTheYear as defined in SAE J2735
- Column F: Message generation timestamp in DSecond as defined in SAE J2735 within the current minute
- Column G: Current day of the current year and time of message generation by the RSU. Computed from Columns E and F
- Column H: Time difference in milliseconds within current minute from message received time Column B and message generation time in Column G
- Column I: Time difference in milliseconds (DSecond) from the previous message generation time in Column F.

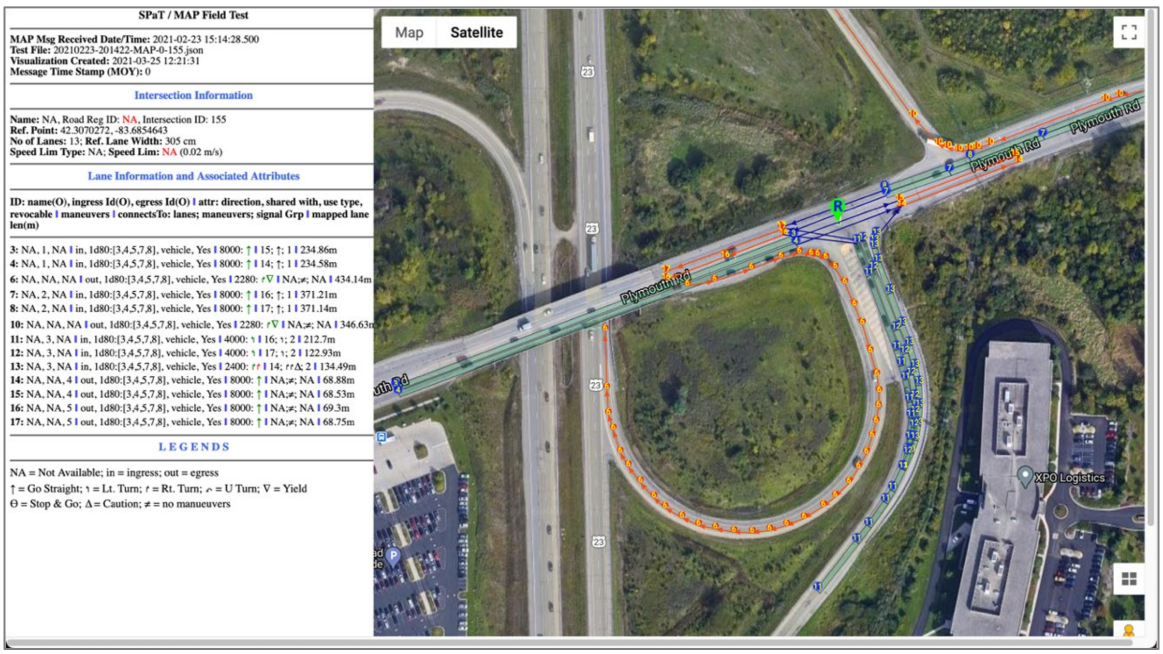
Columns G, H and I show large a variation in time between consecutive generated message timestamps from the RSU. It should also be noted that the message revision count in Column D is out of sequence except for message number 593 and 600 which indicates 100 ms time difference in Column I.

5.1.4.3 Observation - MAP Message:

The MAP message contains:

- Mapped lanes: 13
- Ingress lanes: 7
- Egress lanes: 6

Figure 27 shows visualization of the MAP message for this intersection.



Source: Imagery © 2021 Google, Imagery © 2021 Maxar Technologies Map Data ©2021. Overlaid data by CAMP Vehicle-to-Infrastructure (V2I-4) Consortium

Figure 27: Intersection MAP for Site ID# 155 - Plymouth Rd. & North US-23 Exit

5.1.5 Intersection ID# 107:

Intersection Description:	E. Eisenhower Pkwy. & State St.
Test Date and Start of Time (UTC):	2021-02-23 20:37:51.031
Number of SPaT Messages:	None – No SPaT messages received
Total Test Time:	Not available

