Connected Intersections Message Monitoring Systems Requirements & Prototype Development (CIMMS)

Concept of Operations – UPDATE

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Prepared by

Contents

1. Introduction 2
   1.1 PROJECT SCOPE 3
2. References 5
3. Current System 6
   3.1 BACKGROUND AND OBJECTIVES 6
   3.2 OPERATIONAL POLICIES AND CONSTRAINTS 9
   3.3 DESCRIPTION OF CURRENT SYSTEM 9
   3.4 MODES OF OPERATION 11
   3.5 USER CLASSES AND OTHER INVOLVED PERSONNEL 11
   3.6 SUPPORT ENVIRONMENT 12
4. Justification and Nature of Changes 13
   4.1 JUSTIFICATION FOR CHANGES 13
   4.2 USER NEEDS 14
   4.3 USER NEEDS VALIDATION 19
   4.4 PRIORITIES AMONG CHANGES 22
   4.5 CHANGES CONSIDERED BUT NOT INCLUDED 27
5. Concept for New System 28
   5.1 BACKGROUND, OBJECTIVES, AND SCOPE 28
   5.2 OPERATIONAL POLICIES AND CONSTRAINTS 28
   5.3 DESCRIPTION OF PROPOSED SYSTEM 31
      5.3.1 *Primary Components* 32
      5.3.2 *Interfaces* 32
      5.3.3 *V2X Messages* 33
      5.3.4 *Security* 33
      5.3.5 *Proposed Algorithms* 34
   5.4 MODES OF OPERATION 48
   5.5 USER CLASSES AND OTHER INVOLVED PERSONNEL 48
   5.6 SUPPORT ENVIRONMENT 49
6. Use Cases and Operational Scenarios 50
   6.1 USE CASE 1: EVENT DETECTION (NOT USING BSM) 50
   6.2 USE CASE 2: EVENT DETECTION (USING BSM) 51
   6.3 USE CASE 3: ASSESSMENT OF EVENTS AND NOTIFICATION 52
   6.4 USE CASE 4: PERFORMANCE REPORTS 53
   6.5 USE CASE 5: CHANGE CONFIGURATION 54
7. Summary of Impacts 55
   7.1 OPERATIONAL IMPACTS 55
   7.2 ORGANIZATIONAL IMPACTS 55
   7.3 IMPACTS DURING DEVELOPMENT 56
8. Analysis of the Monitoring System 58
   8.1 SUMMARY OF IMPROVEMENTS 58
   8.2 DISADVANTAGES AND LIMITATIONS 58
   8.3 ALTERNATIVES AND TRADEOFFS CONSIDERED 59
9. Notes 60

Appendix A. Questionnaire Results Summary 61

Tables

Table 1 - Concept of Operations Revisions/Updates 1
Table 2. Typical Message Correctness Verification Methods 8
Table 3: Message Monitor Project Engagement Meetings 14
Table 4: IOO Traffic Operations User Needs 15
Table 5: OEM User Needs 19
Table 6: User Needs Prioritization 23
Table 7: Example List of Intersecting Connections 43
Table 8: Example Event State Data and Output 44
Table 9: Example Time Change Details Data and Output 47
Table 10: Use Case 1: Event Detection (not using BSM) 50
Table 11: Use Case 2: Event Detection (using BSM) 51
Table 12: Use Case 3: Assessment of Events and Notification 52
Table 13: Use Case 4: Performance Reports 53
Table 14: Use Case 5: Change Configuration 54

Figures

Figure 1: Existing System Diagram 10
Figure 2: Proposed System Context Diagram 31
Figure 3: Visual Representation of Logic for determining Signal State when a Vehicle Crosses a Stop Line 36
Figure 4: Visual Representation of Logic for determining Signal State when a Vehicle Stops at a Stop Line 38
Figure 5: Visual Representation of Logic for determining Direction of Travel 39
Figure 6: Visual Representation of Logic for determining Alignment Between Connections and Vehicle Movements 40
Figure 7: Conflict Detection Example 42

Acronyms

BSM .... Basic Safety Message
CI .... Connected Intersection(s)
CIP .... Connected Intersection Project
CV .... Connected Vehicle
ECLA .... External Control Local Application
IEEE .... Institute of Electrical and Electronics Engineers
IOO .... Infrastructure Owner/Operator
ITS .... Intelligent Transportation System
MAP .... MapData
OBU .... Onboard Unit
OEM .... Original Equipment Manufacturer
PFS .... Pooled Fund Study
PSID .... Product Service Identifier
RLVW .... Red Light Violation Warning
RSU .... Roadside Unit
SAE .... Society of Automotive Engineers
SCMS .... Security and Credentials Management System
SPaT .... Signal Phase and Timing
TSC .... Traffic Signal Controller
V2X .... Vehicle-to-Everything
V2V .... Vehicle-to-Vehicle
V2I .... Vehicle-to-Infrastructure

Distribution and Updates

This draft report is located on the CIMMS shared projects folders, along with a comment response matrix to track the disposition of all comments received. The final, approved version is intended to be published on the CV PFS website - https://engineering.virginia.edu/cv-pfs

Table 1 - Concept of Operations Revisions/Updates

Description	Issue Date	Author(s)	QA/QC
Preliminary Draft	April 13,2022	Chris Toth, WSP	Tom Timcho, WSP Frank Perry, WSP Tony English, Neaera Virginia Lingham, WSP
Draft	May 16, 2022	Chris Toth, WSP	Tom Timcho, WSP Frank Perry, WSP Tony English, Neaera Virginia Lingham, WSP
Revised Draft	June 15, 2022	Chris Toth, WSP	Tom Timcho, WSP Frank Perry, WSP Tony English, Neaera Virginia Lingham, WSP
Final Draft for Approval	July 13, 2022	Chris Toth, WSP	Tom Timcho, WSP Frank Perry, WSP Tony English, Neaera Virginia Lingham, WSP

1. Introduction

This Concept of Operations (ConOps) serves as the first in a series of engineering documents intended to describe the development of the Connected Intersections Message Monitoring System (referred to as the Message Monitor, henceforth).

The purpose of the ConOps is to clearly convey a high-level view of the system to be developed. Unlike a typical ConOps that documents high-level user needs, this document will more directly consider what each user needs the system to do. This document frames the overall system, sets the technical course for the project, and serves as a bridge between early project motivations and the technical requirements. The ConOps is intended to be technology independent, focuses on the functionality of the proposed system, and forms the basis of the project.

The ConOps also serves to communicate the user's needs for, and expectations of, the proposed Message Monitor system. The document gives stakeholders the opportunity to provide input as to how the proposed system should function. The document is intended to help form a consensus among all stakeholders to create a single vision for the system moving forward.

This ConOps has the goal of describing a system that ideally can integrate with as many CV system architectures as practical, both current and future. To achieve this however, it must characterize the existing system architecture as general in nature, placing some constraints on the existing system. As the requirements are developed in a future task, this approach will continue to be used. However, the design of the system will consider the conditions (within the constraints set in the ConOps and the System Requirements) of a particular existing architecture, and will be configured to operate with that architecture, but will be flexible enough that modifications can be relatively easily made to accommodate the specific conditions of other architectures.

The structure of this document follows IEEE Std. 1362-1998 containing the following sections:

- **Section 1** provides a document overview.
- **Section 2** identifies all documents referenced and interviews conducted in developing this document.
- **Section 3** describes the current and supporting system architectures. This section provides a description of the problem(s) to be addressed and is tailored to describe the motivation for the development of the proposed Message Monitor system.
- **Section 4** describes the features that motivate development of the project. This section provides a transition from Section 3, which describes the current and supporting systems, to Section 5, which describes the proposed system.
- **Section 5** describes the proposed system resulting from the features described in Section 4. It describes the proposed system at a high-level, indicating the operational features that are to be provided, without specifying design details.

- **Section 6** describes the Use Cases and Operational Scenarios which presents how the project is envisioned to operate from various perspectives.
- **Section 7** describes the impacts the project will have on the stakeholders, users, and system owners/operators.
- **Section 8** provides an analysis of the impacts presented in Section 7.
- **Section 9** Includes additional information to aid in the understanding of the ConOps.

1.1 PROJECT SCOPE

Since the inception of Connected Vehicle (CV) technology, researchers have sought new and innovative ways to use CV to improve transportation safety, mobility, and efficiency. Most of these efforts have focused on the ability of vehicles to react to the data they receive from other vehicles and from the infrastructure. Forward Collision Warning, Red-Light Violation Warning, Curve Speed Warning, etc., are all examples of critical CV safety applications that utilize CV data and as more data becomes available, these applications continue to mature. In parallel, numerous advances to ensure timely and authenticated data is being provided to the CV environment continue. Robust fiber networks and the investment in the Security Credential Management Systems (SCMS) serve as proof of those investments. The assumption, however, has generally been that once a site had deployed and validated the broadcast messages, the data would remain correct. Two issues arise from this thinking:

- **Accuracy** – as has been the focus of the current Connected Intersection project (CIP), and others before it, validation of message content goes beyond conformance to the SAE J2735 standard. To truly be considered conformant to the needs of OEMs, deployers need to ensure that broadcast messages truly match what is happening at the intersection. For instance, signal indications on the traffic signal must match those in the SPAT message.
- **Consistency and Changes** – The validation of message content is not only needed at the time when CV equipment is deployed, but also throughout active operations of a CV system. Signal timing patterns change, geometries change, and devices fail – it is important to confirm that these changes are properly accounted for in the CV system simultaneously after the changes are made. Only limited capabilities exist to determine if a device is even operational, so it is not a simple matter to determine if it is operating correctly.

The current CI project is focused on validating a site's ability to conform to the newly published ITE CI design guidance, guidance which the OEMs agree will uniformly support advanced safety applications, such as RLVW. CIP is a validation of the guidance itself, feedback which will be provided to the industry. It's important to note that in practice, use of the guidance would typically only occur at deployment however, and similarly validate a sites' ability to conform to the guidance.

But what happens after a site validates in conformance to the guidance? Agencies don't have the bandwidth or budgets to subject every intersection to the same rigors as the CIP on a repetitive basis or over an extended period of time. Many agencies are also preparing to leverage increasingly larger amounts of Vehicle-to-Everything (V2X) data from intersections and from vehicles, especially as the number of V2X-equipped vehicles increases. This ConOps proposes that this V2X data can be leveraged to continuously validate the correct operation of the infrastructure over a long-term time horizon. The broad goal of this Connected Intersection Message Monitoring System is to evaluate this potential.

Note that the scope for this project (initial implementation of the message monitor) is limited to receiving CV messages from a CV system, and using SPaT, MAP, and the BSM (driver behavior that provides a proxy for actual ground truth conditions) to assess the accuracy of data within SPaT and MAP messages. , The accuracy of data in MAP and SPaT messages was initially cited as being a priority and by limiting to these three messages, it simplifies the data and interfaces required between the existing system and the message monitor and minimizes the pre-requisites for the existing system. Any system for which CV data will be assessed should be able to produce and forward CV data to a message monitor. Data from other (non-CV) sources, while useful for assessing SPaT and MAP accuracy, may not be available at every intersection. Thus, data from non-CV sources was not included for this initial implementation of the message monitor.

Other needs that have been identified during this process, such as the ability to assess message performance, generic message requirements, and position corrections are documented, but not considered in the initial implementation of the message monitor. However, the message monitor will be designed in a way that allows the modification/addition of interfaces and algorithms so that data from other sources can be utilized and so other needs can be addressed in future system development efforts.

2. References

- SAE J2735 2016-03. V2X Communications Message Set Dictionary. 2016
  https://www.sae.org/standards/content/j2735_201603/
- SAE J2735 2020-07. V2X Communications Message Set Dictionary. 2020
  https://www.sae.org/standards/content/j2735_202007
- CTI 4501 v01 – Connected Intersections (CI) Implementation Guide 2021
  http://www.ite.org/pub/76270782-B7E4-7F75-BC72-D5E318B14C9A
- CTI 4001 v01 - Roadside Unit (RSU) Standard 2021
  http://www.ite.org/pub/764FB228-0F6C-BA02-6D7B-16A86B1F8108
- SAE J2945/B Recommended Practices for Signalized Intersection Applications *work in progress*
  https://www.sae.org/standards/content/j2945/b/
- Operational Data Environment open-source decoder for MAP/SPaT/BSM 2021 *latest version*
  https://github.com/usdot-jpo-ode/jpo-ode
- CTI 4502 v01.00 – Connected Intersections Validation Report 2022
  https://www.ite.org/pub/?id=59A8D354-F7B1-6A18-6FCC-1CECE6ACDE5B
- CV PFS MAP Guidance Document 2022
  https://engineering.virginia.edu/sites/default/files/common/Centers/CTS/CVPFS/resources/MAP%20Guidance%20Document%20-%20Revision%20%231%20%28June%202022%29.pdf
- SPaT Challenge Overview Accessed July 2022
  https://transportationops.org/spatchallenge

3. Current System

3.1 BACKGROUND AND OBJECTIVES

Transportation agencies throughout the country have begun to deploy CV components alongside traditional roadway infrastructure (e.g., traffic signal controllers) and in vehicles to demonstrate the feasibility of using electronic messages to enable applications that improve safety, improve mobility, and communicate traveler information to drivers of equipped vehicles.

From the perspective of an Infrastructure Owner Operator (IOO), the primary function of current CV deployments is to enable select CV Vehicle-to-Infrastructure (V2I) applications. RLVW is supported by many CV deployments due to its relationship and use of the SPaT message, the response to the SPaT Challenge, and the resounding focus on the connected intersection, though other applications are typically also deployed. Efforts to deploy CV equipment tend to focus on specific localized needs, which lead to slightly different implementations of the same application in different deployments. Furthermore, multiple vendors that agencies may use to deploy CV equipment, will have slightly different implementations as well. Specific localized needs and differences in vendor equipment often result in applications between deployments not being interoperable, despite using the same messaging standards. To promote interoperability, OmniAir currently performs testing (defining a set of expected operations under different conditions) to certify RSU and OBU performance, but a large amount of work still needs completed. The ITE CI Guidance attempts to provide some consistency on what data is required for the RLVW application, specifying the use of certain optional elements in SAE J2735 and defining how message elements should be used and interpreted. CV deployment typically involves integration with other IOO-managed devices, such as traffic signal controllers, to enable the electronic communication of data with CV roadside equipment. Among many other tasks, the CV roadside equipment contains functionality that allows the processing and conversion of data from a traffic signal controller into an SAE J2735-compliant Signal Phase and Timing (SPaT) message for broadcast.

Management of a CV system also involves the configuration of other types of messages that are broadcast from CV roadside equipment such as SAE J2735 Map Data (MAP) message. The mechanism by which CV components are managed provides an interface that allows a user to configure or check the status of CV components. This may include, but is not limited to:

- Uploading an encoded message for broadcast
- Configuring RSU communications (with other roadside devices, and transmission channels)
- A message generation tool with a graphical user interface that allows the user to generate a message to broadcast.
- Making captured CV data available – this may be text-based or visual in nature.
- Monitoring basic operations of the system

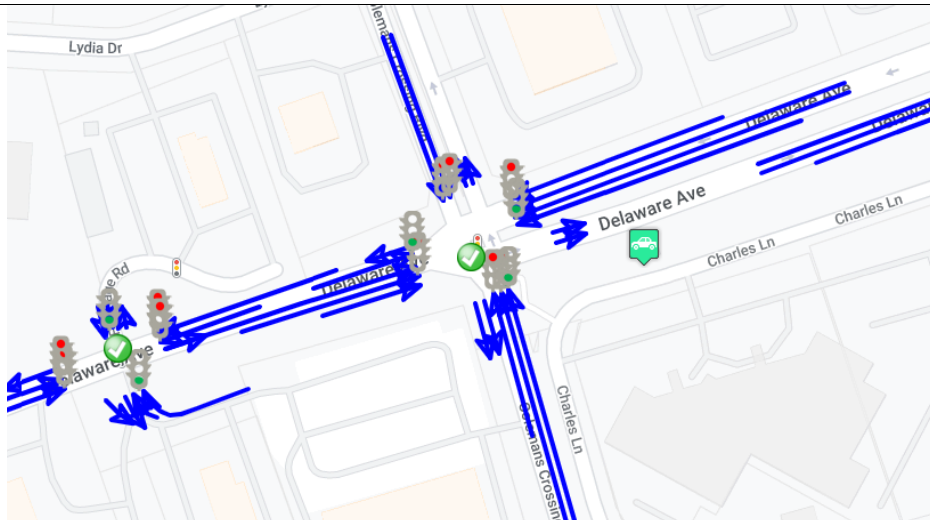
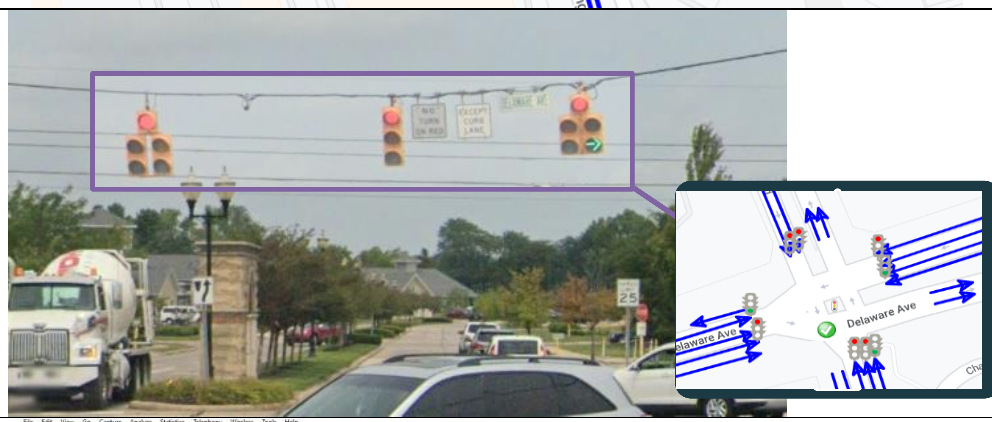
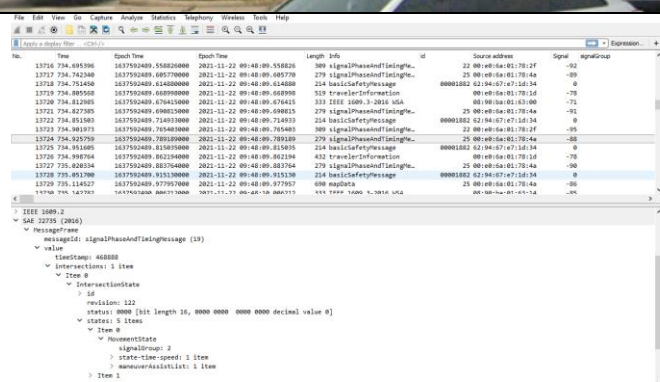
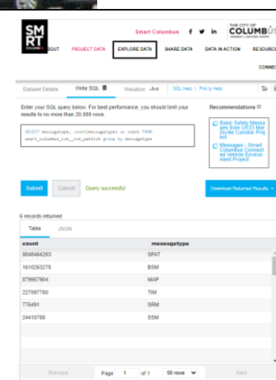
While the IOO is ultimately responsible for the content broadcast from roadside devices, the management of CV equipment may be performed by the roadside equipment manufacturer or by a third-party.

