CAMP LLC

Vehicle-to-Infrastructure (V2I-5) Consortium

Connected Intersection SPaT Accuracy Assessment

Supporting Basic Red Light Violation Warning

Version 0.6

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List of Acronyms

Acronym	Definition
AGP	Assured Green Period
CAMP	Crash Avoidance Metrics Partners LLC
CI	Connected Intersection
CV	Connected Vehicle
I2V	Infrastructure to Vehicle
IFM	Immediate Forward Mode
ITE	Institute of Transportation Engineers
JSON	JavaScript Object Notation
OBU	On-board Unit
OTA	Over the Air
PCAP	Packet Capture
RLVW	Red Light Violation Warning
RSU	Roadside Unit
SAE	SAE International
SPaT	Signal Phase and Timing
TSC	Traffic Signal Controller
V2I	Vehicle-to-Infrastructure

Connected Intersection SPaT Accuracy Assessment
Supporting Basic Red Light Violation Warning

Background

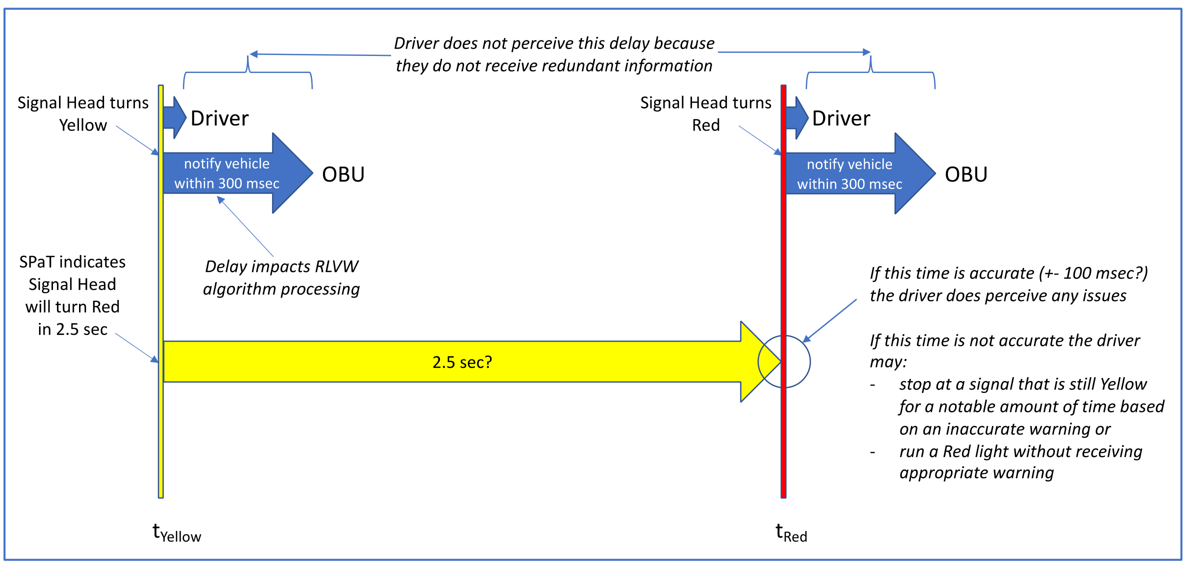
The Society of Automotive Engineers (SAE) J2735 SPaT message standard specifies the content and format of signal phase and timing information broadcast by a Connected Intersection (CI) using Infrastructure to Vehicle (I2V) communications to support in-vehicle safety and mobility applications such as Red Light Violation Warning (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.

Basis for Assessment

The purpose of this assessment procedure is to verify that 1) the duration of the yellow phase predicted by the Traffic Signal Controller (TSC) at the transition from green to yellow is accurate and 2) 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 transmitted 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, green to yellow or yellow to red, in this illustration, 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

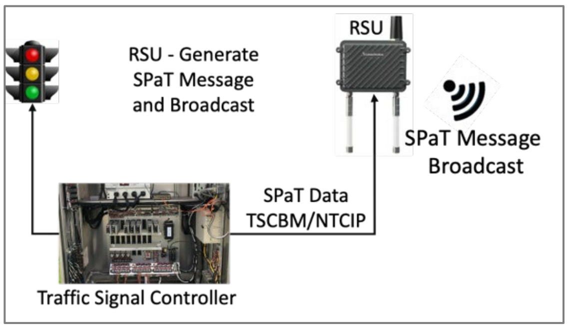
Figure 1: Impact of Signal Head Action vs SPaT Timing on Basic RLVW

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 broadcasting SPaT information.