5.1.5.1 Observation - SPaT Messages:

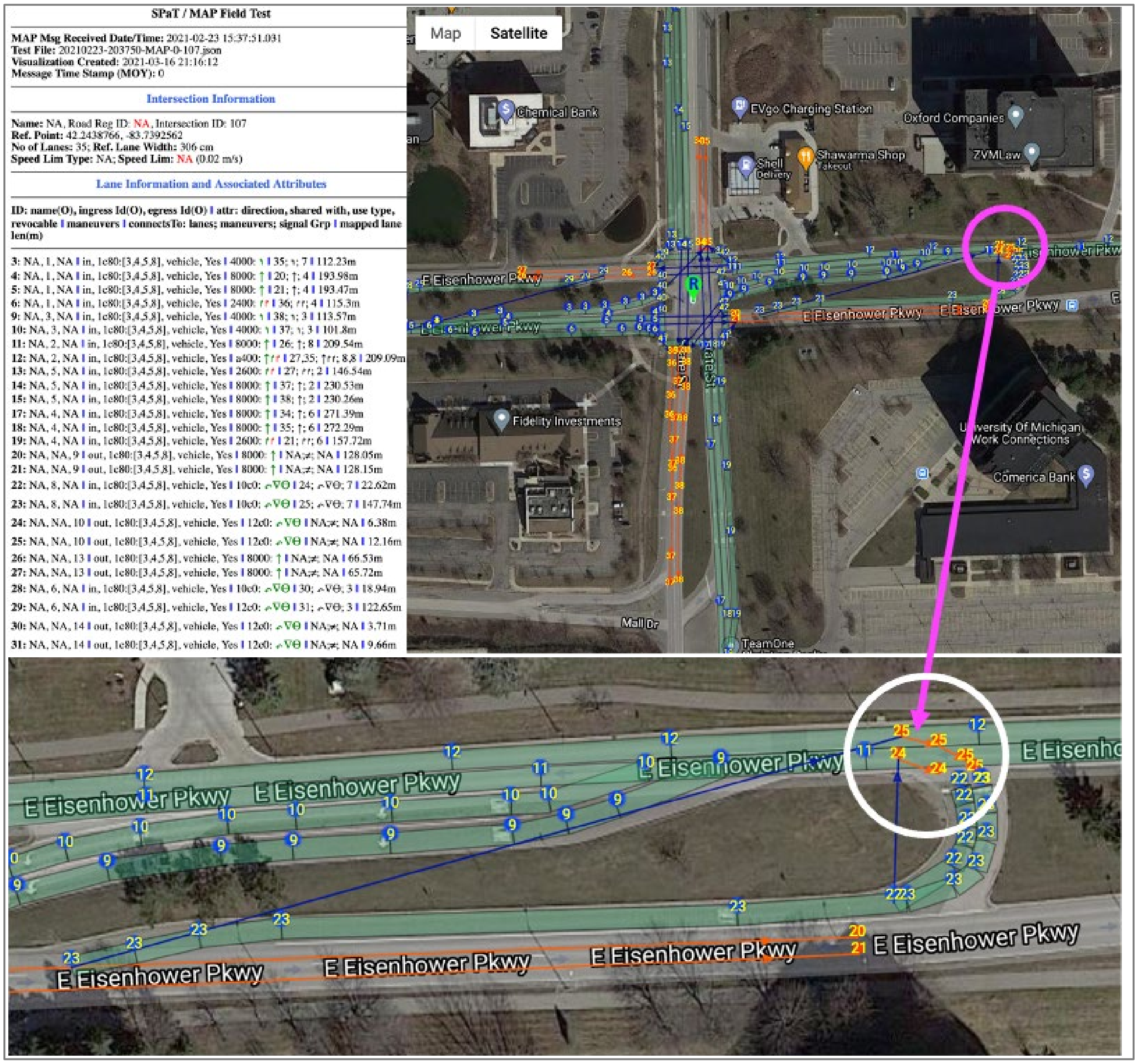
At this intersection, SPaT messages were not broadcast, only the MAP message was broadcast. The likely reason given was that the security certificate for SPaT has expired and, as per the security system requirement, no message is broadcast for invalid or expired certificate.

5.1.5.2 Observation - MAP Message:

The MAP message contains:

- Mapped lanes: 35
- Ingress lanes: 18
    - Egress lanes: 13
    - Crosswalk lanes: 4

Figure 28 shows visualization of the MAP message for this intersection. As shown highlighted, the mapped ingress lanes ID# 22 and ID# 23 connect to egress lanes ID# 24 and ID# 25, respectively. The mapped nodes defined for the egress lanes are in reverse order. As defined in the CI guidance, the first node point indicates the stop point and not the last node point as defined in the broadcast MAP message. For egresses, the first node indicates where the outbound lane begins.



Source: Imagery © 2021 Google, Imagery © 2021 Maxar Technologies Map Data ©2021. Overlaid data by CAMP Vehicle-to-Infrastructure (V2I-4) Consortium

Figure 28: Intersection MAP for Site ID# 107 – E. Eisenhower Pkwy. & State St.

5.1.6 Intersection ID# 37:

Intersection Description:	Ellsworth Rd. & State St.
Test Date and Start of Time (UTC):	2021-02-23 20:39:18.007
Number of SPaT Messages:	None – No SPaT messages received
Total Test Time:	Not available

5.1.6.1 Observation - SPaT Messages:

This traffic circle is not signalized and hence SPaT messages were not broadcast, only the MAP message was broadcast.

