CAMP LLC

Vehicle-to-Infrastructure (V2I-5) Consortium

Connected Intersection Performance Assessment

Supporting Basic Red Light Violation Warning

December 7, 2022

Table of Contents

List of Figures

List of Tables

List of Acronyms

Acronym	Definition
AGP	Assured Green Period
CAMP	Crash Avoidance Metrics Partners LLC
CI	Connected Intersection
CORS	Continously Operating Reference Station
CV	Connected Vehicle
CV PFS	Connected Vehicle Pooled Fund Study
C-V2X	Cellular Vehicle-to-Everything
DGPS	Differential Global Positioning System
GPS	Global Positioning System
GNSS	Global Navigation Satellite System
HDOP	Horizontal Dilution of Precision
I2V	Infrastructure to Vehicle
IOO	Infrastructure Owner / Operator
IFM	Immediate Forward Mode
ITE	Institute of Transportation Engineers
JSON	JavaScript Object Notation
MAP	SAE J2735 Map Message
NAD83	North American Datum 1983
NTRIP	Network Transport of RTCM via Internet Protocol
NMEA	National Marine Electronics Association
OBU	On-board Unit
OEM	Original Equipment Manufacturer
OTA	Over the Air
PCAP	Packet Capture
PPS	Precise Positioning System
RLVW	Red Light Violation Warning
RSU	Roadside Unit
RTCM	Radio Technical Commission for Maritime Services

Acronym	Definition
SAE	SAE International
SPaT	Signal Phase and Timing
SPS	Standard Positioning System
TSC	Traffic Signal Controller
V2I	Vehicle-to-Infrastructure
WAAS	Wide Area Augmentation System
WGS84	World Geodetic System 1984

Connected Intersection MAP Utility Assessment
Supporting Basic Red Light Violation Warning

Background

The Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure 5 (V2I-5) Consortium (Ford, GM, Nissan) conducted the Connected Intersection Verification Project to support deployment of Connected Intersections (CIs) supporting Red Light Violation Warning (RLVW). During the period from August 2021 to December 2022, the Project Team evaluated the performance of several CI deployments to understand the impact of SPaT (Signal Phase and Timing) data accuracy, message latency and broadcast periodicity as well as MAP (SAE J2735 Map Message) data accuracy on in-vehicle warning performance. This document summarizes field experience to date, establishes test procedures for SPaT and MAP assessment from the vehicle perspective and proposes minimum acceptance criteria.

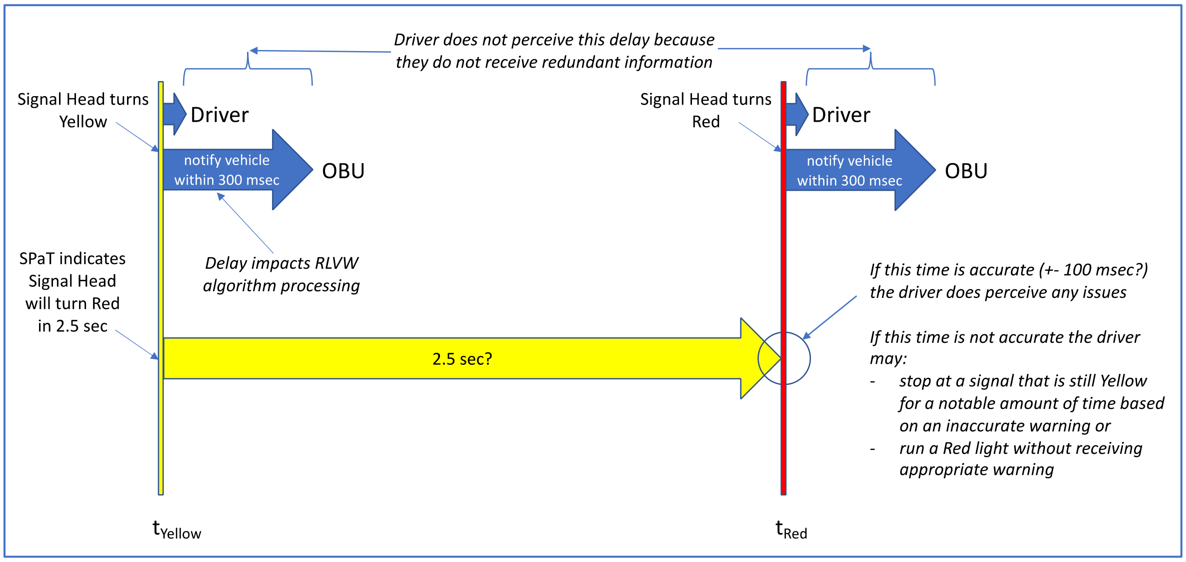
Basis for SPaT Assessment

The Society of Automotive Engineers (SAE) J2735 SPaT message standard specifies the content and format of signal phase and timing information broadcast by a CI using Infrastructure to Vehicle (I2V) communications to support in-vehicle safety and mobility applications such as RLVW. The Institute of Transportation Engineers (ITE) CI Guidelines [1] further specifies the desired SPaT data elements necessary to support RLVW. Basic RLVW only operates within the yellow phase time interval of a through movement which obviates the ITE requirements associated with Assured Green Period (AGP) for initial deployment.

The purpose of this assessment procedure is to verify that the duration of the yellow phase predicted by the Traffic Signal Controller (TSC) at the transition from green to yellow is accurate and that the broadcast of this information by the Roadside Unit (RSU) maintains a stable periodicity.

Yellow Phase Duration Accuracy

Basic RLVW operates using the yellow to red transition time information provided by the TSC at the transition from green to yellow and broadcast in the SPaT message by the RSU. As illustrated in Figure 1, the accuracy of this timepoint is different from the 300 msec maximum latency requirement specified in the ITE Guidelines for communicating phase transition information. While the magnitude of this latency is relevant to RLVW algorithm processing and time available to warn a driver, it is not directly perceived by the driver. When a phase transition occurs, either green to yellow or yellow to red, as noted in the illustration below, the driver sees the phase change on the signal head and the vehicle OBU receives the SPaT transmission. Neither has redundant information available with which to assess the magnitude of transmission delays.



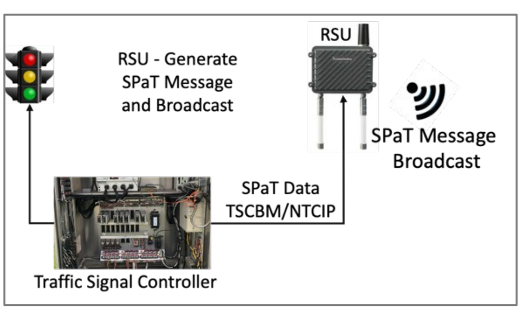
Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle to Infrastructure 5 (V2I-5) Consortium, 2022

Figure 1: Impact of Signal Head Action vs SPaT Timing on Basic RLVW

However, the performance of the Basic RLVW algorithm and the driver response to it are critically dependent on the accuracy of the start of yellow phase duration information provided in the SPaT message. If this time is inaccurate, the resulting driver behavior may be inappropriate, and the error is readily apparent. If the time estimate provided is shorter than what occurs, the RLVW algorithm will warn the driver to stop too early resulting in stopping at the intersection while the signal head remains yellow, potentially for a notable amount of time, thereby reducing driver confidence in the warning system. If the time estimate is longer than what occurs, the RLVW algorithm warning will be too late for the driver to take appropriate action, thereby resulting in entering the intersection after the signal phase turns red.

SPaT Transmission Periodicity

The performance of the RLVW algorithm is also critically dependent on receipt of a stable data stream from the CI. The following two methodologies are in practice to generate and broadcast SPaT information.

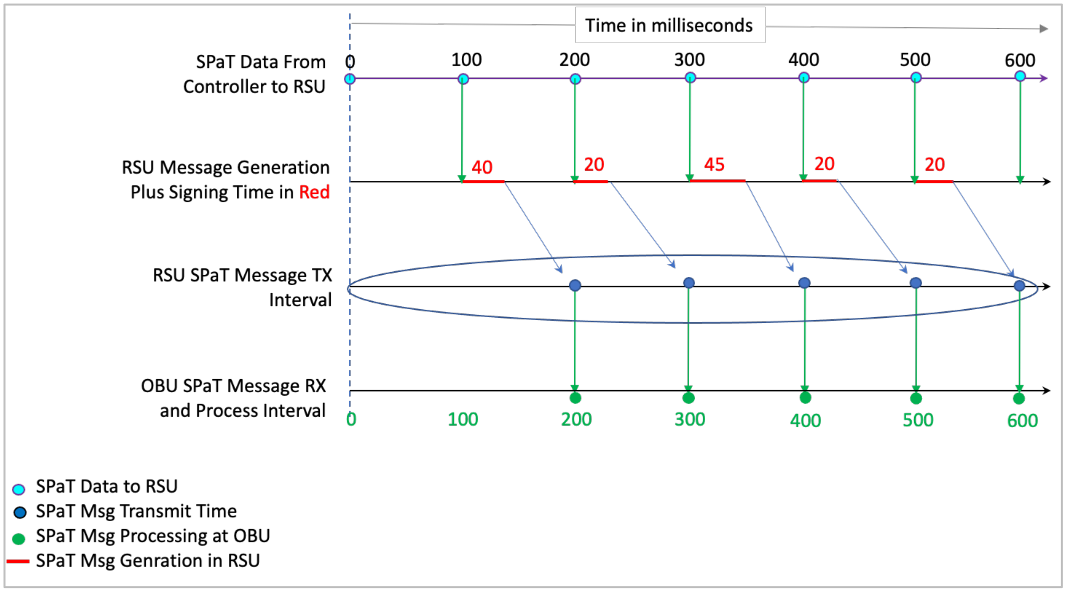


Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle to Infrastructure 5 (V2I-5) Consortium, 2022

Figure 2: RSU - Generate SPaT Message and Broadcast Mode

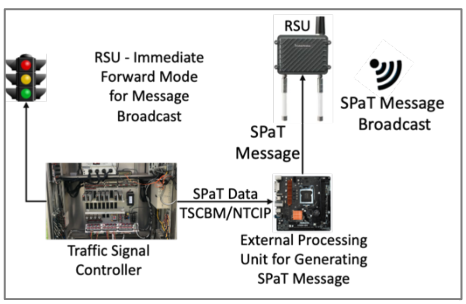
1. Generate and Broadcast Mode: In this method, shown in Figure 2, the TSC generates SPaT data and provides it to the RSU using User Datagram Protocol (UDP) over an ethernet interface. The RSU generates Unaligned Packed Encoding Rule (UPER) encoded SPaT messages for broadcast as per the SAE J2735 standard specification. The message generated is either signed with a security certificate or has a security digest attached and is queued for broadcast.

As shown in the example in Figure 3, SPaT data is provided to the RSU at 100 ms intervals. The RSU then generates SPaT messages which are broadcast at 100 ms intervals to the vehicle On-board Unit (OBU). The OBU receives and processes the data for use by the RLVW application by also using 100 msec intervals, but these are not synchronized with broadcast timing.



Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle to Infrastructure 5 (V2I-5) Consortium, 2022

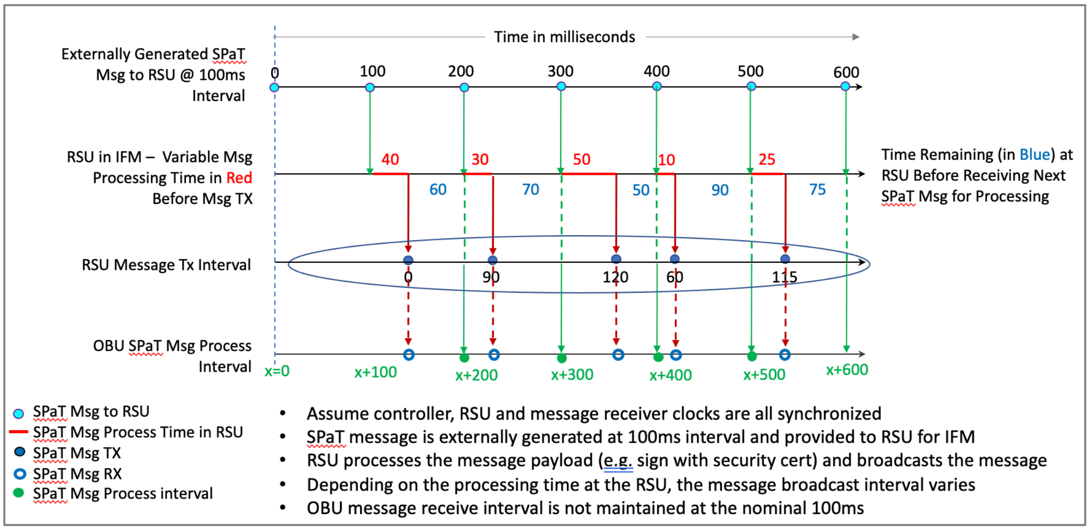
Figure 3: RSU - SPaT Message Generate and Broadcast Mode Time Interval



Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle to Infrastructure 5 (V2I-5) Consortium, 2022

Figure 4: RSU - Generate SPaT Message and Broadcast Mode

2. Immediate Forward Mode (IFM): In this method, shown in Figure 4, the TSC generates SPaT data and provides it to an external processing unit using UDP over an ethernet interface. The external processor generates the SPaT messages as per the SAE J2735 standard specification, and it provides the messages to the RSU for broadcast using UDP over an ethernet interface. The RSU either signs the message with a security certificate or attaches a security digest and immediately broadcasts the message. As illustrated in Figure 5, while the SPaT messages are generated every 100 msec and transferred to the RSU for processing (e.g., message security), the total processing time at the RSU, shown here in blue, is non-deterministic resulting in the IFM transmission period varying from the nominal 100 msec value. This causes fluctuations in the message received timing at the OBU. The OBU also processes the information in 100 msec cycles, but the OBU cycle timing is not synchronized with the message broadcast cycle timing.

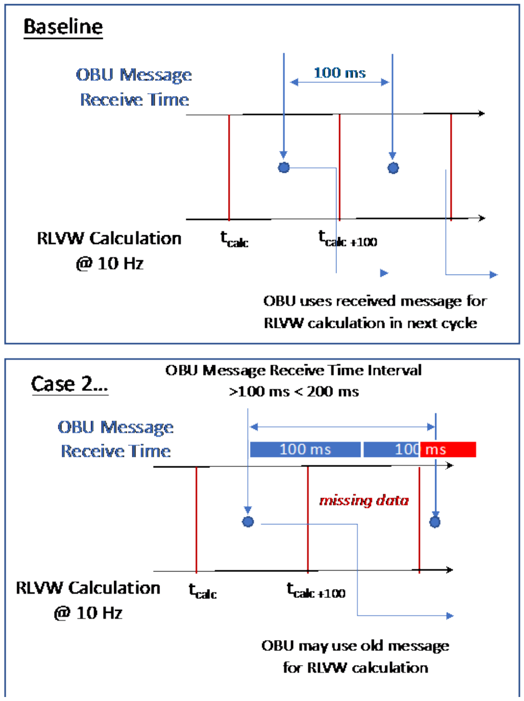


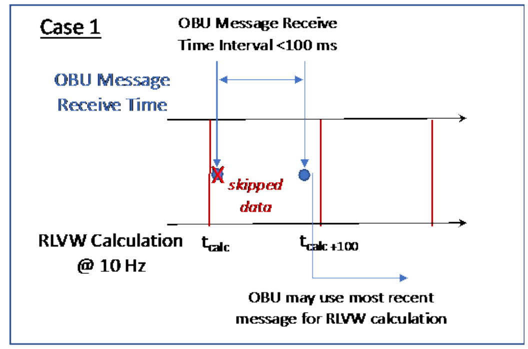
Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle to Infrastructure 5 (V2I-5) Consortium, 2022

Figure 5: SPaT Message Generate, Process and Broadcast Time Interval in Immediate Forward Mode

In the illustration above, the initial TSC message spends 40 msec in RSU processing before transmission. This leaves 60 msec before the RSU receives the next SPaT message of which it takes 30 msec to process and broadcast. The result at the OBU is a 90 msec interval between the first two successive messages. The third successive message interval is 120 msec due to variation in the RSU processing time. As this process continues, it causes significant instability in received message periodicity.

Because of this fluctuation in message reception, the data used in the RLVW calculation suffers from skipped and missed data as illustrated in Figure 6. Consider the baseline case where the OBU message receive interval is the nominal 100 msec and the RLVW algorithm samples the data stream at 100 msec intervals. In this case, the RLVW calculation operates with fresh data every cycle. In Case 1, the OBU message time interval is less than 100 msec with two messages received by the OBU within the same 100 msec sample interval. In this case, the RLVW algorithm may use the most recent message for calculation thus skipping the previous message resulting in lost data. In Case 2, the OBU receive interval is greater than 100 msec but less than 200 msec and is aligned with the sampling sequence such that the inter-message gap spans more than one receive interval. In this case, the RLVW calculation experiences missing data and may use data one cycle older in the calculation. This phenomenon is expected to scale as the receive time interval grows.





Result

OBU Message Receive Time Interval	Potential Effect on RLVW Calculation
<100 ms	0 - 1 skipped messages
> 100 < 200 ms	0 - 1 missed messages
> 200 < 300 ms	1 - 2 missed messages
> 300 < 400 ms	2 - 3 missed messages
…	…

Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle to Infrastructure 5 (V2I-5) Consortium, 2022

Figure 6: Effect(s) of OBU Message Receive Time Interval Variability on RLVW Calculation

SPaT Data Collection

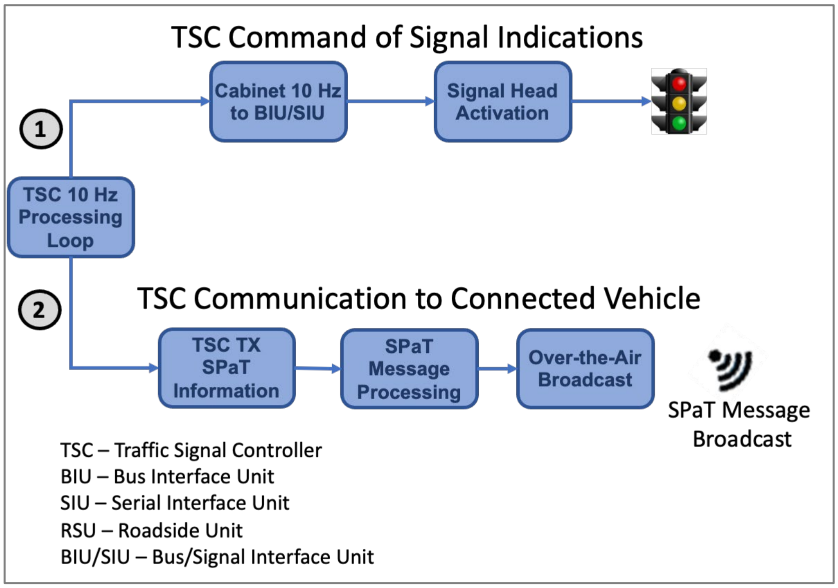
Figure 7 illustrates the flow of SPaT information in a CI architecture for signal activation and SPaT message generation and broadcast. This report focuses on assessment of SPaT from TSC to the message broadcast. The following data elements are required for end-to-end assessment of SPaT.

Traffic Signal Controller Data:

a. All timestamps are in UTC in milliseconds
b. Event code to indicate start and end of signal phase to determine duration
c. Event parameter code to indicate signal phase and other events. Refer to Automated Traffic Signal Performance Measures (ATSPM) [*2*] for more detail.

SPaT Message:

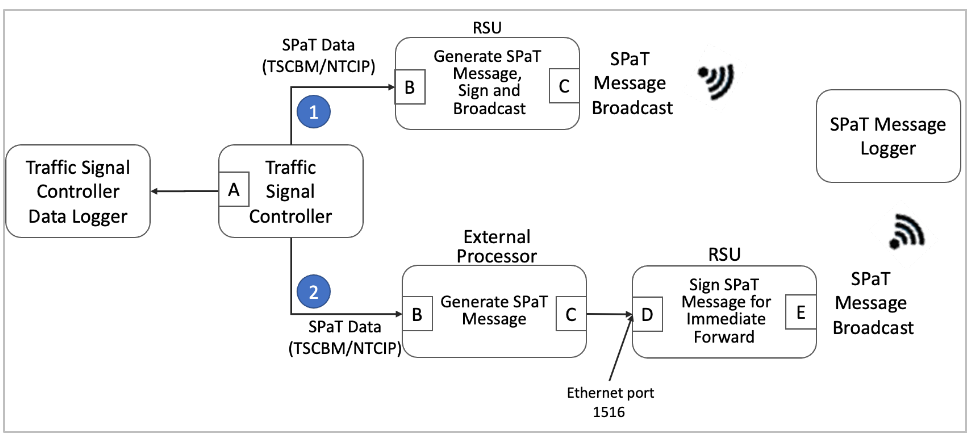
d. Timestamp in UTC at either departure or arrival of SPaT message
e. UPER encoded SPaT message including UTC timestamp in milliseconds. Refer ITE/CI Field Test Report [*3*] for more detail.



Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle to Infrastructure 5 (V2I-5) Consortium, 2022

Figure 7: SPaT Information Flow – 1) TSC to Signal Activation and 2) Generate SPaT Message for Broadcast

In practice, two methods are commonly used to deploy SPaT from a TSC to the RSU for broadcast. These are illustrated in Figure 8 along with message test points used for performance analysis. In the first method, the SPaT message is generated and signed by the RSU for broadcast. While in the second method, an external processor is used to generate the SPaT message before transmitting it to the RSU for message signing and broadcast.



Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle to Infrastructure 5 (V2I-5) Consortium, 2022

Figure 8: Test Points for SPaT Verification and Assessment

For SPaT assessment and verification, the following test points are used to collect data for the two methods.

Method 1:

1. Test Point A: Timestamp of TSC generated start and end of events (signal phases) to determine start time of phase and duration.

2. Test Point B: Timestamp of SPaT data at the input port of RSU to determine time of arrival of the SPaT data for processing.
3. Test Point C: Timestamp at the output port of RSU for message broadcast to determine processing time to generate message and apply appropriate security credentials for broadcast.

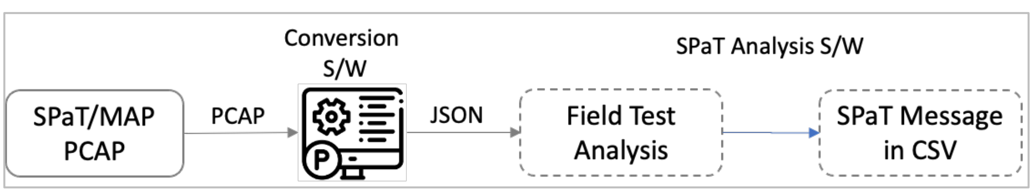
Method 2:

1. Test Point A: Timestamp of TSC generated start and end of events (signal phases) to determine start time of phase and duration.
2. Test Point B: Timestamp of SPaT data at the input port of the external processor to determine time of arrival of the SPaT data for message generation.
3. Test Point C: Timestamp either at the output port of the external processor or the input port of RSU to determine message generation process time. It is assumed that there is no significant delay in the interface between the external processor and the RSU using UDP over ethernet.
4. Test Point D: Timestamp at the output port of RSU to determine process time for applying appropriate security credentials before the message broadcast.

In general, all communication between the subsystems is in UDP over ethernet for minimum communication delay between the subsystems. The over-the-air (OTA) message broadcast from the RSU received by the OBU has a minimum delay. The timestamps at the indicated test points allow evaluation of time synchronization between subsystems.

At the test point A, the TSC data for signal phase activation is required in csv format. ATSPM or other equivalent tools can be used to capture the data to determine the start time and duration of a signal phase. At the other test points, different methods can be employed for data collection. The most common method used is to collect binary data packets using a packet capture (PCAP) tool called Wireshark Network Analysis Tool [4]. It also allows exporting of the captured PCAP to csv format.

To process and analyze captured SPaT messages in PCAP, it requires all data elements in binary be extracted for each object in the message. This requires the PCAP to convert to JavaScript Object Notation (JSON) using the CAMP developed conversion software tool for converting to csv format using the CAMP developed SPaT analysis software tool. Figure 9 shows the process flow for converting PCAP to JSON and to SPaT message in csv.



Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle to Infrastructure 5 (V2I-5) Consortium, 2022

Figure 9: Process to Convert PCAP to JSON

SPaT Field Data Analysis

Currently there are no commercial off-the-shelf integrated tools available to capture and analyze CI data across the test points identified from the TSC all the way to broadcast of UPER encoded SPaT messages. CAMP developed a tool to analyze captured SPaT messages [5]. The tool was further enhanced for

ITE/CI Field Verification [5] to assess conformance of SPaT and MAP messages (test point at message broadcast) per the CI Implementation Guide, that included the following:

- Verify the broadcast SPaT and MAP messages conform to the message structure with the SAE J2735 standard.
- Verify all required data elements in the message are as per the CI Implementation Guide.
- Verify all data elements that are present in the message are within the proper limits (value ranges) as specified in the SAE J2735 specification.
- Analyze inter message time interval of received messages with the message generation time to measure periodicity and processing time latency per message basis.