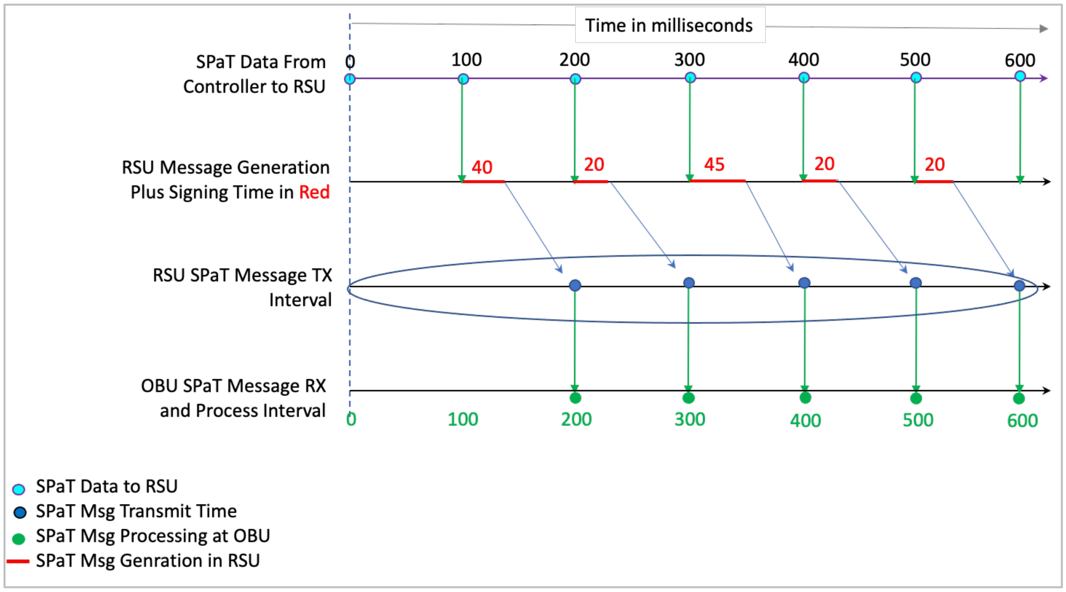
1. Generate and Broadcast Mode: In this method, shown in Figure 2, the TSC generates SPaT data and provides it to the Roadside Unit (RSU) using User Datagram Protocol (UDP) over an ethernet interface. The RSU generates Unaligned Packed Encoding Rule (UPER) encoded SPaT messages for broadcast as per the 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.



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

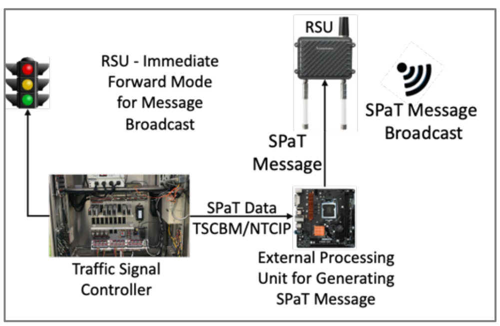
Figure 2: RSU - Generate SPaT Message and Broadcast Mode

As shown in 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 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

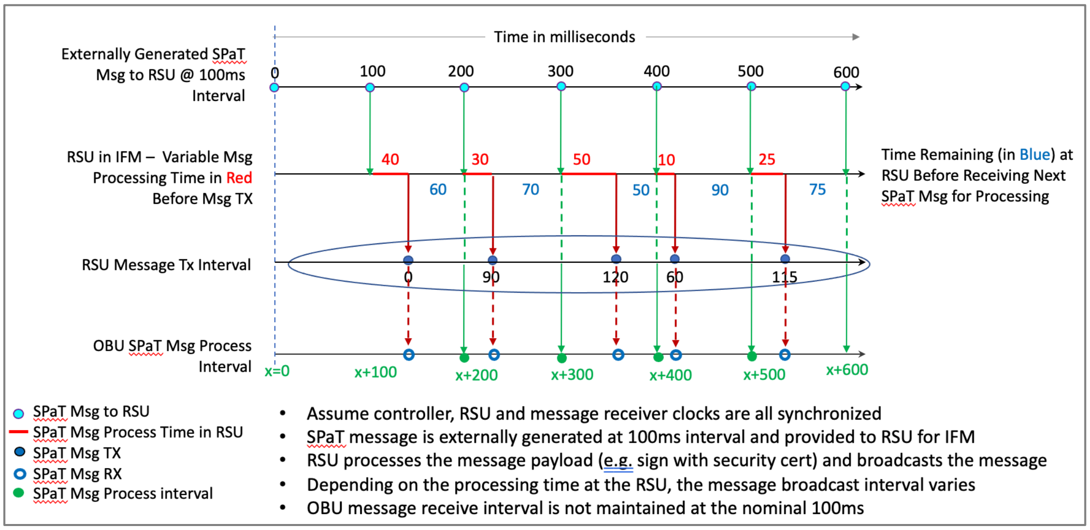
Figure 3: RSU - SPaT Message Generate and Broadcast Mode Time Interval