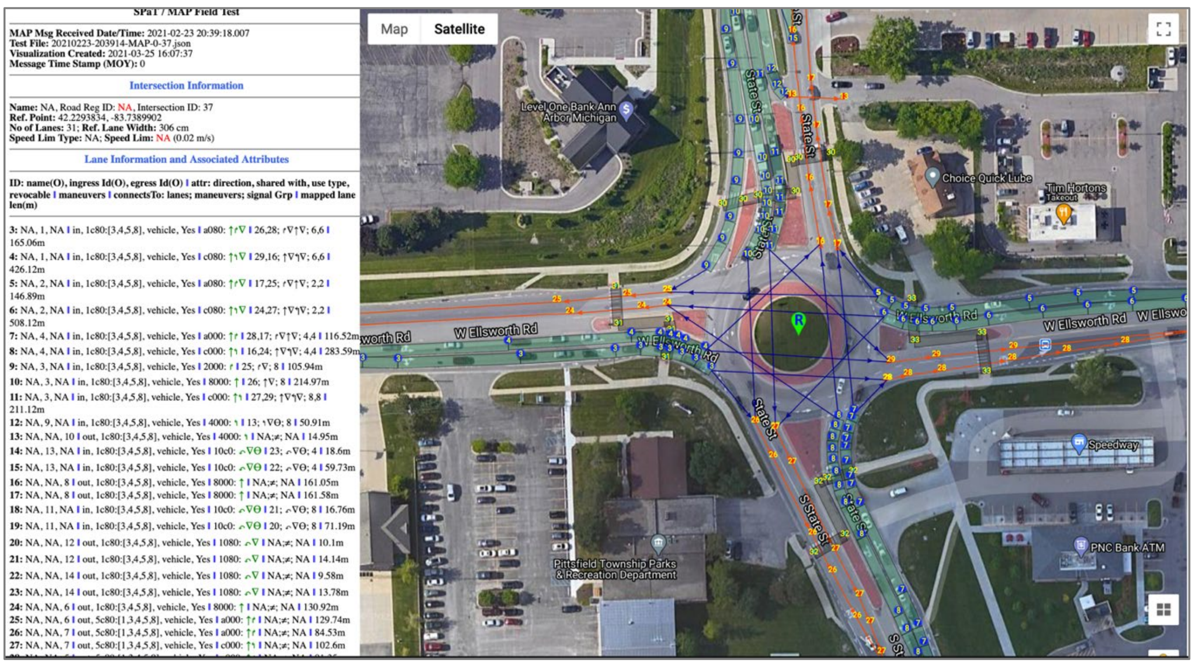
5.1.6.2 Observation - MAP Message:

The MAP message contains:

- o Mapped lanes: 31
- o Ingress lanes: 14
- o Egress lanes: 13
- o Crosswalk lanes: 4

No MAP message anomalies were observed.

Figure 29 shows visualization of the MAP message for the traffic circle test site.



Source: Imagery © 2021 Google, Imagery © 2021 Maxar Technologies Map Data ©2021. Overlaid data by CAMP Vehicle-to-Infrastructure (V2I-4) Consortium

Figure 29: Intersection MAP for Site ID# 37 - Ellsworth Rd. & State St. Traffic Circle

6 Summary

As a step towards ensuring implementation of safety and mobility applications based on connected traffic signal information, vehicle manufacturers need to be certain that the information provided by the traffic signal controller system via the Roadside Unit (RSU) is timely, accurate and nationally consistent as per the relevant standards. This report describes the development of test tool and analysis software to test and verify Connected Intersections for OTA SPaT and MAP messages for the in-vehicle RLVW application. This effort is largely targeted at the infrastructure side of the interface.

The CAMP technical team worked with the M-City CCI Project Team to identify candidate intersections for bench-level and field-level tests and established test procedures to evaluate intersection performance at the lane level and timing patterns at the message level. Since it is not feasible to anticipate and exercise all possible edge cases for any particular intersection control system in the field, message-level performance from the signal controller to the SPaT message from the RSU is performed in a laboratory setting and application-level performance tests in the field were conducted for six intersections for SPaT and MAP broadcast messages. The broadcast did not include RTCM position corrections since these are not supported by the deployed RSUs.

6.1 SPaT and MAP Message Logging Tool

The CAMP TMT worked with the previously developed test tool developer and enhanced the tool to log OTA binary encoded messages in a format conformant with SAE J2735 using JavaScript Object Notation (JSON) Encoding Rule (JER). This enhanced capability allowed portability of logged messages for post processing, a main objective of this project.

6.2 SPaT and MAP Message Process and Analysis Software

A set of software modules were developed to process collected messages that contain several levels of nested data frames and associated data elements, a generated analysis, and a pass/fail summary report in CSV format and web browser-based MAP message visualization.

<u>Summary Report:</u> The summary report lists all required SPaT and MAP data frames and elements for CI implementation as defined in the CI guidance document for the RLVW application. The generated summary indicates presence or absence of the required data and its value within range as defined in SAE J2735 specification.

<u>MAP Message Visualization:</u> The web browser-based MAP visualization software shows complete lane-level detail of the intersection map that includes associated attributes for each lane in the message. It also shows defined lane geometry overlaid on the Google Satellite View. The lane geometry includes lane IDs, mapped node points, ingress and egress lanes and connections from ingress to egress lanes. Node level detail is shown as a pop-up by placing the mouse cursor on the node.

6.3 Field Test

The CAMP TMT in coordination with Ann Arbor Connected Environment Project conducted filed tests and collected data for six intersections. Prior to selecting intersections for field tests in Ann Arbor, Michigan, the TMT reviewed intersections for varying characteristics of signal operation, intersection geometry, multiple lanes with turn pockets, three-way and four-way intersection and a traffic circle. TMT selected six intersections and conducted field tests. Field tests contained both stationary conditions where it was safe to park and driving through the intersection and where traffic was heavy and unsafe to park for conducting stationary test.