Considering that this project intends to develop a system that assesses various aspects of SPaT and MAP messages, the methods by which messages are assessed under the current system architectures need to be documented. Validating the correctness of messages typically involves various checks, three examples of which are provided in Table 2. In the first example, a management interface (not representative of all management interfaces) is providing a means of visualizing real-time MAP, SPaT, BSM, and other types of message data (a simpler management interface may provide text-based data, which can be post-analyzed/visualized, similar to the final example described below). This can be used as an initial high-level test to determine if the lane geometry data roughly matches the actual roadway geometry and to make sure that the event state is properly progressing from one signal state to the next, and that conflicting movements are not active (green/yellow) at the same time.

The second example shows a field verification being performed by utilizing stand-alone test tools at an intersection, capturing live over-the-air data, and comparing the test tool visualization against the actual signal state in the field to ensure correct operations are occurring. For instance, visual confirmation of signal groups being properly assigned to each connection (and ingress lane, by association) could be made. If real-time camera feeds are available with views of all signal heads, then this step could be performed remotely.

In the final example, CV messages broadcast from the intersection and from vehicles can be captured by a packet capture tool in the field and post-processed to assess various performance measures, long-term message broadcast rates, and/or analyzing vehicle behavior in relation to SPaT and MAP data. This can yield interesting insights to traffic management, such as red-light running rates, vehicle approach speed distributions, and priority/preemption performance.

Table 2. Typical Message Correctness Verification Methods

Remotely observing a visualization of data sent/received by the RSU via a back-office interface	
Comparative observation between data visualized on a test tool and field conditions (e.g., signal state) in real-time	
Post-analysis of CV data received by a data capture device	 

3.2 OPERATIONAL POLICIES AND CONSTRAINTS

Policies and constraints are driven by adherence to standards and industry guidance. Given that the proposed system is expected to be heavily focused on the use of CV data, the policies and constraints listed below are those that primarily relate to the use of CV data within and obtained from a CV system.

V2X Message Set Dictionary - CV technology broadcasts and receives messages that are compliant with SAE J2735 – V2X Message Set Dictionary. This standard defines the types of messages and the data frames and data elements that comprise them. It specifies which data elements are required to be populated and the data format. A standardized message set supports interoperability between devices that comprise the CV Environment (RSUs and OBUs).

Roadside Unit (RSU) Standard (CTI 4001 v01) - The CTI 4001 v01 standard specifies minimum requirements for RSUs and promotes interoperability. RSUs operating in live environments are expected to adhere to this standard, but many requirements are not supported at this time by RSU models, and compliance may vary from one deployment to the next. The standard addresses two mechanisms that RSUs use when transmitting messages. *Store and Repeat* messages are downloaded from a back-office service, stored on the RSU, and broadcast at a rate configured on the RSU – MAP messages, for example. Alternatively, the RSU transmits *Immediate Forward* messages as they are sent to the RSU, SPaT messages, for example. Transmission instructions accompany messages, (transmission channel, PSID, and whether the message should be signed and/or encrypted).

CI Implementation Guide (CTI 4501 v0100) - The CI Implementation Guidance was developed by a consortium of infrastructure owner operators (IOO), original equipment manufacturers (OEM), and standards developers to document an expanded set of requirements and design details that are needed to enable fully featured versions of the RLVW applications. These additional requirements required additional fields from the SAE J2735 message, previously considered ‘optional’, to be included in messages compliant with this guidance. The guidance also serves to refine how each element should be interpreted as well as defines acceptable levels of latency in the production of the SPaT message. IOOs are beginning to consider if their sites are compliant with this guidance and starting to make system modifications to address gaps.

Data Management and Privacy – It is recommended that IOOs that have deployed CV systems or plan to in the near future have privacy policy and data retention plans in place. These plans detail the privacy and security controls for all aspects of the data environment and provide a structure for the agency when handling data (or designing systems that handle this data) to ensure compliance with all applicable laws and regulations and/or other internal data collection restrictions. IOOs may also have deployed OBUs in their operational CV Environment which could have separate terms of use or consent that dictate how data from those OBUs may be used.

3.3 DESCRIPTION OF CURRENT SYSTEM

For the purposes of this project, an existing CV system consists of the components required to generate and encode, at a minimum, the SAE J2735 messages, SPaT, MAP, and BSM messages, the latter from a vehicle-based device. A diagram depicting the context of the existing system (for the purposes of this document) is provided in Figure 1 and described below. Note that there are likely many other components that the existing system may interface with. However, these are not shown in detail on the diagram, as operation of the proposed system is not directly dependent on them.

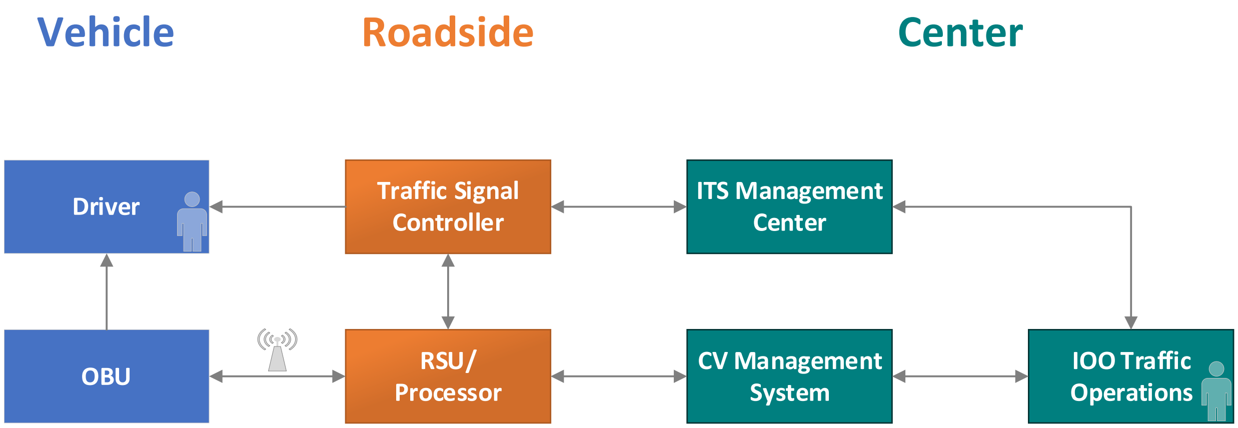


Figure 1: Existing System Diagram

The current system consists of elements that are typically found on CV deployments. The ITS Roadside equipment, for the purposes of this project, is limited to traffic signal controller (TSC) infrastructure. The TSC controls traffic, and drivers are expected to operate their vehicles in accordance with the visual indications provided from the TSC. Considered part of the TSC Infrastructure, an external control local application (ECLA) may be used in some deployments. The ECLA asserts a higher-level control over the TSC, allowing it to assign signal timing duration, run specific coordination pattens, or otherwise manipulate signal timing. The TSC infrastructure interfaces with the RSU/roadside processing equipment to provide signal controller data that is used to populate the SPaT Message. The RSU broadcasts the SPaT message along with the MAP message which are intended to be received by OBUs to enable in-vehicle CV applications. An example of a CV application is red light violation warning which provides a warning to the driver when they may run a red light. These outputs are intended to complement the indications from traffic signals controlled by the TSC. Though not explicitly shown on the diagram, it is also important to acknowledge the network hardware necessary for all of these roadside and center components to interface with each other.

Often, when an agency designs and deploys a roadside CV system, they also equip vehicles to extract useful information from the vehicle, provide a benefit to drivers, and demonstrate system functionality. The roadside and in-vehicle functionality often require thoughtful coordination to ensure the infrastructure produces the data that the vehicle needs to adequately support the application(s) available on the OBU. This coordination has the potential to make it more difficult to determine when there are issues with data in SPaT and MAP messages, as the focus of testing is often directed on achieving in-vehicle application functionality. The interoperable design of CV technology theoretically allows other vehicles to receive and use this same data. However, these other vehicles may require slightly different data than what is produced by the infrastructure or may interpret the data in these messages differently than the in-vehicle devices that are deployed along with the roadside infrastructure, resulting in a system that may not be as interoperable as originally intended. The CI Implementation Guidance serves to define what data and connected vehicle messages are being provided from an interoperable connected intersection and specifically defines what is represented with each piece of data (i.e., how each data element should be interpreted). Some of the requirements cannot be met without upgrades to the functionality of existing equipment to produce this data (including, but not limited to assured green time, subsequent signal state data, and intersection status data). There is currently no system or entity to assure that a given installation meets this guidance.

Traffic Operations Personnel manage and configure the ITS and CV components of their system typically through separate management interfaces (shown as the ITS Management Center and CV Management System, respectively). This may involve changing signal timing plans, configuring MAP messages, or monitoring operations data.

3.4 MODES OF OPERATION

This ConOps will consider normal operations and degraded modes of operation. The Modes are defined as:

- **Operational** – Normal operating condition, the System is operating as designed. CV messages are being broadcast as intended.
- **Degraded Communications** – An error with a system component or communication network that prevents the communication (or timely communication) of a CV message(s). To understand how this condition might affect the proposed system see Section 5.4 Modes of Operation (proposed system).

3.5 USER CLASSES AND OTHER INVOLVED PERSONNEL

The user classes in the existing system primarily relate to roles that are performed within the context of the existing system and not a specific organizational structure, specific staff, or group of persons.

IOO Traffic Operations. IOO Traffic Operations personnel are typically employees of the IOO but may be served by third-party staff. IOO Traffic Operations is responsible for the operations and maintenance of traditional ITS devices, particularly traffic signal controllers. As it relates to the operation of a CV system, IOO Traffic Operations is also responsible to configure the traffic signal controller and/or ECLA to produce the data necessary for CV roadside equipment to populate the SPaT Message. The management of CV components is also the responsibility of IOO Traffic Operations. Responsibilities include the configuration of RSUs via a CV Management System which typically includes but is not limited to communication configuration between roadside devices (including traffic signal controllers), uploading MAP messages, specifying which RSU(s) each message is broadcast from, which channels messages are broadcast on, and other actions that may (or may not) be taken when certain conditions (as indicated in a specific message data element, for example) are present.

Driver. The driver is responsible for properly operating their vehicle in response to traffic control devices, and as available, to the outputs (e.g., warnings, alerts, notifications, etc.) from in-vehicle safety systems, to include both CV equipment and other automated driver assistance systems (ADAS). The OBU uses CV messages broadcast from an RSU (managed by IOO Traffic Operations) to provide the additional indicators to the driver with the intent to further support safe operations of the vehicle. The proper function of these applications relies on accurate infrastructure-based messages, as well as accurate vehicle positioning data. In the context of message monitoring, a driver does not provide direct input to the system, but location, speed, and travel direction data, in the form of the BSM messages broadcast from the driver's vehicle, may be observed by Traffic Operations.

3.6 SUPPORT ENVIRONMENT

Local and Backhaul Connectivity – CV and ITS systems typically utilize electronic communications that allow devices to be networked not only locally at the roadside, but also to an agency-wide wide area network to support remote configuration and monitoring. The backhaul network that provides this connectivity may be wired or wireless in nature and is typically accompanied by an underlying network management capability. A network security protocol is also likely in place to reduce the likelihood of access to the network by unauthorized users.

Security and Credentials Management System. Both the OBUs and RSUs utilize a security credentials management system (SCMS) to enable the exchange of secure, digitally 'signed' messages. A SCMS is designed to provide trusted, secure V2V and V2I communications between entities that previously have not encountered each other and wish to remain anonymous. Additionally, the SCMS allows a vehicle to identify itself in applications that require positive identification (e.g. signal priority and preemption). Security is provided by authenticating the originator of the message and assigning digital certificates used to sign messages produced by the devices. The following types of certificates may be used in a CV Environment:

- Pseudonym certificate. Short term and used by OBUs primarily for basic safety message authentication and misbehavior reporting.
- Identity Certificate. Provides a method to verify the identity of an OBU device to determine if it is authorized to leverage certain intersection-based features such as receiving priority/preemption.
- Application Certificate. RSU-based messages are signed using an application certificate, which provides information on which messages the RSU is allowed to broadcast.

These certificates, which are attached to messages, creating a "signed message", provide an indication that the data received is trustworthy. If a message is not signed with a valid certificate, or if certificates from a particular device is flagged as untrustworthy, then the receiving device is expected to not continue processing or react to that data.

4. Justification and Nature of Changes

4.1 JUSTIFICATION FOR CHANGES

The Message Monitoring System is intended to provide a means of continuous assessment of SPaT and MAP message data to ensure that actual field conditions are accurately reflected in these messages. Input from the PFS panel and feedback received from stakeholders were used to identify shortcomings of the existing system, and subsequently areas of improvement that the Message Monitoring system can address. The current system has limitations that make it inadequate for assessing SPaT and MAP messages, described in the bulleted list below:

- The current system does not provide ongoing assurance that CV equipment at an intersection is operating correctly. Existing connected intersections were developed as research or pilot projects without a focus on rigorous verification of operation. As CIs move from research and pilots to production with regular drivers, the ongoing CI data must be correct.
    - There isn't currently a standardized approach to create MAP messages which may lead to inconsistencies between MAP message content between different deployments. The CV PFS MAP Guidance Document attempts to improve MAP message consistency. However, it is not known what degree of testing is being performed to assess adherence to this guidance, especially over time.
    - Similarly, there is not a standardized approach for the generation of signal groups that are not already defined using the 8-phases typically used in a traffic signal controller (i.e., overlaps, protected-permissive, etc.). These issues lead to inaccuracies in these messages that differ between deployment sites, that are not being quickly identified and corrected.
    - If ground conditions change (e.g., pavement markings, lane control, etc.) or configuration is updated (e.g., signal phasing), then the data contained in SPaT and MAP may no longer be correct, but there is no mechanism that indicates that there may be an issue, allowing the continued broadcast of inaccurate data.
- Current real-time methods of monitoring CV data are limited to a few simple displays that still require human assessment.
    - For example, the display of signal state data (from SPaT) overlayed on roadway geometry data (MAP) and vehicle markers that indicate the location of vehicles from BSMs.
- Current post processing methods are limited because they do not allow for real-time continuous assessment of CV data.
    - Back-end systems that currently support data management and processing are complex and potentially expensive (depending on the amount of data stored at any one time). Many of these systems are set up to ingest, query, and display data – not to perform processes on an automated basis or provide notification regarding issues with application-level CV data.

- If CV data capture is performed in the field (for example, using a WireShark capture software), it must be collected and saved/exported prior to any analyses being performed. By its nature, real-time processing cannot be performed.

4.2 USER NEEDS

It is crucial to engage the project panel, which includes members of the Connected Vehicle Pooled Fund Study (CV PFS), and other stakeholders identified by the project team to understand the needs of users of the proposed message monitor system. Stakeholders have representation from multiple groups including PFS members, IOOs, OEMs, standards development organizations, traffic signal controller manufacturers, and consultants in the CV system engineering and development space. Multiple meetings and review cycles were held to engage stakeholders. A list of these working group and stakeholder meetings and activities, and those in attendance are provided in Table 3.

Table 3: Message Monitor Project Engagement Meetings

Meeting	Date	Group	Attendees/Respondents
CIMMS Workshop at Mid-Year Meeting	3/28/22	CV PFS Members	Amanda Hamm, Mallory Artusio, Blaine Leonard, Chuck Felice, Brian Smith, Govind Vadakpat, Nick Hegemier, Jianming Ma, John Hibbard, Lee Smith, John Roberts, Ray Starr, Alan Davis, Ahmad Jawad,
PFS Mid-Year Meeting	3/29/22	CV PFS Members	Amanda Hamm, Mallory Artusio, Anne Reshadi, Blaine Leonard, Chuck Felice, Cory Johnson, Fred Heery, Gunnar Rhone, Joe Gorman, Jon Storey, Brian Smith, Govind Vadakpat, Nick Hegemier, Jianming Ma, John Hibbard, Lee Smith, John Roberts, Kathy Asmussen, Kody McKarthy, Ray Starr, Alan Davis, Ahmad Jawad, Hyungjun Park
CV PFS Monthly Call	4/19/22	CV PFS Members	Brian Simi, Ray Starr, Lee Smith, Jon Storey, Jianming Ma, Blaine Leonard, Amanda Hamm, Mallory Artusio, Brian Smith,
Stakeholder Outreach Questionnaire	5/16/22-6/6/22	CV PFS Members, Stakeholders	Laszlo Kaufmann, Jay Parikh, Anthony Gasiorowski, Steve VanSickle, Arijit Bose, Jingtao Ma, Ralph Boaz, Michael Maile, Justin Anderson, Larry Head, Steve Griffith, Ed Leslie, Tom Lusco, Walton L Fehr, Kevin Balke, Patrick Chan, Ray Starr, Randal Roebuck, Nick Hegemier, Manny Insignares, Timothy Regan, Raj Ponnaluri, Michael Maile, Jim Misener *14 respondents did not provide a name.*
Stakeholder Outreach Webinar	Mid-June, *TBD*	CV PFS Members, Stakeholders	*TBD*

At a high level, it was generally agreed that IOOs need to know when a roadside device is potentially broadcasting errant data (does not meet CI requirements), so that corrective action can be taken. OEMs (and by extension drivers) need correct CV data so that in-vehicle V2I applications (specifically RLVW) can function consistently and reliably. Furthermore, accurate CV data broadcast from the roadside has the potential to improve reliability / redundancy of automated vehicle (AV) detection of signal state data.