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 User Datagram Protocol (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.

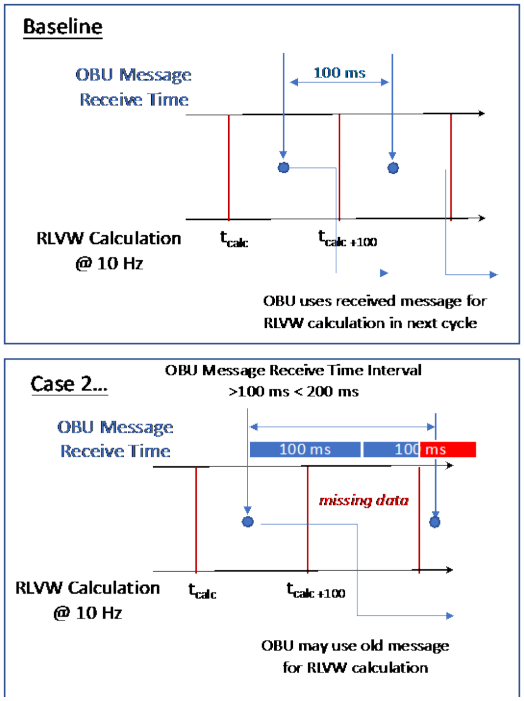


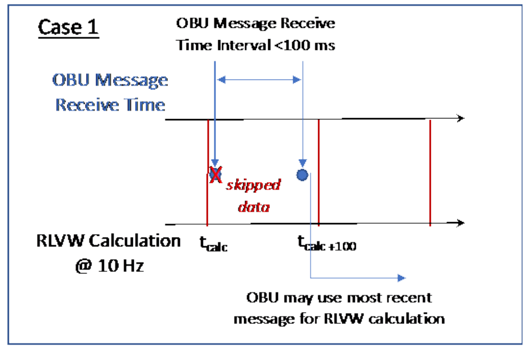
Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle to Infrastructure 5 (V2I-5) Consortium, 2022

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, 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

Data Collection

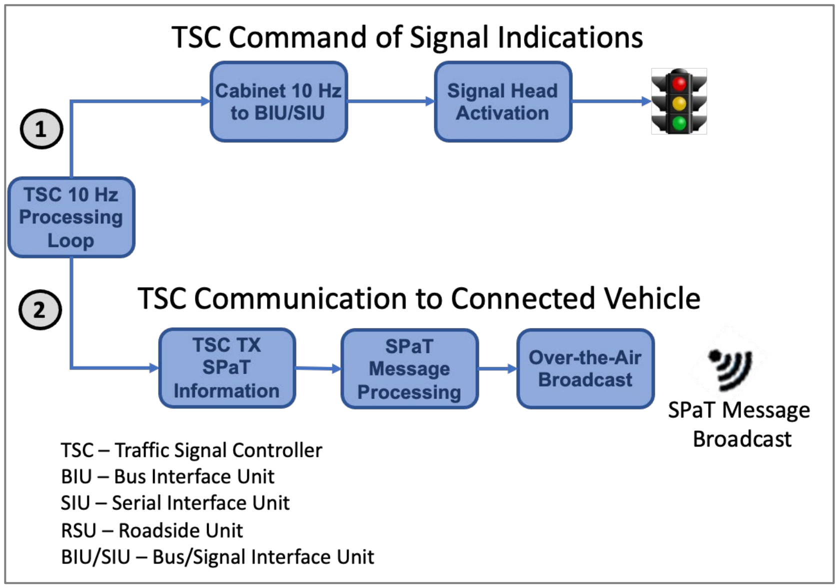
Figure 7 illustrates the flow of SPaT information in a CI architecture for 1) signal activation and 2) SPaT message generation and broadcast. This report focuses on assessment of SPaT from TSC to the message broadcast. The following data elements are required for end-to-end assessment of SPaT.