To ensure required performance of the RLVW application, the predicted time of start of the yellow phase and the duration of the phase for each signal in SPaT message, it must match with the information generated by the signal controller. The ITE/CI field verification did not verify the start of yellow phase and duration from the controller with the broadcast SPaT message. Since it is not feasible to test all potential real-world scenarios in a lab setting, the ITE/CI field test is extended to include end-to-end verification of signal controller produced information to SPaT broadcast in the field.

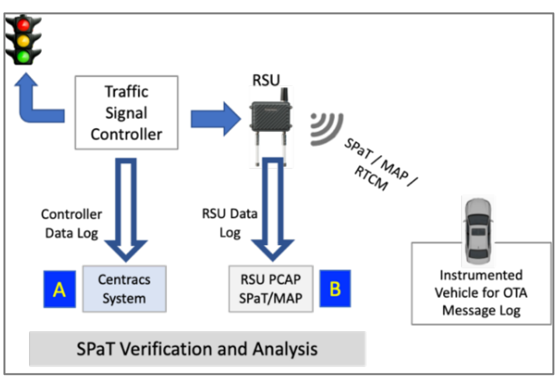
As described in Figure 8, two methods are commonly deployed at CIs to generate and broadcast the SPaT message. Example methods are described in this subsection.

Example Method 1

In this example, the test procedure to capture and analyze SPaT at a deployed CI in Michigan is described. At this site, as shown in Figure 8, the TSC is interfaced with the RSU where the SPaT message is generated, processed for appropriate security credentials, and broadcast.

- Test Site: Moravian Drive and Garfield Road, Clinton Township, Macomb County, Michigan
- Test Date and Duration: Jan. 11, 2022, from 11:55:20 AM to 2:05:00 PM (16:55:20 to 19:05:00 UTC)

As shown in Figure 10, signal controller event data was captured at test point A using the Centracs System at the back office of the county's Traffic Management Center (TMC) connected to the CI over the fiber optics communication link in csv format. At the same time, the SPaT message generated by the RSU and processed for proper security for broadcast in PCAP was collected at test point B where the messages are being broadcast from the RSU.

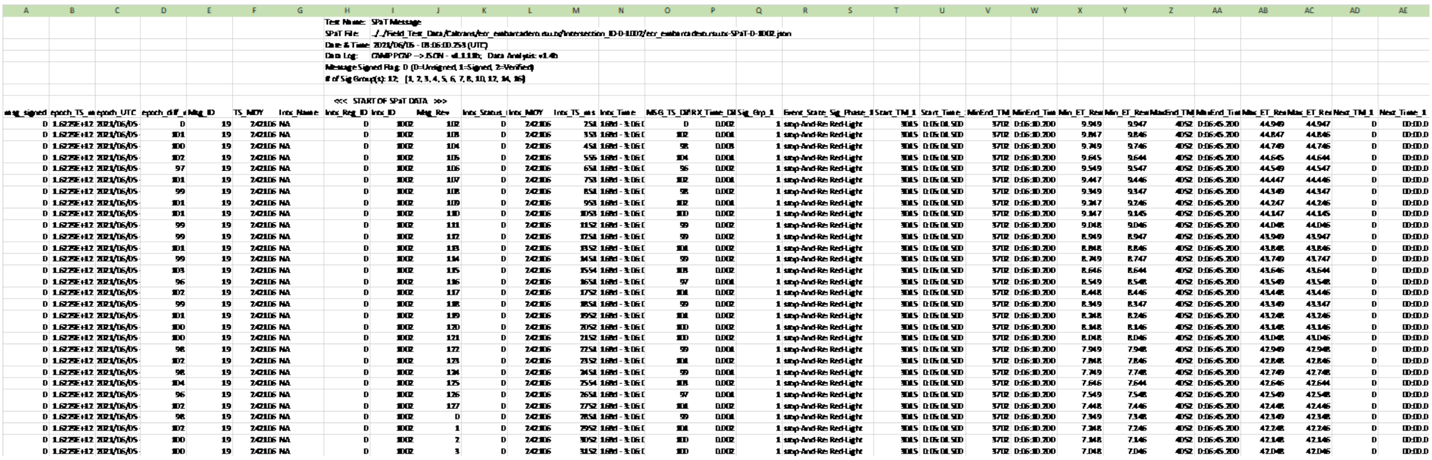


Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle to Infrastructure 5 (V2I-5) Consortium, 2022

Figure 10: Data Collection Test Points – A and B

The logged controller SPaT data is in csv format and the logged SPaT messages from the RSU are in UPER encoded binary format. It is necessary to convert all data to the same format and align timestamps (in UTC) to compare and analyze the start time and duration of the yellow phase in the controller log and in the SPaT message. Since the controller log data is already in csv format, the logged SPaT messages are converted to

JSON and processed to generate the csv format for each message. The conversion of PCAP to JSON conversion data format is described in the ITE/CI Field Test Report. Figure 11 shows a partial list of processed SPaT messages in JSON in csv format in Excel. All common data elements in addition to all mandatory elements for signal group 1 are shown. The full analysis file contains data for all signal groups.



Test Name: SPaT Message
SPaT File: ../../Field_Test_Data/Caltrans/ecr_embarcadero.rsu.ng/Intersection_ID-0-1002/ecr_embarcadero.rsu.rx-SPaT-0-1002.json
Date & Time: 2021/06/05 - 08:06:00.253 (UTC)
Data Log: CAMP PCAP --> JSON - v1.1.1b; Data Analysis: v1.4b
Message Signed Flag: 0 (0=Unsigned, 1=Signed, 2=Verified)
# of Sig Group(s): 12; [1, 2, 3, 4, 5, 6, 7, 8, 10, 12, 14, 16]

<<< START OF SPaT DATA >>>

msg_signed	epoch_TS_m	epoch_UTC	epoch_diff_	Msg_ID	TS_MOY	Intx_Name	Intx_Reg_ID	Intx_ID	Msg_Rev	Intx_Status_	Intx_MOY	Intx_TS_ms	Intx_Time	MSG_TS_Dif	RX_Time_Di
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0	1.6229E+12	2021/06/05 -	101	19	242106	NA	0	1002	103	0	242106	3553	168d - 3:06:0	102	0.001
0	1.6229E+12	2021/06/05 -	100	19	242106	NA	0	1002	104	0	242106	4551	168d - 3:06:0	98	0.003
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0	1.6229E+12	2021/06/05 -	101	19	242106	NA	0	1002	107	0	242106	7553	168d - 3:06:0	102	0.001
0	1.6229E+12	2021/06/05 -	99	19	242106	NA	0	1002	108	0	242106	8551	168d - 3:06:0	98	0.002
0	1.6229E+12	2021/06/05 -	101	19	242106	NA	0	1002	109	0	242106	9553	168d - 3:06:0	102	0.001
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0	1.6229E+12	2021/06/05 -	102	19	242106	NA	0	1002	117	0	242106	17552	168d - 3:06:0	101	0.002
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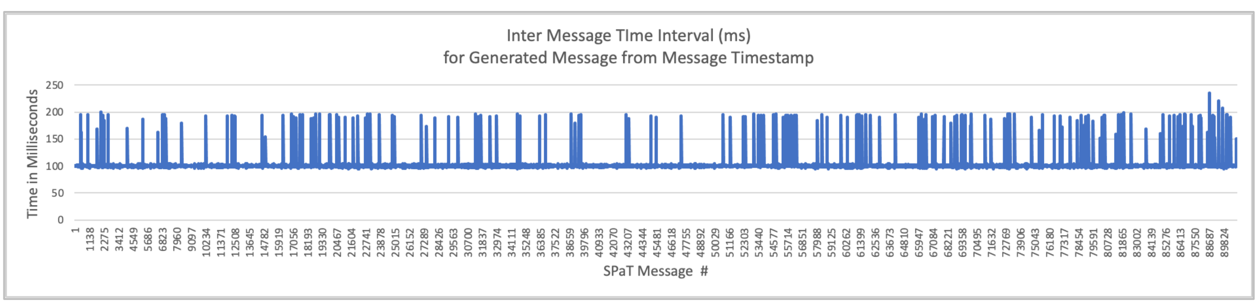
Sig_Grp_1	Event_State_	Sig_Phase_1	Start_TM_1	Start_Time_	MinEnd_TM	MinEnd_Tim	Min_ET_Rem	Min_ET_Rem	MaxEnd_TM	MaxEnd_Tim	Max_ET_Rem	Max_ET_Rem	Next_TM_1	Next_Time_1
1	stop-And-Re	Red-Light	3015	0:05:01.500	3702	0:06:10.200	9.949	9.947	4052	0:06:45.200	44.949	44.947	0	00:00.0
1	stop-And-Re	Red-Light	3015	0:05:01.500	3702	0:06:10.200	9.847	9.846	4052	0:06:45.200	44.847	44.846	0	00:00.0
1	stop-And-Re	Red-Light	3015	0:05:01.500	3702	0:06:10.200	9.749	9.746	4052	0:06:45.200	44.749	44.746	0	00:00.0
1	stop-And-Re	Red-Light	3015	0:05:01.500	3702	0:06:10.200	9.645	9.644	4052	0:06:45.200	44.645	44.644	0	00:00.0
1	stop-And-Re	Red-Light	3015	0:05:01.500	3702	0:06:10.200	9.549	9.547	4052	0:06:45.200	44.549	44.547	0	00:00.0
1	stop-And-Re	Red-Light	3015	0:05:01.500	3702	0:06:10.200	9.447	9.446	4052	0:06:45.200	44.447	44.446	0	00:00.0
1	stop-And-Re	Red-Light	3015	0:05:01.500	3702	0:06:10.200	9.349	9.347	4052	0:06:45.200	44.349	44.347	0	00:00.0
1	stop-And-Re	Red-Light	3015	0:05:01.500	3702	0:06:10.200	9.247	9.246	4052	0:06:45.200	44.247	44.246	0	00:00.0
1	stop-And-Re	Red-Light	3015	0:05:01.500	3702	0:06:10.200	9.147	9.145	4052	0:06:45.200	44.147	44.145	0	00:00.0
1	stop-And-Re	Red-Light	3015	0:05:01.500	3702	0:06:10.200	9.048	9.046	4052	0:06:45.200	44.048	44.046	0	00:00.0
1	stop-And-Re	Red-Light	3015	0:05:01.500	3702	0:06:10.200	8.949	8.947	4052	0:06:45.200	43.949	43.947	0	00:00.0
1	stop-And-Re	Red-Light	3015	0:05:01.500	3702	0:06:10.200	8.848	8.846	4052	0:06:45.200	43.848	43.846	0	00:00.0
1	stop-And-Re	Red-Light	3015	0:05:01.500	3702	0:06:10.200	8.749	8.747	4052	0:06:45.200	43.749	43.747	0	00:00.0
1	stop-And-Re	Red-Light	3015	0:05:01.500	3702	0:06:10.200	8.646	8.644	4052	0:06:45.200	43.646	43.644	0	00:00.0
1	stop-And-Re	Red-Light	3015	0:05:01.500	3702	0:06:10.200	8.549	8.548	4052	0:06:45.200	43.549	43.548	0	00:00.0
1	stop-And-Re	Red-Light	3015	0:05:01.500	3702	0:06:10.200	8.448	8.446	4052	0:06:45.200	43.448	43.446	0	00:00.0
1	stop-And-Re	Red-Light	3015	0:05:01.500	3702	0:06:10.200	8.349	8.347	4052	0:06:45.200	43.349	43.347	0	00:00.0
1	stop-And-Re	Red-Light	3015	0:05:01.500	3702	0:06:10.200	8.248	8.246	4052	0:06:45.200	43.248	43.246	0	00:00.0
1	stop-And-Re	Red-Light	3015	0:05:01.500	3702	0:06:10.200	8.148	8.146	4052	0:06:45.200	43.148	43.146	0	00:00.0
1	stop-And-Re	Red-Light	3015	0:05:01.500	3702	0:06:10.200	8.048	8.046	4052	0:06:45.200	43.048	43.046	0	00:00.0
1	stop-And-Re	Red-Light	3015	0:05:01.500	3702	0:06:10.200	7.949	7.948	4052	0:06:45.200	42.949	42.948	0	00:00.0
1	stop-And-Re	Red-Light	3015	0:05:01.500	3702	0:06:10.200	7.848	7.846	4052	0:06:45.200	42.848	42.846	0	00:00.0
1	stop-And-Re	Red-Light	3015	0:05:01.500	3702	0:06:10.200	7.749	7.748	4052	0:06:45.200	42.749	42.748	0	00:00.0
1	stop-And-Re	Red-Light	3015	0:05:01.500	3702	0:06:10.200	7.646	7.644	4052	0:06:45.200	42.646	42.644	0	00:00.0
1	stop-And-Re	Red-Light	3015	0:05:01.500	3702	0:06:10.200	7.549	7.548	4052	0:06:45.200	42.549	42.548	0	00:00.0
1	stop-And-Re	Red-Light	3015	0:05:01.500	3702	0:06:10.200	7.448	7.446	4052	0:06:45.200	42.448	42.446	0	00:00.0
1	stop-And-Re	Red-Light	3015	0:05:01.500	3702	0:06:10.200	7.349	7.348	4052	0:06:45.200	42.349	42.348	0	00:00.0
1	stop-And-Re	Red-Light	3015	0:05:01.500	3702	0:06:10.200	7.248	7.246	4052	0:06:45.200	42.248	42.246	0	00:00.0
1	stop-And-Re	Red-Light	3015	0:05:01.500	3702	0:06:10.200	7.148	7.146	4052	0:06:45.200	42.148	42.146	0	00:00.0
1	stop-And-Re	Red-Light	3015	0:05:01.500	3702	0:06:10.200	7.048	7.046	4052	0:06:45.200	42.048	42.046	0	00:00.0

Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle to Infrastructure 5 (V2I-5) Consortium, 2022

Figure 11: Partial List of Processed SPaT Messages in CSV

Assessment of Message Periodicity

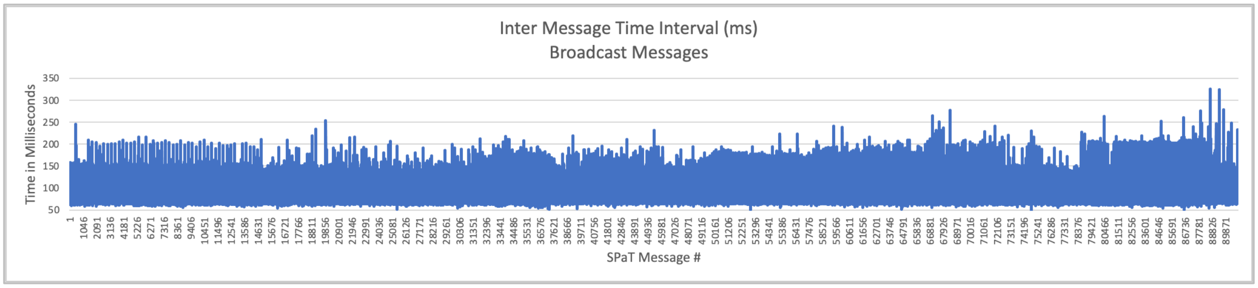
For a RLVW application to perform as intended based on defined 100 ms time interval of the message broadcast, message generation and transmission periodicity is determined using the analysis of received SPaT messages. Figure 12 shows the inter message time interval of a generated message (as provided in the message timestamp) by the RSU. As shown, the nominal time interval of 100 msec is not maintained. From the data, it is inconclusive if the spike in time is due to delays in the controller supplying the SPaT data at 100 msec interval to the RSU or internal processing delay within the RSU. For proper determination, recording of SPaT data arrival time at the RSU (port 1516) is required.



Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle to Infrastructure 5 (V2I-5) Consortium, 2022

Figure 12: Inter Message Time Interval of Generated SPaT Messages

Figure 13 shows inter message time interval at which the message is being broadcast by the RSU. As shown, the inter message time interval of messages transmitted by the RSU is also not maintained at nominal 100 msec. Assuming no OTA transmission delay, the receiver (OBU) will have the same periodicity.



Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle to Infrastructure 5 (V2I-5) Consortium, 2022

Figure 13: Inter Message Time Interval of Broadcast SPaT Messages

Table 1: Inter Message Time Interval of Broadcast SPaT Messages

Inter Message Time Interval		
Inter Msg Time Interval (ms)	Generated SPaT Message	Broadcast SPaT Message
> 150 (50%)	0.21%	2.97%
> 125 (25%)	0.23%	20.15%
> 110 (10%)	0.26%	21.16%
> 105 (5%)	0.34%	23.14%
< 95 (5%)	0.00%	30.75%
< 90 (10%)	0.00%	26.38%
< 80 (20%)	0.00%	23.44%

Table 1 shows an analysis of the variation of inter message time intervals for generated and broadcast SPaT messages.

Signal Controller Data Analysis

Timestamp	Intersection Name	Event	Detail
16:56:21.407	Garfield at Moravian	Phase Yellow	Phase 2
16:56:21.407	Garfield at Moravian	Phase Yellow	Phase 6
16:56:25.707	Garfield at Moravian	Phase Red	Phase 2
16:56:25.707	Garfield at Moravian	Phase Red	Phase 6
16:56:27.707	Garfield at Moravian	Phase Green	Phase 4
16:56:27.707	Garfield at Moravian	Phase Green	Phase 8
16:56:47.817	Garfield at Moravian	Phase Yellow	Phase 4
16:56:47.817	Garfield at Moravian	Phase Yellow	Phase 8
16:56:52.143	Garfield at Moravian	Phase Red	Phase 4
16:56:52.143	Garfield at Moravian	Phase Red	Phase 8
16:56:54.113	Garfield at Moravian	Phase Green	Phase 2
16:56:54.113	Garfield at Moravian	Phase Green	Phase 6
16:57:07.707	Garfield at Moravian	Local Zero	1
16:58:01.413	Garfield at Moravian	Phase Yellow	Phase 2
16:58:01.413	Garfield at Moravian	Phase Yellow	Phase 6
16:58:05.710	Garfield at Moravian	Phase Red	Phase 2

Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle to Infrastructure 5 (V2I-5) Consortium, 2022

Figure 14: TSC Log Data from Centracs System

For the desired signal phase #2, extract the start time and the duration of the yellow phase. Figure 14 shows a sample of the controller log data captured by the Centracs System. The Event column provides signal phase information, and the Detail column provides the signal phase number for the start of the event at the recorded Timestamp. The basic level 1 RLVW application is based on the indicated start of yellow phase and its duration. For example, start of yellow phase for signal phase #2 is 16:56:21:407, and the duration is 4.3 s until the start of red phase at 16:56:25.707.

Similarly, the next step is to extract relevant information for the same signal phase #2 from the generated SPaT message log file in csv. The start time of the yellow phase is equal to the last message timestamp of the green phase before the ending of the green phase plus the time remaining in the current green phase. As shown in Figure 15, highlighted in light green (msg #9240), the message timestamp is shown in the column labeled Intx_Time before turning to yellow (column Sig_Phase_2). The start time of yellow phase equals to 16:56:21.299 + 0.002 (column min_ET_Remain_2) = 16:56:21.301 UTC. The duration equals the remaining minimum end time (column min_ET_Remain_2) highlighted in light yellow (msg #9241) for yellow phase plus time used by the green phase before the end. As shown in the table in Figure 14, the duration is 4.201 sec + (100 – 2) msec = 4.299 sec.

Since the yellow phase is in fixed time operation, the minEndTime and maxEndTime values should be the same as per the CI Implementation Guide (optional in J2735). However, “-1” indicates value not provided in the message.

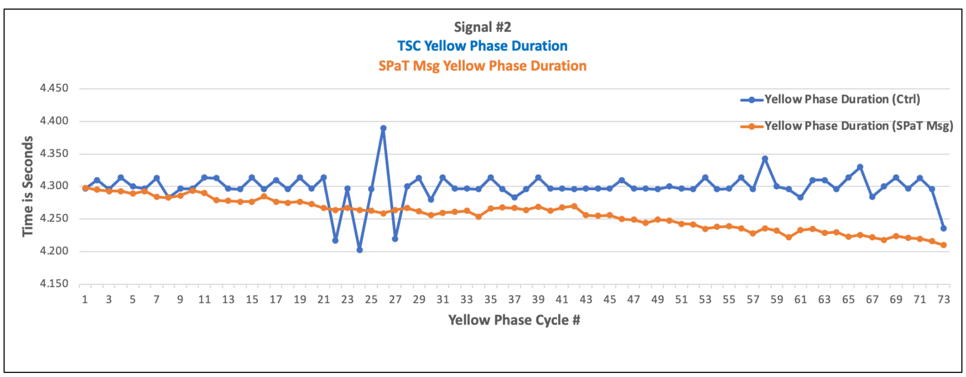
msg #	Msg Rx TS - epoch_UTC	epoch_diff_ms	Intx_Time	MSG_TS_Diff_ms	RX_Time_Diff_ms	Sig_Grp_2	Event_State_2	Sig_Phase_2	MinEnd_TM_2	MinEnd_Time_2	Min_ET_Remain_2	Min_ET_Remain_epoch_2	MaxEnd_TM_2	MaxEnd_Time_2	Max_ET_Remain_2	Max_ET_Remain_epoch_2
9239	2022/01/11 - 16:56:21.168	99	10d - 16:56:21.098	100	70	2	permissive-M	Perm-Green	33812	0:56:21.200	0.102	0.032	33879	0:56:27.900	6.802	6.732
9240	2022/01/11 - 16:56:21.270	102	10d - 16:56:21.198	100	72	2	permissive-M	Perm-Green	33812	0:56:21.200	0.002	-0.07	33879	0:56:27.900	6.702	6.63
9241	2022/01/11 - 16:56:21.369	99	10d - 16:56:21.299	101	70	2	permissive-c	Perm-Yellow	33855	0:56:25.500	4.201	4.131	-1	00:00.0	-3381.4	-3381.47
9242	2022/01/11 - 16:56:21.468	99	10d - 16:56:21.398	99	70	2	permissive-c	Perm-Yellow	33855	0:56:25.500	4.102	4.032	-1	00:00.0	-3381.5	-3381.57
9243	2022/01/11 - 16:56:21.607	139	10d - 16:56:21.498	100	109	2	permissive-c	Perm-Yellow	33855	0:56:25.500	4.002	3.893	-1	00:00.0	-3381.6	-3381.71
9244	2022/01/11 - 16:56:21.674	67	10d - 16:56:21.598	100	76	2	permissive-c	Perm-Yellow	33855	0:56:25.500	3.902	3.826	-1	00:00.0	-3381.7	-3381.77
9245	2022/01/11 - 16:56:21.768	94	10d - 16:56:21.698	100	70	2	permissive-c	Perm-Yellow	33855	0:56:25.500	3.802	3.732	-1	00:00.0	-3381.8	-3381.87
9246	2022/01/11 - 16:56:21.901	133	10d - 16:56:21.798	100	103	2	permissive-c	Perm-Yellow	33855	0:56:25.500	3.702	3.599	-1	00:00.0	-3381.9	-3382
9247	2022/01/11 - 16:56:21.972	71	10d - 16:56:21.898	100	74	2	permissive-c	Perm-Yellow	33855	0:56:25.500	3.602	3.528	-1	00:00.0	-3382	-3382.07
9248	2022/01/11 - 16:56:22.067	95	10d - 16:56:21.998	100	69	2	permissive-c	Perm-Yellow	33855	0:56:25.500	3.502	3.433	-1	00:00.0	-3382.1	-3382.17
9249	2022/01/11 - 16:56:22.168	101	10d - 16:56:22.099	101	69	2	permissive-c	Perm-Yellow	33855	0:56:25.500	3.401	3.332	-1	00:00.0	-3382.2	-3382.27
9250	2022/01/11 - 16:56:22.290	122	10d - 16:56:22.198	99	92	2	permissive-c	Perm-Yellow	33855	0:56:25.500	3.302	3.21	-1	00:00.0	-3382.3	-3382.39
9251	2022/01/11 - 16:56:22.372	82	10d - 16:56:22.298	100	74	2	permissive-c	Perm-Yellow	33855	0:56:25.500	3.202	3.128	-1	00:00.0	-3382.4	-3382.47

Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle to Infrastructure 5 (V2I-5) Consortium, 2022

Figure 15: List of SPaT Message Log for Signal Phase #2

Analysis of Start Time and Duration of Yellow Phase

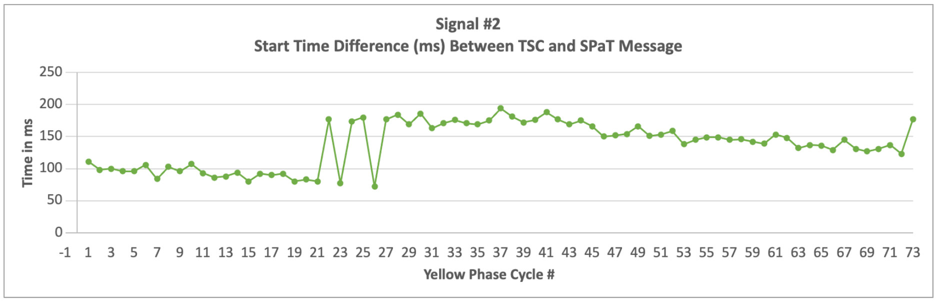
The graph in Figure 16 shows an analysis of the yellow phase duration for signal phase #2 of 74 cycles. The blue line shows duration indicated by the TSC, and the orange line indicates the equivalent information contained in the broadcast SPaT message. The duration set by the controller averages to 4.299 sec while the SPaT message is 4.257 sec.



Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle to Infrastructure 5 (V2I-5) Consortium, 2022

Figure 16: Yellow Phase Duration in TSC and in SPaT Message

Figures 17 shows the time difference in start time of the yellow phase between the TSC and in the SPaT message.



Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle to Infrastructure 5 (V2I-5) Consortium, 2022

Figure 17: Difference in Yellow Phase Start Time - TSC vs. SPaT Message

Equipment Time Source

At this deployed CI, different pieces of equipment use different time sources to synchronize the internal clock.

- Traffic Signal Controller – Network Time Protocol (NTP) Server
- Controller log – Centracs data log server at the backend
  - Communication latency between the controller and the Centracs system - unknown
- RSU – GPS
  - SPaT message generation in RSU
  - SPaT/MAP message log at the RSU

Analysis Summary

- Periodicity of SPaT data from the TSC and the message generation by the RSU are within ±10 msec of nominal 100 msec which are well within 1% of total messages. However, the variation in broadcast periodicity is very high at 21.16%. This could be attributed to the processing of the Security Credential Management System (SCMS) security credentials and/or other message processing in the RSU.
- There is fairly good agreement between the duration (minEndTime) in the SPaT message and the actual yellow phase duration reported by the TSC.
- Clock drift observed in the logged controller data indicates that internal clock synchronization is done at a specified time duration and not based on certain amount of time drift.
- Message timestamp occurs earlier than the controller timestamp. Different time sources and network latencies may have contributed to the logged SPaT message time earlier than the controller time.

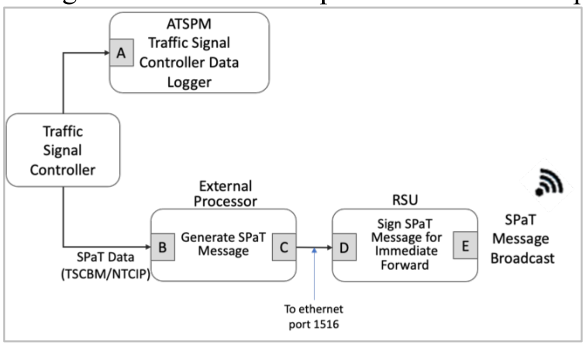
Example Method 2

In this example, the test procedure to capture and analyze SPaT at a deployed CI in Utah is described using the second method shown in Figure 8. At this site, the TSC is interfaced with an external processor to generate the SPaT message from SPaT data provided in the Traffic Signal Controller Broadcast Message (TSCBM) format. The SPaT message generated is transmitted to an RSU which applies appropriate SCMS security to the message before OTA broadcast, in this case using IFM.

- Test Site: SR 224 and Canyons Resort Drive, Park City, Utah

- Test Date and Duration: May 17, 2022, from 1:12 PM (MDT) to 4:12 PM (MDT) (19:12:20 to 23:12:00 UTC)

Figure 18 shows test points for logged data. All logged information packets include UTC timestamp used to align data across all test points and determine process time.



Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle to Infrastructure 5 (V2I-5) Consortium, 2022

Figure 18: Test Points for Capturing SPaT Data

Test Point A: Signal controller event data log data in csv. It is recorded using the ATSPM data logging tool to determine start time and duration of yellow phase as per the TSC.

Test Point B: SPaT data in TSCBM or NTCIP format from the TSC at the input to the external processing unit. This data is recorded in binary as PCAP before SPaT message is generated.

Test Point C: After generating the SPaT message, at the output port of external processor.

Test Point D: At the ethernet port 1516, SPaT message as PCAP is input to the RSU for SCMS security credential processing and message broadcast.

Test Point E: SPaT message as PCAP at the point of OTA message is broadcast in IFM.

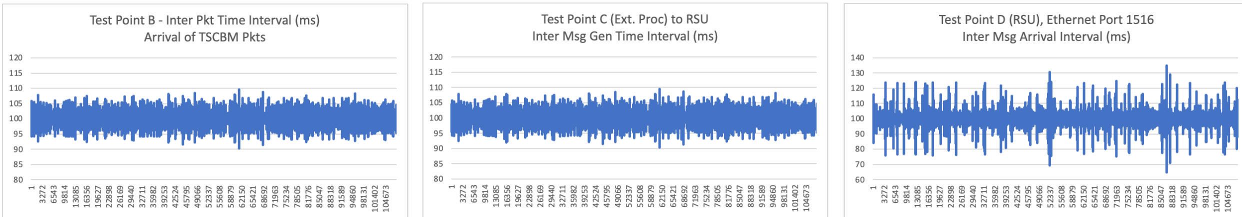
SPaT processing and communication time can be determined as follows:

- SPaT data communication time from the TSC to the external processor = Timestamp at test point B – Timestamp at test point A
- SPaT message generation time = Timestamp at test point C – Timestamp at test point B
- Communication from the external processor to RSU = Timestamp at test pint D (RSU port 1516) – Timestamp at test point C (out from external processor)
- SPaT message processing for appropriate SCMS security for OTA broadcast in IFM = Timestamp at test point E – Timestamp at test point D

As previously described in example 1, all logged data is converted to csv format for processing and analysis.

Analysis of Message Periodicity

Figure 19 shows analysis and graphs of SPaT information process time interval (periodicity) at three test points. Test point B for the arrival of TSCBM at the external processing unit, test point C at the external processor after generating the message before transmitting to RSU, and at the test point D at the arrival of RSU at ethernet port #1516.



Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle to Infrastructure 5 (V2I-5) Consortium, 2022

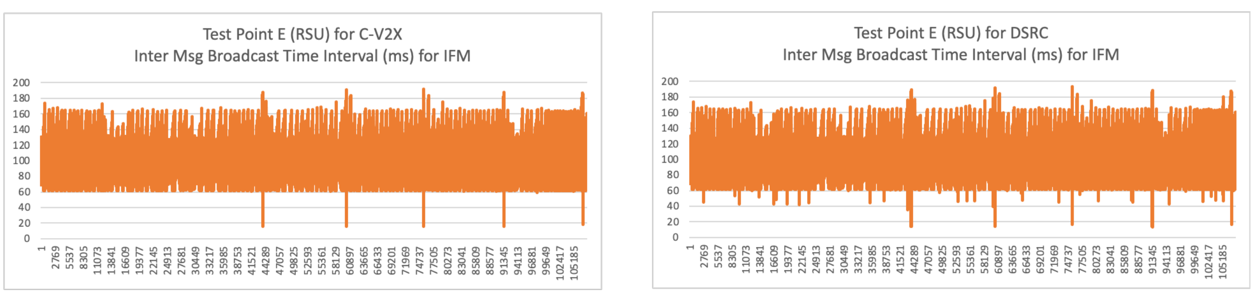
Figure 19: Inter Packet Processing Time Interval at Test Points B (Ext. Proc), C (Ext. Proc.) and D (RSU)

Table 2 shows the minimum and maximum inter packet time interval and percentage of ± 5 and ±10 msec time interval from nominal 100 ms for all close to 108,000 messages. As shown, the time interval at test points B and C are maintained within ±10 msec. However, some delay is observed in receiving packets at the RSU. This could be due to packet logging delay at the RSU.

Table 2: Min and Max Inter Packet Time Interval and Percentage at Test Points B and C (Ext. Proc)

Description	Test Point B - Inter Pkt Time Interval (ms) Arrival of TSCBM Pkts	Test Point C (Ext. Proc) to RSU Inter Msg Gen Time Interval (ms)	Test Point D (RSU), Ethernet Port 1516 Inter Msg Arrival Interval (ms)
Min Time Interval (ms)	90.250	90.317	64.835
Max Time Interval (ms)	109.533	109.464	134.902
Occurrence Percentage (±5% and ±10%) from Nominal 100 ms			
Min Interval < 95 ms	0.10%	0.11%	0.67%
Max Interval > 105 ms	0.13%	0.13%	0.69%
Min Interval < 90 ms	0.00%	0.00%	0.34%
Max Interval > 110 ms	0.00%	0.00%	0.34%

Similarly, Figure 20 shows an analysis and graphs of the SPaT message OTA broadcast time interval (periodicity) at test point D for C-V2X and DSRC communication links.



Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle to Infrastructure 5 (V2I-5) Consortium, 2022

Figure 20: Inter Message Broadcast Time Interval at Test Points D for C-V2X and DSRC

Table 3 shows the minimum and maximum inter message time interval and percentage of ±5 and ±10 msec time interval from nominal 100 ms for up to 108,000 messages. As shown, the inter message time interval shows significant variation from nominal 100 ms. Data shows increase in time interval every

10th message thus indicating additional time was taken to sign the message with the SCMS security certificate and the time interval for the next message is reduced by the same amount indicating only the digest is attached.

Table 3: Minimum and Maximum Inter Message Time Interval and Occurrence Percentage

Description	Test Point D (RSU) for C-V2X Inter Msg Broadcast Time Interval (ms) for IFM	Test Point D (RSU) for DSRC Inter Msg Broadcast Time Interval (ms) for IFM
Min Time Interval (ms)	15.541	13.686
Max Time Interval (ms)	192.080	193.458
Occurrence Percentage (± 5% and ±10%) from Nominal 100 ms		
Min Interval < 95 ms	15.97%	16.15%
Max Interval > 105 ms	13.95%	14.18%
Min Interval < 90 ms	14.59%	14.64%
Max Interval > 110 ms	13.06%	13.13%

As shown, the inter message time interval is significantly higher from nominal 100 ms. It observed in other tests that the RSU is not able to maintain the nominal time interval in IFM as illustrated in Figure 5.

Analysis of Start Time and Duration of Yellow Phase

As described in example 1, the logged SPaT message in PCAP at test point E is converted to JSON and processed to generate data in the csv format. Figure 21 shows an excerpt of messages in csv format. All common data elements in addition to all mandatory elements for signal phase 1 are shown. The entire file contains data for all signal phases. Required data elements (as per ITE CI Implementation Guide [1]) for the current phase show minEnd and maxEnd time marks from either current hour or top of next hour and time remaining in the phase. The start time of the current phase and the time of next phase are only conditionally required in the CI Implementation Guide. A "-1" for this value indicates not available in the SPaT message.

msg signed	Epoch TS (ms)	Epoch UTC date/time	epoch Time Interval (ms)	Msg ID	Timestamp MOY	Intx Name	Intx Reg ID	Intx ID	Msg Rev	Intx Status Obj	Msg MOY	Msg TS (ms)	Intx_Time
1	1652814764266	2022/05/17 - 19:12:44.266	0	19	196992 (136d 19:12:00)	StateRte224	NA	7707	116	400	196992	44250	136d - 19:12:44.250
1	1652814764367	2022/05/17 - 19:12:44.367	101	19	196992 (136d 19:12:00)	StateRte224	NA	7707	117	400	196992	44351	136d - 19:12:44.351
1	1652814764467	2022/05/17 - 19:12:44.467	100	19	196992 (136d 19:12:00)	StateRte224	NA	7707	118	400	196992	44450	136d - 19:12:44.450
1	1652814764566	2022/05/17 - 19:12:44.566	99	19	196992 (136d 19:12:00)	StateRte224	NA	7707	119	400	196992	44550	136d - 19:12:44.550
1	1652814764667	2022/05/17 - 19:12:44.667	101	19	196992 (136d 19:12:00)	StateRte224	NA	7707	120	400	196992	44650	136d - 19:12:44.650
1	1652814764768	2022/05/17 - 19:12:44.768	101	19	196992 (136d 19:12:00)	StateRte224	NA	7707	121	400	196992	44750	136d - 19:12:44.750
1	1652814764886	2022/05/17 - 19:12:44.886	118	19	196992 (136d 19:12:00)	StateRte224	NA	7707	122	400	196992	44850	136d - 19:12:44.850
1	1652814764996	2022/05/17 - 19:12:44.996	110	19	196992 (136d 19:12:00)	StateRte224	NA	7707	123	400	196992	44950	136d - 19:12:44.950
1	1652814765067	2022/05/17 - 19:12:45.067	71	19	196992 (136d 19:12:00)	StateRte224	NA	7707	124	400	196992	45050	136d - 19:12:45.050
1	1652814765167	2022/05/17 - 19:12:45.167	100	19	196992 (136d 19:12:00)	StateRte224	NA	7707	125	400	196992	45150	136d - 19:12:45.150
1	1652814765266	2022/05/17 - 19:12:45.266	99	19	196992 (136d 19:12:00)	StateRte224	NA	7707	126	400	196992	45250	136d - 19:12:45.250
1	1652814765367	2022/05/17 - 19:12:45.367	101	19	196992 (136d 19:12:00)	StateRte224	NA	7707	127	400	196992	45350	136d - 19:12:45.350
1	1652814765466	2022/05/17 - 19:12:45.466	99	19	196992 (136d 19:12:00)	StateRte224	NA	7707	1	400	196992	45450	136d - 19:12:45.450
1	1652814765567	2022/05/17 - 19:12:45.567	101	19	196992 (136d 19:12:00)	StateRte224	NA	7707	2	400	196992	45550	136d - 19:12:45.550
1	1652814765666	2022/05/17 - 19:12:45.666	99	19	196992 (136d 19:12:00)	StateRte224	NA	7707	3	400	196992	45650	136d - 19:12:45.650
1	1652814765769	2022/05/17 - 19:12:45.769	103	19	196992 (136d 19:12:00)	StateRte224	NA	7707	4	400	196992	45750	136d - 19:12:45.750
1	1652814765870	2022/05/17 - 19:12:45.870	101	19	196992 (136d 19:12:00)	StateRte224	NA	7707	5	400	196992	45850	136d - 19:12:45.850
1	1652814765993	2022/05/17 - 19:12:45.993	123	19	196992 (136d 19:12:00)	StateRte224	NA	7707	6	400	196992	45950	136d - 19:12:45.950
1	1652814766067	2022/05/17 - 19:12:46.067	74	19	196992 (136d 19:12:00)	StateRte224	NA	7707	7	400	196992	46050	136d - 19:12:46.050
1	1652814766166	2022/05/17 - 19:12:46.166	99	19	196992 (136d 19:12:00)	StateRte224	NA	7707	8	400	196992	46150	136d - 19:12:46.150

Epoch TS (ms)	MSG Time Interval (ms)	Time Diff (Msg TS-RX) (ms)	Sig #1	Event State #1	Sig Ph #1	Start TM 1	Start Time #1	Min End TM #1	Min End Time #1 (Ctr/Top of Hr)	Min End Time Remain #1	Min End Time Remain epoch #1	Max End TM #1	Max End Time #1 (Ctr/Top of Hr)	Max End Time Remain #1	Max End Time Remain epoch #1	Next TM #1	Next Time #1
1652814764266	0	16	1	stop-And-Re	Red-Light	-1	00:00.0	8533	0:14:13.300	89.05	89.034	8533	0:14:13.300	89.05	89.034	-1	00:00.0
1652814764367	101	16	1	stop-And-Re	Red-Light	-1	00:00.0	8533	0:14:13.300	88.949	88.933	8533	0:14:13.300	88.949	88.933	-1	00:00.0
1652814764467	99	17	1	stop-And-Re	Red-Light	-1	00:00.0	8533	0:14:13.300	88.85	88.833	8533	0:14:13.300	88.85	88.833	-1	00:00.0
1652814764566	100	16	1	stop-And-Re	Red-Light	-1	00:00.0	8533	0:14:13.300	88.75	88.734	8533	0:14:13.300	88.75	88.734	-1	00:00.0
1652814764667	100	17	1	stop-And-Re	Red-Light	-1	00:00.0	8533	0:14:13.300	88.65	88.633	8533	0:14:13.300	88.65	88.633	-1	00:00.0
1652814764768	100	18	1	stop-And-Re	Red-Light	-1	00:00.0	8533	0:14:13.300	88.55	88.532	8533	0:14:13.300	88.55	88.532	-1	00:00.0
1652814764886	100	36	1	stop-And-Re	Red-Light	-1	00:00.0	8533	0:14:13.300	88.45	88.414	8533	0:14:13.300	88.45	88.414	-1	00:00.0
1652814764996	100	46	1	stop-And-Re	Red-Light	-1	00:00.0	8533	0:14:13.300	88.35	88.304	8533	0:14:13.300	88.35	88.304	-1	00:00.0
1652814765067	100	17	1	stop-And-Re	Red-Light	-1	00:00.0	8533	0:14:13.300	88.25	88.233	8533	0:14:13.300	88.25	88.233	-1	00:00.0
1652814765167	100	17	1	stop-And-Re	Red-Light	-1	00:00.0	8533	0:14:13.300	88.15	88.133	8533	0:14:13.300	88.15	88.133	-1	00:00.0
1652814765266	100	16	1	stop-And-Re	Red-Light	-1	00:00.0	8533	0:14:13.300	88.05	88.034	8533	0:14:13.300	88.05	88.034	-1	00:00.0
1652814765367	100	17	1	stop-And-Re	Red-Light	-1	00:00.0	8533	0:14:13.300	87.95	87.933	8533	0:14:13.300	87.95	87.933	-1	00:00.0
1652814765466	100	16	1	stop-And-Re	Red-Light	-1	00:00.0	8533	0:14:13.300	87.85	87.834	8533	0:14:13.300	87.85	87.834	-1	00:00.0
1652814765567	100	17	1	stop-And-Re	Red-Light	-1	00:00.0	8533	0:14:13.300	87.75	87.733	8533	0:14:13.300	87.75	87.733	-1	00:00.0
1652814765666	100	16	1	stop-And-Re	Red-Light	-1	00:00.0	8533	0:14:13.300	87.65	87.634	8533	0:14:13.300	87.65	87.634	-1	00:00.0
1652814765769	100	19	1	stop-And-Re	Red-Light	-1	00:00.0	8533	0:14:13.300	87.55	87.531	8533	0:14:13.300	87.55	87.531	-1	00:00.0
1652814765870	100	20	1	stop-And-Re	Red-Light	-1	00:00.0	8533	0:14:13.300	87.45	87.43	8533	0:14:13.300	87.45	87.43	-1	00:00.0
1652814765993	100	43	1	stop-And-Re	Red-Light	-1	00:00.0	8533	0:14:13.300	87.35	87.307	8533	0:14:13.300	87.35	87.307	-1	00:00.0
1652814766067	100	17	1	stop-And-Re	Red-Light	-1	00:00.0	8533	0:14:13.300	87.25	87.233	8533	0:14:13.300	87.25	87.233	-1	00:00.0
1652814766166	100	16	1	stop-And-Re	Red-Light	-1	00:00.0	8533	0:14:13.300	87.15	87.134	8533	0:14:13.300	87.15	87.134	-1	00:00.0

Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle to Infrastructure 5 (V2I-5) Consortium, 2022

Figure 21: Excerpt of Processed SPaT Message in csv

Figure 22 shows a list of extracted and processed ATSPM TSC logged data and the same for timestamp aligned SPaT data for start time and duration of the yellow phase for signal phase #2 for the first 25 out of 98 cycles. Event codes 8 and 9 (columns E and I) in the ATSPM log indicate start time and end time, respectively, and the duration is 5 sec.

The message timestamp in column O for the SPaT message shows the start time of the phase, and the minimum time remaining in column T (same as column X) shows the duration of the phase in seconds. Column M shows the time difference between the start of yellow in SPaT messages and in the TSC ATSPM log. Column C, UTC timestamp of the ATSPM log, is over 5 s behind the SPaT message timestamp (column O). It should be noted that the timestamp resolution of ATSPM data is tenth of a second while the SPaT message is in milliseconds.

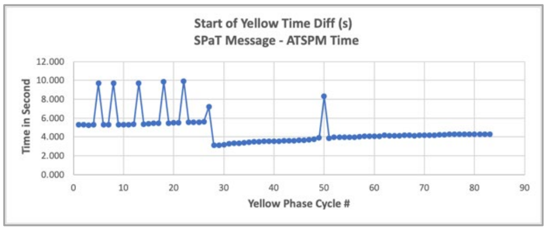
The highlighted elements in column M show greatly increased time differences, and column T shows greatly reduced duration of the yellow phase for the cycle indicating anomalous data in the SPaT message.