SPaT Message: Analysis of SPaT messages revealed the following:

- All intersections include required data elements in SPaT as defined in the SAE J2735 specification. The additional required data elements specified in the CI guidance document for RLVW application is required to be added in the message once the guidance is published.
- For all intersections except one, message timestamp that provides minute of the year (DE_MinuteOfTheYear) is off by several hours from the time the test was conducted.
- The computed time difference between the consecutive messages from the RSU provided in the message as timestamp (DE_DSecond) data element in milliseconds within the minute does not remain consistent at 100ms (10Hz message frequency). Often the time different periodically deviates significantly between messages as observed in the analysis.
- Similarly, the computed time difference between the consecutive messages received at the OBU (epoch time) also shows a similar pattern indicating time variation at the source.
- All intersections that are operating signals in actuated mode, when the green phase goes into rest mode, the min end time associated is shows as zero or below zero milliseconds remaining. This is due to the processing time at the RSU for converting SPaT data to SPaT message, signing with the security certificate, and placing in queue for broadcast at the interval of 100ms.
- Two intersections did not broadcast SPaT messages. The likely reason given was that the security certificate for SPaT has expired. As per the security system requirement, no message is broadcast for invalid or expired certificate.

<u>MAP Message:</u> Visualization of MAP messages for the tested intersections revealed the following:

- All intersections include required data elements in MAP as defined in the SAE J2735 specification. The additional data elements specified in the CI guidance document for RLVW application is required to be added in the message once the guidance is published.
- At one intersection, the node points for egress lanes are sequenced in reverse order. The first node point is not at the stop point. For egresses, the first node indicates where the outbound lane begins.
- At one intersection, there is a missing map definition of a right only turn lane in broadcast MAP message.
- At one intersection, outdated MAP message is being broadcast. The lane definitions in the MAP message are not revised to reflect the reconfigured lanes.

It is anticipated that these field test results would provide technical input to multiple Standards Development Organizations (SDOs) developing guidelines for connected signalized intersections.

7 References

[1] Conformance to Clarifications for Consistent Implementations (CCI's) to Ensure Interoperability of Connected Signalized Intersections in the Ann Arbor Connected Environment with a National Deployment, March 2020.

[2] SAE J2735 Dedicated Short Range Communications (DSRC) Message Set Dictionary, Version MAR2016.

[3] SPaT Challenge Verification Document Revised - October 30, 2017, Version 1.2.

[4] System Design Details (SDD) for the Connected Intersections (CI) Implementation Guide, Draft v1.08, March 30, 2021.

[5] Cooperative Automated Transportation Clarification for Consistent Implementations to Ensure National Interoperability for Connected Signalized Intersections, Draft version 1.9.5, June 2020.

[6] Test Procedure for Verifying SPaT and MAP Messages, Connected Signalized Intersection, Version 1.2, September 2019.

[7] Connected Intersection (CI) Bench Test Setup Methodology, December 2020.

[8] Bench Testing Baseline Test Cases for CAMP CCI – SPaT/Map/RSU Conformance, December 2020.

[9] Bench Testing Operational Test Cases for CAMP CCI – SpaT/Map/RSU Conformance, April 2021.

[10] Dedicated Short Range Communications (DSRC) Message Set Dictionary™ ASN file J2735ASN_201603.

Appendix A SPaT and MAP Message Formats

Figure 30 shows an example of a SPaT message format as described in Subsection 3.3. In addition to the SPaT message payload in JSON, epoch time, message ID and signed message indicator are in text format.

Unix Epoch in Milliseconds since Jan 1, 1970

Message ID

SPaT Message in JSON

1610557070717,19,'{"messageId":19,"value":{"intersections":[{"id":{"id":173},"revision":89,"status":"0000","moy":19230,"timeStamp":45484,"states":[{"signalGroup":2,"state-time-speed":[{"eventState":"protected-Movement-Allowed","timing":{"minEndTime":34654,"maxEndTime":35244}}]},{"signalGroup":4,"state-time-speed":[{"eventState":"stop-And-Remain","timing":{"minEndTime":34711,"maxEndTime":35301}}]},{"signalGroup":5,"state-time-speed":[{"eventState":"stop-And-Remain","timing":{"minEndTime":34654,"maxEndTime":34654}}]},{"signalGroup":6,"state-time-speed":[{"eventState":"protected-Movement-Allowed","timing":{"minEndTime":34700,"maxEndTime":35380}}]}]}]}}',0

Signed Message Indicator

Figure 30: Example - Logged SPaT Message

Figure 31shows an example of a MAP message format as described in subsection 3.3. In addition to the MAP message payload in JSON, epoch time, message ID and signed message indicator are in text format.