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:

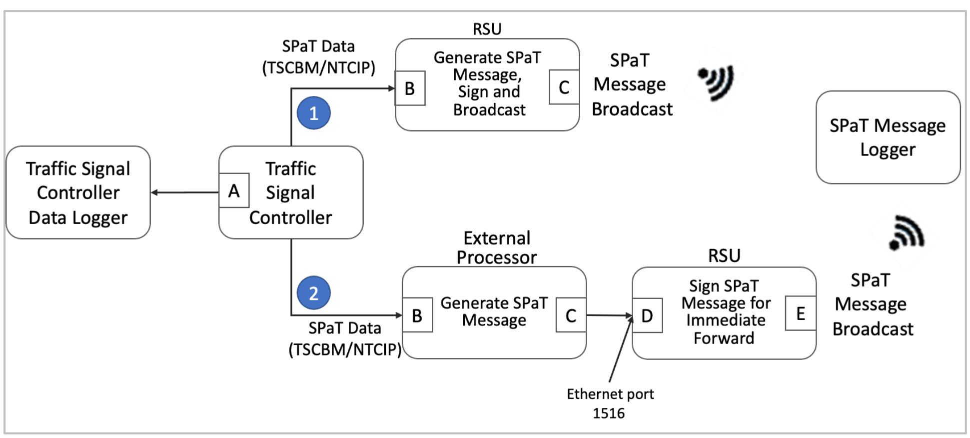
d. Timestamp in UTC at either departure or arrival of SPaT message
e. UPER encoded SPaT message including UTC timestamp in milliseconds. Refer ITE/CI Field Test Report [*3*] for more detail.



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.

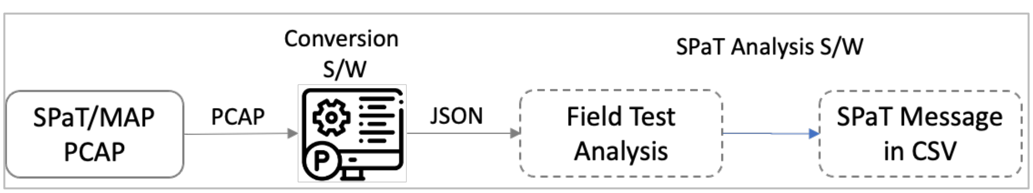
Method 2:

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 first 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

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 [4] 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, predicted time of start of 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.

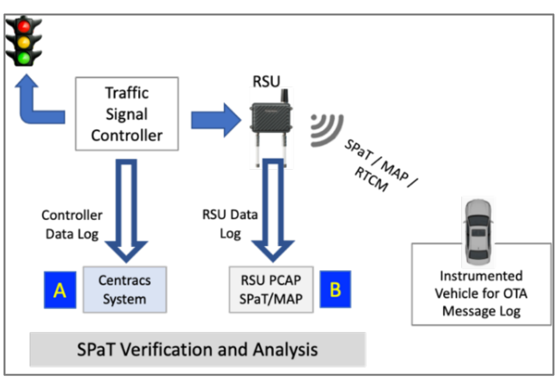
As described in Figure 8, two methods are commonly deployed at CIs to generate and broadcast the SPaT message. Example methods are described in this subsection.