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y
Sig Phase #2 ATSPM - TSC Log for Start and End of Yellow Phase for Signal #2										SPaT Message Broadcast for Start of Yellow Phase for Signal Phase #2														
Cycle #	Local Time	UTC Time	In Sec	Start of Event	Local Time	UTC Time	In Sec	End of Event	Duration (S)	epoch_UTC	epoch UTC (s)	Start of Yellow Time Diff Bet SPaT & ATSPM	epoch diff (ms)	Intx_Time	Sig Grp	Sig Phase 2	MinEnd TM 2	MinEnd Time 2	Min ET Remain 2	Min ET Remain epoch 2	MaxEnd TM 2	MaxEnd Time 2	Max ET Remain 2	Max ET Remain epoch 2
1	13.13:21.500	19.13:21.500	69201.5	8	13.13:26.500	19.13:26.500	69206.5	9	5.000	19.13:26.767	69206.77	5.267	105	136d - 19:13:26.746	2	Perm-Yellow	8117	0:13:31.700	4.954	4.933	8117	0:13:31.700	4.954	4.933
2	13.15:01.500	19.15:01.500	69301.5	8	13.15:06.500	19.15:06.500	69306.5	9	5.000	19.15:06.768	69306.77	5.268	100	136d - 19:15:06.751	2	Perm-Yellow	9117	0:15:11.700	4.949	4.932	9117	0:15:11.700	4.949	4.932
3	13.16:41.500	19.16:41.500	69401.5	8	13.16:46.500	19.16:46.500	69406.5	9	5.000	19.16:46.759	69406.76	5.259	101	136d - 19:16:46.742	2	Perm-Yellow	10117	0:16:51.700	4.958	4.941	10117	0:16:51.700	4.958	4.941
4	13.18:21.500	19.18:21.500	69501.5	8	13.18:26.500	19.18:26.500	69506.5	9	5.000	19.18:26.776	69506.78	5.276	100	136d - 19:18:26.760	2	Perm-Yellow	11117	0:18:31.700	4.940	4.924	11117	0:18:31.700	4.940	4.924
5	13.20:01.500	19.20:01.500	69601.5	8	13.20:06.500	19.20:06.500	69606.5	9	5.000	19.20:11.173	69611.17	9.673	88	136d - 19:20:11.155	2	Perm-Yellow	12117	0:20:11.700	0.545	0.527	12117	0:20:11.700	0.545	0.527
6	13.21:41.500	19.21:41.500	69701.5	8	13.21:46.500	19.21:46.500	69706.5	9	5.000	19.21:46.777	69706.78	5.277	100	136d - 19:21:46.760	2	Perm-Yellow	13117	0:21:51.700	4.940	4.923	13117	0:21:51.700	4.940	4.923
7	13.23:21.500	19.23:21.500	69801.5	8	13.23:26.500	19.23:26.500	69806.5	9	5.000	19.23:26.807	69806.81	5.307	65	136d - 19:23:26.775	2	Perm-Yellow	14117	0:23:31.700	4.925	4.893	14117	0:23:31.700	4.925	4.893
8	13.25:01.500	19.25:01.500	69901.5	8	13.25:06.500	19.25:06.500	69906.5	9	5.000	19.25:11.200	69911.20	9.700	104	136d - 19:25:11.180	2	Perm-Yellow	15117	0:25:11.700	0.520	0.500	15117	0:25:11.700	0.520	0.5
9	13.26:41.500	19.26:41.500	70001.5	8	13.26:46.500	19.26:46.500	70006.5	9	5.000	19.26:46.806	70006.81	5.306	100	136d - 19:26:46.790	2	Perm-Yellow	16117	0:26:51.700	4.910	4.894	16117	0:26:51.700	4.910	4.894
10	13.28:21.500	19.28:21.500	70101.5	8	13.28:26.500	19.28:26.500	70106.5	9	5.000	19.28:26.806	70106.81	5.306	99	136d - 19:28:26.790	2	Perm-Yellow	17117	0:28:31.700	4.910	4.894	17117	0:28:31.700	4.910	4.894
11	13.30:01.500	19.30:01.500	70201.5	8	13.30:06.500	19.30:06.500	70206.5	9	5.000	19.30:06.805	70206.81	5.305	100	136d - 19:30:06.788	2	Perm-Yellow	18117	0:30:11.700	4.912	4.895	18117	0:30:11.700	4.912	4.895
12	13.31:41.500	19.31:41.500	70301.5	8	13.31:46.500	19.31:46.500	70306.5	9	5.000	19.31:46.815	70306.82	5.315	100	136d - 19:31:46.799	2	Perm-Yellow	19117	0:31:51.700	4.901	4.885	19117	0:31:51.700	4.901	4.885
13	13.33:21.500	19.33:21.500	70401.5	8	13.33:26.500	19.33:26.500	70406.5	9	5.000	19.33:31.214	70411.21	9.714	104	136d - 19:33:31.197	2	Perm-Yellow	20117	0:33:31.700	0.503	0.486	20117	0:33:31.700	0.503	0.486
14	13.35:01.500	19.35:01.500	70501.5	8	13.35:06.500	19.35:06.500	70506.5	9	5.000	19.35:06.839	70506.84	5.339	92	136d - 19:35:06.822	2	Perm-Yellow	21118	0:35:11.800	4.978	4.961	21118	0:35:11.800	4.978	4.961
15	13.36:41.500	19.36:41.500	70601.5	8	13.36:46.500	19.36:46.500	70606.5	9	5.000	19.36:46.872	70606.87	5.372	75	136d - 19:36:46.855	2	Perm-Yellow	22118	0:36:51.800	4.945	4.928	22118	0:36:51.800	4.945	4.928
16	13.38:21.500	19.38:21.500	70701.5	8	13.38:26.500	19.38:26.500	70706.5	9	5.000	19.38:26.928	70706.93	5.428	124	136d - 19:38:26.883	2	Perm-Yellow	23118	0:38:31.800	4.917	4.872	23118	0:38:31.800	4.917	4.872
17	13.40:01.500	19.40:01.500	70801.5	8	13.40:06.500	19.40:06.500	70806.5	9	5.000	19.40:06.937	70806.94	5.437	116	136d - 19:40:06.903	2	Perm-Yellow	24119	0:40:11.900	4.997	4.963	24119	0:40:11.900	4.997	4.963
18	13.41:41.500	19.41:41.500	70901.5	8	13.41:46.500	19.41:46.500	70906.5	9	5.000	19.41:51.335	70911.34	9.835	100	136d - 19:41:51.318	2	Perm-Yellow	25119	0:41:51.900	0.582	0.565	25119	0:41:51.900	0.582	0.565
19	13.43:21.500	19.43:21.500	71001.5	8	13.43:26.500	19.43:26.500	71006.5	9	5.000	19.43:26.960	71006.96	5.460	86	136d - 19:43:26.942	2	Perm-Yellow	26119	0:43:31.900	4.958	4.940	26119	0:43:31.900	4.958	4.94
20	13.45:01.500	19.45:01.500	71101.5	8	13.45:06.500	19.45:06.500	71106.5	9	5.000	19.45:06.983	71106.98	5.483	99	136d - 19:45:06.967	2	Perm-Yellow	27119	0:45:11.900	4.933	4.917	27119	0:45:11.900	4.933	4.917
21	13.46:41.500	19.46:41.500	71201.5	8	13.46:46.500	19.46:46.500	71206.5	9	5.000	19.46:46.999	71207.00	5.499	104	136d - 19:46:46.979	2	Perm-Yellow	28119	0:46:51.900	4.921	4.901	28119	0:46:51.900	4.921	4.901
22	13.48:21.500	19.48:21.500	71301.5	8	13.48:26.500	19.48:26.500	71306.5	9	5.000	19.48:31.420	71311.42	9.920	99	136d - 19:48:31.404	2	Perm-Yellow	29120	0:48:32	0.596	0.580	29120	0:48:32	0.596	0.58
23	13.50:08.000	19.50:08.000	71408	8	13.50:13.000	19.50:13.000	71413	9	5.000	19.50:13.541	71413.54	5.541	99	136d - 19:50:13.524	2	Perm-Yellow	30185	0:50:18.500	4.976	4.959	30185	0:50:18.500	4.976	4.959
24	13.51:45.000	19.51:45.000	71505	8	13.51:50.000	19.51:50.000	71510	9	5.000	19.51:50.551	71510.55	5.551	100	136d - 19:51:50.534	2	Perm-Yellow	31155	0:51:55.500	4.966	4.949	31155	0:51:55.500	4.966	4.949
25	13.53:21.500	19.53:21.500	71601.5	8	13.53:26.500	19.53:26.500	71606.5	9	5.000	19.53:27.063	71607.06	5.563	77	136d - 19:53:27.046	2	Perm-Yellow	32120	0:53:32	4.954	4.937	32120	0:53:32	4.954	4.937

Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle to Infrastructure 5 (V2I-5) Consortium, 2022

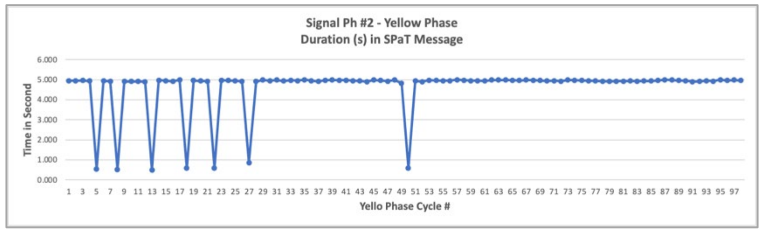
Figure 22: Extracted List of Start of Yellow Phase and Duration by TSC and Broadcast SPaT Message

Figure 23 shows the time difference in the start of the yellow phase between the broadcast SPaT message and the TSC ATSPM timestamp. Figure 24 shows the duration data in the broadcast SPaT message.



Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle to Infrastructure 5 (V2I-5) Consortium, 2022

Figure 23: Time Difference in Start of Yellow Phase Between SPaT Message and Controller ATSPM Time



Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle to Infrastructure 5 (V2I-5) Consortium, 2022

Figure 24: Duration of Yellow Phase in SPaT Message

Equipment Time Source

At this deployed CI, different pieces of equipment use different time sources to synchronize the internal clock and to establish each timestamp.

- Traffic Signal Controller – Network Time Protocol (NTP) Server
- Controller log – ATSPM data logging software tool
- External Processor – GPS
  - SPaT message generation in external processing unit
- RSU - GPS
  - SCMS security credential and message broadcast in IFM

Analysis Summary

- Periodicity of SPaT message generation within ±10 msec from nominal 100 ms is maintained well within 1% of total messages by the external processor. However, the broadcast periodicity for the same is very high at over 13%. This is due to the processing delay in applying SCMS security credentials for both SPaT and MAP messages before broadcasting in IFM. As observed in the inter message broadcast time interval, signing of every 10th SPaT message takes approximately 30 msec. The artifact of message signing delay induces same amount of reduction in time for the next broadcast of SPaT message. The reason is the next packet of SPaT messages from the external processor is continuously arriving to the RSU at 100 ms. Since the next message is not signed (only the digest is attached), the RSU immediately broadcasts the message causing shorter time interval from the previous message as illustrated in Figure 5.
- As highlighted in Figure 22 and shown in Figures 23 and 24, the yellow phase duration indicated in SPaT message (minEndTime) appears significantly different from the ATSPM data.
- There is approximately a 5 s difference between the ATSPM timestamp and the generated message timestamp. For RLVW application to perform as intended, all equipment clocks must be synchronized using the same time source and internal clock drift should be maintain to a minimum.

SPaT Performance Analysis

Using lessons learned from field testing, this section develops and applies specific pass / fail performance criteria for CI SPaT broadcast to support Basic RLVW.

The National Cooperative Highway Research Program (NHCRP) has defined the yellow change interval in Guidelines for Timing Yellow and All-Red Intervals at Signalized Intersections [6] to be between 3.0 and 5.6 seconds for speeds up to 55 mph (based on an 85th percentile approach speed estimation of posted speed limit +7 mph). Yellow phase values for approach speeds up to 70 mph are extrapolated for analysis in Table 1.

Research sponsored by the Federal Highway Administration (FHWA) developed an in-vehicle RLVW application under the Cooperative Intersection Collision Avoidance System Limited to Stop Sign and Traffic Signal Violations (CICAS-V) Project [7]. A distance-to-warn algorithm was developed to alert drivers of potential red light violations based on analysis of naturalistic driving data and extensive human factors research.

Table 4 combines the NCHRP yellow phase change interval with the CICAS-V RLVW distance-to-warn, converts this into time-to-warn, and derives a resulting warning time error budget for different approach speeds (note that the in-vehicle RLVW is only active at speeds of 20 mph or greater). This error budget indicates the maximum tolerable combination of yellow change interval inaccuracy and communication delay to successfully operate the RLVW system.

Table 4: RLVW Dist-to-Warn, NCHRP Yellow Change Interval and Error Budget

Speed Limit (MPH)	NCHRP - Yellow Change Interval (s)*	RLVW Dist-to-Warn (m)	RLVW Time-to-Warn (s)	Error Budget (s)
70	6.00	166.64	5.32	0.677
65	6.00	143.60	4.94	1.060
60	5.80	122.43	4.56	1.237
55	5.60	102.88	4.18	1.317
50	5.20	85.04	3.80	1.397
45	4.80	66.99	3.33	1.471
40	4.50	52.75	2.95	1.551
35	4.10	40.21	2.57	1.531
30	3.70	29.35	2.19	1.512
25	3.40	20.19	1.81	1.594
20	3.00	12.71	1.42	1.579
15	3.00	--	--	--
10	3.00	--	--	--

* - Based on 85th percentile approach speed estimation of posted speed limit +7 mph

SPaT Performance Criteria

Three elements of CI SPaT performance are analyzed to assess suitability to support Basic RLVW. Based on the error budget analysis under worst case conditions, each of the following three elements should be accurate / stable within a tolerance of a few hundred milliseconds:

1. The yellow phase duration / change interval accuracy:

   The duration indicated in the SPaT message broadcast (minEndTime at the onset of yellow) should match actual performance by the TSC within ± 100 ms. *Note: Since the TSC SPaT generation cycle is time based (every100 msec) and not event based, this tolerance excludes any time remaining in the cycle at the end of the green phase. For example, if the time remaining in the green phase is 20 ms when the SPaT is generated, the next SPaT cycle would indicate the start of yellow 80 ms late. The 80 ms is excluded from the ± 100 ms tolerance.*

2. The yellow phase broadcast latency:

   The start time of yellow phase indicated by the TSC must be broadcast in the SPaT message within 300 ms (per ITE CI deployment guidance). *Note: This assumes that all CI clocks are synchronized to UTC time (per ITE CI deployment guidance) so that the differences in yellow phase start time between TSC and RSU observed in field testing are eliminated*.

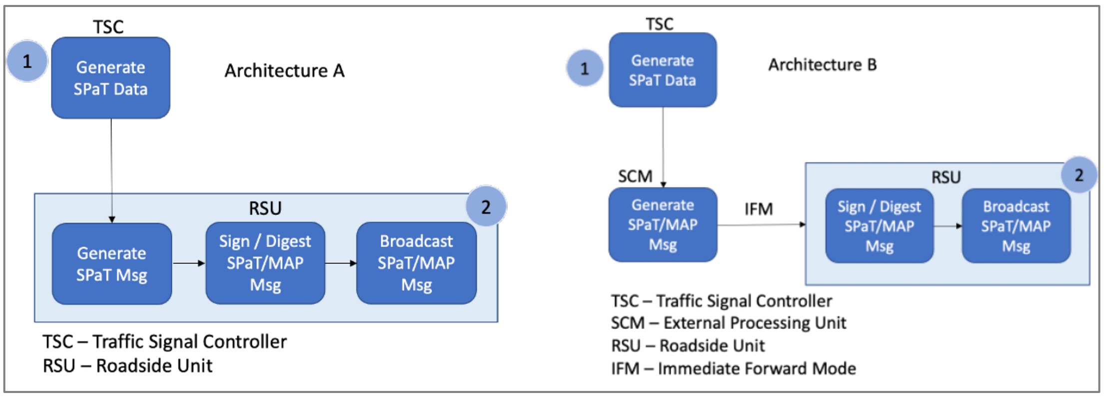
3. SPaT message broadcast periodicity:

   The nominal SPaT inter message broadcast interval of 100 msec (10 Hz) can be delayed by no more than an additional 100 msec to limit the potential for dropped / missed messages based on the jitter analysis discussion in the SPaT Transmission Periodicity section. *Note: The ITE CI deployment guidance specifies 100 ± 1 message broadcast in a 10 second interval. At the extreme, a broadcast that held all 100 messages for 9 seconds and then sent out a burst of the 100 cached messages in 1 second would comply. This would result in an information delay longer than the expected maximum yellow phase duration of 6 seconds and render RLVW useless. The criteria proposed is an initial attempt to stabilize SPaT broadcast intervals to make the information more usable to the vehicle.*

These elements and associated performance criteria are based on field observations and engineering analysis to date. Further assessment using simulation and field operational experience is needed to clarify their impact on basic RLVW algorithm performance and then refine the requirements. This includes developing additional criteria for the duration of signal operation that needs to be evaluated to comprehend the impacts of timing plan changes and external inputs on SPaT performance as well as the need for the ongoing state of health monitoring.

Yellow Phase Duration Accuracy:

As previously discussed in Figure 8 under SPaT Data Collection, Figure 25 illustrates two common CI implementation architectures in which SPaT data from the TSC is sent (A) directly to the RSU. The SPaT message is then generated and signed with a security certificate or a digest is attached before the message broadcast or (B) to an external processing unit where the SPaT message is generated and sent to the RSU to sign the message with a security certificate or a digest is attached and broadcast in IFM.



Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle to Infrastructure 5 (V2I-5) Consortium, 2022

Figure 25: Connected Intersection Implementation Architecture

The following example analysis uses data taken from a CI located at State Rte. 224 and Village Round Drive in Utah (intersection ID # 7707), which utilizes architecture B. Table 5 shows the TSC ATSPM event data log in CSV format. The event code indicates start or end of an event and the event parameter indicates the associated signal group. Event code 8 indicates the start of the yellow phase, and Event code 9 represents the end of the yellow phase. The time difference between the associated timestamps provides the actual yellow phase duration.

Table 5: Example ATSPM TSC Log

Rec #	SignalID	UTC Timestamp	EventCode	EventParam
1	7707	2022-07-27 18:30:01.500	7	2
2	7707	2022-07-27 18:30:01.500	7	5
3	7707	2022-07-27 18:30:01.500	8	2
4	7707	2022-07-27 18:30:01.500	8	5
5	7707	2022-07-27 18:30:05.600	9	5
6	7707	2022-07-27 18:30:05.600	10	5
7	7707	2022-07-27 18:30:06.500	9	2
8	7707	2022-07-27 18:30:06.500	10	2
9	7707	2022-07-27 18:30:07.800	11	5
10	7707	2022-07-27 18:30:08.000	11	2

Table 6 shows relevant data elements extracted for analysis from the SPaT message log. The log is generated from logged PCAP for broadcast SPaT messages. In the SPaT message, the yellow phase duration is indicated by the minEndTime remaining (Col. I) at the onset of yellow at the generation of the SPaT message, and the minEndTime remaining from message received (Col. J) indicates the duration at the time the message is broadcast by the RSU. The time difference between the two provides RSU message processing time before message broadcast.

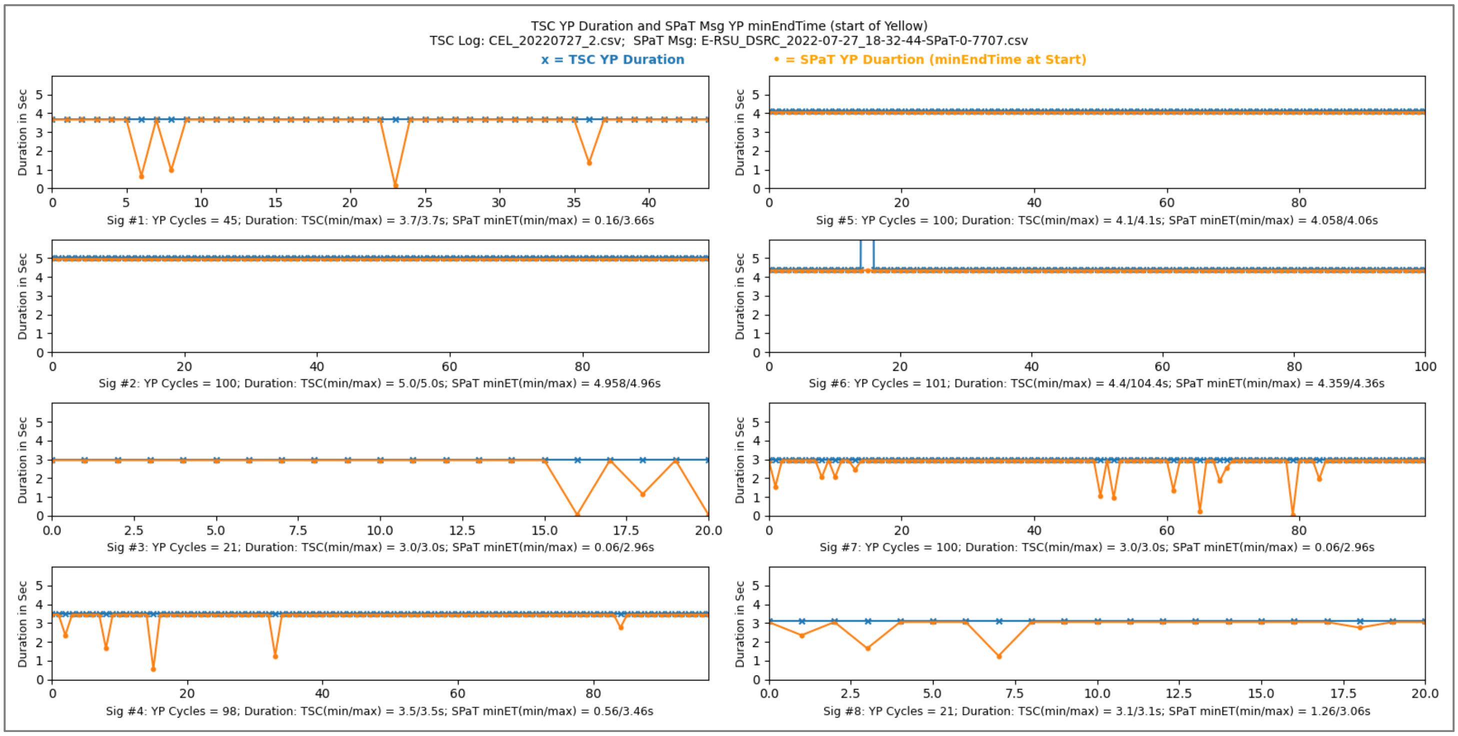
Table 6: Example Relevant SPaT Message Elements for Analysis

A	B	C	D	E	F	G	H	I	J	K	L	M	N
Cycle #	Received Message Timestamp	Received Inter Msg Time Interval (ms)	Intx_Time (Msg Timestamp)	Signal #2	Phase Indication	minEndTime Time Mark	minEndTime (Current / top of Hr)	minEndTime Remaining (s)	minEndTime Remaining from Msg Received (s)	maxEndTime Time Mark	maxEndTime (Current / top of Hr)	maxEndTime Remaining (s)	maxEndTime Remaining from Msg Received
1	2022/05/17 - 19:13:26.767	105	136d - 19:13:26.746	2	Perm-Yellow	8117	0:13:31.700	4.954	4.933	8117	0:13:31.700	4.954	4.933
2	2022/05/17 - 19:15:06.768	100	136d - 19:15:06.751	2	Perm-Yellow	9117	0:15:11.700	4.949	4.932	9117	0:15:11.700	4.949	4.932
3	2022/05/17 - 19:16:46.759	101	136d - 19:16:46.742	2	Perm-Yellow	10117	0:16:51.700	4.958	4.941	10117	0:16:51.700	4.958	4.941
4	2022/05/17 - 19:18:26.776	100	136d - 19:18:26.760	2	Perm-Yellow	11117	0:18:31.700	4.940	4.924	11117	0:18:31.700	4.940	4.924
5	2022/05/17 - 19:20:11.173	88	136d - 19:20:11.155	2	Perm-Yellow	12117	0:20:11.700	0.545	0.527	12117	0:20:11.700	0.545	0.527
6	2022/05/17 - 19:21:46.777	100	136d - 19:21:46.760	2	Perm-Yellow	13117	0:21:51.700	4.940	4.923	13117	0:21:51.700	4.940	4.923
7	2022/05/17 - 19:23:26.807	65	136d - 19:23:26.775	2	Perm-Yellow	14117	0:23:31.700	4.925	4.893	14117	0:23:31.700	4.925	4.893
8	2022/05/17 - 19:25:11.200	104	136d - 19:25:11.180	2	Perm-Yellow	15117	0:25:11.700	0.520	0.500	15117	0:25:11.700	0.520	0.5
9	2022/05/17 - 19:26:46.806	100	136d - 19:26:46.790	2	Perm-Yellow	16117	0:26:51.700	4.910	4.894	16117	0:26:51.700	4.910	4.894
10	2022/05/17 - 19:28:26.806	99	136d - 19:28:26.790	2	Perm-Yellow	17117	0:28:31.700	4.910	4.894	17117	0:28:31.700	4.910	4.894

To examine broadcast data accuracy, the yellow phase duration for each signal group from the TSC ATSPM event log data is compared to the yellow phase duration in the SPaT message determined from the minEndTime data element.

Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle to Infrastructure 5 (V2I-5) Consortium, 2022

Figure 26 shows plots of yellow phase duration from the TSC data log and the respective SPaT message for eight signal groups. The duration reported in the TSC log is shown in blue and the SPaT message in orange. For the basic RLVW application, given that all clocks are synchronized to UTC time, the time difference between the indicated yellow phase duration by the TSC and in the SPaT message shall be within ± 100 ms. As the figure shows, except for the signal group #2 and #5, the yellow duration indicated in the SPaT message (minEndTime at start of yellow) differs significantly (> 200ms) for several cycles.

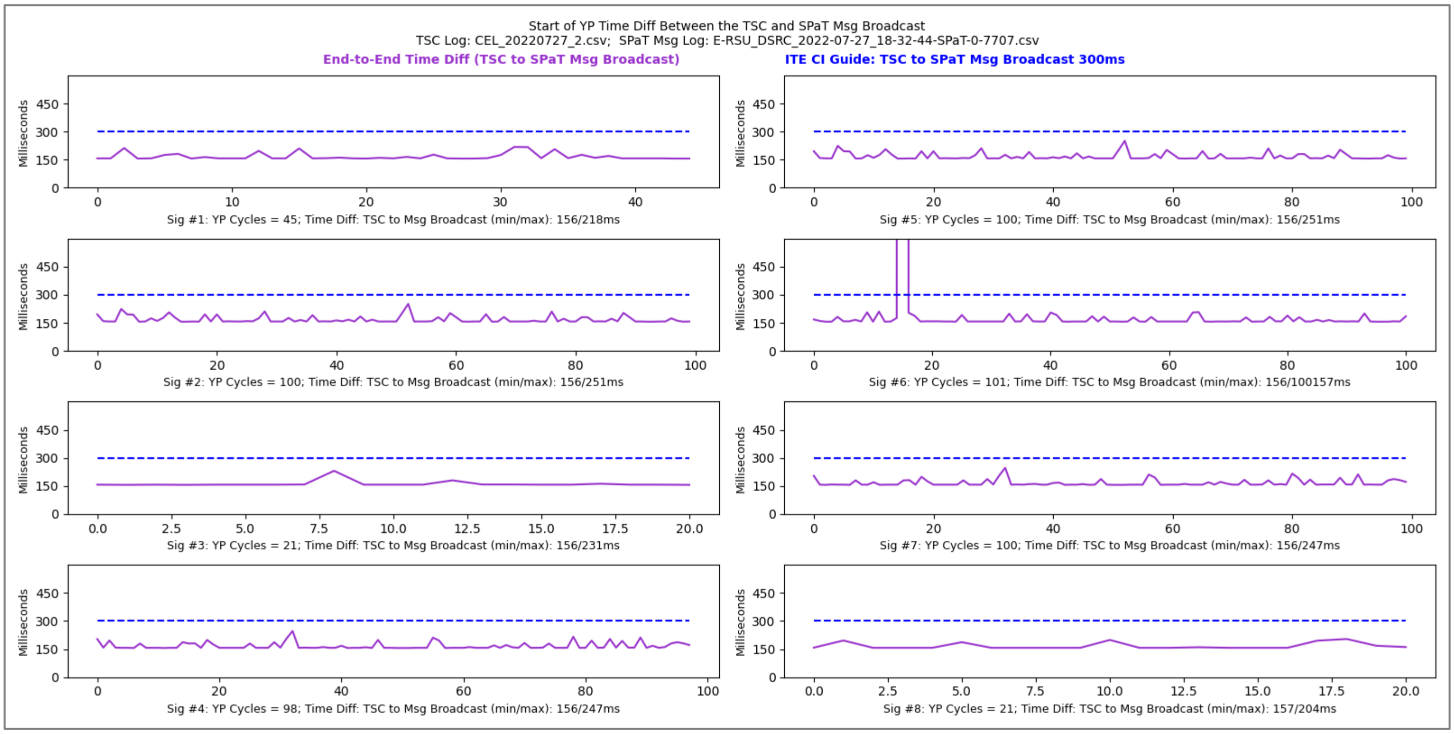


Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle to Infrastructure 5 (V2I-5) Consortium, 2022

Figure 26: Yellow Phase Duration - TSC Log vs. SPaT Message

Yellow Phase Broadcast Latency:

The yellow phase start time for each signal group is determined from the TSC event log timestamp data, and the SPaT message generation time is derived from DE_MinuteOfTheYear and DE_DSecond timestamp data elements as shown in column D in Table 6. Column B shows the timestamp of each SPaT message broadcast by the RSU. Figure 27 shows the time difference between the TSC logged start time of the yellow phase and the timestamp of the SPaT message broadcast thus indicating end-to-end process time in milliseconds. Total allowable delay from TSC data generation to RSU message broadcast must be no greater than 300 msec. Note the anomaly in signal group 6 which significantly exceeds this threshold.