Collectively, feedback from these stakeholder engagement meetings culminated in a list of specific user needs (as they relate to what they need from the proposed system) as summarized in Table 4 (IOO needs) and Table 5 (OEM needs). The needs are prioritized for implementation readiness in Table 6 in Section 4.4. Proposed system constraints which were previously included in this table have been documented in Section 5.2.

The first IOO user need is built around the structure of the message requirements defined in the CI Implementation Guidance (CTI 4501 Section 3.3.3). This need is subdivided further into message performance requirements, generic message requirements, signal timing data requirements, roadway geometry data requirements, and messaging requirements, again to align with sub-requirements of the message requirements. Since this initial focus of the message monitor will be on the correctness of data in SPaT and MAP messages, sub-needs are defined one level further for the signal timing data requirements and roadway geometry data requirements.

Table 4: IOO Traffic Operations User Needs

Need #	Title	Description	Rationale
Primary Functions			
UN-001	Message Requirements	The IOO User needs a solution that is capable of assessing messages being broadcast (CTI 4501 – Section 3.3.3).	To evaluate if messages being broadcast adhere to the CI Implementation Guidance message requirements
UN-001.1	Message Performance Requirements	The IOO User needs a solution that is capable of assessing message performance requirements (CTI 4501 – Section 3.3.3.1).	To evaluate if message uniformity, robustness, conciseness, advance notification, timeliness, and quality assurance are sufficient for meeting requirements.
UN-001.2	Generic Message Requirements	The IOO User needs a solution that is capable of assessing generic message requirements (CTI 4501 – Section 3.3.3.2).	To evaluate if time accuracy, message revision, and timestamps are sufficient for meeting requirements.
UN-001.3	Signal Timing Data Requirements	The IOO User needs a solution that is capable of assessing signal timing data requirements (CTI 4501 – Section 3.3.3.3).	To evaluate if the data in SPaT messages accurately reflects actual conditions.
UN-001.3.1	Intersection Identification	The IOO User needs a solution that is capable of assessing intersection identification requirements (CTI 4501 – Section 3.3.3.3.1).	To provide correct and unique identification of the intersection referenced by the SPaT message.
UN-001.3.2	Intersection Status	The IOO User needs a solution that is capable of assessing intersection status requirements (CTI 4501 – Section 3.3.3.3.2).	To provide correct data regarding the status of a connected intersection in the SPaT message.
UN-001.3.3	Current Movement State	The IOO User needs a solution that is capable of assessing current movement state requirements (CTI 4501 – Section 3.3.3.3.3).	To provide correct data regarding the movement state at the intersection in the SPaT message.
UN-001.3.4	Next Movement State	The IOO User needs a solution that is capable of assessing next movement state requirements (CTI 4501 – Section 3.3.3.3.4).	To provide correct data regarding the next movement state in the SPaT message.

Need #	Title	Description	Rationale
UN-001.3.5	Time Change Details	The IOO User needs a solution that is capable of assessing time change details requirements (CTI 4501 – Section 3.3.3.3.5).	To provide correct data regarding Time Change Details in the SPaT message.
UN-001.3.6	Next Allowed Movement	The IOO User needs a solution that is capable of assessing next allowed movement requirements (CTI 4501 – Section 3.3.3.3.6).	To provide correct data regarding when a movement at an intersection is next allowed to proceed (e.g., green, flashing yellow) in the SPaT message.
UN-001.3.7	Enabled Lanes	The IOO User needs a solution that is capable of assessing enabled lanes requirements (CTI 4501 – Section 3.3.3.3.7).	To provide correct data regarding which revocable lanes are currently active.
UN-001.3.8	SPaT Accuracy	The IOO User needs a solution that is capable of assessing SPaT accuracy requirements (CTI 4501 – Section 3.3.3.3.8).	So that the signal states in SPaT correctly reflect the physical signal indications at the intersection.
UN-001.4	Roadway Geometry Data Requirements	The IOO User needs a solution that is capable of assessing roadway geometry data requirements (CTI 4501 – Section 3.3.3.4).	To evaluate if the data in MAP messages accurately reflects actual conditions.
UN-001.4.1	Intersection Geometry	The IOO User needs a solution that is capable of assessing intersection geometry requirements (CTI 4501 – Section 3.3.3.4.1).	To provide correct data about the lanes in and around an intersection.
UN-001.4.2	Lane Attributes	The IOO User needs a solution that is capable of assessing lane attributes requirements (CTI 4501 – Section 3.3.3.4.2).	To provide correct data describing the allowed use of a lane.
UN-001.4.3	Lane Maneuvers	The IOO User needs a solution that is capable of assessing lane maneuvers requirements (CTI 4501 – Section 3.3.3.4.3).	To provide correct data describing each maneuver that is allowed for that lane at the stop line for ingress lanes and at the first node point for the downstream lane.
UN-001.4.4	Connections Between Lanes	The IOO User needs a solution that is capable of assessing connection between lanes requirements (CTI 4501 – Section 3.3.3.4.4).	To provide correct data describing connections between a lane entering or within an intersection, and the downstream lane.
UN-001.4.5	Speed Limit Data	The IOO User needs a solution that is capable of assessing speed limit data requirements (CTI 4501 – Section 3.3.3.4.5).	To provide correct data about the speed limit for a lane.
UN-001.4.6	Revocable Lanes	The IOO User needs a solution that is capable of assessing revocable lanes requirements (CTI 4501 – Section 3.3.3.4.6).	To provide correct data for lanes with usage that is different at different times.
UN-001.4.7	MAP Accuracy	The IOO User needs a solution that is capable of assessing MAP accuracy requirements (CTI 4501 – Section 3.3.3.4.7).	To provide data that accurately reflects the physical location and dimensions of all travel lanes traversing the intersection within defined tolerances.

Need #	Title	Description	Rationale
UN-001.4.8	SPaT-MAP Synchronization	The IOO User needs a solution that is capable of assessing SPaT MAP synchronization requirements (CTI 4501 – Section 3.3.3.4.8).	To determine if roadway geometry data being broadcast reflects the current operating state used to generate the signal timing.
UN-001.5	Positioning Data Requirements	The IOO User needs a solution that is capable of assessing positioning data requirements (CTI 4501 – Section 3.3.3.5).	To evaluate if positioning correction content and real-time kinematics requirements are being satisfied.
UN-001.6	Security Requirements	The IOO User needs a solution that is capable of assessing security requirements (CTI 4501 – Section 3.3.4).	To determine if messages are from a trusted source.
UN-002	Basic Validation	The IOO User needs a solution that is able to perform basic checks using only SPaT/MAP messages in the absence of BSM messages or data from other systems.	To determine if there are any fundamental issues with SPaT and MAP data.
UN-003	Validation using BSMs	The IOO User needs a solution that is able to check the accuracy of SPaT/MAP messages using BSMs.	To determine if actual driver behavior (used as a proxy for signal state and intersection geometry data) matches expected behavior based on SPaT and MAP data.
UN-004	Event Generation	The IOO User needs a solution that is able to generate events (adhering and non-adhering).	To understand whether broadcast messages are in line with or deviate from actual events of the signal.
UN-005	Logging	The IOO User needs a solution that logs event outputs from validation algorithms (both adhering and non-adhering behaviors), assessments, issuance of notifications, and the suspension of a message broadcast.	Logged data (over a period of time) are needed to perform assessments, and the results of assessments are needed over a period of time to understand how performance varies over time.
UN-006	Assessment of Events	The IOO User needs a solution that will support a probabilistic or statistical assessment of events that provides useful data for IOO Traffic Operations.	Assessment of event data used to generate data to be included in performance reports, and to determine if there is a potential issue with some aspect of SPaT or MAP data.
UN-007	Continuous Assessment	The IOO User needs a solution that is able to perform an assessment every time new event data are generated.	To have the most up-to-date assessment data (used to determine if the system should take action - see UN-008 and UN-009) as more event data is generated.
UN-008	Generate Notifications	The IOO User needs a solution that can generate notifications to the operator or designee.	To have knowledge of a potential issue in a SPaT or MAP message, so that it can be further examined.
UN-009	Suspend Message Broadcast	The IOO User needs a solution that can suspend SPaT/MAP broadcasts without the need for human intervention.	So that errant messages are not being provided to approaching vehicles.

Need #	Title	Description	Rationale
UN-010	Performance Reports	The IOO User needs a solution that makes performance reports available that indicates both historical and up-to-date performance of SPaT and MAP messages.	To have knowledge of the overall performance of various aspects of SPaT and MAP messages.
UN-011	Non-Interfering	The IOO User needs a solution that will not disrupt or interfere with normal (non-CV) intersection operations.	So that it does not negatively impact existing operations.
Operations			
UN-012	Automated Operations	The IOO User needs a solution that can perform validation algorithms and assessments without the need for human intervention.	To minimize human input required for the system to operate.
UN-013	Continuous Operations	The IOO User needs a solution that can perform assessments on a continuous basis.	So that the system is able to continuously validate the data that is in SPaT and MAP messages.
UN-014	Near Real-Time Operations	The IOO User needs a solution that can perform validation algorithms and assessments in a timely manner.	So that potential issues with SPaT and MAP messages can be detected as soon as practicable.
UN-015	Scalability	The IOO User needs a solution that is scalable, able to support any number of locations.	So that a single instance of the Message Monitor can be used to support evaluation of SPaT and MAP messages from multiple locations on the same network.
UN-016	Security	The IOO User needs a solution that utilizes standard security practice and prevents unauthorized access to the solution or other devices on the same network.	So that the Message Monitor cannot be used as a gateway for unauthorized users to access devices on the existing system.
UN-017	Third- Party Certification	The IOO user needs a solution that supports 3rd party certification.	So that other parties have the ability to perform message verification activities and monitor message performance.
Configuration			
UN-018	Algorithm Parameter Configuration	The IOO User needs a solution that allows certain algorithm parameters to be modified.	To modify the operation of validation algorithms to improve the quality of outputs and to allow for revisions when standards change.
UN-019	Notification Configuration	The IOO User needs a solution that allows the threshold for providing a notification to be configurable.	To accommodate different agencies that will have different needs, priorities, and tolerances for receiving notifications.
UN-020	Suspend Configuration	The IOO User needs a solution that allows the threshold for message suspension to be configurable.	To accommodate different agencies that will have different needs, priorities, and tolerances for suspending message broadcast.

Need #	Title	Description	Rationale
UN-021	Notification Type	The IOO User needs a solution that allows notification methods to be configurable.	So that the IOO can choose how a notification should be provided and who it should be provided to.
Software / Application			
UN-022	Non-proprietary	The IOO User needs a non-proprietary solution.	So that the system is openly available, can be freely accessed, and to allow different IOOs to collaborate.
UN-023	Algorithm Modification	The IOO User needs a solution with source code that allows algorithms be easily modified and/or added	To improve existing algorithm function or new algorithms to verify adherence to other requirements.
UN-024	Interface Modification	The IOO User needs a solution that can be modified to be compatible with a variety of external systems	So new interfaces can be added to receive/send data from/to other external systems. This allows data from other (new) sources to be used in algorithms and for the system to provide other types of outputs/commands to other systems to improve overall capability.

Table 5: OEM User Needs

Need #	Title	Description	Rationale
UN-101	Confidence	The OEM User needs a solution that will provide a high confidence in the accuracy of the system outputs	So that data in the messages is considered trustworthy
UN-102	Self-Monitoring	The OEM User needs a solution that will prevent errant messages from broadcasting	To minimize the likelihood that an OBU will receive a message with an issue that affects proper application operation
UN-103	Reliable	The OEM User needs a solution that is regularly available	So that SPaT and MAP messages can be trusted over time.
UN-104	Interoperability	The OEM User needs a solution that functions similarly regardless of deployment location	So that SPaT and MAP messages from different intersections in the same region can be equally trusted
UN-105	Third- Party Certification	The OEM user needs a solution that supports 3rd party certification.	So that other parties have the ability to perform message verification activities and monitor message performance.

4.3 USER NEEDS VALIDATION

- Stakeholder outreach was conducted through a targeted questionnaire that was open from 5/16/22 through 6/6/22. Responses were solicited from the project stakeholder list, which includes 90 representatives from IOO, OEM, consultant, standards, and university groups who have experience with CV data. A total of 38 responses were received. The questionnaire asked questions that are fundamental to understanding the nature of the issues at hand, defining the current and proposed systems, prioritize what the system will do, and understand the benefits and potential issues that the proposed system may encounter. A summary of questionnaire responses is provided in Appendix A. A summary of questionnaire results is provided in the bullets below:

- Respondents indicated that the Public Sector/IOO, Traffic Signal Controller Vendor, and the RSU Vendor were the most responsible for ensuring the SPaT and MAP are accurate and valid. This is not a surprise given that in most instances, the IOO hires a distributor and/or consultant to provide support for TSC and RSU equipment, and in some cases may (also) work directly with equipment vendors to provide this support. This falls in line with the thinking that it is ultimately the IOO that is responsible for SPaT/MAP accuracy, but this task could be contracted out to a TSC or RSU vendor.
- Confidence in SPaT and MAP accuracy appears to be somewhat mixed. On a scale of *very unconfident*, *unconfident*, *neutral*, *somewhat confident*, and *confident*, most respondents indicated they were s*omewhat confident* or *confident* in SPaT and MAP accuracy. However, this result appears to be somewhat weighted by the number of consultants, vendors, and IOOs that completed the questionnaire, as these roles were more likely to indicate confidence than other roles. This result could also have been impacted by respondents from these groups who may not have thoroughly tested their installations – that is they may not yet be aware of issues that exist. A lesser number of respondents indicated *very unconfident* or *unconfident*. These respondents were more likely to be an OEM or indicated *other* role (System architect, Testing & Verification, OEM Technology Partner) in the response. This cannot be disregarded as these roles represent who will be using SPaT and MAP data.
- When asked about what issues have been noticed, a respondent was most likely to have selected *other* and provided an extended response. The issues experienced are multiple and in some cases nuanced. Many of the open ended responses indicate issues with the MAP geometry (4), various issues (e.g. values do not logically progress or are incorrect) with the time-to-change details in SPaT (4) and phasing/matching SPaT data to MAP data (2). When taken in conjunction with other responses, the most common issue relates to the intersection geometry. Issues with signal groups mismatching or being incorrectly applied to connections also ranks highly. Given that several users had similar open ended responses regarding the signal change timing, this also warrants consideration when prioritizing user needs. Open ended responses indicates that time change details are most likely to be incorrect when using a complex timing plan – particularly those with overlaps.
    - Question 9 confirms this assessment. The top 2 issues identified include those with lane level accuracy (geometry) or the alignment of time data. The *other* text responses further confirm this.
- Over 70% of respondents were not sure how long an inaccuracy had been present in SPaT or MAP messages when found or indicated the issue had been present for many weeks or since deployment. This is an indication that the source of issues is not being immediately identified and the issue is likely present (unnoticed) for an extended period of time.
- Respondents were most likely to indicate that a SPaT and/or MAP message should stop being broadcast if an issue is determined. Email alerts to the controlling agency was the next-most

selected answer, followed by text alerts to the controlling agency. Email and text alerts to approved users were the least popular answers. *Other* responses indicated the need for an error event in the system and the system log or reporting to another central management system which handles notification.

- Integration with existing systems was cited as the primary benefit of an open source solution, IOOs were most likely to indicate that support is an important benefit of open source software. Many OEM respondents indicated they were not sure how important an open source solution was. This falls in line with the idea that the system should be the responsibility of other parties. Many *other* responses indicate that open source software is important for providing transparency into the processes used to determine message validity and to ensure ease of integration with other systems.
- When provided with a list of SPaT and MAP message aspects, most respondents indicated that each aspect was either *important*, or *very important* to be correct (on a scale of *very unimportant*, *unimportant*, *neutral*, *important*, and *very important*). This indicates that there is a desire for all components of the messages to be correct but looking at the number of respondents that selected *very important* provides a method of prioritizing which aspects respondents value the most. Respondents were most likely to indicate that it is *very important* for the actual signal state to be properly reflected in SPaT and MAP (93%), ensuring that the lane points direction are properly defined in the MAP message (85%), and that the correct protected/permissive control is provided (77%). The aspects of least concern are the lane width, stop bar location, and lane centerline accuracy. Open-ended responses on a related question reenforce the desire for accurate timestamp data and the association of SPaT data to MAP data.
- Some respondents indicated a low threshold of misalignments between SPaT and MAP messages before triggering an alert in the system. However, most respondents were uncertain, indicating that there is some nuance to this question. Most respondents were likely to indicate that the threshold is location-specific, and *other* responses indicated that this could be time-specific and dependent on which aspect of SPaT and/or MAP is being checked. These responses lead to a conclusion that it would be prudent to consider a probabilistic or statistical assessment of each aspect of the message when determining if the system should take action.
- A majority of respondents indicated that the controlling agency should respond to a SPaT or MAP issue in less than 1 hour or between 1 and 12 hours. *Other* responses indicated that the amount of time should vary based on the complexity of the issue at hand or depending on the type of action taken.
- System integration and operations were the two leading areas where respondents indicated the potential for issues. Fewer, but still significant portion of respondents nearly equally indicated policy changes, funding, training, and technology changes could cause potential issues. *Other* responses indicated issues related to the accuracy of outputs and having enough BSM data. This means that needs that can be addressed without complex interfaces and needs that focus on system useability should be prioritized.