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 a 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 transmitted 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 1) convert all data to the same format and 2) align timestamps (in UTC) to compare and analyze start time and duration of 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 csv format for each message. The conversion of PCAP to JSON conversion data format is described in 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.du.tg/Intersection_ID-0-1002/ecr_embarcadero.rsu.tx-SPaT-0-1002.json
Date & Time: 2021/06/05 - 08:06:00.253 (UTC)
Data Log: CAMP PCAP --> JSON - v1.11b; 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	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
0	1.6229E+12	2021/06/05-	0	19	242106	NA	0	1002	102	0	242106	251	16th - 3:06:0	0	0.002	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
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0	1.6229E+12	2021/06/05-	100	19	242106	NA	0	1002	104	0	242106	451	16th - 3:06:0	98	0.003	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
0	1.6229E+12	2021/06/05-	102	19	242106	NA	0	1002	105	0	242106	555	16th - 3:06:0	104	0.001	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
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0	1.6229E+12	2021/06/05-	101	19	242106	NA	0	1002	109	0	242106	953	16th - 3:06:0	102	0.001	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
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0	1.6229E+12	2021/06/05-	99	19	242106	NA	0	1002	112	0	242106	1251	16th - 3:06:0	99	0.002	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
0	1.6229E+12	2021/06/05-	101	19	242106	NA	0	1002	113	0	242106	1352	16th - 3:06:0	101	0.002	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
0	1.6229E+12	2021/06/05-	99	19	242106	NA	0	1002	114	0	242106	1451	16th - 3:06:0	99	0.002	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
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0	1.6229E+12	2021/06/05-	96	19	242106	NA	0	1002	116	0	242106	1651	16th - 3:06:0	97	0.001	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
0	1.6229E+12	2021/06/05-	102	19	242106	NA	0	1002	117	0	242106	1752	16th - 3:06:0	101	0.002	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
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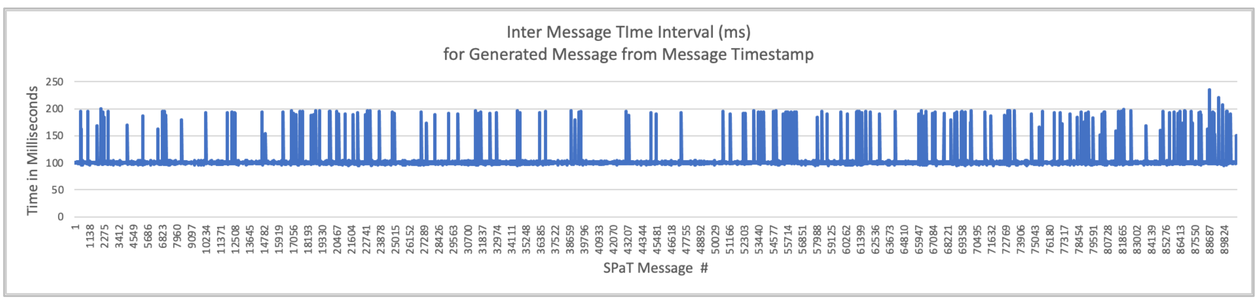
0	1.6229E+12	2021/06/05-	100	19	242106	NA	0	1002	121	0	242106	2152	16th - 3:06:0	100	0.002	1	stop-And-Re	Red-Light	3015	0:05:01.500	3702	0:06:10.200	8.048	8.046	4052	0:06:45.200	43.048	43.046	0	00:00.0
0	1.6229E+12	2021/06/05-	98	19	242106	NA	0	1002	122	0	242106	2251	16th - 3:06:0	99	0.001	1	stop-And-Re	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
0	1.6229E+12	2021/06/05-	102	19	242106	NA	0	1002	123	0	242106	2352	16th - 3:06:0	101	0.002	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
0	1.6229E+12	2021/06/05-	98	19	242106	NA	0	1002	124	0	242106	2451	16th - 3:06:0	99	0.001	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
0	1.6229E+12	2021/06/05-	104	19	242106	NA	0	1002	125	0	242106	2554	16th - 3:06:0	103	0.002	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
0	1.6229E+12	2021/06/05-	96	19	242106	NA	0	1002	126	0	242106	2651	16th - 3:06:0	97	0.001	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
0	1.6229E+12	2021/06/05-	102	19	242106	NA	0	1002	127	0	242106	2752	16th - 3:06:0	101	0.002	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
0	1.6229E+12	2021/06/05-	98	19	242106	NA	0	1002	0	0	242106	2851	16th - 3:06:0	99	0.001	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
0	1.6229E+12	2021/06/05-	102	19	242106	NA	0	1002	1	0	242106	2952	16th - 3:06:0	101	0.002	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
0	1.6229E+12	2021/06/05-	100	19	242106	NA	0	1002	2	0	242106	3052	16th - 3:06:0	100	0.002	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
0	1.6229E+12	2021/06/05-	100	19	242106	NA	0	1002	3	0	242106	3152	16th - 3:06:0	100	0.002	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