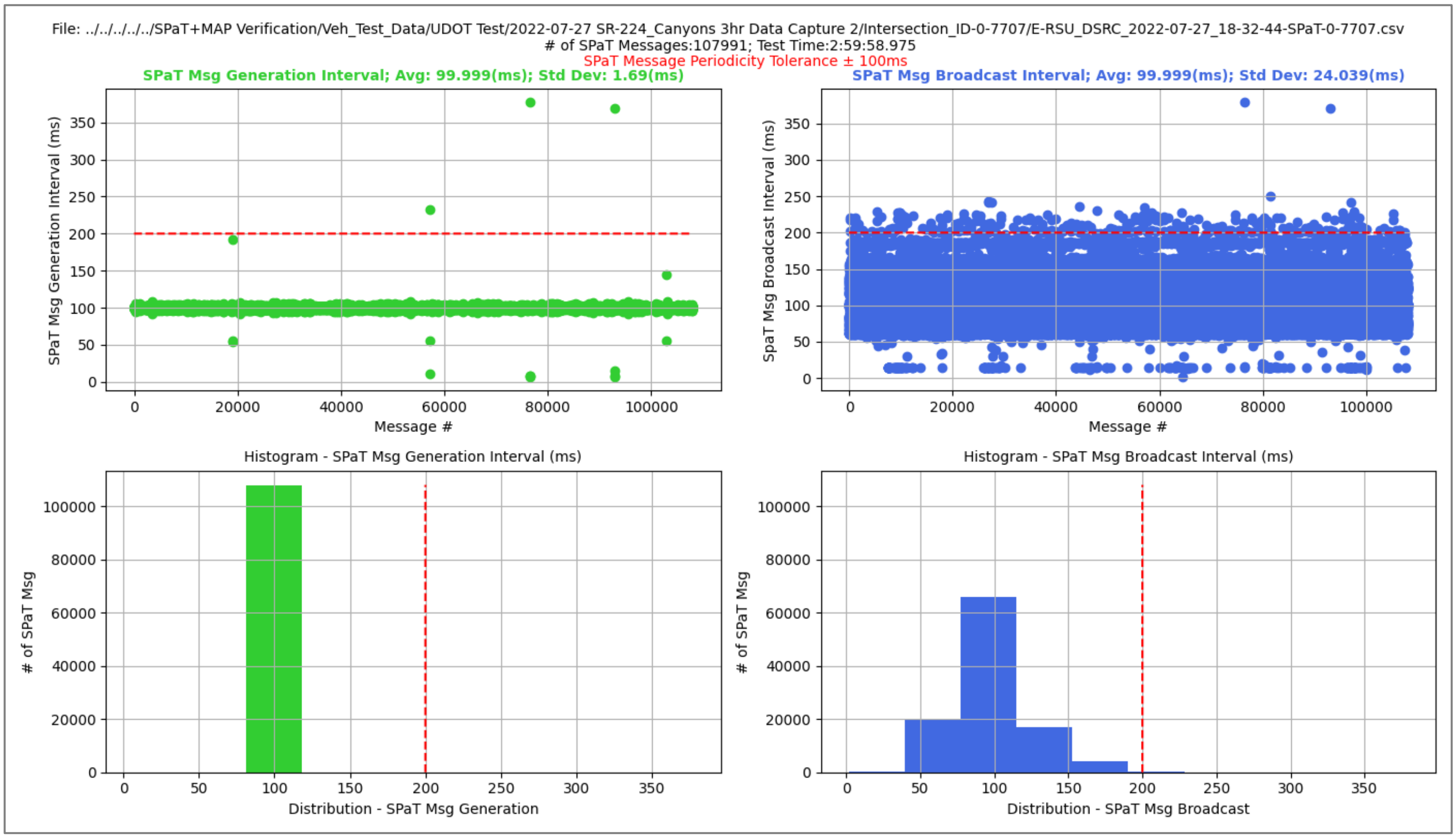


Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle to Infrastructure 5 (V2I-5) Consortium, 2022

Figure 27: Time Difference Between TSC Yellow Phase Determination and SPaT Message Broadcast Time

SPaT Message Broadcast Periodicity:

Figure 28 shows the inter-message time intervals for SPaT message generation (Green) which is derived using DE_MinuteOfTheYear and DE_DSecond data elements and the message broadcast (Blue) from the RSU. The red dashed line indicates the maximum allowable jitter threshold of 200 ms. As shown, message generation is well maintained at the nominal 100 ms interval (standard deviation 1.69 ms). However, the inter message broadcast interval varies significantly (standard deviation 24.039 ms) exceeding the 200 msec threshold.



Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle to Infrastructure 5 (V2I-5) Consortium, 2022

Figure 28: Analysis of SPaT Message Generation and Broadcast Periodicity

Pass/Fail Assessment:

The three message performance criteria analyzed are used as the pass/fail criteria for SPaT broadcast. Table 7 shows the summary report for the CI examined. As shown, the report is in two parts: 1) Yellow Phase processing Time of SPaT data from the TSC to the SPaT broadcast and 2) Yellow Phase duration (change interval) between the TSC and SPaT message.

Table 7: CI SPaT Broadcast Analysis Summary

*** CI TSC & SPaT Message Yellow Phase Analysis Summary for RLVW - v0.5 ***

Test Name: SPaT - Test Location:

Report Created: 2022-09-26; 09:44:53

TSC Log: ATSPM

Intersection ID: 7707

TSC Log File: CEL_20220727_2.csv

SPaT File: E-RSU_DSRC_2022-07-27_18-32-44-SPaT-0-7707.csv

# of SPaT Messages Processed: 107991

	<<<<<< =============== YP Processing Time Analysis: TSC to SPaT Broadcast =============== >>>>>>								
Signal	<---------- TSC to SPaT Msg ---------->			<----- RSU Msg Process (Jitter) ----->			<-End-to-End: TSC to SPaT Broadcast ->		
Group #	Max (ms)	Pass / Fail	Remark	Max (ms)	Pass / Fail	Remark	Max (ms)	Pass / Fail	Remark
1	142	Pass		78	Pass		218	Pass	
2	142	Pass		110	Pass		251	Pass	
3	141	Pass		90	Pass		231	Pass	
4	141	Pass		106	Pass		247	Pass	
5	142	Pass		110	Pass		251	Pass	
6	100140	-- Fail --	> 200ms	69	Pass		100157	-- Fail --	> 300ms
7	141	Pass		106	Pass		247	Pass	
8	141	Pass		64	Pass		204	Pass	

	<<<<<< ======== Yellow Phase Duration Analysis Panel ======== >>>>>>														
Signal	<---------- TSC: YP Duration ---------->					<---------- SPaT: YP Duration (minEndTime @ Start) ---------->					<---------- SPaT: YP Duration at Msg Broadcast ---------->				
Group #	Min (s)	Max (s)	Time Diff (s)	Pass / Fail	Remark	Msg Min (s)	Msg Max (s)	Time Diff (s)	Pass / Fail	Remark	RX Min (s)	RX Max (s)	Time Diff(s)	Pass / Fail	Remark
1	3.7	3.7	0	Pass		0.16	3.66	3.5	-- Fail --	> 200ms	0.135	3.644	3.484	-- Fail --	> 200ms
2	5	5	0	Pass		4.958	4.96	0.002	Pass		4.849	4.944	-0.014	Pass	
3	3	3	0	Pass		0.06	2.96	2.9	-- Fail --	> 200ms	0.043	2.944	2.884	-- Fail --	> 200ms
4	3.5	3.5	0	Pass		0.56	3.46	2.9	-- Fail --	> 200ms	0.52	3.444	2.884	-- Fail --	> 200ms
5	4.1	4.1	0	Pass		4.058	4.06	0.002	Pass		3.949	4.044	-0.014	Pass	
6	4.4	104.4	100	???	Unequal	4.359	4.36	0.001	Pass		4.29	4.344	-0.015	Pass	
7	3	3	0	Pass		0.06	2.96	2.9	-- Fail --	> 200ms	0.043	2.944	2.884	-- Fail --	> 200ms
8	3.1	3.1	0	Pass		1.26	3.06	1.8	-- Fail --	> 200ms	1.243	3.043	1.783	-- Fail --	> 200ms

Notes:

Following pass/fail criteria are used

1. Yellow Phase Duration: Reported time difference between the TSC and the broadcast SPaT message > ± 100ms
2. RSU Process Time (Jitter): Reported time difference between the generated SPaT message time and message broadcast time > ± 100ms
3. Yellow Phase SPaT Broadcast Time: End-to-end time difference from TSC to SPaT message broadcast > 300ms (as per ITE CI guideline)

Basis for MAP Assessment

The SAE J2735 MAP message standard specifies the content and format of the geometric intersection description broadcast by a CI using I2V communications to support in-vehicle safety and mobility applications such as Basic RLVW. The ITE CI Guidelines and Connected Vehicle Pooled Fund Study (CV PFS) MAP Guidance document [8] specifies desired common practices for creating MAP messages describing connected intersections and position correction data to equipped vehicles.

The purpose of this assessment procedure is to verify that the MAP message and position correction data broadcast by a CI can be successfully utilized by an equipped vehicle to position itself on the correct approach lane to operate in-vehicle applications such as Basic RLVW utilizing the correct SPaT data for the actual lane of travel.

Verification of the connected intersection geometry contained in a MAP message is based on how well the connected vehicle matches itself to the correct lane using the positional information provided. It is assumed that the CI is broadcasting Radio Technical Commission for Maritime Services (RTCM) v3.x position corrections, as specified in the CI Guidance document, and that the vehicle is instrumented to use this information to improve its positional accuracy. The MAP verification procedures use vehicle path data collected by driving through the intersection in a prescribed manner.

This document describes two MAP message assessment / verification procedures. First, an optional MAP segment accuracy assessment procedure is provided for use by the Infrastructure Owner / Operators (IOOs) interested in understanding the accuracy of their MAP messages including the means to assess / correct various errors that may be present. Second, an automotive Original Equipment Manufacturer (OEM) MAP verification procedure is provided to evaluate the utility of a MAP broadcast to enable vehicles to properly map match to the correct through approach lane segment(s) and determine the proper signal phase information to operate Basic RLVW. This includes test validity and MAP utility pass / fail criteria.

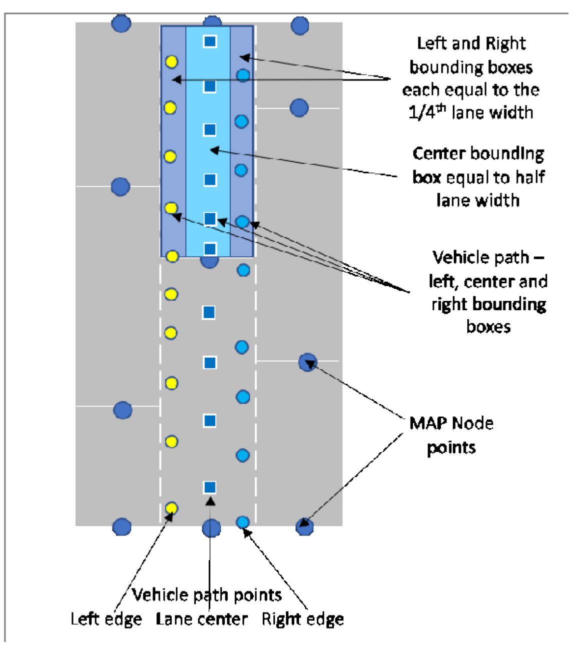
MAP Segment Accuracy

This process is recommended for IOOs to check the accuracy of their MAP messages prior to utility assessment testing. It involves overlaying the intersection geometry defined in the MAP messages on Google satellite view for initial visual verification, and then overlaying vehicle path data collected by driving through the intersection onto the lane geometry provided in the MAP message for analysis.

The logic used to make this assessment involves establishing three levels of virtual bounding boxes between each set of sequential node points contained in the MAP message for each ingress lane at a CI to indicate the vehicle position is close to the left edge, to the right edge or within the center of the lane. If the node points that describe the lane geometry are not appropriately placed (e.g., shifted either to the left or right by 1/4th the lane width from the required lane center), the vehicle lane determination may indicate an incorrect lane match. As illustrated in Figure 29, the analysis tool creates three virtual bounding boxes. The center box is equal to ½ the lane width between two node points that describe a lane segment. The left and right boxes are equal to ¼ of the lane width for the same lane segment.

Vehicle position data collected by driving each ingress lane and centering the vehicle in lane, close to the left lane edge, and close to the right lane edge, is then compared to the lateral limits of each virtual bounding box on the approach.

- MAP bias due to a shift in node placement to the left or right from lane center will result in either a left or right edge assessment failure causing incorrect lane identification
- Excessive node point spacing for a lane segment's curvature will result in a center assessment failure
- Successfully verifying crossing approaches at an intersection indicates proper placement of the MAP reference point



Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle to Infrastructure 5 (V2I-5) Consortium, 2022

Figure 29: MAP Assessment Procedure using Virtual Bounding Boxes

Equipment and Personnel

The following items and personnel are needed to execute the drive procedure described above and collect the data elements described in the next section.

- A light duty passenger vehicle which can be easily maneuvered within the approach lane to maintain the position on center or at the right / left edges of the lane without crossing the lane boundaries.
- An On Board Unit (OBU) capable of receiving CI MAP, position correction and SPaT broadcast data in Packet Capture (PCAP) format as well as logging vehicle position data at 10 Hz for post processing. The OBU should be equipped with automotive grade or higher accuracy Global Navigation Satellite System (GNSS) capable of applying RTCM corrections v3.3 as prescribed in the CI implementation guide received from the infrastructure.
- A driver to follow the lane as indicated and a test engineer to initiate and terminate data collection for each test run.

Data Elements

To perform the MAP Segment Accuracy assessment, the following vehicle position data elements are required at 10Hz as the vehicle is driven on different ingress lanes through the intersection.

1. Timestamp in UTC for each record
2. Vehicle Speed (meters per second)
3. Vehicle Latitude in degrees (accuracy to 7 decimal places)
4. Vehicle Longitude in degrees (accuracy to 7 decimal places)
5. Vehicle Altitude in meters (for future use)
6. Vehicle Heading in degrees
7. Number of satellites being tracked
8. Horizontal Dilution of Precision (HDOP)
9. GNSS Fix Quality to indicate type of position correction utilized:
   0 = invalid
   1 = Global Positioning System (GPS) fix (Standard Positioning Service (SPS))
   2 = Differential GPS (DGPS) fix
   3 = PPS (Precise Positioning Service (PPS)) fix
   4 = Fixed Real Time Kinematic
   5 = Float Real Time Kinematic
   6 = Estimated (dead reckoning) (2.3 feature)
   7 = Manual input mode
   8 = Simulation mode

Data Collection Method(s)

Vehicle path data can be collected using one of the following two methods:

Method 1: OBU-based data logging system:

Any OBU-based system capable of applying RTCM 3.3 position corrections and collecting the data elements specified at 10Hz can be used for data collection. Such a system should do the following.

- Allow the user to start / stop / pause data collection

- Generate unique file names based on date and time
- Log data in .csv format for post processing

A vehicle data log generated using an OBU-based system is shown in Figure 30.

TimeStamp Formatted	Speed (m/s)	Latitude	Longitude	Elevation (m)	Heading (deg)	Matched Lane ID	Dist To Stop Bar (m)	Intersection ID	Signal Phase	TimeToNext Phase (sec)	ThreatState	Num Satellites	HDOP	FixQuality
2022/03/09-15:55:25.177	15.6	42.5664645	-82.950936	152.07	178.35	1	126.4	2515	MPS_PERMISSIVE_MOVEMENT_ALLOWED	55.8	0	9	0.97	2
2022/03/09-15:55:25.277	15.6	42.5664503	-82.950936	152.06	178.37	1	124.9	2515	MPS_PERMISSIVE_MOVEMENT_ALLOWED	55.7	0	9	0.97	2
2022/03/09-15:55:25.377	15.6	42.5664362	-82.950935	152.06	178.17	1	123.3	2515	MPS_PERMISSIVE_MOVEMENT_ALLOWED	55.6	0	9	0.97	2
2022/03/09-15:55:25.477	15.7	42.5664222	-82.950935	152.07	178.34	1	121.7	2515	MPS_PERMISSIVE_MOVEMENT_ALLOWED	55.5	0	9	0.97	2
2022/03/09-15:55:25.577	15.7	42.566408	-82.950934	152.07	178.47	1	120.2	2515	MPS_PERMISSIVE_MOVEMENT_ALLOWED	55.4	0	9	0.97	2
2022/03/09-15:55:25.677	15.7	42.5663938	-82.950933	152.08	178.35	1	118.6	2515	MPS_PERMISSIVE_MOVEMENT_ALLOWED	55.3	0	9	0.97	2
2022/03/09-15:55:25.777	15.7	42.5663797	-82.950933	152.1	178.45	1	117	2515	MPS_PERMISSIVE_MOVEMENT_ALLOWED	55.2	0	9	0.97	2
2022/03/09-15:55:25.877	15.7	42.5663656	-82.950932	152.12	178.41	1	115.5	2515	MPS_PERMISSIVE_MOVEMENT_ALLOWED	55.1	0	9	0.97	2
2022/03/09-15:55:25.977	15.7	42.5663515	-82.950932	152.12	178.25	1	113.9	2515	MPS_PERMISSIVE_MOVEMENT_ALLOWED	55	0	9	0.97	2
2022/03/09-15:55:26.077	15.7	42.5663374	-82.950931	152.12	178.32	1	112.3	2515	MPS_PERMISSIVE_MOVEMENT_ALLOWED	54.9	0	9	0.97	2
2022/03/09-15:55:26.177	15.7	42.5663233	-82.95093	152.13	178.41	1	110.7	2515	MPS_PERMISSIVE_MOVEMENT_ALLOWED	54.8	0	9	0.97	2

Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle to Infrastructure 5 (V2I-5) Consortium, 2022

Figure 30: Example Vehicle Path Data Logged Using an OBU

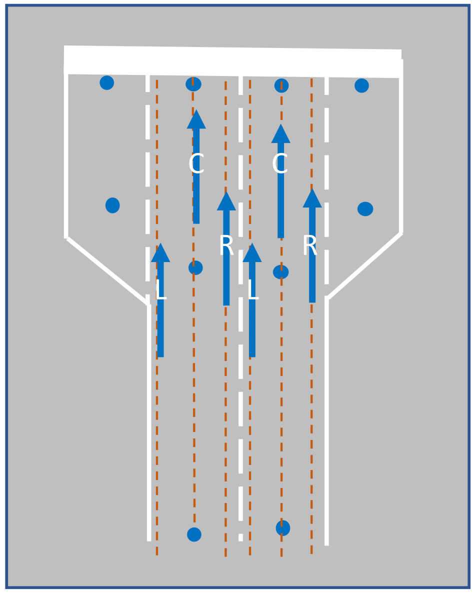
Method 2: Log National Marine Electronics Association (NMEA) sentences at 10 Hz:

- User needs to start / stop / pause data collection as needed for ingress lanes
- Separately provide the following:
  a. Intersection ID and description
  b. List of lane IDs on which the vehicle was driven for path data collection
  c. For each lane driven, intended vehicle drive type as:
     - Left edge
     - Right edge
     - Lane center
  d. Intersection MAP message either in JavaScript Object Notation (JSON) (as defined in the CI field validation report [9]) or in a PCAP file. A MAP message in PCAP format will require translation to JSON to overlay the intersection geometry on Google satellite view for analysis.

Test Procedure

For each ingress lane:

- Bring the vehicle to the posted speed limit at a distance greater than the extent of the MAP data for the lane of travel being evaluated (requires knowledge of the specific MAP configuration) and initiate data logging.
- As illustrated in Figure 31, maintain vehicle position either on center or close to the left /right lane boundary without allowing the nearest tire to touch the lane marking, until the vehicle reaches the stop bar.
- Terminate data logging at the stop bar for each individual test run.



Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle to Infrastructure 5 (V2I-5) Consortium, 2022

Figure 31: Vehicle Drive Path for MAP Assessment Data Logging

Data Analysis

Assessment of MAP segment accuracy is comprised of two evaluation steps using the data collected from driving through the intersection in the manner described.

Visual Verification

The initial visual verification is performed by overlaying the broadcast MAP message onto the Google satellite view. All node points for the ingress lanes are used to formulate virtual bounding boxes. The analysis software is a web application in JavaScript that uses Google's geometry and drawing library API to overlay the intersection geometry from the MAP message, to draw virtual bounding boxes and to plot vehicle position information as shown in screen capture in Figure 32. The left panel provides the intersection map detail as defined in the MAP message. The assessment of how well the MAP matches the image is performed by visual inspection of ingress lane boundary and stop bar alignment on all approaches.

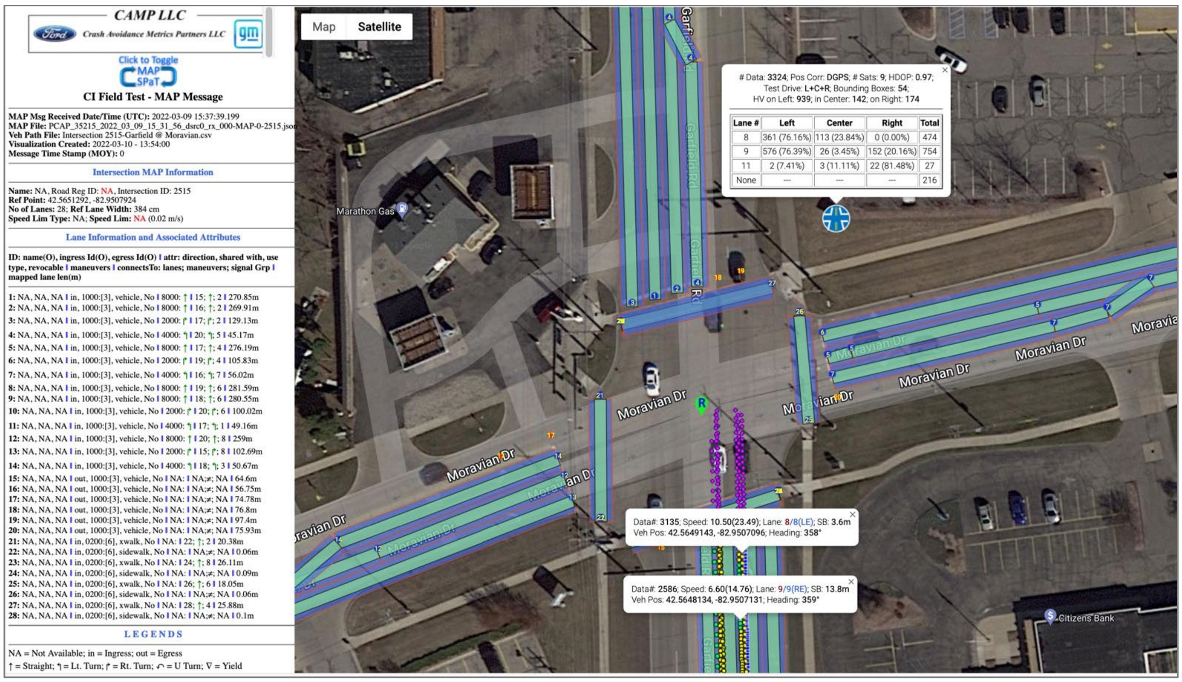
Path Data Analysis

Path data analysis is performed by drawing three additional virtual bounding boxes for each ingress lane segment. The left and right bounding box each of 1/4th lane width is represented by blue color and the middle box of half the lane width is represented by magenta color. Vehicle position information is represented by colored dots as follows:

- Purple dots indicate the vehicle is outside the mapped ingress lanes area.
- Yellow dots indicate the vehicle is on the left (1/4 lane width) bounding box.
- Blue dots with white boarder indicate the vehicle is in the middle (half lane width) bounding box.
- Cyan dots indicate the vehicle is on the right (1/4 lane width) bounding box.