4.4 PRIORITIES AMONG CHANGES

There are a limited number of use cases that can be addressed in the initial development of the Message Monitor system, so prioritization of the user needs, especially as they relate to the CI signal timing and intersection geometry data requirements, needs to be completed to determine which needs can be most readily met through the initial system. It will not be possible or practical to assess all CI requirements, as the CV system functionality to meet these requirements does not exist or has been implemented on very few (if any) CV deployment sites.

For example, there has been much discussion about basic RLVW and full RLVW - -which differentiates RLVW that functions based only on current state data versus both current and/or future state data. However, future signal state data is not capable of being provided by current TSCs. With these technology limitations in mind, it will be of interest to focus on CI requirements that can be assessed using data that is commonly available (or minimally expected) in SPaT and MAP messages, and that are considered the greatest impact on the proper function of OBU-based applications that rely on SPaT and MAP data.

Feedback received during CV PFS project meetings and stakeholder outreach questionnaire results (summarized and interpreted above) are used to prioritize and narrow down which of the CI requirements (and their respective user needs) will be addressed on the initial implementation of the Message Monitor.

Ready to implement now – Aspects of SPaT and MAP messages that have the greatest desire to be correct and are technically feasible given the capabilities of today's technology. These are the needs that the initial implementation of the Message Monitor will intend to address.

Desirable - Aspects of SPaT and MAP messages that are desired to be correct but require complex interfaces or extensive development of the proposed system. These needs could be addressed in subsequent development efforts after the conclusion of this project.

Future Implementation – Desired but not technically possible (e.g., external equipment limitations are known to be the cause of issues), not high priority, or not immediately desired. These needs should only be addressed once capabilities of the existing system have improved to the point where the existing system is capable of providing certain data elements or once higher-priority needs have been met.

Note that only the needs of IOOs are considered in this prioritization as they will more directly have an impact on the system development moving forward.

Table 6: User Needs Prioritization

Need #	Title	Priority	Rationale
		Primary Functions	
UN-001	Message Requirements	*see sub-needs*	-
UN-001.1	Message Performance Requirements	Ready	PFS Panel has indicated that high-level checks regarding broadcast rate and verification of CI Implementation Guide minimum message requirements are needed.
		Future	The focus of the initial implementation of the message monitor will be on the correctness of data in SPaT and MAP messages
UN-001.2	Generic Message Requirements	Future	The focus of the initial implementation of the message monitor will be on the correctness of data in SPaT and MAP messages
UN-001.3	Signal Timing Data Requirements	*see sub-needs*	
UN-001.3.1	Intersection Identification	Ready	The need for the SPaT message to include signal timing data, the road regulator identifier and the intersection reference identifier are core components of matching SPaT to MAP data and ensuring that ground conditions accurately match the data in messages.
UN-001.3.2	Intersection Status	Future	The intersection status data element was not mentioned as being a high-priority item. Furthermore, properly specifying certain bits in this bitstring is generally considered beyond current capabilities of the existing system.
UN001.3.3	Current Movement State	Ready	It is imperative that the movement state is provided for each signal group. Furthermore, stakeholders expressed a desire that movement state conflicts e.g. (protected vs. permissive) are resolved within the SPaT message, which should be possible to access using CV data made available from today's existing system. This includes conflicts for both vehicle and crosswalk lanes.
UN-001.3.4	Next Movement State	Future	Value for the next movement state is not ready to be assessed given the limitations of today's TSC SPaT generation capabilities.
UN-001.3.5	Time Change Details	Ready	Questionnaire respondents indicated a desire for accurate timestamp details (minEndTime, maxEndTime) for current movement states. In the absence of preemption or another interruption, the minEndTime should not decrease, and the

Need #	Title	Priority	Rationale
			maxEndTime should not increase during the green and red interval values. Yellow interval durations are generally fixed (minEndTime and maxEndTime and equal and do not vary). It is possible to assess the correctness of these timestamps using sequences of SPaT data.
		Future	Time change details for the next movement state (CTI 4501 3.3.3.3.5.7, 3.3.3.3.5.8) are not ready to be assessed given the limitations of today's TSC SPaT generation capabilities.
UN-001.3.6	Next Allowed Movement	Future	The start time for the next time the movement will be active are not ready to be assessed given the limitations of today's TSC SPaT production capabilities
UN-001.3.7	Enabled Lanes	Desirable	The need to account for special conditions at intersections that require the use of enabled lanes was not explicitly indicated by stakeholders but should be considered due to the potential ease of implementation.
UN-001.3.8	SPaT Accuracy	Ready	It is highly desirable for SPaT messages to accurately reflect the physical signal indications. This is possible to assess using SPaT, MAP and BSM data.
UN-001.4	Roadway Geometry Data Requirements	*see sub-needs*	-
UN-001.4.1	Intersection Geometry	Ready	The need for the MAP message to include intersection geometry data, the road regulator identifier and the intersection reference identifier are core components of matching SPaT to MAP data.
		Desirable	Stakeholders provided some indication that the accuracy of points that define each lane has some level of importance but is not as important as other aspects of SPaT and MAP message. Furthermore, BSM data (i.e., driver trajectories) even when aggregated may not necessarily represent the actual lane centerline – especially around curves and locations where lanes taper.
UN-001.4.2	Lane Attributes	Ready	Stakeholders indicated the direction of travel as being one of the more important aspects of lane attributes that should be correct.
		Desirable	Stakeholders indicated that other MAP lane attributes are important, but only moderately so. Lane attributes (lane sharing, lane type) cannot necessarily be easily assessed using data available in BSMs.
UN001.4.3	Lane Maneuvers	Desirable	Stakeholders indicated that MAP lane maneuvers are important, but only moderately so. Some of the processing to determine the correctness of this data (e.g., lane control, and restrictions) may not be available (e.g., for crosswalks) or are not necessarily straightforward to determine.
UN-001.4.4	Connections Between Lanes	Ready	The inclusion of connections, the specification of an egress lane and signal group is a core components of matching SPaT to MAP data and ensuring data in messages accurate represents ground signal state conditions.
UN-001.4.5	Speed Limit Data	Future	Accurate speed limit data was not found to be a high-priority need, and may be difficult to properly assess with MAP and BSM data (driver behavior not necessarily reflective of speed limit)
UN-001.4.6	Revocable Lanes	Desirable	The need to account for special conditions at intersections that require the use of revocable lanes was not explicitly indicated by stakeholders but should be considered due to the potential ease of implementation.

Need #	Title	Priority	Rationale
UN-001.4.7	MAP Accuracy	Desirable	The need to ensure MAP messages that accurately reflect the physical location and dimensions of all travel lanes is expected to be simply confirmed by inspection (note, this is not the same as the lane centerline node accuracy).
UN-001.4.8	SPaT-MAP Synchronization	Ready	The need for the MAP message to include the road regulator identifier and the intersection reference identifier are core components of matching SPaT to MAP data and ensuring that ground conditions accurately match the data in messages.
UN-001.5	Positioning Data Requirements	Future	The focus of the initial implementation of the message monitor will be on the correctness of data in SPaT and MAP messages
UN-001.6	Security Requirements	Ready	There is a need to determine if SPaT, MAP, and BSM have been signed to indicate it is from a trusted source, and is considered technically feasible
		Desirable	All other security requirements are capable of being verified, but implementation may require extensive development.
UN-002	Basic Validation	Ready	Processing only SPaT and/or MAP messages may be required to perform certain message accuracy assessments and is considered to be technically feasible.
UN-003	Validation using BSMs	Ready	Processing BSM messages (in conjunction with SPaT and MAP messages) is one of the core components of this project. It is required to perform message accuracy assessments and is considered to be technically feasible.
UN-004	Event Generation	Ready	Algorithms are used to process data from external to generate event data. The generation of event data is considered to be technically feasible.
UN-005	Logging	Ready	The output of a single assessment is stored on the system. The logging of individual event data is necessary for longer term assessments. The logging of data is considered to be technically feasible.
UN-006	Assessment of Events	Ready	Secondary assessment (probabilistic or statistical analysis / aggregation) of logged individual assessment data is considered to be technically feasible.
UN-007	Continuous Assessment	Ready	The continuous assessment of CV data (as CV data becomes available to the system) is considered to be technically feasible.
UN-008	Generate Notifications	Ready	An email notification would be a desirable solution but making notification data available through the system would be an acceptable solution that is less technically complicated.
UN-009	Suspend Message Broadcast	Desirable	Suspending message broadcast is anticipated to require an additional interface with other components in the existing system, requiring significant development effort. In order to prove the concept for this project, the 'suspension' of message broadcast may be recommended in a notification (see UN-008).
UN-010	Performance Reports	Ready	The project panel has indicated that performance reports for each aspect of SPaT and/or MAP messages that are assessed for each intersection should be made available through the system. This is considered to be technically feasible.
UN-011	Non-Interfering	Ready	The ability for the system to not interfere with operations of components of the existing system is considered to be technically feasible.
Operations			

Need #	Title	Priority	Rationale
UN-012	Automated Operations	Ready	The ability for the system to process data without human intervention is one of the core components of this project and is considered technically feasible
UN-013	Continuous Operations	Ready	The ability for the system to continuously assess event data is one of the core components of this project and is considered technically feasible
UN-014	Near Real-Time Operations	Ready	Near-real time operations are expected to provide results in a manner that is timely enough for providing notification and is considered technically feasible.
UN-015	Scalability	Ready	The project panel has indicated that the solution should support local and remote deployment. A remote deployment is easily scalable as long as intersections are network-connected. Local deployments are scalable so long as the deploying agency is willing to deploy the solution at each location.
UN-016	Security	Ready	Security is a foundational need for any system that uses network communications to interface with another system.
UN-017	Third-Party Certification	Future	The project panel has indicated intent for the Message Monitor to be used for third-party certification of messages. This will be considered for future development, as it may be complex to implement and is not integral for providing proof of concept.
		Configuration	
UN-018	Algorithm Parameter Configuration	Ready	The project panel has indicated that the solution needs to be configurable so that algorithm parameters can be adjusted for local conditions and/or local preferences. This is considered to be technically feasible.
UN-019	Notification Configuration	Ready	The project panel has indicated that the solution needs to be configurable so that parameters (thresholds that the results of a probabilistic or statistical analysis are compared against) for issuing a notification can be adjusted to reflect local conditions and/or local preferences. This is considered to be technically feasible.
UN-020	Suspend Configuration	Ready	The project panel has indicated that the solution needs to be configurable so that parameters (thresholds that the results of a probabilistic or statistical analysis are compared against) for suspending a message can be adjusted to reflect local conditions and/or local preferences. This is considered to be technically feasible.
UN-021	Notification Type	Desirable	As far as notifications go, questionnaire respondents were most likely to indicate that the system could provide a notification (email/text) to the system manager. However, the addition of such a feature is considered desirable as it involves an external interface that requires additional development that does not significantly prove the main concept of this project. Rather, making notification data available through the system is considered to be sufficient.
		Software / Application	
UN-022	Non-proprietary	Ready	Stakeholders have indicated that the ability for the system to integrate with various types of existing systems is important and that it is openly accessible. It is expected that software can be developed to accommodate this need.
UN-023	Algorithm Modification	Ready	Questionnaire respondents indicated that the ability to understand the processes involved is important. Furthermore, not all algorithms will be developed at once, so the system needs to

Need #	Title	Priority	Rationale
			be capable of adding new algorithms. Existing algorithms may need to be modified to be improved. It is expected that software can be developed to accommodate this need.
UN-024	Interface Modification	Ready	Several stakeholders have indicated that other data sources could be used to verify if requirements are being met. The initial system will focus on CV data, but system interfaces should be modifiable to accommodate new data sources. It is expected that software can be developed to accommodate this need.

4.5 CHANGES CONSIDERED BUT NOT INCLUDED

During the development of this ConOps and in continued discussions with project panel members, many potential needs were discussed, but not included, as they were considered to be outside of the scope or distract from demonstrating the primary concept of the project. A system that is designed in an open-source fashion could potentially integrate these changes during subsequent system development activities.

- Use of High-Resolution Traffic Signal Controller Data as an input to the validation algorithms
- Use of CV Data to generate performance measures for traffic management
- Assessment of roadside message types other than SPaT and MAP.

5. Concept for New System

5.1 BACKGROUND, OBJECTIVES, AND SCOPE

The CV PFS has initiated activities that aim to create a formal mechanism for initial and long-term **validation** of CV data produced at intersections that would ultimately be considered acceptable for use by CV-equipped OEM vehicles. The Message Monitor is the first of what is likely several prototypes necessary to achieve that end. It will be important to keep this in mind as the system is developed.

The user needs indicate a desire to assess the correctness of various aspects of SPaT and MAP messages. However, actual state of the signal indications data and the actual intersection geometry data are not readily available on a continuous basis but may be further investigated in future projects. This project focuses on the analysis of driver behavior and vehicle trajectories (derived from BSMs from CVs), as a proxy for these data.

The ability to continuously monitor SPaT, MAP, and BSM messages to determine if the data broadcast by IOOs is consistent with actual vehicular movement is predicated on the fact that certain driver behavior is highly predictable when responding to traffic control devices. Lane changes aside, a driver will use roadway markings to guide the vehicle through the roadway network and accompanying signage to understand which movements are permitted from each lane at intersections. Similarly, drivers respond to traffic signal indications maintaining speed, stopping, and accelerating as necessary; and understanding right-of-way. The traffic control devices that drivers respond to are intended to be reflected in SPaT and MAP messages:

- MAP messages essentially capture roadway markings and data about which movements are permitted from each lane at an intersection, and
- SPaT messages provide the state of traffic control devices and an indication of right-of-way for each movement.

Vehicular movement data is captured in BSMs – which can be compared to SPaT and MAP data to determine when there is a conflict between vehicular movement and expected behavior under a given situation (as indicated by SPaT and MAP). If a conflict is noted, then there is a possibility that some part of the SPaT or MAP data may be incorrect, or drivers are responding to some other roadway event. The project goal is to effectively pinpoint when these deviations are occurring so that they can be brought to the attention of the system owner in a time-sensitive manner so that corrective actions may be taken. This may also include automatically suspending the broadcast of SPaT and/or MAP at the intersection.

5.2 OPERATIONAL POLICIES AND CONSTRAINTS

The same Operational Polices and Constraints applicable to the existing system will also be applicable to the proposed system. Further, the proposed system is expected to account for requirements specified in the CI Implementation Guidance requirements and is expected to be open source.

Open Source Development and Architecture Based on feedback from the project panel as part of stakeholder engagement, there is a desire for the proposed system to use open-source software practices consistent with those currently in use by FHWA, such as the ITS Code Hub. This allows for wide distribution in a similar fashion to the Open Source Connected Vehicle Tools on the USDOT website, transparency into the algorithms used, and for modifications to be made to the proposed system after the conclusion of this project to address other needs that stakeholders may have. This includes the ability to interface with other existing system components that are not specifically designed for in this project.

Furthermore, the Message Monitor needs to support a range of deployment experience / capabilities. Different deployment agencies have different specific needs that the Message Monitor will need to support, so it is important to consider how the system can be flexible enough to accommodate this range of needs.

To this end, it needs to be compatible with today's typical intersection deployment (i.e., signal controller, network switch/router, MMU).

The Message Monitor needs to be implemented using equipment that is vendor agnostic. That is, it is not tied to a specific hardware or software solution. Furthermore, it shall be capable of being deployed using different architectures, to include both local and remote (i.e., edge vs. cloud) solutions.

V2X Message Set Dictionary - The proposed system will only accept data from a roadside device that is capturing messages that adhere to the SAE J2735 V2X Message Set Dictionary Standard. Section 3.2 indicates how the V2X Message Set Dictionary is used in the context of the current system.

Roadside Unit (RSU) Standard (CTI 4001 v01) – The proposed system will leverage the RSUs 'Store and Repeat' and 'Immediate Forward' message functionality as required by the CTI 4001 v01 standard. When properly configured, the immediate forward functionality will allow the RSU to send SPaT and MAP to the Message Monitor as they are broadcast and to send BSMs to the Message Monitor as they are received. The RSU (current system) must be CTI 4001 v01-compliant so that it can communicate with the proposed system.

CI Implementation Guide (CTI4501 v0100) – The proposed system is limited to assessing SPaT and MAP conformance to requirements and design details in the CI Guidance. Section 3.2 indicates how CI Guidance is used in the context of the current system.

Typical Intersection – Algorithms (that output event data) will be initially developed with the most common types of intersections in mind. Characteristics of this common intersection are as follows:

- All necessary intersection geometry data (ingress lanes, egress lanes, connections, etc.) can be communicated in a single MAP message. That is, more than one MAP message is not required to understand where all lanes and connections at an intersection are located.
- Intersection geometry coordinates encoded in the MAP message use the offset or explicit method of specifying subsequent lane points, not the computed lanes method.
- A vehicle does not have to traverse more than one connection to traverse the entire intersection.

- All ingress and egress approaches in a MAP message meet at a single intersection
  - e.g., no complex intersections/signalized traffic circles that have more than one merge and diverge conflict point (each) to make a given movement through the intersection, or
  - e.g., no intersections with offset approaches with storage lanes between the offset approaches.
- All necessary signal state data can be communicated using a single SPaT message.

These characteristics allow for nearly all multi-leg intersections to be accommodated by algorithms that will be developed for the initial deployment.