Unix Epoch in Milliseconds since Jan 1, 1970

Message ID

MAP Message in JSON

1614111268500,18,'{"messageId":18,"value":{"msgIssueRevision":0,"layerType":"intersectionData","layerID":1,"intersections":[{ "id":{"id":155},"revision":4,"refPoint":{"lat":423070272,"long":-
836854643,"elevation":240},"laneWidth":305,"laneSet":[{"laneID":3,"ingressApproach":1,"laneAttributes":{"directionalUse":"80" ,"sharedWith":"1d80","laneType":{"vehicle":{"value":"01","length":8}}},"maneuvers":"8000","nodeList":{"nodes":[{"delta":{"nod
e-XY4":{"x":-2413,"y":-823}}},{"delta":{"node-XY6":{"x":-22038,"y":-
8276}}}]},"connectsTo":[{"connectingLane":{"lane":15,"maneuver":"8000"},"signalGroup":1}]},{"laneID":4,"ingressApproach":1,"laneAttributes":{"directionalUse":"80","sharedWith":"1d80","laneType":{"vehicle":{"value":"01","length":8}}},"maneuvers":"8000
","nodeList":{"nodes":[{"delta":{"node-XY4":{"x":-2269,"y":-1209}}},{"delta":{"node-XY6":{"x":-22032,"y":-
8213}}}]},"connectsTo":[{"connectingLane":{"lane":14,"maneuver":"8000"},"signalGroup":1}]},{"laneID":6,"laneAttributes":{"directionalUse":"40","sharedWith":"1d80","laneType":{"vehicle":{"value":"01","length":8}}},"maneuvers":"2280","nodeList":{"nodes"
:[{"delta":{"node-XY6":{"x":-8285,"y":-3451}}},{"delta":{"node-XY3":{"x":1487,"y":265}}},{"delta":{"node-XY4":{"x":2051,"y":671}}},{"delta":{"node-XY3":{"x":1610,"y":633}}},{"delta":{"node-XY2":{"x":1017,"y":264}}},{"delta":{"node-XY2":{"x":679,"y":-
94}}},{"delta":{"node-XY1":{"x":327,"y":-60}}},{"delta":{"node-XY1":{"x":449,"y":-172}}},{"delta":{"node-XY2":{"x":529,"y":-519}}},{"delta":{"node-XY2":{"x":563,"y":-868}}},{"delta":{"node-XY3":{"x":528,"y":-1217}}},{"delta":{"node-XY3":{"x":405,"y":-
1035}}},{"delta":{"node-XY3":{"x":444,"y":-1501}}},{"delta":{"node-XY3":{"x":391,"y":-1315}}},{"delta":{"node-XY2":{"x":99,"y":-928}}},{"delta":{"node-XY2":{"x":-43,"y":-841}}},{"delta":{"node-XY2":{"x":-138,"y":-819}}},{"delta":{"node-XY2":{"x":-184,"y":-
798}}},{"delta":{"node-XY2":{"x":-344,"y":-920}}},{"delta":{"node-XY2":{"x":-440,"y":-805}}},{"delta":{"node-XY2":{"x":-533,"y":-809}}},{"delta":{"node-XY2":{"x":-745,"y":-769}}},{"delta":{"node-XY2":{"x":-659,"y":-533}}},{"delta":{"node-XY3":{"x":-1051,"y":-
639}}},{"delta":{"node-XY2":{"x":-965,"y":-427}}},{"delta":{"node-XY2":{"x":-947,"y":-240}}},{"delta":{"node-XY2":{"x":-951,"y":-123}}},{"delta":{"node-XY3":{"x":-1049,"y":37}}},{"delta":{"node-XY2":{"x":-984,"y":156}}},{"delta":{"node-XY2":{"x":-
961,"y":202}}},{"delta":{"node-XY2":{"x":-898,"y":414}}},{"delta":{"node-XY2":{"x":-926,"y":553}}},{"delta":{"node-XY2":{"x":-646,"y":539}}},{"delta":{"node-XY2":{"x":-749,"y":838}}},{"delta":{"node-XY2":{"x":-680,"y":888}}},{"delta":{"node-XY2":{"x":-
420,"y":755}}},{"delta":{"node-XY3":{"x":-412,"y":1267}}},{"delta":{"node-XY2":{"x":-260,"y":854}}},{"delta":{"node-XY3":{"x":-92,"y":1417}}},{"delta":{"node-XY4":{"x":-
102,"y":3235}}}]}},{"laneID":7,"ingressApproach":2,"laneAttributes":{"directionalUse":"80","sharedWith":"1d80","laneType":{"v ehicle":{"value":"01","length":8}}},"maneuvers":"8000","nodeList":{"nodes":[{"delta":{"node-
XY4":{"x":2717,"y":1542}}},{"delta":{"node-XY4":{"x":3503,"y":1250}}},{"delta":{"node-XY5":{"x":5179,"y":1957}}},{"delta":{"node-XY6":{"x":11371,"y":4248}}},{"delta":{"node-XY5":{"x":7667,"y":2827}}},{"delta":{"node-
XY5":{"x":7134,"y":2740}}}]},"connectsTo":[{"connectingLane":{"lane":16,"maneuver":"8000"},"signalGroup":1}]},{"laneID":8,"ingressApproach":2,"laneAttributes":{"directionalUse":"80","sharedWith":"1d80","laneType":{"vehicle":{"value":"01","length":8}}},"
maneuvers":"8000","nodeList":{"nodes":[{"delta":{"node-XY4":{"x":2605,"y":1856}}},{"delta":{"node -XY5":{"x":4732,"y":1693}}},{"delta":{"node-XY6":{"x":11946,"y":4477}}},{"delta":{"node-XY6":{"x":8516,"y":3202}}},{"delta":{"node-
XY6":{"x":9668,"y":3612}}}]},"connectsTo":[{"connectingLane":{"lane":17,"maneuver":"8000"},"signalGroup":1}]},{"laneID":10,"laneAttributes":{"directionalUse":"40","sharedWith":"1d80","laneType":{"vehicle":{"value":"01","length":8}}},"maneuvers":"2280"