Each vehicle position dot contains the following information which can be viewed by clicking on it as illustrated in Figure 32.

- Data#: logged data point #
- Speed: vehicle speed in m/s and mph
- Lane: determined lane number by the RLVW application, the independent algorithm and indication of left, middle or right bounding box from the virtual bounding box
- SB: distance to stop bar from the current location by the RLVW application
- Veh Pos: current vehicle position in latitude and longitude
- Heading: current vehicle heading angle



Imagery © 2022 Google, Imagery © 2022 Maxar Technologies Map Data ©2022. Overlaid Information by an Application
Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle to Infrastructure 5 (V2I-5) Consortium, 2022

Figure 32: Screenshot of MAP Assessment Visualization and Data Analysis

Appendix A – GNSS Position Trace Assessment provides illustration(s) of several types of MAP segment errors that may be identified using this method as well as a decision tree to assist in the interpretation of driving data.

The analysis software identifies the lane and counts the number of times the vehicle position is located within each bounding box for each ingress lane. The percentage of the total number of vehicle position counts, matched lane counts, and matched bounding box counts are determined. Figure 33 shows the test assessment analysis provided by clicking on the icon in the visualization.

Intersection ID: **2515; Garfield & Moravian**;
Veh Pos Corr Applied: **DGPS**; No of Sats: **9**; HDOP: **0.97**;
Drive Type: **L+C+R**; Bounding Boxes: **54**;
Veh in Left Box: **939**; Center Box: **142**; Right Box: **174**

Lane #	Left	Center	Right	Total
8	361 (76.16%)	113 (23.84%)	0 (0.00%)	474
9	576 (76.39%)	26 (3.45%)	152 (20.16%)	754
11	2 (7.41%)	3 (11.11%)	22 (81.48%)	27
None	---	---	---	216

Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle to Infrastructure 5 (V2I-5) Consortium, 2022

Figure 33: Path Data Analysis

Where:

- Veh Pos Corr Applied: Position correction applied as reported by "Fix Quality" by the GPS/GNSS receiver
- No of Sats: Number of satellites in view as reported by the GPS/GNSS receiver
- HDOP: Horizontal Dilution of Precision as reported by the GPS/GNSS receiver
- Drive Type: Indicates drive type where, L = Left Edge, C = Lane Center, R = Right Edge
- Bounding Boxes: Number of ingress lane segments containing bounding boxes
- Veh Pos:
    - Left Box: Indicates number of times the vehicle position indicated in the left bounding boxes (number of times the vehicle close to the left edge of ingress lanes)
    - Center Box: Indicates number of times the vehicle position indicated in the center or middle bounding boxes (number of times the vehicle close to the lane center of ingress lanes)
    - Right Box: Indicates number of times the vehicle position indicated in the right bounding boxes (number of times the vehicle close to the right edge of ingress lanes)

In this example, the vehicle was driven northbound in lanes 8 and 9. The vehicle was driven on the left edge and the lane center on lane 8, while on the left edge, lane center and right edge on lane 9. The vehicle also matched lane 11. Lane 11 is the start of the left turn lane pocket that overlays on lane 9 (not visible in the figure). The vehicle did not match any lane for 216 vehicle position points. These position points are for when the vehicle was driven outside the intersection map coming out of a parking lot.

Survey of Strategic Node Points

The analysis of the intersection map geometry described above does not quantitatively assess stop bar location. It would be beneficial to also conduct a GNSS survey of several points at each intersection stop location to determine if there is any bias/shift of node points in the broadcast MAP message not identified by vehicle path data analysis or visual inspection. This should be done by selecting points on the lane boundary (lane marker) at each stop bar, the computing lane center from the lane width, and comparing this data to the first node point node point in each ingress lane in the MAP message.

RSU Broadcast Range

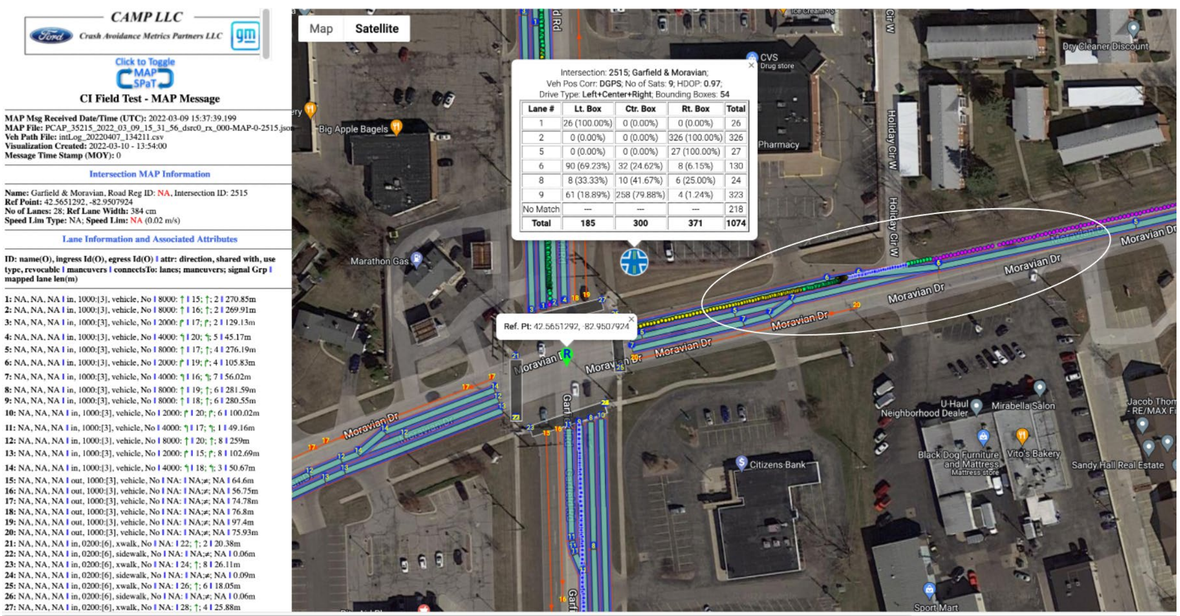
For the RLVW application, the Roadside Unit (RSU) broadcast range must be at least the length of geometry defined in the MAP message for each ingress lane. This can be confirmed by examining the data present at the last node point for each ingress lane to confirm reception of SPaT, MAP and RTCM data.

MAP Issue Identification

The analyses below illustrate application of the MAP Segment Accuracy assessment process and tools to identify specific issues at deployed intersections. MAP messages for both intersections shown were generated from Lidar survey data. Vehicle position data was collected by driving all ingress lanes in each of the four available directions using a CAMP/Denso OBU with Wide Area Augmentation System (WAAS) position corrections applied.

Example 1 – Incorrect Reference Point

MAP data analysis for the intersection of Garfield Road and Moravian Drive in Macomb County, Michigan is shown in Figure 34. Vehicle path data collected northbound in lane 9 and southbound in lane 2 align with the MAP provided and places the vehicle in the correct lane. However, vehicle path data collected westbound in lane 5, highlighted by the white ellipse, does not align with the MAP and the vehicle is incorrectly matched to lane 6.



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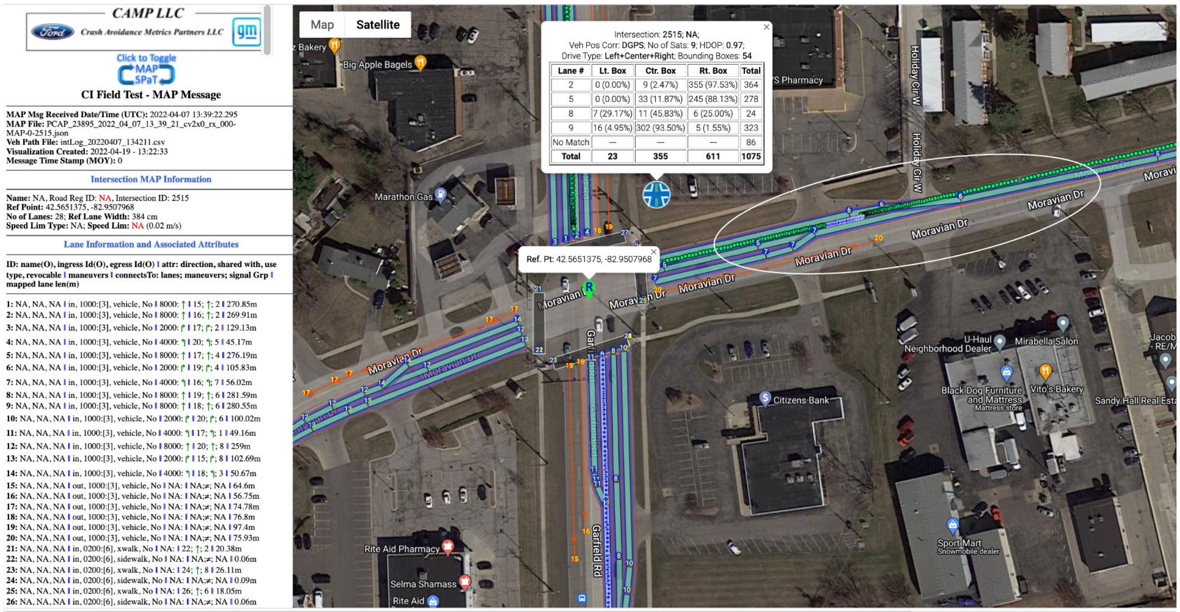
Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle to Infrastructure 5 (V2I-5) Consortium, 2022

Figure 34: Intersection MAP with Reference Point in NAD83 Datum

Further investigation revealed that the reference point for the MAP message was based on the North America Datum 1983 (NAD83) [10] utilized in the laser survey. However, the SAE J2735 specification requires map representation provided to the vehicle to utilize the World Geodetic System 1984 (WGS84) datum [10]. The WGS84 datum has moved 100 meters [11] from the prior utilized prime meridian while the NAD83 datum has not moved. Since the node points that describe lane geometry are defined as XY offsets from the reference, use of the incorrect datum for the reference point causes the lanes defined in the MAP to appear as shifted slightly south causing the incorrect lane determination observed on the westbound approach.

Figure 35 shows the same intersection after converting the MAP reference point from NAD83 to WGS84 datum. The reference point conversion adjusted lane placements accordingly and the same vehicle path data collected in lane 5 on the westbound approach now correctly aligns with the MAP data.

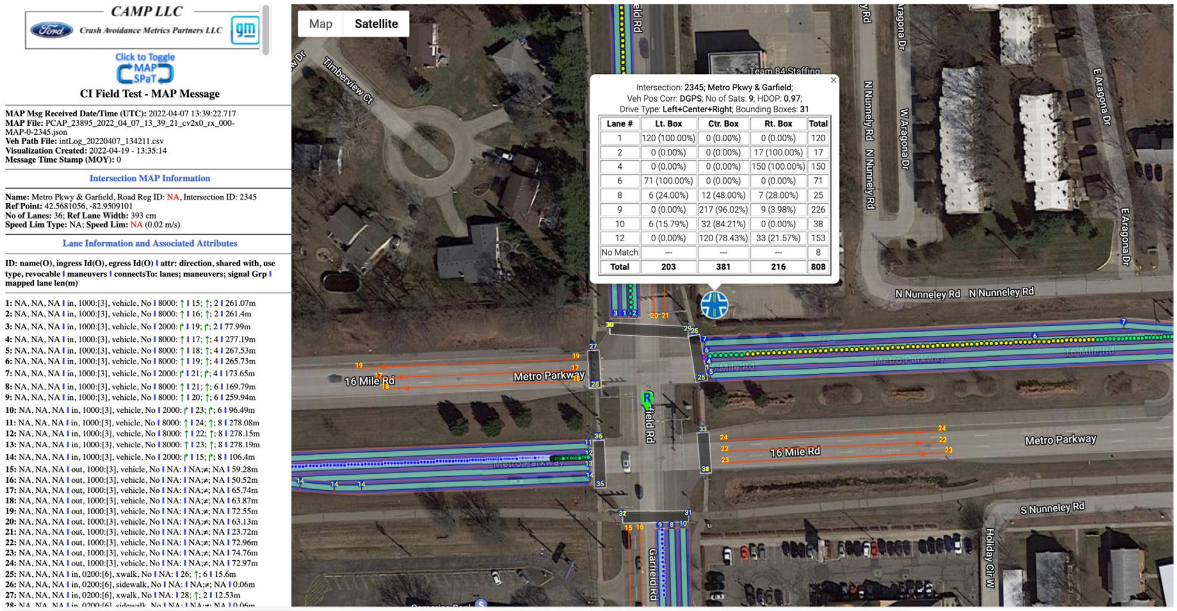


Imagery © 2022 Google, Imagery © 2022 Maxar Technologies Map Data ©2022. Overlaid Information by an Application
Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle to Infrastructure 5 (V2I-5) Consortium, 2022

Figure 35: Intersection MAP with Reference Point in WGS84 Datum

Example 2 – Incorrect Lane Width

MAP data analysis for the intersection of Garfield Road and Metropolitan Parkway in Macomb County, Michigan is shown in Figure 36. In this example, the vehicle path data analysis shows a high percentage of correctly determined lanes, apart from lanes 8 and 10. Vehicle path data recorded in lanes 8 and 10 is the result of the test vehicle crossing these lanes to position itself in lane 9 prior to driving through the intersection. The data collection software is currently being updated to enable the test operator to easily start / stop data collection to eliminate such artifacts.



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Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle to Infrastructure 5 (V2I-5) Consortium, 2022

Figure 36: Intersection MAP with Wider Over lapping Lane Width

Examination of the map data provided shows the lane width indicated in MAP message as 393 cm for all approaches which is wider than the normal width of 360 cm. This appears to be true for Metropolitan Parkway (east/west direction) and for Garfield Road in the northbound direction but not for Garfield Road in the southbound direction. Based on measurements made using the Google Earth satellite view, the lane width for Metropolitan Parkway is approximately 390 cm, while the lane width for Garfield Road southbound approach is only 360 cm. Applying an incorrect lane width in the analysis tool results in a bounding box that is too wide and overlaps the bounding boxes for adjacent lanes. Figure 37 shows an expanded view of the bounding boxes for the southbound approach with lane 1 changed to white to help visualize the lateral overlap with lanes 2 and 3 shown in cyan. This overlap may cause incorrect lane determination when the vehicle is driven close to the lane edges.

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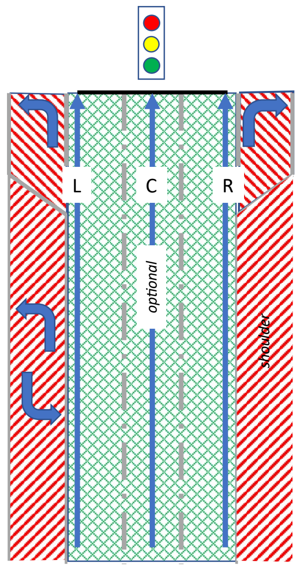
Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle to Infrastructure 5 (V2I-5) Consortium, 2022

Figure 37: Bounding Box Overlap on Southbound Approach

MAP Utility Verification

This process is utilized to verify that a vehicle can properly match itself to the through approach lanes of a CI using broadcast MAP and RTCM data. Figure 38 illustrates a multi-lane approach to a single signal phase where the green cross hatching indicates the valid map matching region for Basic RLVW, and the red diagonal stripped areas are invalid. For multiple lanes utilizing the same signal phase, this assessment involves driving the left and right lane edges for the outer lanes of the through approach and monitoring the vehicle's lane selection performance. Previous work developing similar test procedures for CI assessment to support RLVW can be found on CAMP's website [13].



Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle to Infrastructure 5 (V2I-5) Consortium, 2022

Figure 38: Through Lane Map Matching Assessment

Equipment and Personnel

The following items and personnel are needed to execute the drive procedure described above and collect the data elements described in the next section.

- A light duty passenger vehicle which can be easily maneuvered within the approach lane to maintain position on center or at the right / left edges of the lane without crossing the lane boundaries.
- An OBU capable of receiving CI MAP, position correction and SPaT broadcast data in PCAP format as well as logging vehicle position data at 10 Hz for post processing. The OBU should be equipped with an automotive grade GNSS capable of applying RTCM v3.3 corrections as prescribed by the CI implementation guide received from the infrastructure. CAMP has developed this capability using a Denso dual-mode Dedicated Short-range Communication (DSRC) and Cellular Vehicle-to-Everything (C-V2X) Hercules OBU with an external ublox EVK-M91 Global Navigation Satellite System (GNSS) receiver and custom data logging software (CAMP/Denso OBU).
- A driver to follow the lane as indicated and a test engineer to initiate and terminate data collection for each test run.

Data Elements

To perform the MAP Segment Accuracy Assessment, the following vehicle position data elements are required at 10Hz as the vehicle is driven on different ingress lanes through the intersection.

1. Timestamp in UTC for each record
2. Vehicle Speed (meters per second)
3. Vehicle Latitude in degrees (accuracy to 7 decimal places)
4. Vehicle Longitude in degrees (accuracy to 7 decimal places)
5. Vehicle Altitude in meters (for future use)
6. Vehicle Heading in degrees
7. Number of satellites being tracked
8. Horizontal Dilution of Precision (HDOP)
9. GNSS Fix Quality to indicate type of position correction utilized:
   0 = invalid
   1 = Global Positioning System (GPS) fix (Standard Positioning Service (SPS))
   2 = Differential GPS (DGPS) fix
   3 = PPS (Precise Positioning Service (PPS)) fix
   4 = Fixed Real Time Kinematic
   5 = Float Real Time Kinematic
   6 = Estimated (dead reckoning) (2.3 feature)
   7 = Manual input mode
   8 = Simulation mode

The CAMP/DENSO OBU based data logging tool is also equipped with CAMP's version of a RLVW application to log the following additional test parameters which provide additional data needed for MAP Utility Verification.

10. Intersection ID from the MAP message
11. Host vehicle's matched lane number (id) as defined in the MAP message
12. Distance to stop bar in meters as computed in the application from the current vehicle position
13. RLVW application performance
14. Current signal phase of the host vehicle lane
15. Time remaining in the current phase in milliseconds
16. RLVW application warning status

Data Collection Method

The CAMP/DENSO OBU based data logging system:

- Allows user to start / stop / pause data collection
- Generates unique file name based on date and time
- Logs data in .csv format for processing

A vehicle data log generated using the CAMP/DENSO OBU is shown in Figure 39.

TimeStamp Formatted	Speed (m/s)	Latitude	Longitude	Elevation (m)	Heading (deg)	Matched Lane ID	Dist To Stop Bar (m)	Intersection ID	Signal Phase	TimeToNext Phase (sec)	ThreatState	Num Satellites	HDOP	FixQuality
2022/03/09-15:55:25.177	15.6	42.5664645	-82.950936	152.07	178.35	1	126.4	2515	MPS_PERMISSIVE_MOVEMENT_ALLOWED	55.8	0	9	0.97	2
2022/03/09-15:55:25.277	15.6	42.5664503	-82.950936	152.06	178.37	1	124.9	2515	MPS_PERMISSIVE_MOVEMENT_ALLOWED	55.7	0	9	0.97	2
2022/03/09-15:55:25.377	15.6	42.5664362	-82.950935	152.06	178.17	1	123.3	2515	MPS_PERMISSIVE_MOVEMENT_ALLOWED	55.6	0	9	0.97	2
2022/03/09-15:55:25.477	15.7	42.5664222	-82.950935	152.07	178.34	1	121.7	2515	MPS_PERMISSIVE_MOVEMENT_ALLOWED	55.5	0	9	0.97	2
2022/03/09-15:55:25.577	15.7	42.566408	-82.950934	152.07	178.47	1	120.2	2515	MPS_PERMISSIVE_MOVEMENT_ALLOWED	55.4	0	9	0.97	2
2022/03/09-15:55:25.677	15.7	42.5663938	-82.950933	152.08	178.35	1	118.6	2515	MPS_PERMISSIVE_MOVEMENT_ALLOWED	55.3	0	9	0.97	2
2022/03/09-15:55:25.777	15.7	42.5663797	-82.950933	152.1	178.45	1	117	2515	MPS_PERMISSIVE_MOVEMENT_ALLOWED	55.2	0	9	0.97	2
2022/03/09-15:55:25.877	15.7	42.5663656	-82.950932	152.12	178.41	1	115.5	2515	MPS_PERMISSIVE_MOVEMENT_ALLOWED	55.1	0	9	0.97	2
2022/03/09-15:55:25.977	15.7	42.5663515	-82.950932	152.12	178.25	1	113.9	2515	MPS_PERMISSIVE_MOVEMENT_ALLOWED	55	0	9	0.97	2
2022/03/09-15:55:26.077	15.7	42.5663374	-82.950931	152.12	178.32	1	112.3	2515	MPS_PERMISSIVE_MOVEMENT_ALLOWED	54.9	0	9	0.97	2
2022/03/09-15:55:26.177	15.7	42.5663233	-82.95093	152.13	178.41	1	110.7	2515	MPS_PERMISSIVE_MOVEMENT_ALLOWED	54.8	0	9	0.97	2

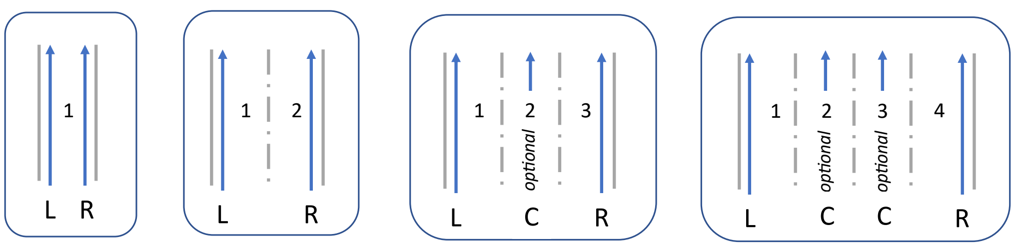
Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle to Infrastructure 5 (V2I-5) Consortium, 2022

Figure 39: Example Vehicle Path Data Logged Using the CAMP/Denso OBU

Test Procedure

For each test run:

- Bring the vehicle to the posted speed limit at a distance greater than the extent of the MAP data for the lane of travel being evaluated (requires knowledge of the specific MAP configuration) and initiate data logging.
- As illustrated in Figure 40, maintain vehicle position close to the left / right lane boundaries of the combined set of through lanes (associated with the same signal group) without allowing the nearest tire to touch the lane marking until the vehicle reaches the stop bar. Collecting data along individual lane centers is considered optional.
- Terminate data logging at the stop bar for each individual test run.



Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle to Infrastructure 5 (V2I-5) Consortium, 2022

Figure 40: Example Vehicle Drive Path for MAP Utility Assessment Data Logging

Test Validity

Valid runs must indicate minimum GNSS quality [12] for the entire run as follows:

- HDOP <= 1.0 (smaller is better)
- # Satellites >= 9 (more is better)

Pass/Fail Criteria

For each CI approach evaluated, map matching to the group of through lane segments must be maintained for the entire run for both L and R drive paths for at least 7 out of 8 runs each with starting distance at least 10 sec from the stop bar for the 85th percentile speed determined as the posted speed plus 7 mph.