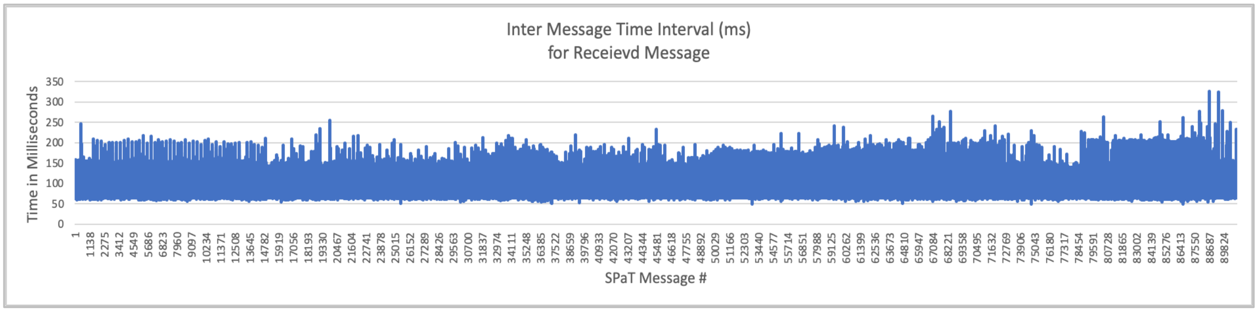
For a RLVW application to perform as intended based on defined 100 ms time interval of the message broadcast, message generation and transmission periodicity is determined using analysis of received SPaT messages. Figure 12 shows the inter message time interval of generated message (as provided in the 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 transmitted 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 Transmitted 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 start time and duration of the yellow phase. Figure 14 shows a sample of controller log data captured by the Centracs System. The Event column provides signal phase information, and the Detail column provides 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), message timestamp in column 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.

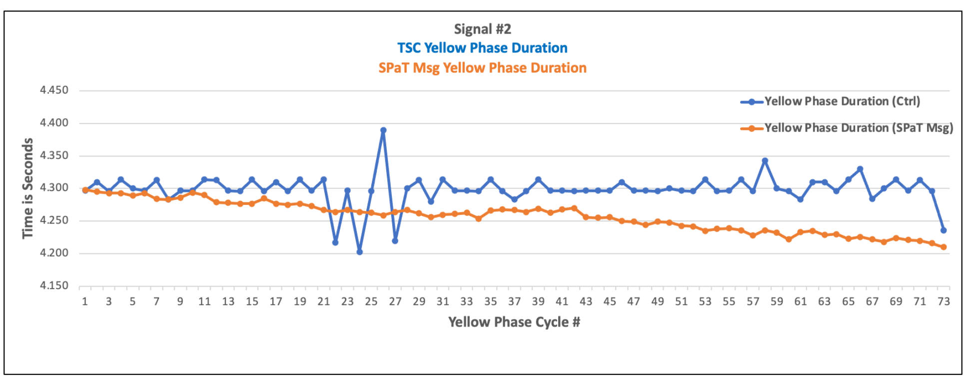
msg #	Msg Rx TS - epoch_UTC	epoch_ diff_ms	Intx_Time	MSG_TS_ Diff_ms	RX_Time_ Diff_ms	Sig_ Grp_ 2	Event_State _2	Sig_Phase_ 2	MinEnd_ TM_2	MinEnd_Time _2	Min_ET_ Remain _2	Min_ET_ Remain_ epoch_2	MaxEnd_ TM_2	MaxEnd_Ti me_2	Max_ET_ Remain_ 2	Max_ET_ Remain_ epoch_2
9239	2022/01/11 - 16:56:21.168	99	10d - 16:56:21.098	100	70	2	permissive-N	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-N	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

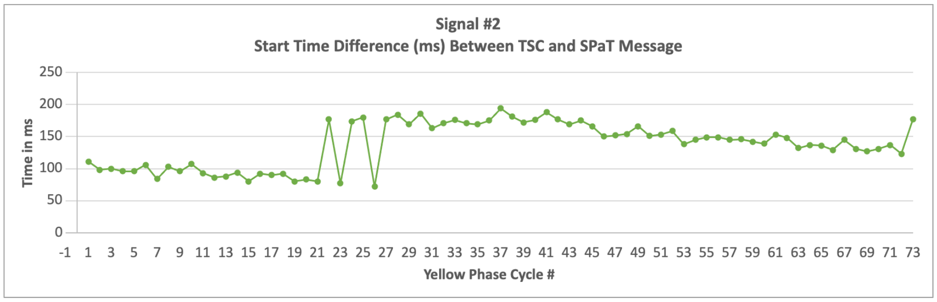
The graph in Figure 16 shows an analysis of yellow phase duration for signal phase #2 of 74 cycles. The blue line shows duration indicated by the TSC, and the orange line indicates the equivalent information contained in the broadcast SPaT message. The duration set by the controller averages to 4.299 sec while in 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 time difference in start time of 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 Duration - 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 mses of nominal 100 ms, 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 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 logged SPaT message time earlier than the controller time.