,"nodeList":{"nodes":[{"delta":{"node-XY6":{"x":18067,"y":7570}}},{"delta":{"node-XY4":{"x":-2479,"y":-547}}},{"delta":{"node-XY2":{"x":-738,"y":-233}}},{"delta":{"node-XY5":{"x":-6444,"y":-2439}}},{"delta":{"node-XY2":{"x":-716,"y":-209}}},{"delta":{"node-
XY1":{"x":-416,"y":-83}}},{"delta":{"node-XY2":{"x":-581,"y":-41}}},{"delta":{"node-XY2":{"x":-609,"y":143}}},{"delta":{"node-XY1":{"x":-496,"y":194}}},{"delta":{"node-XY3":{"x":-1423,"y":1538}}},{"delta":{"node-XY6":{"x":-
11422,"y":15803}}}]}},{"laneID":11,"ingressApproach":3,"laneAttributes":{"directionalUse":"80","sharedWith":"1d80","laneType" :{"vehicle":{"value":"01","length":8}}},"maneuvers":"4000","nodeList":{"nodes":[{"delta":{"node -XY3":{"x":1059,"y":-
1106}}},{"delta":{"node-XY3":{"x":682,"y":-1786}}},{"delta":{"node-XY4":{"x":1526,"y":-4074}}},{"delta":{"node-XY2":{"x":261,"y":-876}}},{"delta":{"node-XY2":{"x":234,"y":-785}}},{"delta":{"node-XY3":{"x":248,"y":-1226}}},{"delta":{"node-XY2":{"x":75,"y":-
882}}},{"delta":{"node-XY3":{"x":-57,"y":-1166}}},{"delta":{"node-XY2":{"x":-116,"y":-726}}},{"delta":{"node-XY2":{"x":-274,"y":-940}}},{"delta":{"node-XY3":{"x":-591,"y":-1183}}},{"delta":{"node-XY2":{"x":-375,"y":-664}}},{"delta":{"node-XY3":{"x":-937,"y":-
1311}}},{"delta":{"node-XY2":{"x":-670,"y":-883}}},{"delta":{"node-XY4":{"x":-2151,"y":-
2699}}}]},"connectsTo":[{"connectingLane":{"lane":16,"maneuver":"4000"},"signalGroup":2}]},{"laneID":12,"ingressApproach":3,"laneAttributes":{"directionalUse":"80","sharedWith":"1d80","laneType":{"vehicle":{"value":"01","length":8}}},"maneuvers":"400
0","nodeList":{"nodes":[{"delta":{"node-XY3":{"x":1412,"y":-979}}},{"delta":{"node-XY3":{"x":599,"y":-1603}}},{"delta":{"node-XY4":{"x":1246,"y":-3315}}},{"delta":{"node-XY3":{"x":483,"y":-1289}}},{"delta":{"node-XY3":{"x":340,"y":-1177}}},{"delta":{"node-
XY3":{"x":204,"y":-1297}}},{"delta":{"node-XY2":{"x":27,"y":-861}}},{"delta":{"node-XY2":{"x":-70,"y":-748}}},{"delta":{"node-XY3":{"x":-359,"y":-
1465}}}]},"connectsTo":[{"connectingLane":{"lane":17,"maneuver":"4000"},"signalGroup":2}]},{"laneID":13,"ingressApproach":3,"laneAttributes":{"directionalUse":"80","sharedWith":"1d80","laneType":{"vehicle":{"value":"01","length":8}}},"maneuvers":"240
0","nodeList":{"nodes":[{"delta":{"node-XY4":{"x":2163,"y":-708}}},{"delta":{"node-XY1":{"x":-2,"y":-6}}},{"delta":{"node-XY1":{"x":-106,"y":-353}}},{"delta":{"node-XY1":{"x":-13,"y":-303}}},{"delta":{"node-XY2":{"x":234,"y":-784}}},{"delta":{"node-
XY3":{"x":636,"y":-1704}}},{"delta":{"node-XY3":{"x":661,"y":-1772}}},{"delta":{"node-XY3":{"x":432,"y":-1127}}},{"delta":{"node-XY3":{"x":318,"y":-1225}}},{"delta":{"node-XY2":{"x":193,"y":-949}}},{"delta":{"node-XY3":{"x":39,"y":-1233}}},{"delta":{"node-
XY2":{"x":-86,"y":-981}}},{"delta":{"node-XY2":{"x":-152,"y":-819}}},{"delta":{"node-XY2":{"x":-249,"y":-685}}},{"delta":{"node-XY2":{"x":-431,"y":-
921}}}]},"connectsTo":[{"connectingLane":{"lane":14,"maneuver":"2420"},"signalGroup":2}]},{"laneID":14,"egressApproach":4,"laneAttributes":{"directionalUse":"40","sharedWith":"1d80","laneType":{"vehicle":{"value":"01","length":8}}},"maneuvers":"8000"
,"nodeList":{"nodes":[{"delta":{"node-XY4":{"x":3531,"y":976}}},{"delta":{"node-XY1":{"x":20,"y":8}}},{"delta":{"node-
XY5":{"x":6445,"y":2416}}}]}},{"laneID":15,"egressApproach":4,"laneAttributes":{"directionalUse":"40","sharedWith":"1d80","la neType":{"vehicle":{"value":"01","length":8}}},"maneuvers":"8000","nodeList":{"nodes":[{"delta":{"node -
XY4":{"x":3409,"y":1284}}},{"delta":{"node-
XY5":{"x":6414,"y":2459}}}]}},{"laneID":16,"egressApproach":5,"laneAttributes":{"directionalUse":"40","sharedWith":"1d80","la neType":{"vehicle":{"value":"01","length":8}}},"maneuvers":"8000","nodeList":{"nodes":[{"delta":{"node -XY4":{"x":-2985,"y":-
620}}},{"delta":{"node-XY4":{"x":-3244,"y":-1222}}},{"delta":{"node-XY4":{"x":-3251,"y":-
1242}}}]}},{"laneID":17,"egressApproach":5,"laneAttributes":{"directionalUse":"40","sharedWith":"1d80","laneType":{"vehicle": {"value":"01","length":8}}},"maneuvers":"8000","nodeList":{"nodes":[{"delta":{"node-XY4":{"x":- 3121,"y":-244}}},{"delta":{"node-
XY1":{"x":26,"y":-71}}},{"delta":{"node-XY5":{"x":-6398,"y":-2349}}}]}}]}]}}',0