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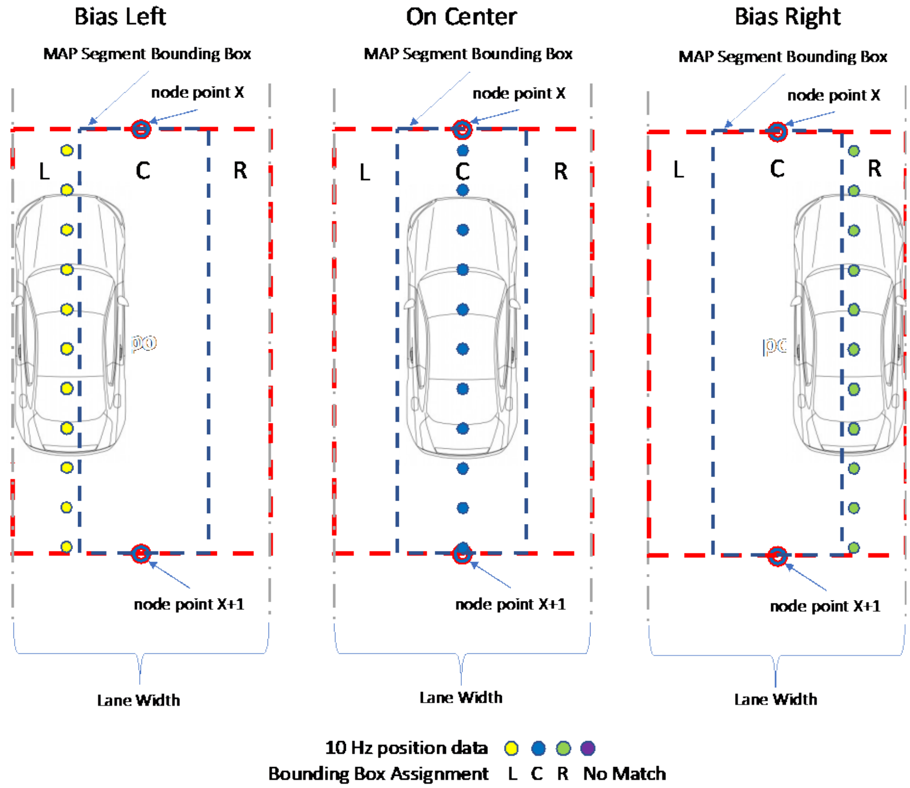
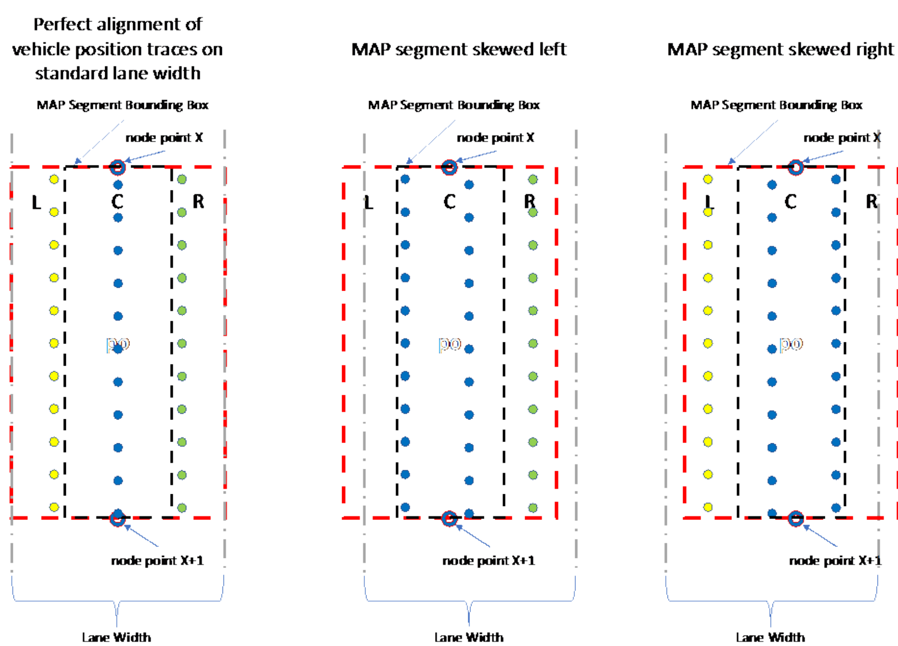
Appendix A – GNSS Position Trace Assessment for MAP Accuracy



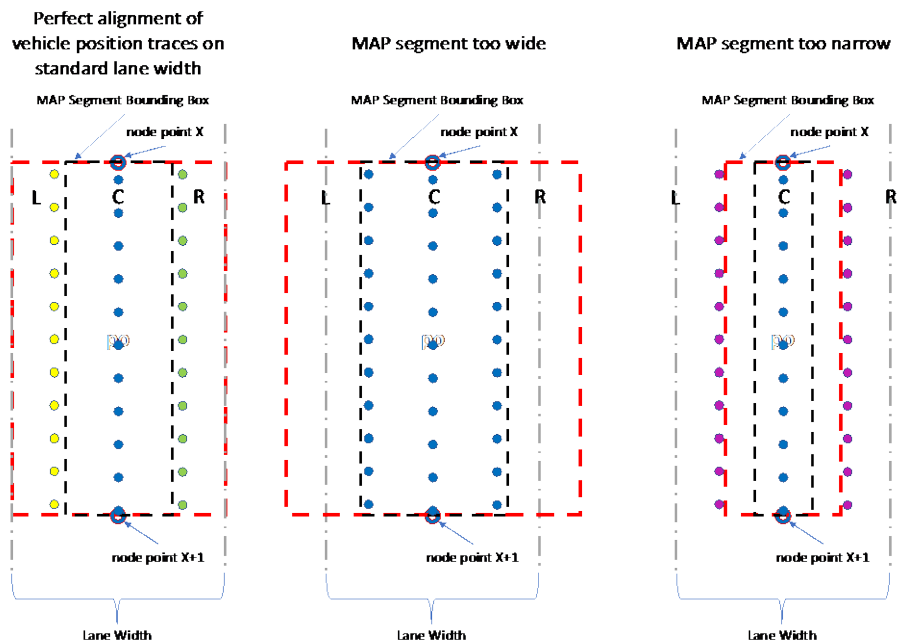
Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle to Infrastructure 5 (V2I-5) Consortium, 2022

Figure 41: Driving Positions for Data Collection



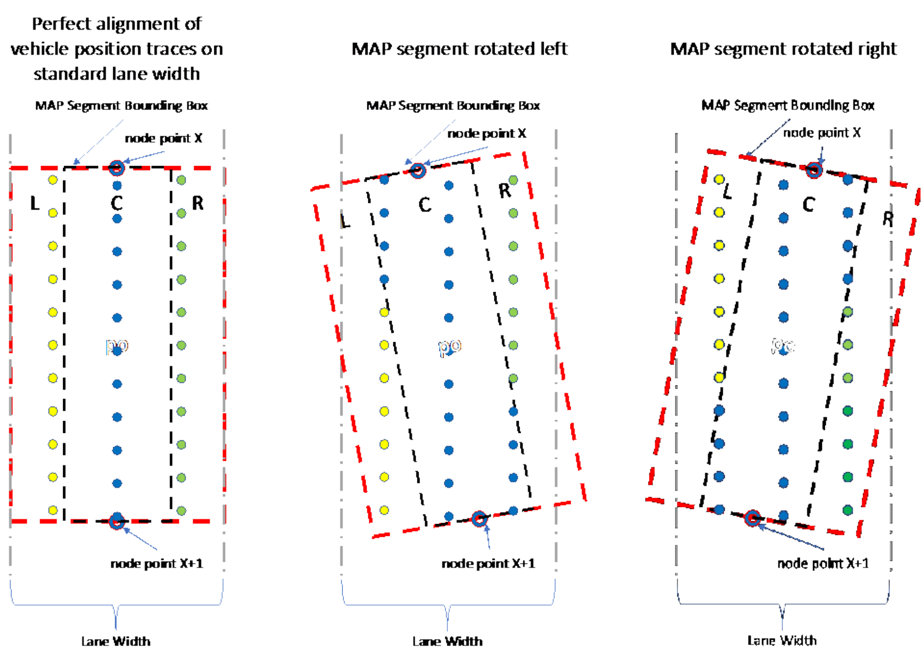
Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle to Infrastructure 5 (V2I-5) Consortium, 2022

Figure 42: Drive Data Interpretation - MAP Segment Skewed



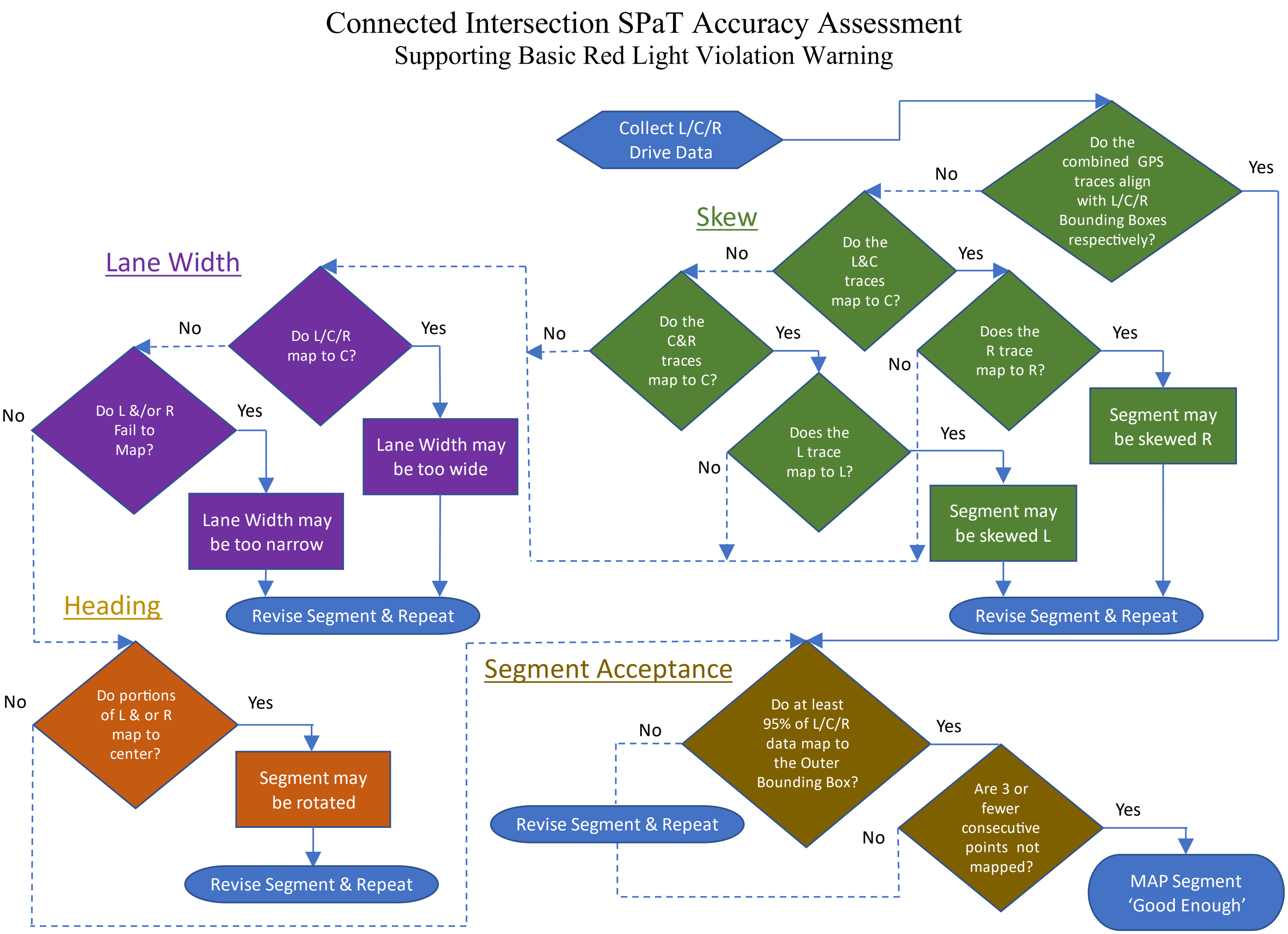
Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle to Infrastructure 5 (V2I-5) Consortium, 2022

Figure 43: Drive Data Interpretation - Incorrect MAP Segment Width



Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle to Infrastructure 5 (V2I-5) Consortium, 2022

Figure 44: Drive Data Interpretation - Incorrect MAP Segment Heading



Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle to Infrastructure 5 (V2I-5) Consortium, 2022

Figure 45: Drive Data Interpretation

Appendix B –MAP Utility Verification Example

MAP Assessment: Moravian Avenue and Garfield Road, Clinton Township, Macomb County, Michigan

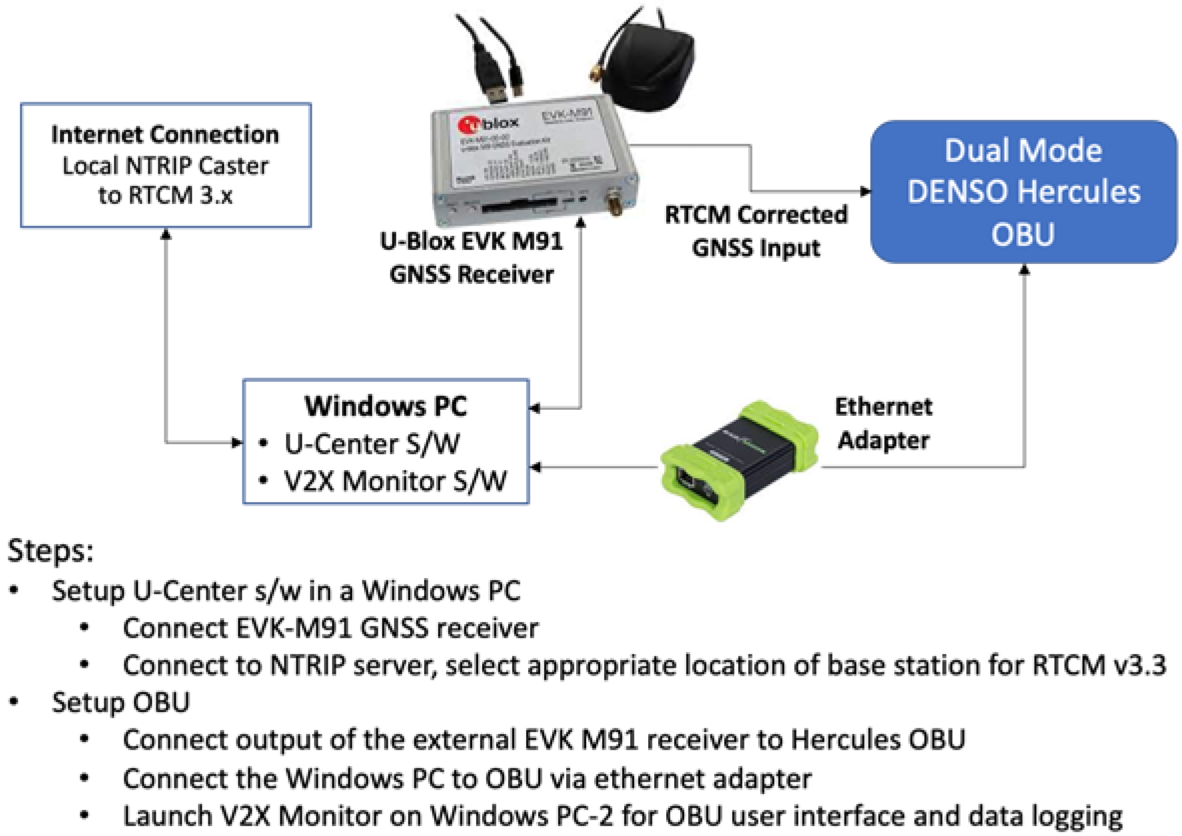
Date of Test: Oct. 27, 2022

Connected Intersection Location: Moravian Drive and Garfield Road, Clinton Township, Macomb County, Michigan

Position Correction Setup:

As per the CI implementation guide, RTCM v3.3 position correction was used during testing to improve vehicle positioning. At the time of testing, there was no CI-equipped RSU in South-Eastern Michigan that broadcast RTCM v3.3 correction in SAE J2735 message format. Instead, Figure 46 shows the test setup used to obtain position corrections over the internet.

User registration is required (user id and password) in order to connect to a local Network Transport of RTCM via Internet Protocol (NTRIP) caster and access RTCM corrections from a nearby Continuously Operating Reference Stations (CORS). U-Center software from U-Blox was set up on a Windows PC at the prescribed serial communication baud rate and connected via serial port to a U-Blox GNSS EVK-M91 receiver. The U-Center software also acts as an NTRIP client connected to a nearby CORS that supports RTCM v3.3 over an internet connection. All the available messages from the CORS were used for testing. The software applies the corrections received to the external GNSS receiver. The output of the GNSS receiver is sent to the OBU over the serial interface.



Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle to Infrastructure 5 (V2I-5) Consortium, 2022

Figure 46: Setup for RTCM v3.x Position Correction Using NTRIP Caster

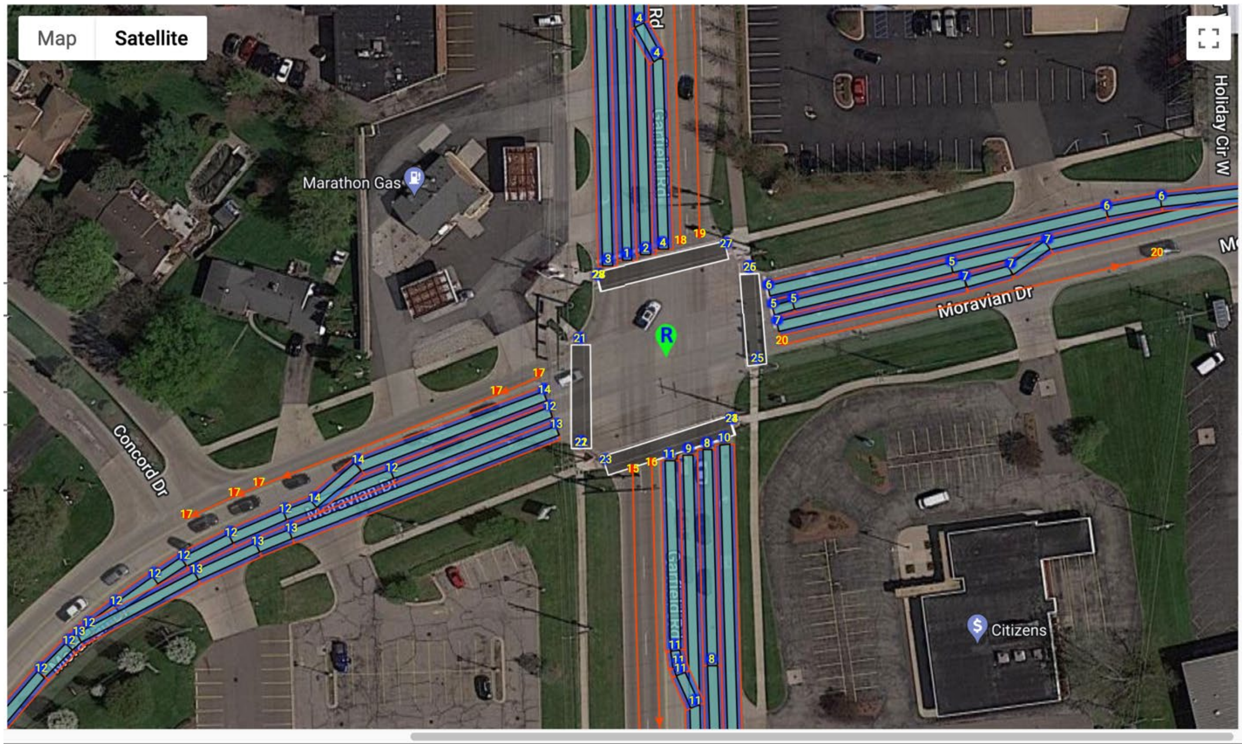
Test Runs on East and West Bound Approaches:

Table 8 shows 30 test runs driving as close as possible to the right edge and the left edge of the through lanes on the east and west bound approaches of Moravian Drive. A data recording error resulted in only capturing 7 runs for east / west left edge testing.

Table 8: Test Runs on East and West Bound Approaches

No	Approach	Drive Type	MAP Lane ID	Test Runs
Travel Road: Moravian Drive				
1	East Bound	Right Edge	12	8
2	West Bound	Right Edge	5	8
3	East Bound	Left Edge	12	7
4	West Bound	Left Edge	5	7

Figure 47 provides a satellite view of the CI used to evaluate the test procedure with MAP data superimposed. The east and west bound approaches have one straight through lane (5 and 12) and the north and south bound approaches have two through lanes (1 & 2 and 8 & 9).



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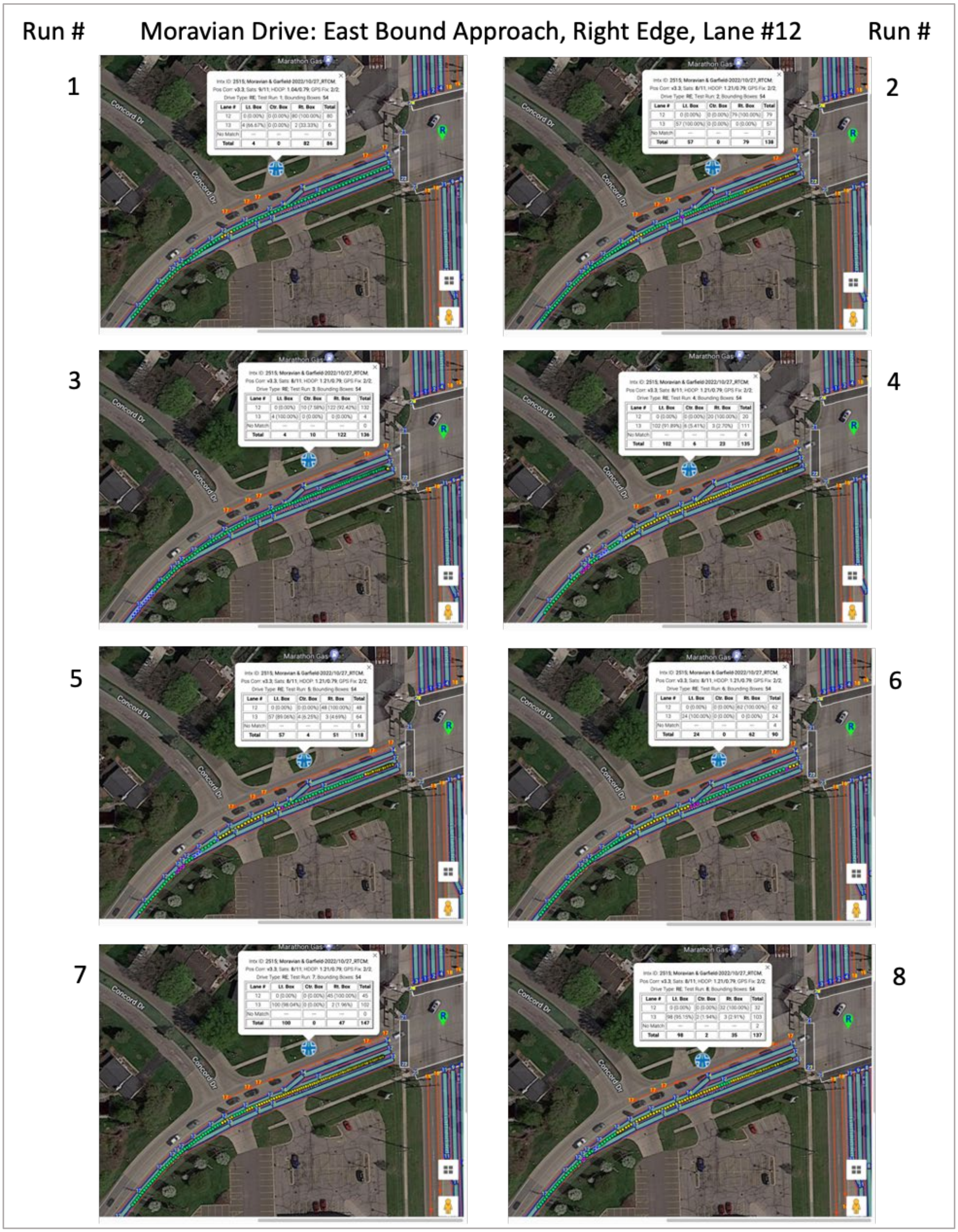
Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle to Infrastructure 5 (V2I-5) Consortium, 2022

Figure 47: Screenshot of MAP Layout of CI Under Test

Figure 48 shows the MAP assessment visualization and associated matched lane table for each test run on the east bound approach on Moravian Drive driven close to the right edge of lane #12.