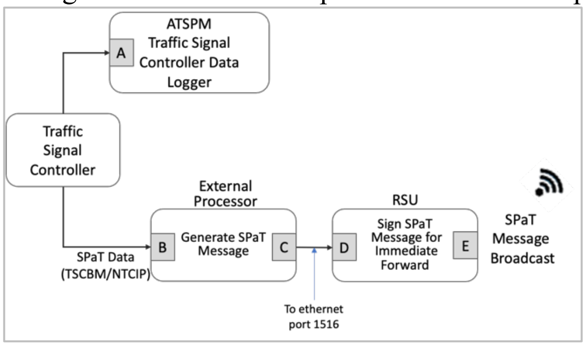
Example Method 2

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 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 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 broadcast in IFM.

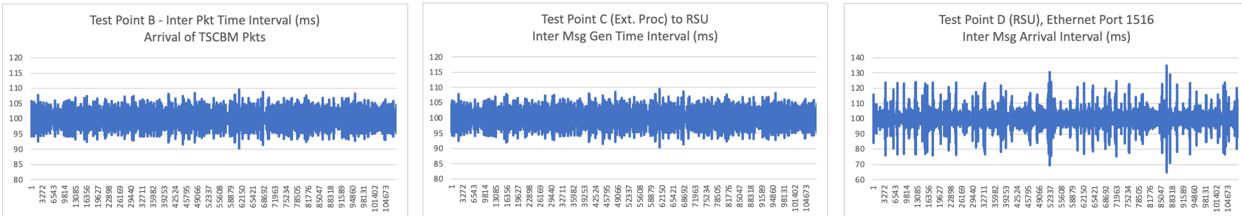
SPaT processing and communication time can be determined as follows:

- 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

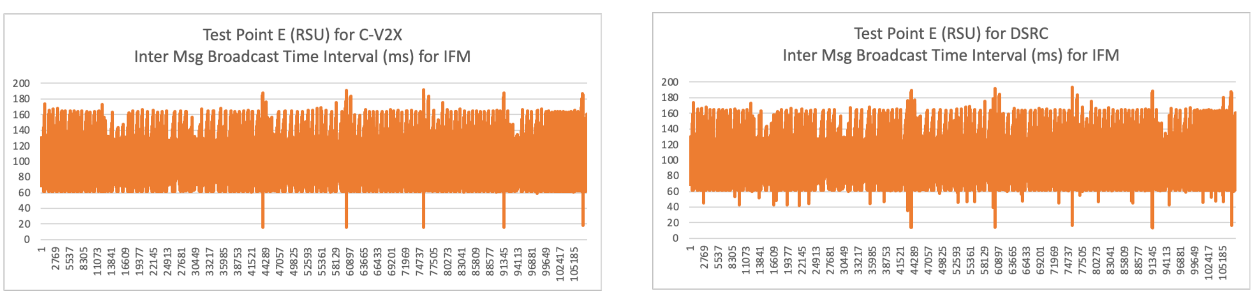
Figure 19: Inter Packet Processing Time Interval at Test Points B (Ext. Proc), C (Ext. Proc.) and D (RSU)

Table 2 shows the minimum and maximum inter packet time interval and percentage of ± 5 and ±10 msec time interval from nominal 100ms for all close to108,000 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 100ms			
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 analysis and graphs of 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 all close 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 indicating additional time taken to sign message with 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 100ms		
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, logged SPaT message in PCAP at test point E are converted to JSON and processed to generate data in 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 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 TSC ATSPM log. Column C, UTC timestamp of 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.

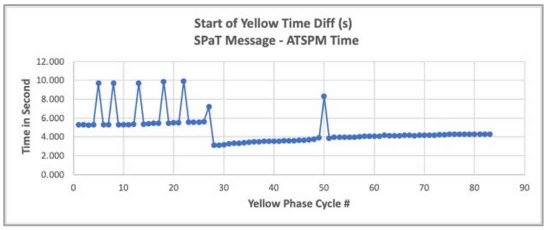
The highlighted elements in column M show greatly increased time difference and column T shows greatly reduced duration of the yellow phase for the cycle indicating anomalous data in the SPaT message.