The MAP message is flexible enough to accommodate some very complex intersection types (e.g., single intersection with offset signals, roundabouts). However, developing an algorithm to accommodate all intersection types is prohibitively difficult. While the initial system may be capable of executing algorithms using SPaT and MAP from complex intersections, the results may not be accurate, since the algorithm may not be designed to account for the specific complex features found at that particular intersection. However, the open source nature of the message monitor allows for further development to accommodate analysis of these more complex intersection types as the need arises outside of this project.

Data Element Time Association. The primary functionalities of this system rely on the relationship between SPaT, MAP, and BSM data. This relationship may be, in part, temporal in nature. For any type of temporal associating of data, the message monitor will only use time data contained in messages, and not any timestamps associated with the capturing of the message (as recorded by the unit that captured the message). This is due to the fact that the timestamp in the message should be directly associated with all other data in the message (such as a vehicle position in a BSM, or a signal state in a SPaT message). Latency in communication and capturing of a message will be built into a message capture timestamp, and its use is highly discouraged. See Section 7.3 (time synchronization) for more detail.

Data Management and Privacy – The proposed system will be utilizing BSM data from the CV Environment which will be subject to the same data privacy and retention policies that an IOO may have in place. This includes any specific terms of use or consent regarding data captured from OBUs that have been deployed by the IOO. Specific policies may require edge computing to process BSM data into some other intermediate output so that it is compliant. The final design of the proposed system should account for these policies in the handling of such data. Section 3.2 indicates considerations for data management and privacy in the context of the current system.

Position Corrections – OBUs use GNSS along with other sensors to populate the vehicle position data elements in the BSM. Various atmospheric conditions and the presence of physical objects near the receiver can cause the GNSS signals to reflect, resulting in positioning errors. A CV environment attempts to address these errors by broadcasting Radio Technical Commission for Maritime Services (RTCM) Corrections messages from roadside devices. OBUs are expected to apply the corrections data contained in RTCM messages to determine the final reported vehicle position in the BSM. However, it is known that this feature on OBUs is still under development, and not many OBUs currently utilize RTCM messages. It is also possible that RTCM messages may not be available for the OBU to correct its BSM position data. Since the system will use location data from BSMs, it is important to recognize that a position-corrected BSM has the potential to output a different result than a non-position-corrected BSM. Regardless if position correction data is available or if OBUs are leveraging position correction data, there is no data indicating if a position in a BSM has been corrected or not, which means that the system cannot differentiate between corrected and uncorrected position data. The impact of applying message monitor algorithms on corrected vs uncorrected data is not expected to be substantial, as similar algorithms have been applied to develop performance measures in other projects, such as the Smart Columbus Connected Vehicle Environment, where position corrections data was not available to deployed OBUs.The general potential for inaccurate position data to affect the operation of the proposed system is discussed in further detail in Section 8.2.

5.3 DESCRIPTION OF PROPOSED SYSTEM

The proposed system interfaces with the existing system to enable the functionalities necessary for message monitoring. It should integrate with components of the existing system in such a way that CV messages can be processed in near-real time – as (batches of) messages are received – to extract and process data to execute algorithms that are required to meet user needs for message monitoring. A diagram depicting the context of the existing system (for the purposes of this document) is provided in Figure 2 and described below. Note that there are likely many other components that the existing system may interface with. However, these are not shown in detail on the diagram, as operation of the proposed system is not directly dependent on them.

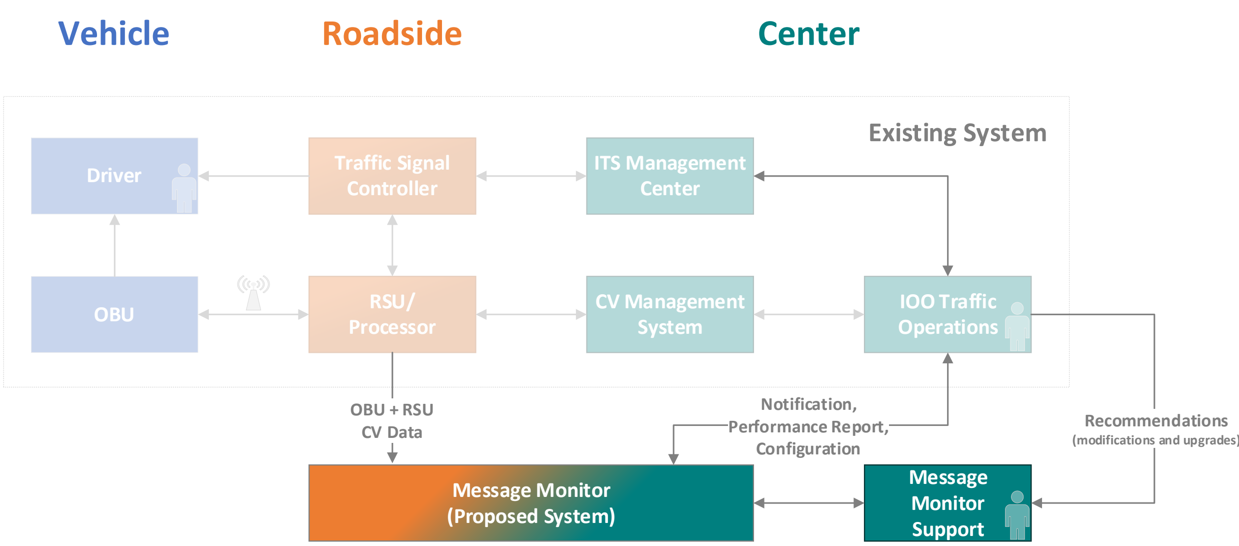


Figure 2: Proposed System Context Diagram

Details regarding the context diagram including interfaces, hardware, messages, security, and functionality are described in the following sections. The reader should reference this figure throughout the following subsections to foster a better understanding of the system concept.

5.3.1 Primary Components

Message Monitor - The Message Monitor is where the primary processing of SPaT, MAP, and BSMs occurs. A direct communications path is established between the RSU/Processor and the Message Monitor so that the system can ingest SPaT, MAP, and BSMs. It processes these messages and generates event-type of data which are stored by the system. It uses this event data in longer-term statistical analyses that indicate whether or not SPaT and MAP message data is correct. This event data and the results of these analyses are made available to IOO Traffic Operations. The Message Monitor could either be located *on-the-edge* (roadside) or at a *center* (remote) – This is why the Message Monitor object is colored in orange and green in Figure 2. The Message Monitor residing on-the-edge could be a computing device co-located with the RSU/Processor. Roadside network connectivity allows the Message Monitor to alternatively be hosted in a center (remote location such as a TMC, or in the cloud). Configuration of the existing system may need to be modified to allow the existing system to send data to the Message Monitor. The Message Monitor provides an interface through which it can be configured by Message Monitor Support.

5.3.2 Interfaces

The proposed system is expected to interact with the existing system over three interfaces, described below:

- RSU/Processor → Message Monitor. This interface is the primary means by which the proposed system receives CV data from the existing system. In a directly integrated system, this is accomplished through a direct communication pathway from the RSU/Processor to the Message Monitor. Infrastructure-based messages, such as SPaT and MAP, are immediately forwarded to the Message Monitor upon broadcast, and vehicle-based messages are immediately forwarded to the Message Monitor upon being received. The Message Monitor may use this interface to provide a command to the RSU/Processor to cease broadcasting a message (based on the results of an assessment). Note that this may alternatively be accomplished by issuing a recommendation to cease broadcast to IOO Traffic Operations.
- Message Monitor → IOO Traffic Operations. This interface is the primary means by which the proposed system provides notifications and performance reports to IOO Traffic Operations. The exact outputs that will be provided depends on the applications (algorithms) being executed by the message monitor and the assessments performed. Applications currently under consideration are described in detail in Section 5.3.6, and the design of outputs over this interface will not be specified until later in the project, as the system is designed and built. As an alternative to ceasing message broadcast, the proposed system may provide a recommendation to cease message broadcast to the IOO Traffic Operations. Settings can be configured through this interface to allow IOO Traffic Operations to modify certain thresholds for event generation, providing notifications, and ceasing message broadcast.
- IOO Traffic Operations → Message Monitor (via Message Monitor Support Staff). This interface completes a feedback loop that will be critical for ensuring that user needs are adequately met for this project. As the system is implemented, feedback from IOO Traffic Operations will be used by the Message Monitor Support Staff to make minor modifications to the algorithms on the Message

Monitor in order to provide outputs that are at the desired level of detail for the IOO Traffic Operations. For the duration of this project, the role of the Message Monitor Support Staff can be performed by the system developer, but in the long-term, this role will likely become the responsibility of the IOO Traffic Operations. It is important to note that the system will be developed in an open-source fashion so that IOO staff can use project documentation as a resource for making modifications to the system as needed.

5.3.3 V2X Messages

V2X Messages are used in the wireless communication of data between vehicles and infrastructure. The V2X Message Set Dictionary (SAE J2735) enumerates message types used in CV environments, along with the data frames and data elements of which they are comprised. Of importance to this project are SPaT, MAP, and BSM for which descriptions are provided below.

- **Signal Phase and Timing (SPaT).** The SPAT message is used to communicate data regarding the signal state of a given intersection. It contains the signal indication for every phase of the intersection, phase timing data, crosswalk status, and a signal group, which allows the data to be paired to the physical layout of the intersection described in the MAP message, described below.
- **MapData (MAP).** The MAP message contains the intersection geometry, the layout of all approaches/receiving lanes, crosswalks, vehicle pathways through an intersection (connections), and provides recommended movement speeds. Signal groups are defined for each connection and are used to pair SPaT data with the appropriate connection (which can then be associated with an ingress approach lane).
- **Basic Safety Message (BSM).** The BSM conveys safety data about a given vehicle. Broadcast from a vehicle, the BSM data is organized into two parts. Part I data is comprised of required data elements including but not limited to vehicle size, position (latitude/longitude), speed, heading, acceleration, and brake system status. This data is used to support safety-critical applications that rely on frequent transmission of data. BSM Part II data is comprised of optional data elements that generally provide weather data (e.g., roadway surface condition, temperature, air pressure) and vehicle data (e.g., vehicle classification, wiper status, traction control status, exterior lights status).

5.3.4 Security

The automated and continuously-available nature of the Message Monitor will require the use of networked devices on both the existing and proposed system. Networked devices are vulnerable to malicious attacks if not properly protected. Section 3.4.4 and Section 4.3.4 of the CI Implementation Guidance (CTI 4501 v01) provides security requirements and security details, respectively, for connected intersections. Given that the Message Monitor intends to interface with a connected intersection, it is important to understand the security requirements and details provided in these sections in order to be compliant with the guidance. The types of network and communications security requirements provided in this guidance utilizes standard industry practice as a foundation for securing access between connected intersections devices and other devices that they may interface with – such as the message monitor.

It will be important to coordinate with the agency (or department) responsible for managing the network on which the Message Monitor will be installed to ensure system operations are not hampered by the network security mechanisms in place and ensure that the Message Monitor does not provide a gateway through which other devices on the network can be accessed by unauthorized users.

5.3.5 Proposed Algorithms

Initial list of needs related to system function were provided in Section 4.2 and prioritized in Section 4.3. Only needs that are considered ready to implement (based on the rationale provided in Section 4.3) are considered for algorithm development. Five example algorithms are provided to address these ready-to-implement user needs. Note that the algorithms presented are not final, and are only intended to provide the reader with an understanding of the basic processes involved for each algorithm

- Determine Signal State when a Vehicle Crosses a Stop Line
    - SPaT indicates a movement is Green (protected-Movement-Allowed) -> BSM shows vehicles at constant speed on indicated Movement
- Determine Signal State when a Vehicle Stops at the Stop Line
    - SPaT indicates a movement is Red (stop-And-Remain) -> BSM shows vehicles on ingress lane with 0 or minimal velocity
- Vehicle Travel Direction
    - Alignment between Lane direction (ingressPath, egressPath) in the MAP message vs. actual direction of vehicle movement
- Alignment between Connections and Vehicle Movements
    - Alignment between connections and actual vehicle travel paths through the intersection.
- Signal State Conflict Monitor
    - Deduces or uses user-provided information about conflicting signal states to check for SPaT message event state and MAP message connection incongruencies:
    - Checks to make sure any connection with a 'protected-movement-allowed' event state (matched using signal group) does not cross over another connection with any other state other than 'stop-and-remain' event state.
    - Checks to make sure there are no conflicting connections with a 'permissive-movement-allowed' event state (matched using signal group) at the same time.
- Time Change Details
    - minEndTime and maxEndTime values behave in a predictable fashion – minEndTime does not decrease and maxEndTime does not increase.

- The event state changes as indicated by the minEndTime and maxEndTime. minEndTime should be equal to the maxEndTime when the event state changes, and this should be close to the actual time the event state changes

Determine Signal State when a Vehicle Crosses a Stop Line

The MAP message provides the intersection geometry data that is used to determine which intersection approach a vehicle is on. Specifically, the first point in each ingress approach lane geometry is used to determine the location of the stop line for each approach. The MAP messages use position offsets to calculate the location of lane centerline coordinates. To find the first point of each ingress lane (i.e., the location of the center of the stop line), the intersection reference latitude/longitude point is adjusted by the first offset value provided for the lane.

A fixed-distance buffer is applied to the location of stop line point at the end of each lane. This buffer is used as an initial means of filtering BSM data by location and has a configurable radius (initially set at 15 feet). The heading of the vehicle (extracted from the BSM) is also compared to the heading of the lane (i.e. the arctangent of the next x-y lane point offset) associated with the buffer to filter out vehicles that are moving in the incorrect direction relative to the direction of travel for traffic approaching the stop line – this intends to remove information associated with vehicles that are making a different movement through the intersection such as an opposing through movement or an intersecting left turn movement that may cut across or near the approach of interest. A configurable tolerance (initially set at ±20 degrees) from the calculated lane heading is allowed. Vehicle headings that fall outside of this tolerance are filtered out. This is flexible enough to capture vehicles moving across the stop line in the correct direction, but may have started a turning movement, while filtering out traffic that are not moving across the stop line in the correct direction.

At this point, there may be multiple BSMs (from the same vehicle having the same vehicle identifier) that fall within one or more stop line buffers (since they overlap). In this case, BSMs are processed sequentially to determine if one BSM falls closer to any stop line centerpoint than a previously identified BSM. If this is the case, data associated with the BSM (timestamp), the MAP message (lane ID), and the distance between the BSM and the stop line centerpoint are temporarily recorded. This is repeated for all BSMs with the same vehicle ID – once exhausted, The last values recorded contain the ingress lane ID of the stop line that the vehicle passes closest to, and the time when the vehicle is closest. The MAP message is used to determine the connections and signalGroup data associated with the identified lane. If the lane the vehicle is in has more than one connection, and those connections have multiple signal groups, then the egress lane is determined (see *Ingress and Egress Lane Direction of Travel* algorithm) and the connection is determined.

Finally, the SPaT message closest to the BSM timestamp is identified. The signal state of the identified signalGroup indicates the signal state (according to the SPaT message) when the vehicle crosses the stop line. Figure 3 on the following page provides a graphical reference for the logic described above.

It is important to note that typical driver behavior may include, but is not limited to rolling over the stop line as the vehicle comes to a complete stop or stopping before the stop line before crossing the stop line to make a right turn on red. The algorithm will attempt to capture data in the event log that will allow these conditions to be potentially accounted for during the assessment of event data. Some errors are expected, however, more than enough events are expected to properly detect to provide an adequate assessment result for this type of situation.

The Message Monitor creates an event log with the following data at a minimum: Event Type (Vehicle Crossing Stop Line), time (from BSM timestamp), vehicle location (from BSM), intersection id (from MAP), lane id (from MAP), stop line location (from MAP), connection number (from MAP), signalGroup (from SPaT/MAP), and event state from (SPaT). A special designation may be provided for vehicles that come to a complete stop within a certain distance of the stop line before crossing the stop line when turning right on red.

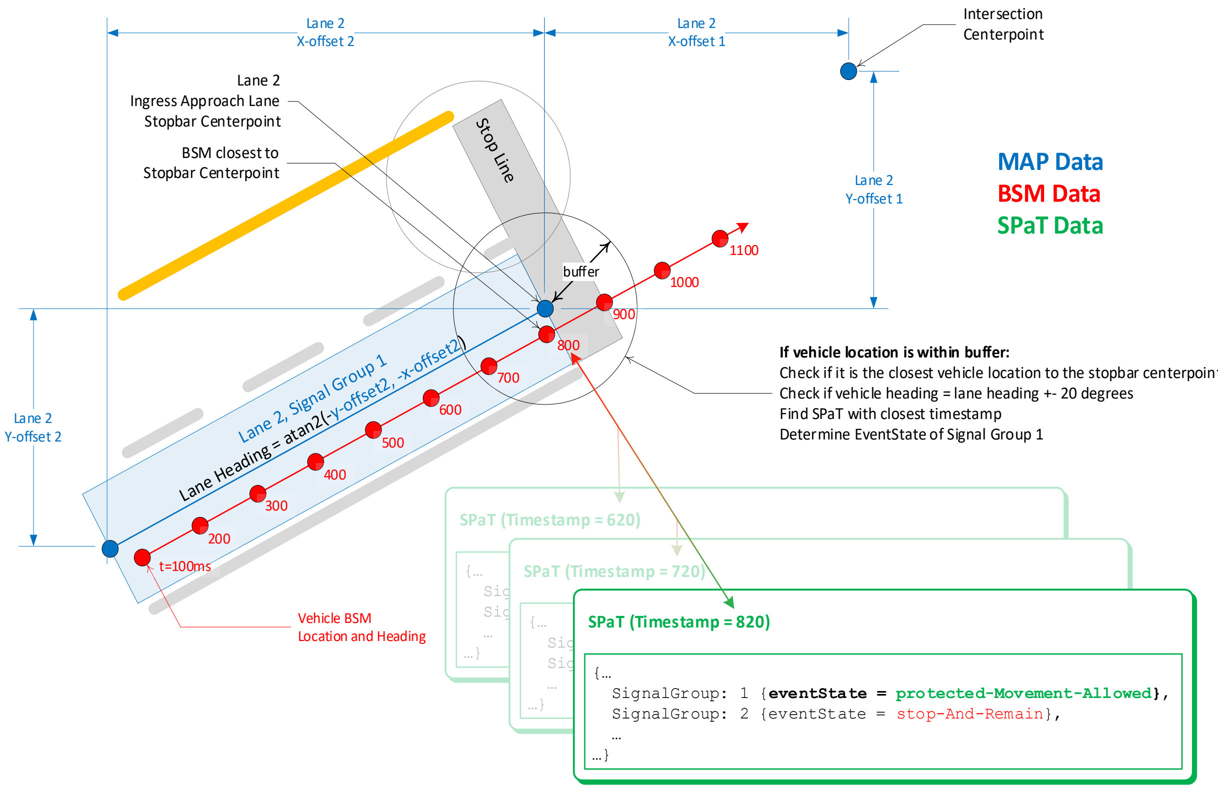


Figure 3: Visual Representation of Logic for determining Signal State when a Vehicle Crosses a Stop Line

Determine Signal State when a Vehicle Stops at a Stop Line

This algorithm follows a similar logic as the *Determine Signal State when a Vehicle Crosses a Stop Line* algorithm, described in the subsection above. The primary difference is this algorithm is looking for instances where the vehicle comes to a complete stop within the fixed-distance buffer at the location of the stop line point at the end of each lane.