Signed Message Indicator

Figure 31: Example – Logged MAP Message

- Unix Epoch in Milliseconds: Message received timestamp in milliseconds since January 1, 1970.
- Message ID: 19 indicates SPaT message, 18 indicates MAP message
- Message: SPaT or MAP message in JSON
- Flag: Indicate message signed = 1, unsigned = 0

Appendix B Mandatory SPaT Message Data for CI Implementation

The following table describing SPaT data is adapted from the System Design Details (SDD) document for the Connected Intersections (CI) Implementation Guide.

Table 7: List of Mandatory SPaT Data for CI Implementation

SAE J2735 Data Frames and Data Elements	SAE J2735 Mandatory	CI Implementation
messageId=DE_DSRC_MessageID=19 (SPAT UPER)	M	M
timeStamp=DE_MinuteOfTheYear	O	M
intersections=DF_IntersectionStateList	M	M
id=DF_IntersectionReferenceID	M	M
region=DE_RoadRegulatorID	O	M
id=DE_IntersectionID	M	M
revision=DE_MsgCount	M	M
status=DE_IntersectionStatusObject	M	M
timeStamp=DE_Dsecond	O	M
enabledLanes=DF_EnabledLaneList=1 to 16 x DE_LaneID	O	C (if a revocable lane is active ("enabled") - See Section 4.3.3.3.7)
states=DF_MovementList=1 to 255 x DF_MovementState	M	M
signalGroup=DE_SignalGroupID	M	M
state-time-speed=DF_MovementEventList	M	M
eventState=DE_MovementPhaseState	M	M
timing=DF_TimeChangeDetails	O	M
startTime=DE_TimeMark	O	C (If available - See Sections 4.3.3.3.5.7 and 4.3.3.3.5.8)

SAE J2735 Data Frames and Data Elements						SAE J2735 Mandatory	CI Implementation
					minEndTime=DE_TimeMark	M	M
					maxEndTime=DE_TimeMark	O	M
					nextTime=DE_TimeMark	O	C (If available - See Sections 4.3.3.3.5.7 and 4.3.3.3.6.1)

Appendix C Mandatory MAP Message Data for CI Implementation

The following table describing MAP data for RLVW application is adapted from the System Design Details (SDD) document for the Connected Intersections (CI) Implementation Guide.