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

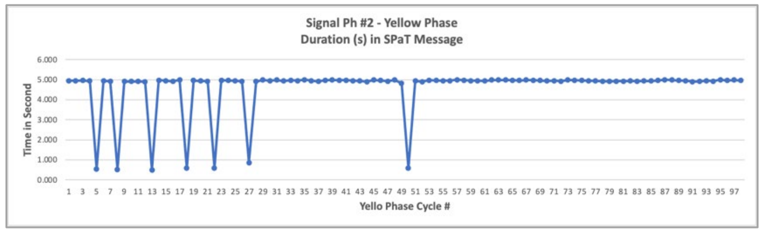
Figure 22: Extracted List of Start of Yellow Phase and Duration by TSC and Broadcast SPaT Message

Figure 23 shows the time difference in start of yellow phase between the broadcast SPaT message and TSC ATSPM timestamp and 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 24: 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 23: Duration of Yellow Phase in SPaT Message

Equipment Time Source

At this deployed CI, different 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 mses 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.

Summary

Basic RLVW operates using the Yellow to Red transition time information provided by the TSC at the transition from Green to Yellow and transmitted in the SPaT message by the RSU. The accuracy of this timepoint is critical for RLVW algorithm to function as intended. The performance of the RLVW algorithm is also critically dependent on receipt of a stable data stream from the CI.

The purpose of this assessment procedure is to verify that the duration of the Yellow Phase predicted by the TSC at the transition from Green to Yellow is accurate and that the broadcast of this information by the RSU maintains a stable periodicity of 100 ms by examining the following

1. Time indicated by the TSC for transition from Green to Yellow phase is accurate and equals the start of Yellow Phase time in the broadcast SPaT message
2. Time duration of Yellow Phase indicated by the TSC equals the duration in the broadcast SPaT message
3. Occurrence and periodicity of broadcast information by the Roadside Unit (RSU) is maintained

Two different methodologies used for deployment of a CI are described for SPaT processing, analysis and assessment for data collection at different test points were examined. Verification and assessment require many steps from converting all logged data from different test points to same format (e.g., csv), extracting converted data for the intended signal phase, and aligning timestamps in the information packet for comparison and analysis from TSC to broadcast of SPaT message. Currently, there are no commercially available integrated tools to accomplish the required assessment.

The CI deployments examined demonstrated significant variability in their performance. In order to ensure SPaT data broadcasts are usable by CVs implementing basic RLVW the following pass / fail performance criteria are proposed for CI verification using data to be sampled over a 24 hour period for at least TBD (7) consecutive days:

Message Periodicity:

- At least TBD (99%) of the time, SPaT data generated by the TSC is within ±10ms of nominal 100ms time interval.
- No more than TBD (1%) of the time, the SPaT data generated by the TSC can be within ±100ms from the nominal time interval
- At least TBD (99%) of the time, SPaT message being broadcast by the CI is within ±10ms of nominal 100ms time interval.
- No more than TBD (1%) of the time, the SPaT message being broadcast by the CI can be within ±100ms from the nominal time interval

Yellow Phase Start Time and Duration Accuracy:

- At least TBD (99%) of the time, the yellow phase start time indicated for any signal (in UTC) is within ±100ms of the start time broadcast in the corresponding SPaT message
- At least TBD (99%) of the time, the yellow phase duration indicated for any signal is within ±100ms of the time duration (minEndTime) broadcast in the corresponding SPaT message.

SPaT message pass/fail criteria are summarized in the following tables.

Table 4: SPaT Message Periodicity Requirements

Periodicity	**Nominal Time Interval (ms)**	**Time Interval Range (ms)**	**Maintain Required Periodicity %**	**Max Allowed Time Interval (ms)**	**Max Allowed Time Interval %**
TSC – Generation of SPaT Data	100	90 - 110	99%	±100	1%
RSU – SPaT Message Broadcast	100	90 - 110	99%	±100	1%

Table 5: SPaT Message Accuracy Requirements

Accuracy	Time Difference Between the TSC SPaT Data and Broadcast SPaT Message (ms)	Allowed Time Difference %
Start Time Yellow Phase	±100	1%
Duration of Yellow Phase	±100	1%

Open Issues:

- *Ongoing State of Health Monitoring - Extend the initial field verification concept into 24x7x365*
- *Data Analysis - CAMP Tools / Website to start - How does this evolve to an automated process??*

References

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