Using a similar process as defined previously for associating MAP, SPaT, and BSMs, when a vehicle is at a compete stop within a buffer (if the vehicle stops within multiple buffers, the closer of the stop line centerpoints is chosen), the SPaT message closest to the BSM timestamp is identified. The signal state of the identified signalGroup indicates the signal state (according to the SPaT message) when the vehicle crosses the stop line. Figure 4 provides a graphical reference for the logic for this algorithm.

It is important to note that typical driver behavior may include, but is not limited to stopping to yield to oncoming traffic or a pedestrian when making a permissive left turn or right turn. The algorithm will attempt to capture data in the event log that will allow these conditions to be potentially accounted for during the assessment of event data. Some errors are expected, however, more than enough events are expected to properly detect to provide an adequate assessment result for these types of situations.

For each vehicle that comes to a stop within a buffer, the Message Monitor creates an event log with the following data at a minimum: Event Type (Vehicle Stopping at Stop Line), vehicle location (from BSM), intersection id (from MAP), lane id (from MAP), stop line location (from MAP), connection number (from MAP), signalGroup (from SPaT/MAP), event state from (SPaT) when vehicle initially comes to a stop, time (from BSM timestamp) when vehicle initially comes to a stop, event state from (SPaT) when vehicle begins moving again after stopping, time (from BSM timestamp) when vehicle begins moving again after stopping, time stopped during red, time stopped during green, and time stopped during yellow. A special designation may be provided for vehicles that come to a complete stop but do not remain stopped for a certain period during a green indication (stopping to yield to oncoming vehicle or pedestrian).

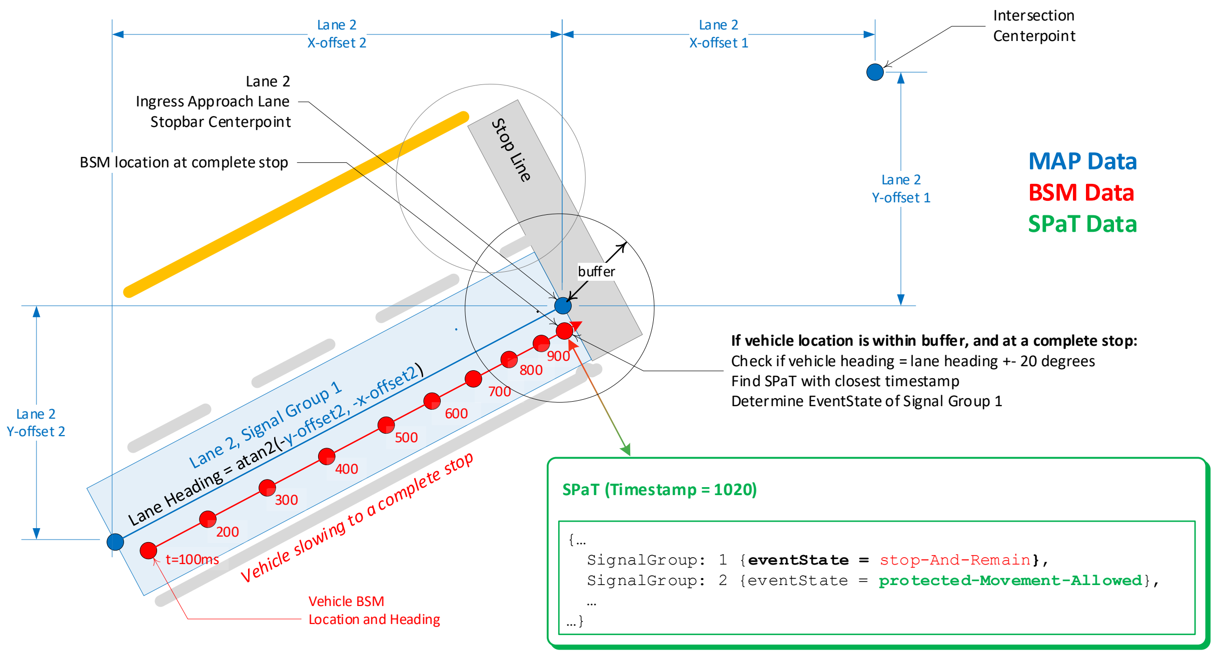


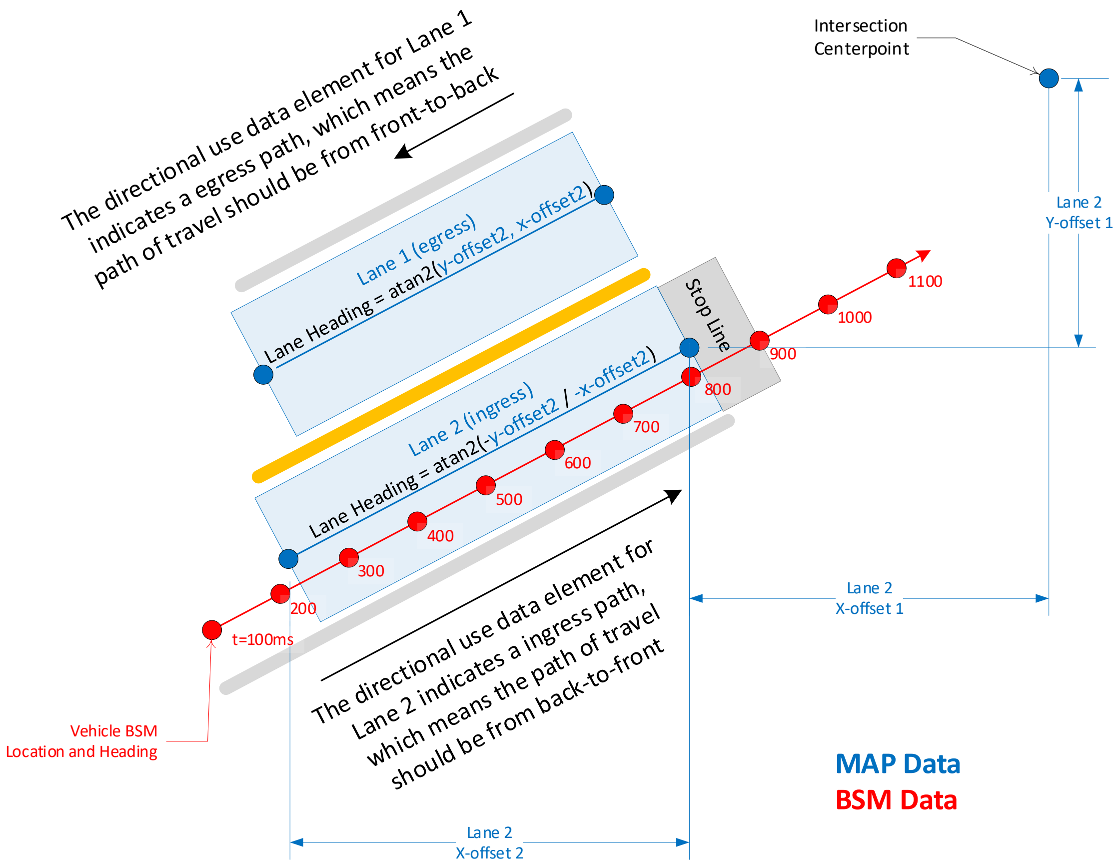
Figure 4: Visual Representation of Logic for determining Signal State when a Vehicle Stops at a Stop Line

Ingress and Egress Lane Direction of Travel

The MAP message provides the lane centerline point data that is used to determine which ingress or egress approach a vehicle is on. Lane node point offsets and lane width offsets are used to generate polygons for each ingress and egress lane segment. A point-in-polygon sub-algorithm is used to determine if a BSM latitude and longitude point falls within each lane segment polygon. If the BSM latitude and longitude falls within the polygon, the vehicle ID, lane ID, and vehicle heading are temporarily recorded. If a configurable minimum number of BSM points from the same vehicle fall within in the lane polygon, the assessment continues.

All headings from the same vehicle are aggregated to the median heading – this represents the vehicle direction of travel within the lane segment. The aggregated heading is compared to the lane heading computed from the offset data, and the difference between these two values is recorded. All timestamps from the same vehicle are aggregated to the median timestamp. Figure 3 provides a graphical reference for the logic described above.

The Message Monitor creates an event log with the following data at a minimum: Event Type (lane direction), time (aggregated BSM timestamp), vehicle direction (aggregated BSM heading), difference between vehicle direction and computed lane direction, intersection id (from MAP), lane id (from MAP), lane segment number (from MAP), lane type (ingress/egress from MAP).



A minimum number of BSM points must fall within the lane polygon
BSM headings from the same vehicle (that fall inside of the polygon) are aggregated to the median heading.
This median vehicle heading is compared against the computed lane heading and this difference is recorded.

*Note that the lane heading equations vary slightly for ingress and egress lanes. Both arguments (offsets) of the atan2 function are positive for the egress lane, and are negative for the ingress lane since points are defined in the opposite order of the lane direction.

Figure 5: Visual Representation of Logic for determining Direction of Travel

Alignment Between Connections and Vehicle Movements

This algorithm leverages many of the same processes that are used in the signal state determination algorithm. MAP messages and BSMs are used to determine which ingress lane stop line centerpoint the vehicle passes closest to – as well as the BSM timestamp when this occurs. Similarly, MAP messages and BSMs are used to determine which egress lane (initial) centerpoint the vehicle passes closest to – as well as the BSM timestamp when this occurs. Both an ingress lane and egress lane must be identified. If the BSM timestamp associated with the egress lane is greater than the BSM timestamp associated with the ingress lane, then it is assumed that the vehicle has traversed the intersection using these identified ingress and egress lanes. If this ingress-egress lane pair matches the ingress and egress lanes associated with the connections (in the MAP message), then the connection id is logged. If there is not a connection id associated with the identified ingress and egress lane ids, then this value is null.

The Message Monitor creates an event log with the following data at a minimum: Event Type (connection), ingress time (from BSM timestamp), egress time (from BSM timestamp), intersection id (from MAP), ingress lane id (from MAP), egress lane id (from MAP), ingress (stop line) location (from MAP), egress (initial) location (from MAP), connection number (from MAP).

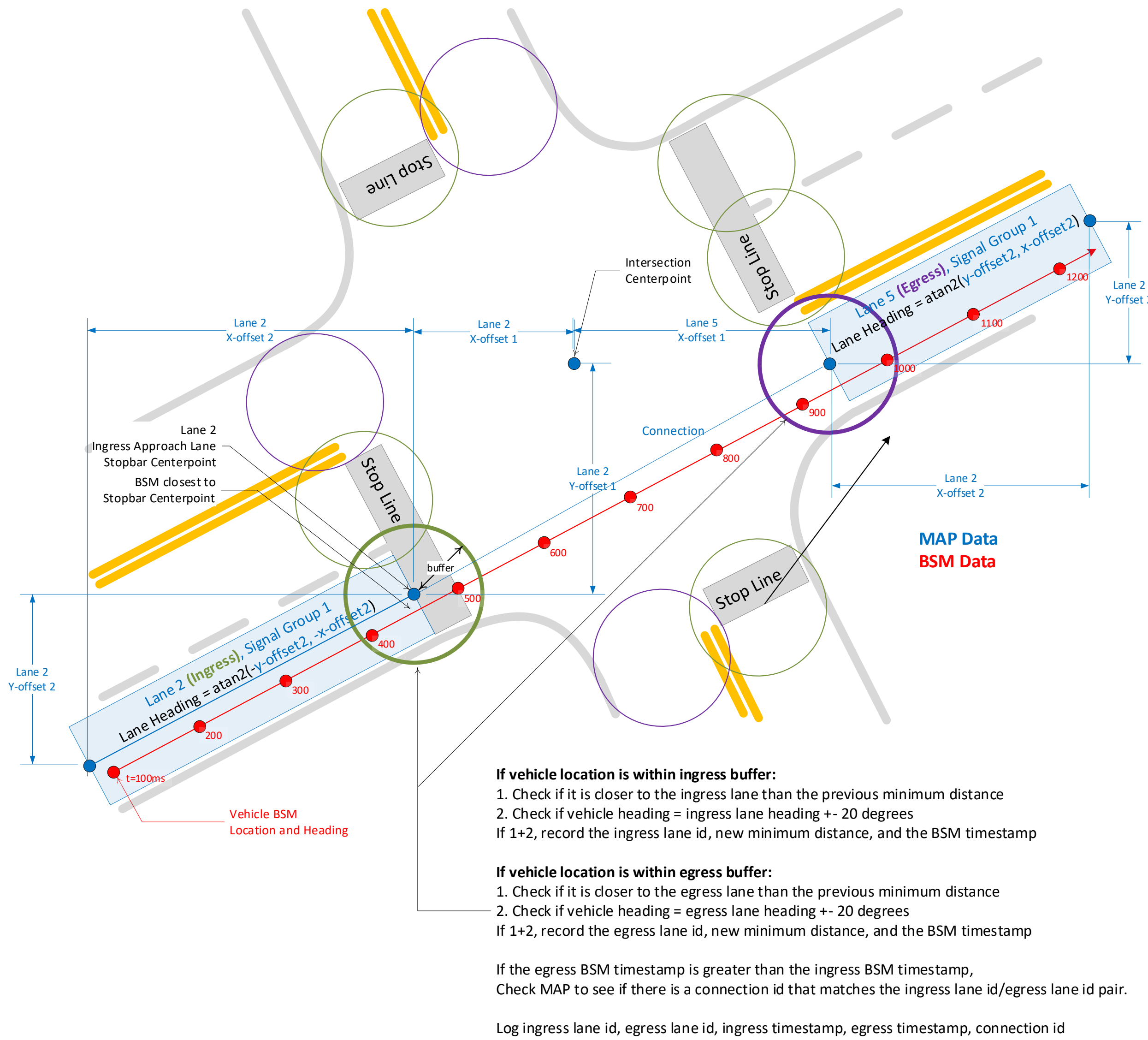


Figure 6: Visual Representation of Logic for determining Alignment Between Connections and Vehicle Movements

Signal State Conflict Monitor

This algorithm determines if there is any conflicting event state data being provided in a SPaT message based on information about the intersection of connections.

The MAP message can be used to determine which connections intersect. A graphical representation of the endpoints of a connection is created by taking the first points of the ingress and egress lanes that it connects. Alternatively, these intersecting connections can be specified as a manually configurable setting for the function.

These endpoints for all possible pairs of connections are used to determine which pairs of connections intersect – generating a list of intersecting connections. The SPaT message is then used to determine the event state for each connection. The event states for each pair of intersecting connections are compared to ensure there is no connection that has a protected green or a protected yellow event state at the same time an intersecting connection as a protected green, permissive green, protected yellow, or permissive yellow event state. That is if the event state for a connection is protected green or protected yellow, then the event state for all other intersecting connections should be red (stop-and-remain). An exception to this rule is made if the intersecting connections originate from the same ingress lane (e.g., an ingress lane allows both a through and a right turn controlled by different signal groups).

There may also be intersecting connections where permissive movements may or may not be allowed to occur simultaneously. For instance, a northbound (NB) through movement could be permissive at the same time as a southbound (SB) permissive left turn movement, but not at the same time as an EB through movement. Even though the connection that represents the NB through would intersect with the connection for the SB left turn and the eastbound (EB) through, the outcomes should be different for both. In order to provide effective output, the system would need to know which of these intersecting connections are allowed to be permissive at the same time. One method of accomplishing this is to allow a user to specify this information as a manually configurable setting.

The figure on the following page shows a 3-leg intersection with a protected-permissive SB left turn and a pseudo overlapping westbound (WB) right turn (the signal groups for these connections / movements are represented as a combination of the numbers of the controlling phases). Table 7, following the figure lists all intersecting connections that are determined from using the start (ingress) and end (egress) points of each connection. This table also indicates which intersecting connections are allowed to be simultaneously permissive – this is likely information that will need to be populated by a user.