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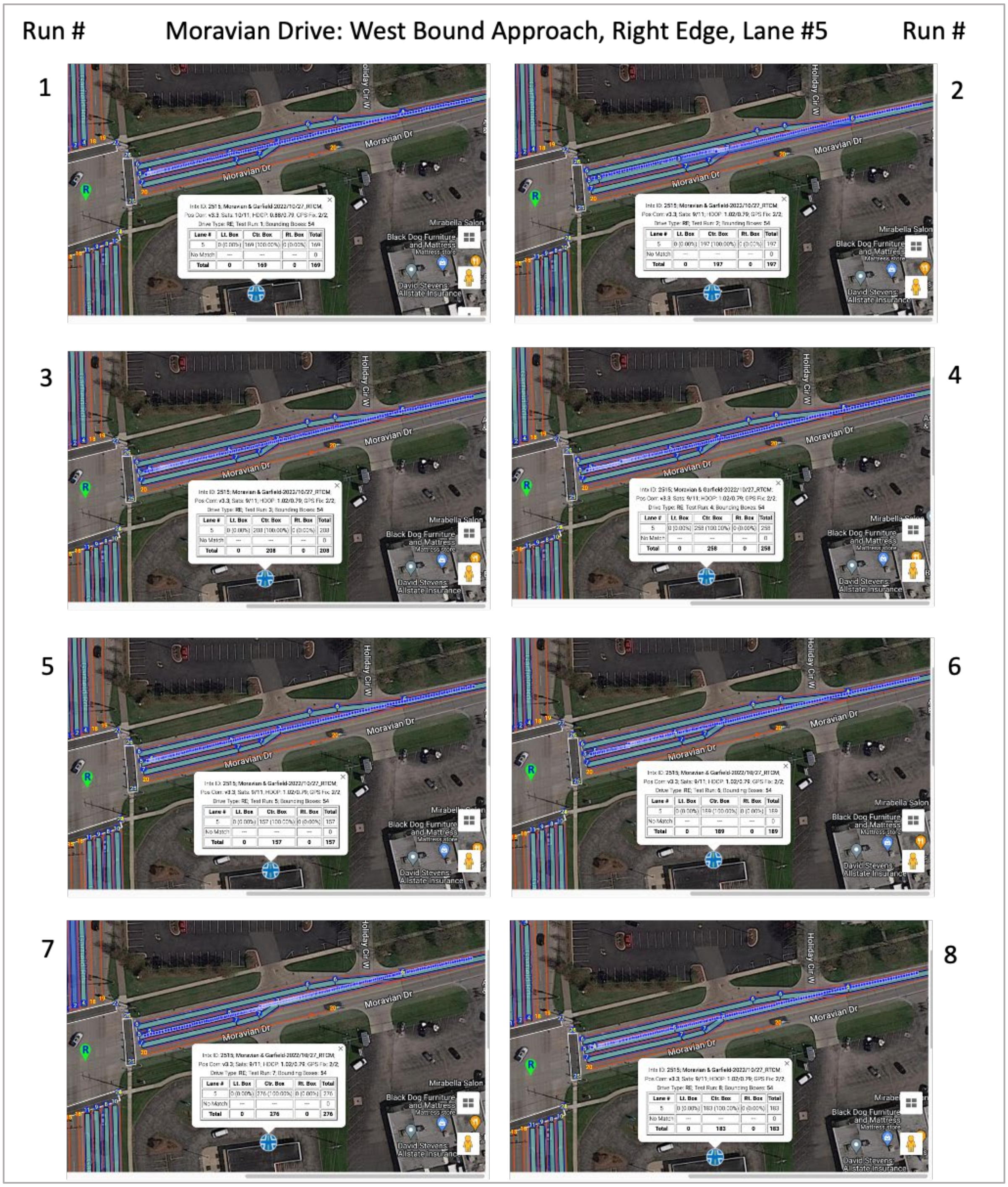
Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle to Infrastructure 5 (V2I-5) Consortium, 2022

Figure 48: MAP Assessment Test Visualization - East Bound Approach, Right Edge of Lane #12

Figure 49 shows the MAP assessment visualization and associated matched lane table for each run for west bound approach on Moravian Drive driven close to the right edge of lane #5.



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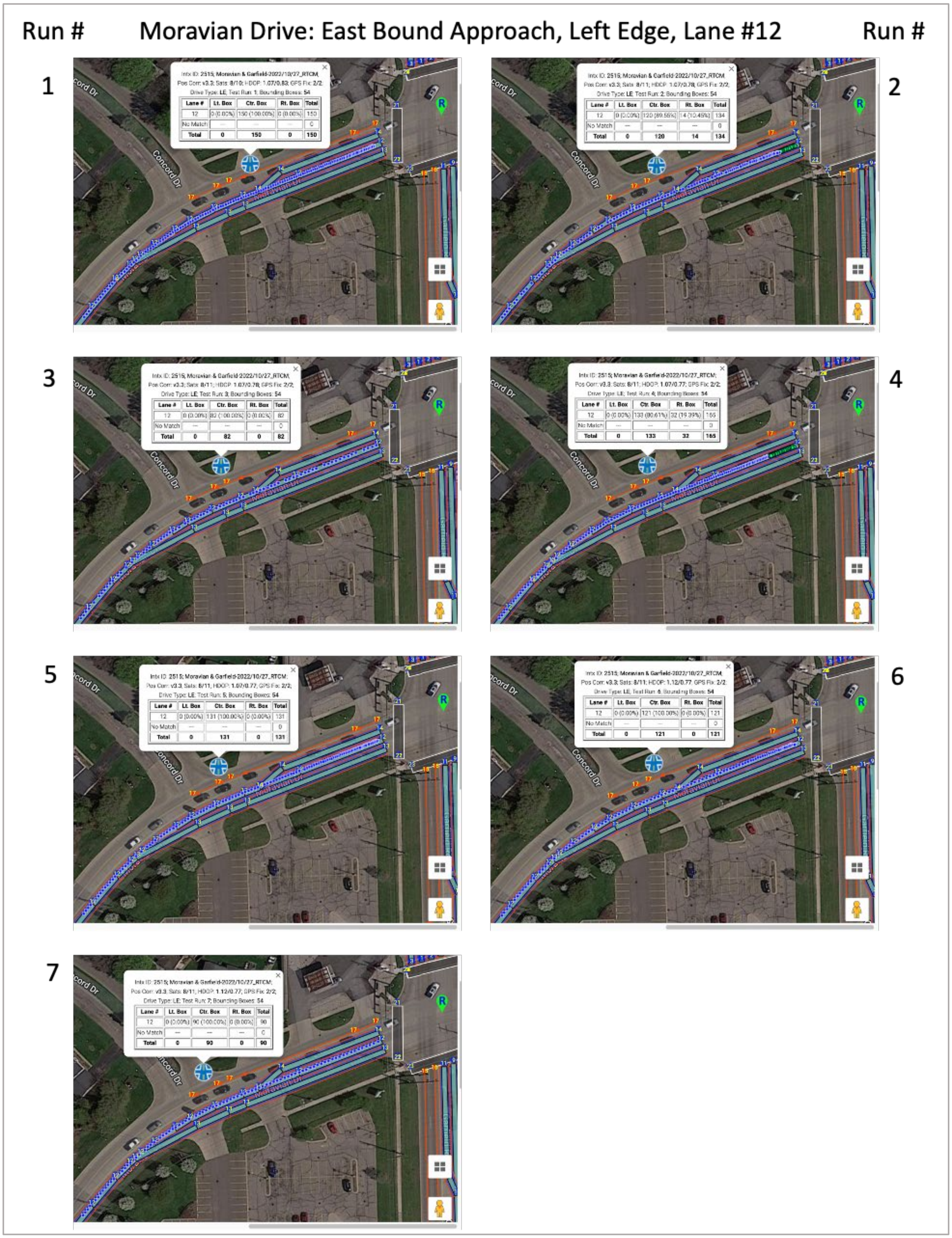
Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle to Infrastructure 5 (V2I-5) Consortium, 2022

Figure 49: MAP Assessment Test Visualization - West Bound Approach, Right Edge of Lane #5

Figure 50 shows the MAP assessment visualization and associated matched lane table for each test run on east bound approach on Moravian Drive driven close to the right edge of lane #12.



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Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle to Infrastructure 5 (V2I-5) Consortium, 2022

Figure 50: MAP Assessment Test Visualization - East Bound Approach, Left Edge of Lane #12

Figure 51 shows MAP assessment visualization and associated matched lane table for each run for west bound approach on Moravian Drive driven close to the left edge of lane #5.

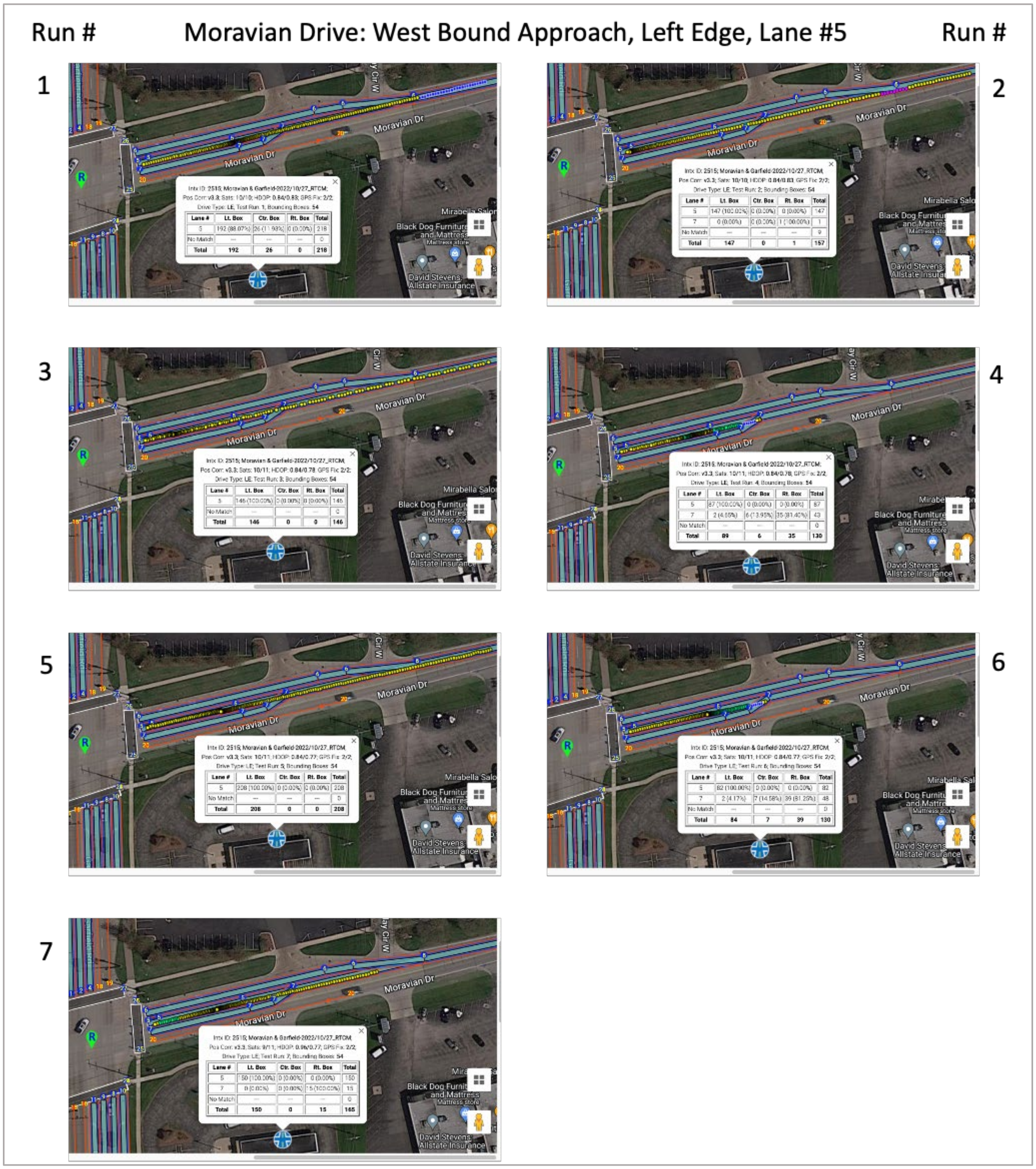

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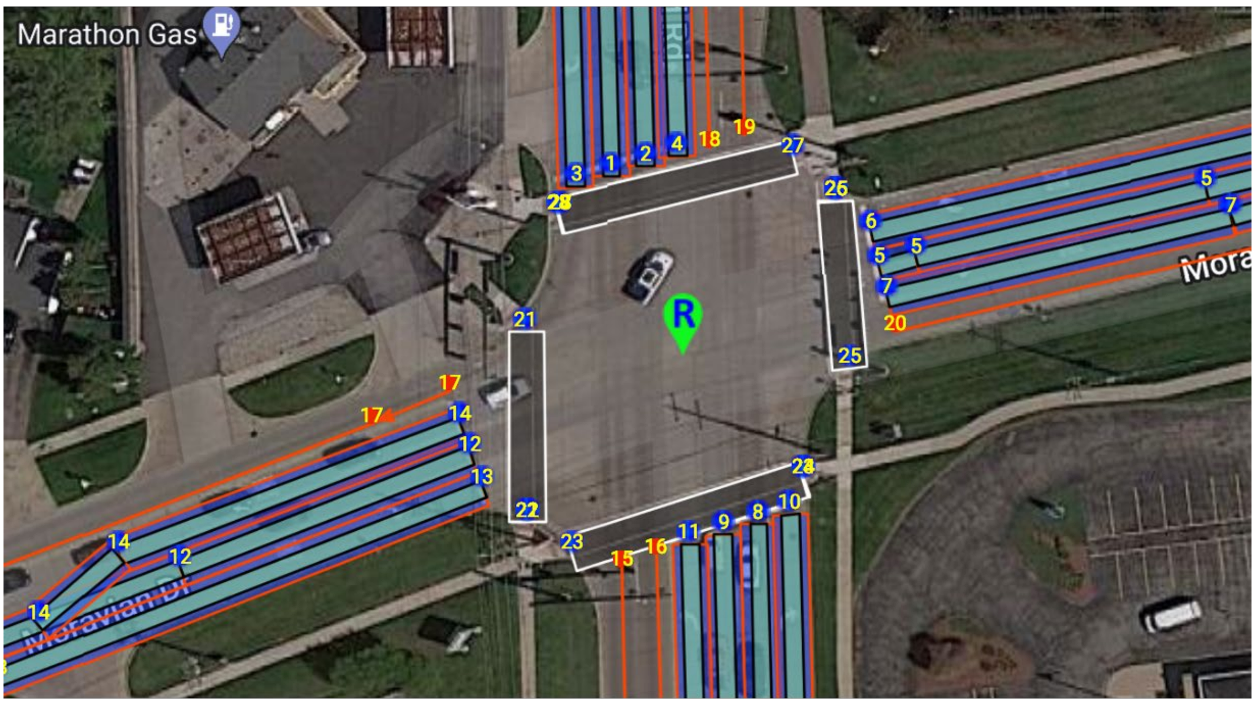
Figure 51: MAP Assessment Test Visualization - West Bound Approach, Left Edge of Lane #5

MAP Assessment on East and West Bound Approaches on Moravian Drive

The test results show that the east as well as the west bound approaches on Moravian Drive did not pass the proposed criteria of the vehicle successfully matching the correct lane for 7 out of 8 runs. All east bound test runs driven close to the right edge of lane #12 failed thus indicating as high as 70% incorrect lane matching to the adjoining lane #13, south of the driven lane. Similarly, three west bound test runs driven close to the left edge of lane #5 failed thus indicating as high as 37% incorrect lane matching to the adjoining lane #7, south of the driven lane.

Figure 52 provides a closer look at the MAP visualization on Google satellite view. Note that the placement of node points that define the lane geometry for east and west bound lanes are not in the lane center. These nodes are shifted to the north resulting in a shift in the virtual bounding box from the actual lane geometry thus causing incorrect lane matching by the vehicle to the adjoining lane. The proposed MAP utility assessment test procedure successfully identified an error in the east / west MAP data.



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Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle to Infrastructure 5 (V2I-5) Consortium, 2022

Figure 52: Placement of Node Points for Lane Geometry Definition

Figure 53 provides an expanded view illustrating the types of lane matching errors observed in east / west testing. Data from run #6 for the east bound approach driving close to the right edge of lane #12 is shown in the left half of the figure. Data from run #7 for the west bound approach driving close to the left edge of lane #5 is shown in the right half of the figure. In this analysis, green dots indicate a match to the right side of a lane, blue to the center of a lane, and yellow to the left side of a lane, regardless of lane number. Thus, on the east bound approach driving close to the right edge of lane #12, the green dots indicate correct lane matching to the right side of lane #12 while the yellow dots indicate incorrect lane matching to the left side of lane #13. Similarly, on the west bound approach driving close to the left edge of lane #5, the yellow dots indicate correct lane matching to the left side of lane #5 while the green dots indicate incorrect lane matching to the right side of lane #7.

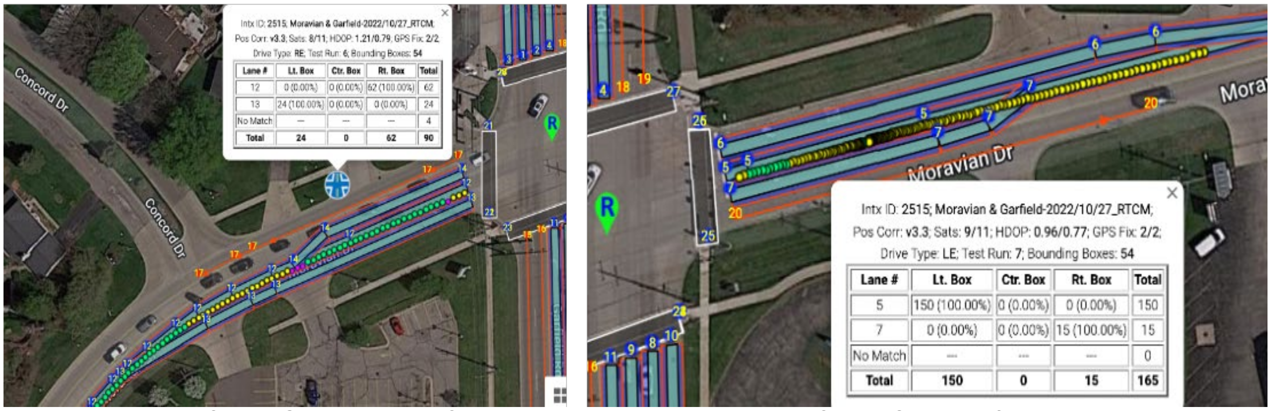

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Figure 53: Failed MAP Assessment of East and West Bound Approaches

Test Runs for North and South Bound Approaches:

Table 9 shows 32 test runs driving as close as possible to the right edge and the left edge of the through lanes on the north and south bound approaches on Garfield Road. Note that since there are two through lanes in each direction, the north bound right and left edges correspond to lanes 8 and 9, respectively, and the south bound right and left edges correspond to lanes 1 and 2.

Table 9: Test Runs for North and South Bound Approaches

No	Approach	Drive Type	MAP Lane ID	Test Runs
Travel Road: Garfield Road				
1	North Bound	Right Edge	8	8
2	South Bound	Right Edge	1	8
3	North Bound	Left Edge	9	8
4	South Bound	Left Edge	2	8

Figure 54 shows the MAP assessment visualization and associated matched lane table for run #1 for the north and south bound approaches on Garfield Road driven close to the right edge of lanes #8 and #1, respectively.

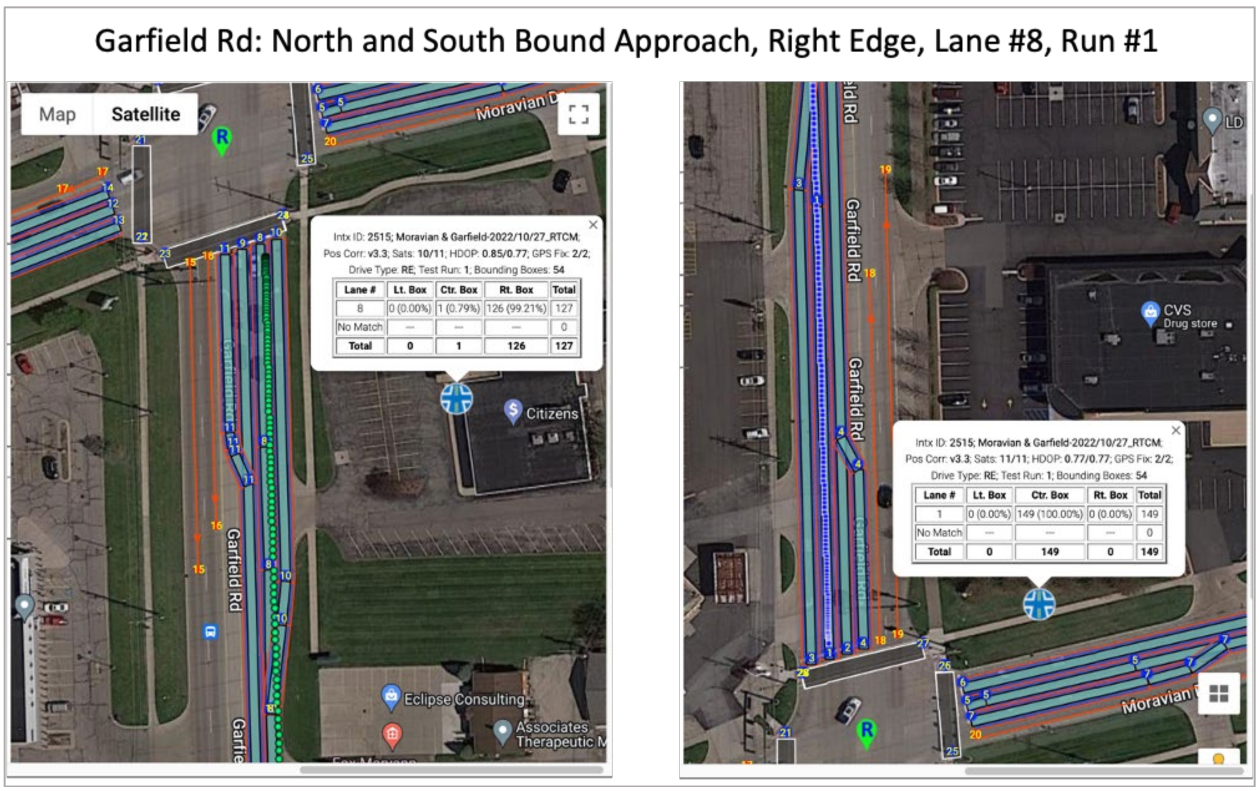

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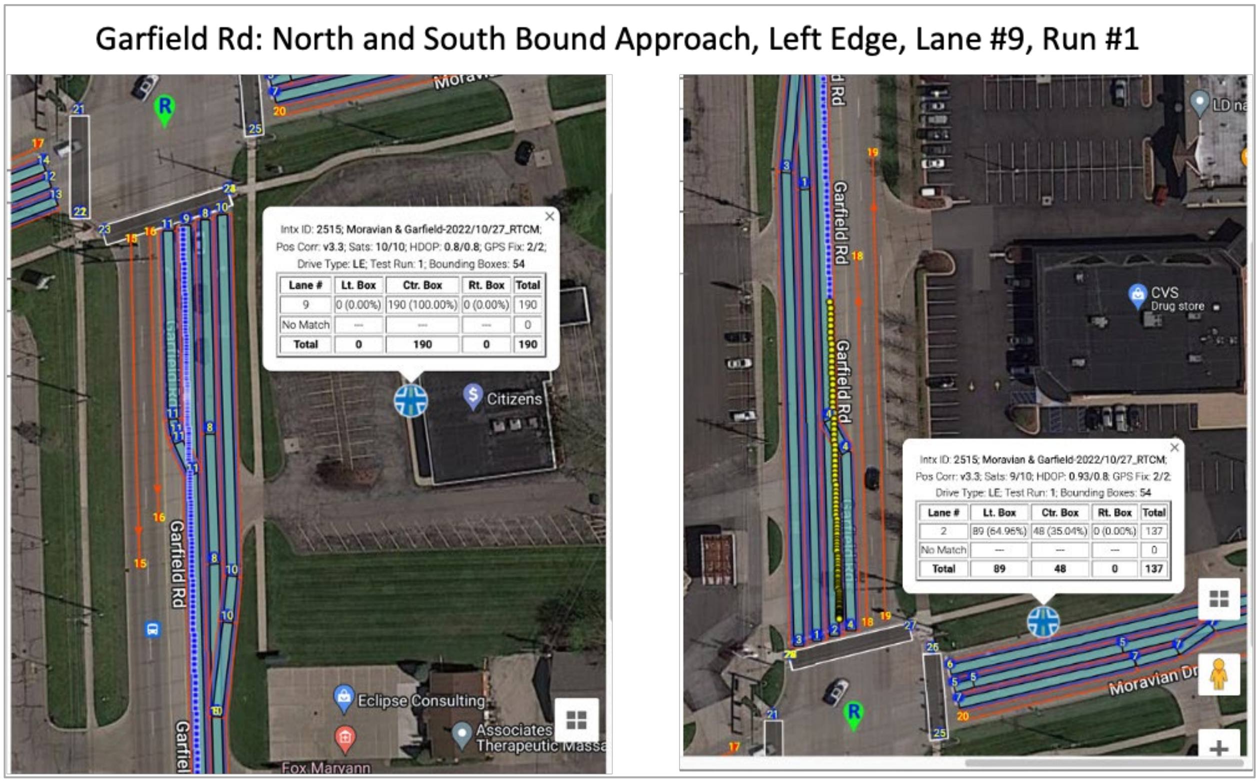
Figure 54: MAP Assessment Test Visualization – North and South Bound Approach, Right Edge of Lane #8 and #1

Figure 55 shows the MAP assessment visualization and associated matched lane table for run #1 for the north and south bound approaches on Garfield Road driven close to the left edge of lanes #9 and #2, respectively.



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Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle to Infrastructure 5 (V2I-5) Consortium, 2022

Figure 55: MAP Assessment Test Visualization – North and South Bound Approach, Left Edge of Lane #9 and #2

MAP Assessment on North and South Bound Approaches on Garfield Road

All 32 test runs show the north and the south bound approaches on Garfield Road correctly matched the driven lanes. The MAP visualization does not show any visual shift in the placement of the node points that define the lane geometry. Since all test runs were successful, only the images for the first test run are provided in this report.