Table 8: List of Mandatory MAP Data for CI Implementation

SAE J2735 Data Frames and Data Elements	SAE J2735 Mandatory	CI Implementation
messageId=DE_DSRCmsgID=18 (MAP UPER)	M	M
msgIssueRevision=DE_MsgCount	M	M
intersections=DF_IntersectionGeometryList=1 to 32 X DF_IntersectionGeometry	O	M
id=DF_IntersectionReferenceID	M	M
region=DE_RoadRegulatorID	O	M
id=DE_IntersectionID	M	M
revision=DE_MsgCount	M	M
refPoint=DF_Position3D	M	M
lat=DE_Latitude	M	M
long=DE_Longitude	M	M
elevation=DE_Elevation	O	M
laneWidth=DE_LaneWidth	O	M
speedLimits=DF_SpeedLimitList=1 to 9 x DF_RegulatorySpeedLimit	O	M
type=DE_SpeedLimitType	C (if speedLimits is included)	M
speed=DE_Velocity	C (if speedLimits is included)	M

SAE J2735 Data Frames and Data Elements	SAE J2735 Mandatory	CI Implementation
laneSet=DF_LaneList=1 to 255 X DF_GenericLane	M	M
laneID=DE_LaneID	M	M
laneAttributes=DF_LaneAttributes	M	M
directionalUse=DE_LaneDirection	M	M
sharedWith=DE_LaneSharing	M	M
laneType=DF_LaneTypeAttributes (revocable)	M	M
maneuvers=DE_AllowedManeuvers	O	M
nodeList=DF_NodeListXY=Choice of DF_NodeSetXY OR DF_ComputedLane	M	M
nodes= DF_NodeSetXY=2 to 63 X DF_NodeXY	M	M
delta=DF_NodeOffsetPointXY	M	M
node-XY1=DF_Node_XY_20b	O.1 (1..*)	O.4 (1..*)
x=DE_Offset_B10	C (if node-XY1 is included)	C (if node-XY1 is included)
y=DE_Offset_B10	C (if node-XY1 is included)	C (if node-XY1 is included)
node-XY2=DF_Node_XY_22b	O.1 (1..*)	O.4 (1..*)
x=DE_Offset_B11	C (if node-XY2 is included)	C (if node-XY2 is included)
y=DE_Offset_B11	C (if node-XY2 is included)	C (if node-XY2 is included)
node-XY3=DF_Node_XY_24b	O.1 (1..*)	O.4 (1..*)
x=DE_Offset_B12	C (if node-XY3 is included)	C (if node-XY3 is included)

SAE J2735 Data Frames and Data Elements	SAE J2735 Mandatory	CI Implementation
y=DE_Offset_B12	C (if node-XY3 is included)	C (if node-XY3 is included)
node-XY4=DF_Node_XY_26b	O.1 (1..*)	O.4 (1..*)
x=DE_Offset_B13	C (if node-XY4 is included)	C (if node-XY4 is included)
y=DE_Offset_B13	C (if node-XY4 is included)	C (if node-XY4 is included)
node-XY5=DF_Node_XY_28b	O.1 (1..*)	O.4 (1..*)
x=DE_Offset_B14	C (if node-XY5 is included)	C (if node-XY5 is included)
y=DE_Offset_B14	C (if node-XY5 is included)	C (if node-XY5 is included)
node-XY6=DF_Node_XY_32b	O.1 (1..*)	O.4 (1..*)
x=DE_Offset_B16	C (if node-XY6 is included)	C (if node-XY6 is included)
y=DE_Offset_B16	C (if node-XY6 is included)	C (if node-XY6 is included)
attributes=DF_NodeAttributeSetXY	O	O
data=DF_LaneDataAttributeList=1 to 8 x DF_LaneDataAttribute	O	O
DF_LaneDataAttribute=Choice	O	C (if data is included)
speedLimits=DF_SpeedLimitList=1 to 9 X DF_RegulatorySpeedLimit	O	C (if data is included)
type=DE_SpeedLimitType	C (if speedLimits is included)	C (if data is included)
speed=DE_Velocity	C (if speedLimits is included)	C (if data is included)
dWidth=DE_Offset_B10	O	C (for differences in lane widths)

SAE J2735 Data Frames and Data Elements	SAE J2735 Mandatory	CI Implementation
dElevation=DE_Offset_B10	O	C (for differences in elevations)
computed=DF_Computed Lane	O	C (For computed lanes)
referenceLaneId=DE_LaneID	C (if computed is selected)	C (For computed lanes)
offsetXaxis=Choice	C (if computed is selected)	C (For computed lanes)
small=DE_DrivenLineOffsetSmall	O.2 (1..*) (if computed is selected)	O.7 (1) (For computed lanes)
large=DE_DrivenLineOffsetLarge	O.2 (1..*) (if computed is selected)	O.7 (1) (For computed lanes)
offsetYaxis=Choice	C (if computed is selected)	C (For computed lanes)
small=DE_DrivenLineOffsetSmall	O.3 (1..*) (if computed is selected)	O.8 (1) (For computed lanes)
large=DE_DrivenLineOffsetLarge	O.3 (1..*) (if computed is selected)	O.8 (1) (For computed lanes)
rotateXY=DE_Angle	O	O (For computed lanes)
connectsTo=DF_ConnectsToList=1 to 16 X DF_Connection	O	M
connectingLane=DF_ConnectingLane	C (if connectsTo is selected)	M
lane=DE_LaneID	C (if connectsTo is selected)	M
maneuvers=DE_AllowedManeuver	O	O
signalGroup=DE_SignalGroupID	O	M