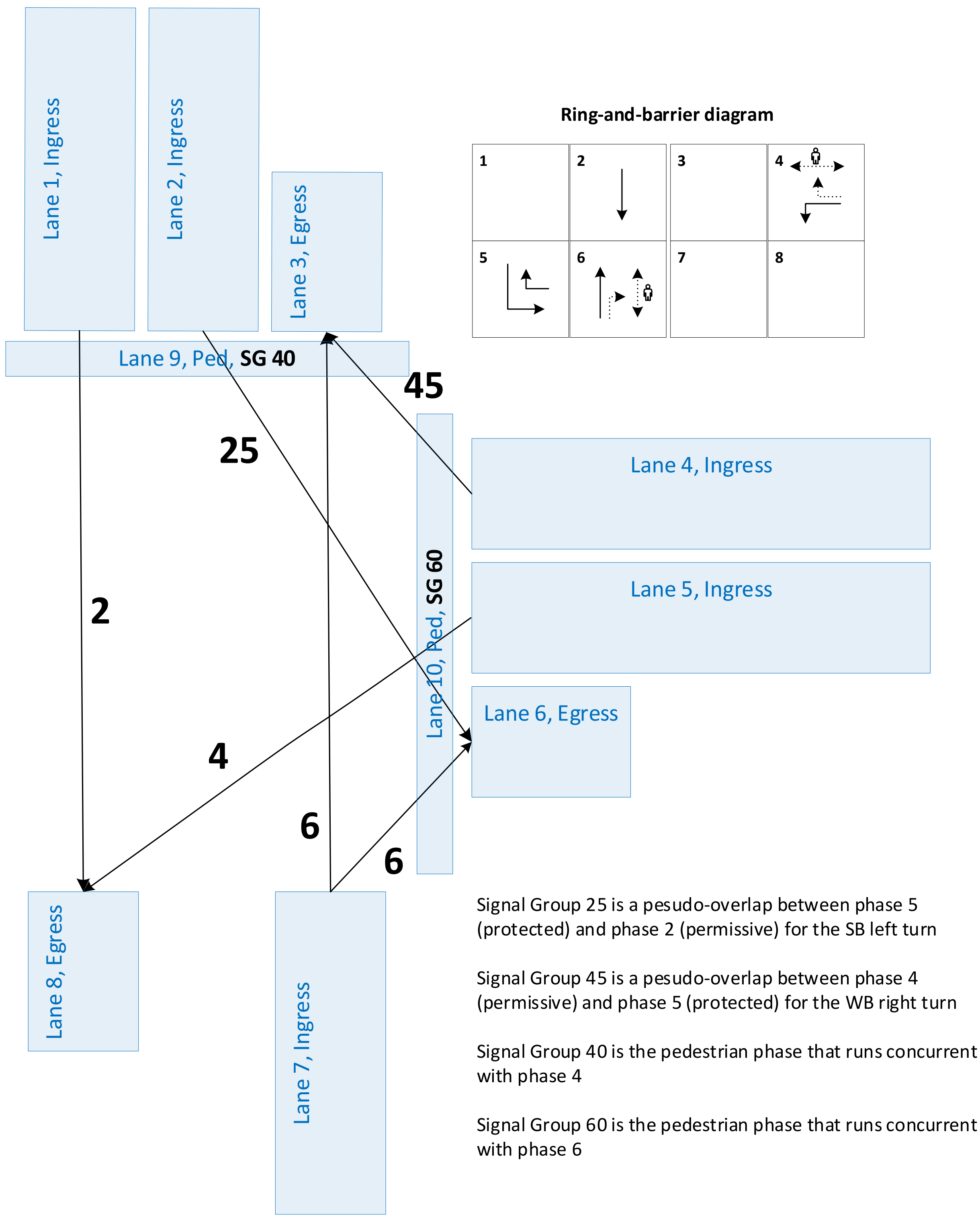


Figure 7: Conflict Detection Example

Table 7: Example List of Intersecting Connections

Intersecting Connections Signal Groups		Can be permissive at same time? (user specified)
SG	SG	
2	4	NO
25	4	NO
25	6	YES
4	6	NO
6	45	NO
2	40	NO
25	40	NO
6	40	NO
45	40	YES
45	60	NO
4	60	NO
25	60	YES
6	60	YES

Table 8 shows the event states of all signal groups for 4 different SPaT messages for the setup above. The first two SPaT messages provide examples of event states that do not conflict. In the first example signal groups 25 and 4 are allowed to both be permissive at the same time, and no other conflicts are present. The second example shows a protected movement for signal group 25 – all other event states for intersecting connections are red, which is expected. In the third example. The third example shows a protected movement for signal group 25 that is simultaneous with a permissive movement for signal group 6 and 60, which is results in a conflict, as the connections for these signal groups intersect, and a protected signal state cannot be active (green or yellow) at the same time as another signal state from an intersecting connection. The final example shows permissive movements for signal group 2 that is simultaneous with a permissive movement with signal group 4 and 40. The example table above indicates that permissive movements cannot be simultaneously active for these signal groups, resulting in a conflict.

When a conflict is noted, the Message Monitor creates an event log with the following data at a minimum: Event Type (Protected Conflict or Permissive conflict), time (from SPaT), intersection id (from MAP), signal group id 1 (from SPaT/MAP), signal group id 2 (from SPaT/MAP), event state 1 (from SPaT), event state 2 (from SPaT).

Table 8: Example Event State Data and Output

Example SPaT	Event State							Output
	SG 2	4	6	25	45	40	60	
	SB T	WB L	NB T	SB L	WB R	E-W Ped	N-S Ped	
1	Permissive green	Red	Permissive green	Permissive green	Red	Permissive green	Red	*none* (OK)
2	Permissive green	Red	Red	Protected Yellow	Red	Red	Red	*none* (OK)
3	Permissive green	Red	**Permissive green**	**Protected Yellow**	Red	Red	**Permissive green**	PROTECTED CONFLICT (25 Protected Yellow, 6 permissive green), (25 Protected Yellow, 60 permissive green)
4	**Permissive green**	**Permissive green**	Red	Red	Permissive green	**Permissive green**	Red	PERMISSIVE CONFLICT (2 permissive green, 4 permissive green), (2 permissive green, 40 permissive green)

Time Change Details Monitor

The SPaT message provides the time change details that are used to determine the amount of time remaining in the current phase. These time change details that are typically of the most interest are the minimum time that the current phase ends and the maximum time that the phase ends, these play the biggest role in communicating when the signal state will next change. Due to limitations of the existing system to produce data regarding future event state, this algorithm will only focus on the current event state.

In order to be reliable, the minimum time that the current phase ends should never decrease, and the maximum time that the current phase ends should never increase (unless the signal state changes). Unknown times may be specified, but once a definite min end time or max end time has been specified, the value should not change back to unknown under non-interrupted conditions (e.g., no preemption). Exceptions may be made for signals that recall to a given phase when no demand is present on an opposing phase.

When a signal state transition is observed, time data in the SPaT message can be compared against the most recent minEndTime and maxEndTime values to determine if the signal transitioned to the subsequent event state at the indicated minEndTime and maxEndTime. Ideally the actual signal state transition is no more than 100ms (configurable) earlier than the minEndTime and no more than 100ms (configurable) greater than the maxEndTime. MinEndTime and MaxEndTime should be equal during all yellow signal states.

Table 9 provides example event state and time change details data for a single signal group. The example data contains highlights a few scenarios that indicate when the algorithm will and will not log an event.

- **Example 1.** In the first example, at first the max end time is unknown. The SPaT data changes to provide an actual value (2400) for the maxEndTime– this is considered normal operation, and no event is generated. The SPaT data changes again to increase the minEndTime (2200 to 2220) – again, this is considered normal operation, and no event is generated. The SPaT data changes again to decrease the minEndTime (2220 to 2200), which is not expected, and an event is generated. The SPaT data changes again to increase the maxEndTime (2400 to 2600), which is not expected, and an event is generated.
- **Example 2.** The next example shows an event state transition from permissive green to permissive yellow. The maxEndTime increases, which is permissible only when the event state changes. Furthermore, the minEndTime (3000) and maxEndTime (3000) specified when the event state was permissive green is within 100 ms (configurable) of the actual time of the transition (3000). This is considered normal operation, and no event is generated.
- **Example 3.** The final example shows an event state transition from permissive green to permissive yellow. However, in this case, the maxEndTime (4010) specified when the event state was permissive green is not within 100 ms (configurable) of the actual time of the transition (4000) (actual difference is 1s). This is not expected operation, and an event is generated.

Table 9: Example Time Change Details Data and Output

Timestamp (0.1 s)	Signal Group 1			SG X					Output
	Event state	minEndTime (0.1 s)	maxEndTime (0.1 s)						
Example 1									
2000-2009	Permissive green	2200	unknown						…
2010-2019	Permissive green	2200	2400						*none* (OK)
2020-2029	Permissive green	2220	2400						*none* (OK)
2030-2039	Permissive green	2200	2400						minEndTime DECREASE(SG:1, timestamp1: 2029, timestamp2: 2030, minEndTime1: 2220, minEndTime2: 2200
2040-2049	Permissive green	2200	2600						maxEndTime INCREASE(SG:1, timestamp1: 2029, timestamp2: 2030, minEndTime1: 2400, minEndTime2: 2600
Example 2									
2990-2999	Permissive green	3000	3000						…
3000-3029	Permissive yellow	3030	3030						*none* (OK)
Example 3									
3990-3999	Permissive green	4050	4200						…
4000-4039	Permissive yellow	4040	4040						minEndTime EVENT STATE TRANSITION(SG:1, minEndTimeTransition:4050, actualTransitionTime: 4000, eventState1: permissive green eventState2: permissive yellow

When a time change detail issue is noted, the Message Monitor creates an event log with the following data at a minimum: Event Type (time change detail issue), time (from SPaT), intersection id (from SPaT), issue type (minEndTime decreases, maxEndTime increases, state transition time issue),

5.4 MODES OF OPERATION

This ConOps will consider normal operations and degraded modes of operation for the proposed system. The Modes are defined as:

- **Operational** – Normal operating condition, the System is operating as designed. CV messages are received and forwarded as intended, algorithms and analysis are computed as intended, notifications are being provided as intended, and configuration capability is available as intended. The use cases in Section 6 only consider operations under normal operating conditions.
- **Degraded Communications** – An error with a system component or communication network that prevents the receipt or forwarding of CV messages, the algorithms and analysis of events, the notifications being provided or configuration capability being available as intended. When this state is observed, the proposed system will not get the data that is needed to generate events and perform assessments. This is primarily an issue when messages being wirelessly broadcast/received do not match the messages being forwarded to the message monitor. That is, messages are being wirelessly broadcast/received from the RSU, but the RSU is not able to forward messages to the message monitor, or the RSU is not wirelessly broadcasting messages, but is forwarding messages to the message monitor. Specific use cases are not designed around a degraded communications condition.

5.5 USER CLASSES AND OTHER INVOLVED PERSONNEL

The user classes in the proposed system primarily relate to roles that are played within the context of the proposed system and not a specific organizational structure, specific staff, or group of persons.

IOO Traffic Operations. One of the current responsibilities of IOO Traffic Operations personnel is the management of messages broadcast from the RSU. The IOO has likely selected staff (or consultants) that perform the CV-related roles performed by IOO Traffic Operations. Once the proposed system is implemented, the responsibilities of IOO Traffic Operations will be expanded to include receiving, interpreting, and acting upon outputs from the proposed system – which indicate that some aspect of the messages being broadcast are not compliant with CI guidance. IOO Traffic Operations personnel will exercise engineering judgement to:

1. Identify the precise issue that is causing a notification to be issued from the system (SPaT or MAP is incorrect, a change in a signal timing plan, change in geometry, construction, officer temporarily directing traffic, latency, etc.)
2. Provide a reasonable resolution that addresses issue at hand based on knowledge and experience with traffic engineering and other disciplines involved in the design of CV systems. This might involve making changes to MAP messages, propose corrections to software that generates the content in SPaT messages, propose corrections that might be causing latency issues, etc.

IOO Traffic Operations can also provide a list of desired system changes to the Message Monitor Support to improve the usefulness of proposed system outputs.

Message Monitor Support – A new role related to the implementation of the proposed system, Message Monitor Support will be responsible for configuring and adjusting the code that affects the functionality and operations of the Message Monitor. They will receive input from IOO Traffic Operations personnel to make these modifications. For the duration of this project, the role of the Message Monitor Support Staff can be performed by the system developer, but in the long-term, this role will likely become the responsibility of the IOO Traffic Operations.

Driver. The driver does not directly interface with the proposed system and has the same role and responsibilities as described in Section 3.5. However, it is important to note that the driver indirectly benefits from the proposed system when the proposed system identifies an issue in a message that is corrected by IOO Traffic Operations. Improved message performance is expected to improve application performance on the Driver's OBU, thereby improving public perception of the technology.

5.6 SUPPORT ENVIRONMENT

The support environment for the proposed system is the same as the support environment for the existing system, described in Section 3.6.

6. Use Cases and Operational Scenarios

This section presents scenarios that capture how the system serves the needs of users when the system is operating under a normal mode of operation. To the extent possible, these use cases describe external events and align with user needs that are ready to implement as outlined in Section 4.4. Use cases are written in a fashion that demonstrates how the Message Monitor is expected to benefit system users and will minimize specifying details regarding the internal workings of the system. Scenarios are developed in this fashion to allow for flexibility in the development of requirements and design.

6.1 USE CASE 1: EVENT DETECTION (NOT USING BSM)

Table 10: Use Case 1: Event Detection (not using BSM)

<table>
<tr><th>Use Case</th><th colspan="2">Event Detection (not using BSM)</th></tr>
<tr><td>Objective</td><td colspan="2">Generate an event when a vehicle crosses a stop line that indicates the signal state and other relevant message-related details.</td></tr>
<tr><td>Operational Events</td><td colspan="2">• Message Monitor generates Event Data using MAP, SPaT</td></tr>
<tr><td>Pre Conditions</td><td colspan="2">• Live SPaT and MAP message are being immediately forwarded to the Message Monitor
• The message monitor is non-proprietary and is capable of being modified</td></tr>
<tr><td rowspan="2">Actors</td><td>Actor</td><td>Role</td></tr>
<tr><td>none</td><td>-</td></tr>
<tr><td rowspan="6">Key Actions and Flow of Events</td><td>Source</td><td>Key Action</td></tr>
<tr><td>Message Monitor</td><td>Ingests SPaT, MAP data</td></tr>
<tr><td>General</td><td>SPaT and MAP messages are continuously produced by the external system and ingested by the Message Monitor</td></tr>
<tr><td>Message Monitor</td><td>Every X minutes (configurable), applies algorithms (configurable) detailed in Section 5.3.5 to:
• determine if there is a signal state conflict
• determine if there is an issue with SPaT time change details.

Also determines if MAP and SPaT are signed.

Note: Processing in batches (i.e., every x minutes) is expected to allow for more efficient processing of data vs. every time a new message is received.</td></tr>
<tr><td>Message Monitor</td><td>Releases raw SPaT, MAP data, and logs event data per algorithms.</td></tr>
<tr><td>General</td><td>The above steps are repeated in perpetuity.</td></tr>
<tr><td colspan="2">Post Conditions</td><td>• Event data is logged on the Message Monitor</td></tr>
<tr><td>User Needs Traceability</td><td colspan="2">• UN-001.3.1, UN-001.3.3, UN-001.3.5, UN-001.3.8, UN-001.4.1a, UN-001.4.2, UN-001.4.4, UN-001.4.8, UN-001.6, UN-002, UN-004, UN-005, UN-011, UN-012, UN-013, UN-014, UN-015, UN-016, UN-022, UN-023, UN-024</td></tr>
<tr><td>System I/O Summary</td><td>• SPaT, MAP</td><td>• Logged Event Data</td></tr>
</table>

6.2 USE CASE 2: EVENT DETECTION (USING BSM)

Table 11: Use Case 2: Event Detection (using BSM)

Use Case	Event Detection (using BSM)	
Objective	Generate an event when a vehicle crosses a stop line that indicates the signal state and other relevant message-related details.	
Operational Events	• Message Monitor generates Event Data using MAP, SPaT, and BSMs	
Pre Conditions	• The OBU and RSU are interoperable (the RSU can receive BSMs) • Live SPaT and MAP message are being immediately forwarded to the Message Monitor • Live BSMs are being immediately forwarded to the Message Monitor • The message monitor is non-proprietary and is capable of being modified	
Actors	Actor	Role
	Driver	Operate vehicle in accordance with traffic control devices
Key Actions and Flow of Events	Source	Key Action
	Driver	Drives toward the Connected Intersection
	RSU	Begins to receive BSMs from the OBU
	Driver	Passes through the Connected Intersection
	RSU	Ceases receiving BSMs from the OBU
	Message Monitor	Ingests SPaT, MAP, and BSM data
	General	*Many CVs drive through the intersection and many events are recorded. i.e., The first five steps are repeated many times.*
	Message Monitor	Every X minutes (configurable), applies algorithms (configurable) detailed in Section 5.3.5 to ingested SPaT, MAP, and BSM data • Determine Signal State when a Vehicle Crosses a Stop Line • Determine Signal State when a Vehicle Stops at a Stop Line • Determine ingress and egress lane direction of travel • Alignment between connections and vehicle movements Also determines if BSMs received are signed. *Note: Processing in batches (i.e., every x minutes) is expected to allow for more efficient processing of data vs. every time a message is received. Furthermore, it is expected to be advantageous to have multiple points of BSM data from a single vehicle as it passes through the intersection before performing any analysis to generate an event based on that vehicle's data.*
	Message Monitor	Releases raw SPaT, MAP, and BSM data, and logs event data per algorithms.
	General	*The above steps are repeated in perpetuity.*
Post Conditions	• Event data is logged on the Message Monitor	
User Needs Traceability	• UN-001.3.1, UN-001.3.3, UN-001.3.5, UN-001.3.8, UN-001.4.1, UN-001.4.2, UN-001.4.4, UN-001.4.8, UN-001.6, UN-003, UN-004, UN-005, UN-011, UN-012, UN-013, UN-014, UN-015, UN-016, UN-022, UN-023, UN-024	
System I/O Summary	• SPaT, MAP, BSM	• Logged Event Data

6.3 USE CASE 3: ASSESSMENT OF EVENTS AND NOTIFICATION

Table 12: Use Case 3: Assessment of Events and Notification

Use Case	Assessment of Events and Notification	
Objective	Generate a notification or recommendation to stop broadcasting based on the outcome of the assessment of event data.	
Operational Events	• Message Monitor performs long-term assessment using event data which is used to inform IOO Traffic Operations	
Pre Conditions	• Event data is being logged on the Message Monitor • The message monitor is non-proprietary and is capable of being modified	
Actors	Actor	Role
	IOO Traffic Operations	Use Message Monitor Outputs to assess SPaT and MAP Message Performance, locate and rectify issues.
Key Actions and Flow of Events	Source	Key Action
	Message Monitor	Generates event logs according to event detection algorithms.
	Message Monitor	If new events (of a given event type) are generated, an assessment of that event type is performed. • For signal state, this could be the percentage of vehicles (configurable) crossing the stop line on red (for a given intersection id, connection, lane id, signalGroup) on red exceeds a configurable threshold. • For direction of travel, this could be a percentage of events (configurable) that are within a certain range (configurable) of the computed lane heading (for a given intersection id, lane id, segment number). • For connections, this could be a percentage of intersection traverse events (configurable) where a connection could be determined. • For signal state conflict monitor, this could be a count of observed conflicts for each pair of intersecting connections. • For Time Change details, this could be a count of minEndTime and maxEndTime issues found for each signal group.
	Message Monitor	Records the outcome of the assessment along with the time the assessment was performed in a system log of assessments.
	Message Monitor	If the result of an assessment exceeds some threshold (configurable), issues a notification (configurable) or recommendation to stop broadcasting (configurable) indicating a potential issue regarding the given intersection id, connection, lane id, signalGroup, etc. May offer potential things to look for in the SPaT and/or MAP message that may be causing this issue. The frequency with which a notification/recommendation containing the same information is output from the system is also a configurable option for each assessment.
	IOO Traffic Operations	Uses the output from the Message Monitor to assist in locating and correcting the SPaT and/or MAP issue.
Post Conditions	• Potential Issues in the SPaT and/or MAP are identified in a timely manner	

	○ Algorithms that require only SPaT and MAP data could provide results much more quickly than those that also require BSMs. Timeliness of outputs from assessments based on BSM data would be dependent on the penetration rate, as some minimum number of observations over time are needed to provide a level of confidence before providing an output. • IOO Traffic Operations modify a message based on output from the Message Monitor. • Drivers experience better CV application performance.	
User Needs Traceability	• UN-006, UN-007, UN-008, UN-014, UN-022, UN-023, UN-024	
System I/O Summary	• Event Log Data	• Assessment Log Data • Notification to IOO Traffic Operations

6.4 USE CASE 4: PERFORMANCE REPORTS

Table 13: Use Case 4: Performance Reports

Use Case	Performance Reports	
Objective	Demonstrate how logged assessment data used to generate performance reports that are requested by IOO Traffic Operations	
Operational Events	• Message monitor organizes assessment data into performance reports • IOO Traffic Operations receives a report of assessments for a specified period of time	
Pre Conditions	• Assessment data is being logged on the Message Monitor • The message monitor is non-proprietary and is capable of being modified	
Actors	Actor	Role
	IOO Traffic Operations	Use Message Monitor Outputs to monitor long-term performance for each assessment.
Key Actions and Flow of Events	Source	Key Action
	Message Monitor	Performs assessments and records the outcome of the assessment along with the time the assessment was performed in a system log of assessments.
	IOO Traffic Operations	Requests a Performance Report from the Message Monitor. The request may contain filters (For example: the types of events, intersections, and timespan).
	Message Monitor	Gathers stored assessment data, based on the filters provided in the request.
	Message Monitor	Arranges the gathered data into a format that is easily understood by the IOO Traffic Operations Personnel This could include but is not limited to: a list of events, a visualization of event-based data, or a tabular or graphical time-series of assessment data. This could be further broken down by intersection, lane, etc., as needed.
	Message Monitor	Outputs the performance report to IOO Traffic Operations.
	IOO Traffic Operations	Reads the report to look at the performance of various aspects of SPaT and MAP messages over the specified time period.
Post Conditions	• IOO Traffic Operations has an understanding of high-level performance, and how performance changes over time.	
User Needs Traceability	• UN-010, UN-022, UN-023, UN-024	
System I/O Summary	• Assessment Log Data	• Performance Report

6.5 USE CASE 5: CHANGE CONFIGURATION

Table 14: Use Case 5: Change Configuration

<table>
<tr><td>Use Case</td><td colspan="2">Change Configuration</td></tr>
<tr><td>Objective</td><td colspan="2">Demonstrate that configuration can be modified to:
adjust algorithm performance.
modify the threshold for the issuance of notifications.
modify the threshold for recommending ceasing the broadcast of a message.</td></tr>
<tr><td>Operational Events</td><td colspan="2">• Message monitor applies the modified configuration.</td></tr>
<tr><td>Pre Conditions</td><td colspan="2">• The message monitor is non-proprietary and is capable of being modified</td></tr>
<tr><td rowspan="2">Actors</td><td>Actor</td><td>Role</td></tr>
<tr><td>IOO Traffic Operations</td><td>Use Message Monitor Outputs to assess Message Monitor Performance</td></tr>
<tr><td rowspan="4">Key Actions and Flow of Events</td><td>Source</td><td>Key Action</td></tr>
<tr><td>IOO Traffic Operations</td><td>Specifies a change in the Message Monitor Configuration Settings. Configuration settings fall into the following categories:
Algorithm configuration
Notification Threshold Configuration
Message Suspension Recommendation Configuration</td></tr>
<tr><td>Message Monitor</td><td>Applies the updated configuration</td></tr>
<tr><td>Message Monitor</td><td>Depending on the configuration(s) modified:
Adjusts the algorithm(s)
Issues notification(s) at the adjusted threshold
Issues message suspension recommendation(s) at the adjusted threshold</td></tr>
<tr><td>Post Conditions</td><td colspan="2">• IOO Traffic Operations can modify Message Monitor operations for specific local conditions and local preferences.</td></tr>
<tr><td>User Needs Traceability</td><td colspan="2">• UN-018, UN-019, UN-020, UN-022, UN-023, UN-024</td></tr>
<tr><td>System I/O Summary</td><td>• Configuration Setting</td><td>• None</td></tr>
</table>

7. Summary of Impacts

7.1 OPERATIONAL IMPACTS

The primary operational impact from the proposed system includes the production of event data that are used in both near and long-term assessments which are accessible by IOO Traffic Operations, and the issuance of outputs to IOO Traffic Operations. This data can be used for research purposes (independent of this project) or as a way of assessing performance of the system. These outputs are expected to help IOO Traffic Operations locate potential issues in SPaT and MAP messages. With this information, IOO Traffic Operations can independently investigate to confirm the presence of an issue or if the notification did not accurately point out an issue. If the issue is confirmed, engineering judgement can be exercised to modify the message to rectify the issue. Otherwise, the system can be configured to modify the thresholds at which an output is provided by the system.

System functionality and action taken by IOOs in response to system outputs will ensure that connected signalized intersections work safely and are interoperable between deployments. Its design should provide a level of technical integrity in its development and testing giving trusted real-time data for vehicles that rely on SPaT and MAP data.

7.2 ORGANIZATIONAL IMPACTS

During the project, the role of the Message Monitor Support will be the responsibility of the project team but in after the project has concluded, this role will likely become the responsibility of the IOO. An IOO that is considering the deployment of the Message Monitor system likely already has staff dedicated to the IOO Traffic Operations role. However, it is important to consider that this role may potentially require staff with a different background than existing IOO Traffic Operations or may require additional training for existing staff to grow into this expanded role (due to the implementation of the Message Monitor). Training may be needed to inform IOO Traffic Operations on how to interpret outputs from the Message Monitor, locate an issue(s) in a message, determine what changes may be needed, and how to make modifications to improve performance.

It is important to recognize that the additional responsibility taken on by IOO Traffic Operations may require additional funding to accommodate the added tasks and attention that active monitoring and addressing issues may entail. An agency that deploys this system should consider the amount of effort needed to correct issues that the Message Monitor is intended to bring attention to. Furthermore, different agencies may have different aspects of SPaT and MAP messages that they desire to monitor or make other customized changes to the open-source software. If the Message Monitor does not already provide the functionality needed to meet a specific agency's needs, then development will be necessary. This will likely entail working with other staff in the agency that will have experience modifying open-source code bases or contracting with a consultant with experience in this area. Either way, if additional functionalities are desired, the agency will need to budget for system development accordingly.

7.3 IMPACTS DURING DEVELOPMENT

Recommended Practices for Signalized Intersection Applications (SAE J2945/B) - complementary to the CI project being performed by ITE, this draft standard outlines how to use SAE J2735 and other related messages (such as SPaT, MAP, SRM, SSM) to support signalized intersection applications and also provides methods for implementing signal priority/preemption over the air. Expected dialogues are specified and more specific requirements for data in messages are specified. As this is a draft standard, intersections are not currently subject to these requirements – however, once published, intersections will need to adhere to this standard. The Message Monitor may provide a means of verifying if this standard is met.

Time Synchronization – The primary functionalities of this system will heavily rely on the relationship between SPAT, MAP, and BSM data. This relationship may be, in part, temporal in nature. The existing system (all vehicle and infrastructure components) should ideally be using the same time source to populate time data elements in their respective messages. Furthermore, these time data elements need to be as accurate as possible with respect to each data element that it is associated with. This allows the message monitor to accurately relate driver behavior (from BSM) to infrastructure status (SPaT and MAP). It is especially important to consider that the time that a message is broadcast or received may not correspond to the time of the data in the message. That is, there is some level of latency in the formation and transmission of messages that must be understood when designing algorithms that require temporal relationships between data from different sources. The complexities of latency involved in the formation and broadcast of the SPaT message are exemplified in the following requirements in the CI Implementation Guidance (CTI4501 v0100):

- **CTI4501 v0100 3.3.3.2.1.4 TSC Infrastructure SPaT Information Average Message Update Latency.** When state changes are sent to the cabinet outputs, the TSC shall transmit the corresponding SPaT information to an RSU within 200 milliseconds between the controller's cabinet output and the controller's Ethernet output to the RSU
    - Additional latency allowance when using an ECLA is currently under discussion.
- **CTI4501 v0100 3.3.2.1.5. TSC Infrastructure Processing Latency.** When there is a change of demand for right-of-way, a TSC infrastructure shall process the input and generate a corresponding SPaT information message within 500 milliseconds of receipt of the cabinet input.
- **CTI4501 v0100 3.3.3.1.5.2 SPaT Message - Broadcast Latency.** A connected intersection shall broadcast SPaT messages that reflects the actual signal indications of the intersection within a latency of no more than 300 milliseconds.
    - The latency is defined as from the time when the signals are commanded to change is asserted by the traffic signal controller to change the signal head indication, to when the SPaT message with the change in signal indication (movement state) is received by the OBU/MU.

The CI guidance also has a requirement for the accuracy of time data in messages to be within 10 milliseconds (ms) of Coordinated Universal Time (UTC). However, it cannot necessarily be assumed that any given site will adhere to this requirement.

With this in mind, it will be important to consider the impacts of both latency and/or the accuracy of any time information in messages when designing algorithms (that use time information) and interpreting the event data and assessment outputs from the message monitor. When finding a site in which to implement the message monitor, care should be taken to select a site that uses a time source that is commonly used by in-vehicle devices, has demonstrated accurate population of time data elements in its infrastructure-based messages, and where message broadcast latency is within acceptable limits and is well-understood.

RGA - The upcoming release of the RGA will impact how roadway geometry information is communicated in electronic messages to vehicles. While this is not anticipated to affect the initial implementation of this project, this is something that should be monitored as this could drastically affect the ability of the system to meet user needs – especially those related to the accuracy of MAP messages.

8. Analysis of the Monitoring System

8.1 SUMMARY OF IMPROVEMENTS

The Message Monitor will provide a means of continuous and automated SPaT and MAP monitoring that will provide improved ability of a deploying agency to identify and correct issues with these messages as they occur. The identification and rectification of issues in SPaT and MAP messages will ultimately benefit the consumers of that data, which are drivers and OBU application developers (and by extension, OEMs that are researching the integration of CV technology in their vehicles). Accurate messages provide a foundation from which applications can properly function.

Furthermore, accurate infrastructure-based messages provide a level of confidence to OEMs that are considering investment in CV technology in their vehicle lineups. Looking forward, the Message Monitor has to potential to play an important role in the initial and continuous long-term validation of SPaT and MAP data that are broadcast from CV equipment at intersections.

8.2 DISADVANTAGES AND LIMITATIONS

The ability of the message monitor to provide accurate outputs to IOO Traffic Operations is dependent on accurate BSM data. Inaccurate positioning may not adequately capture vehicle movements to the degree that is required for the message monitor to provide reliable outputs to IOO Traffic Operations. The system will attempt to utilize clustering algorithms or by use of statistical methods to handle normally occurring variances in vehicle positioning and to account for a normally occurring variance in vehicle positioning errors resulting from not correcting vehicle positioning using RTCM data. However, if these variances are too large, or there are biases in vehicle positioning that are present over time, this will impact the system's ability to provide accurate outputs. As vehicle positioning technologies continue to improve, this expected to become less of an issue.

Different algorithms may require different amounts of data to provide an output. While SPaT and MAP data are readily available, the presence of BSM-producing vehicles may not be upon initial implementation of the message monitor. Many BSM-producing vehicles on the roadway today were deployed on a limited basis as part of projects where roadside CV equipment was also deployed. In these situations, the behavior of certain drivers (and types of drivers) could be over-represented where penetration rates are very low or where certain partner agencies (e.g., transit agencies) have vehicle fleets equipped.

The lower the penetration rate of vehicles, the more time it may take for an assessment to produce an output. Some assessment results that are not as timely due to today's low CV penetration may produce more timely results in the future as penetration rates increase. For the initial system deployment, this can be somewhat mitigated by selecting a site where BSM-producing vehicles are known to operate (where CV equipment has been installed on vehicles as part of a deployment), which should be adequate for demonstrating the overall concept. Furthermore, the behavior of certain drivers (and types of drivers) could be over-represented where penetration rates are very low or where certain partner agencies (e.g., transit agencies) have vehicle fleets equipped.

8.3 ALTERNATIVES AND TRADEOFFS CONSIDERED

A large part of this project placed emphasis on what IOOs could do to help improve the trustworthiness of the data in messages that are produced. A particular focus on the use of data in CV messages was desired. However, there are many other potential concepts for assessing the accuracy of SPaT and MAP messages (or other CV messages) that could be implemented by other parties and could leverage additional sources of data for assessing message accuracy. A brief list of these other concepts is provided in the list below:

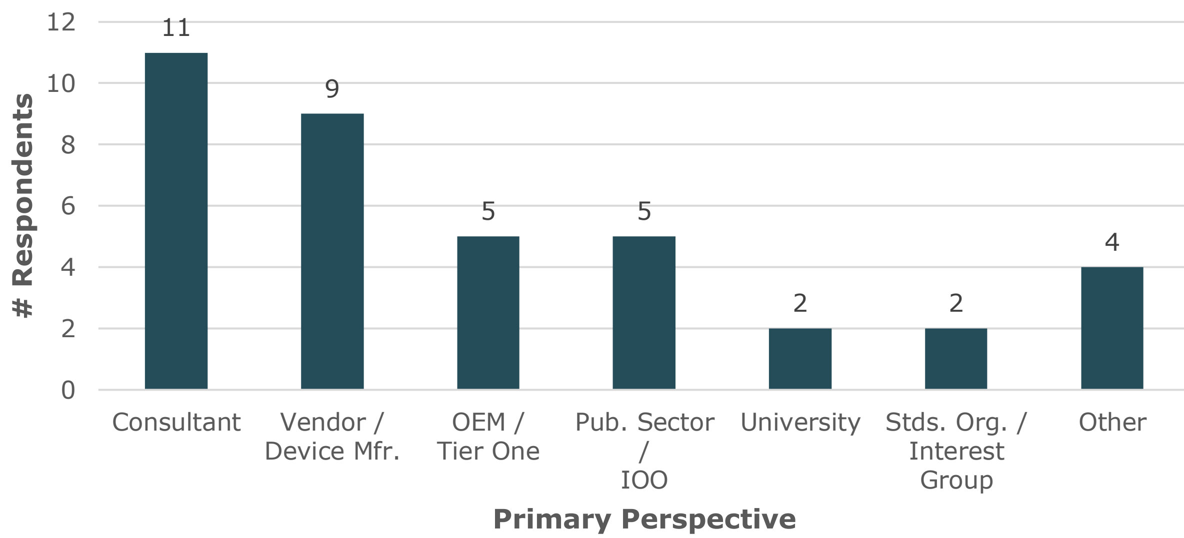
- Vehicle-based checks of SPaT and MAP data and reporting when issues are found. Particularly vehicles that have highly-accurate positioning systems and the ability to detect its surroundings (e.g. signal state, lane control, etc.).
- Enhancing the design of the malfunction monitor unit (cabinet monitor, conflict monitor) to receive SPaT data and compare with actual signal indication (via circuit voltage/current).
- High Resolution Signal Controller Data provides an additional source of ground truth traffic operations data that can be used in monitoring/validation activities and warrants further investigation.

9. Notes

Site-Specific Conditions – There are currently many different implementations of CV systems that use technologies (RSU, processing unit, traffic signal controller, network, etc.) from different vendors. Each of these vendors will have different methods by which their products produce data and provide data to external systems. The selection of an existing CV system that the Message Monitor will initially be designed to integrate with has yet to be determined, which is why this ConOps describes the existing system in a general manner. Typical operational polices and constraints outlined in Section 3.2 and Section 5.2 places some boundaries on the types of existing systems that the Message Monitor should expect to work with. The Message Monitor in its initial implementation will be designed and configured to work with the components of a selected CV deployment site. However, the open-source nature of the Message Monitor will allow modifications to be relatively easily made (e.g., plugins) to accommodate interfaces of equipment used in other systems.

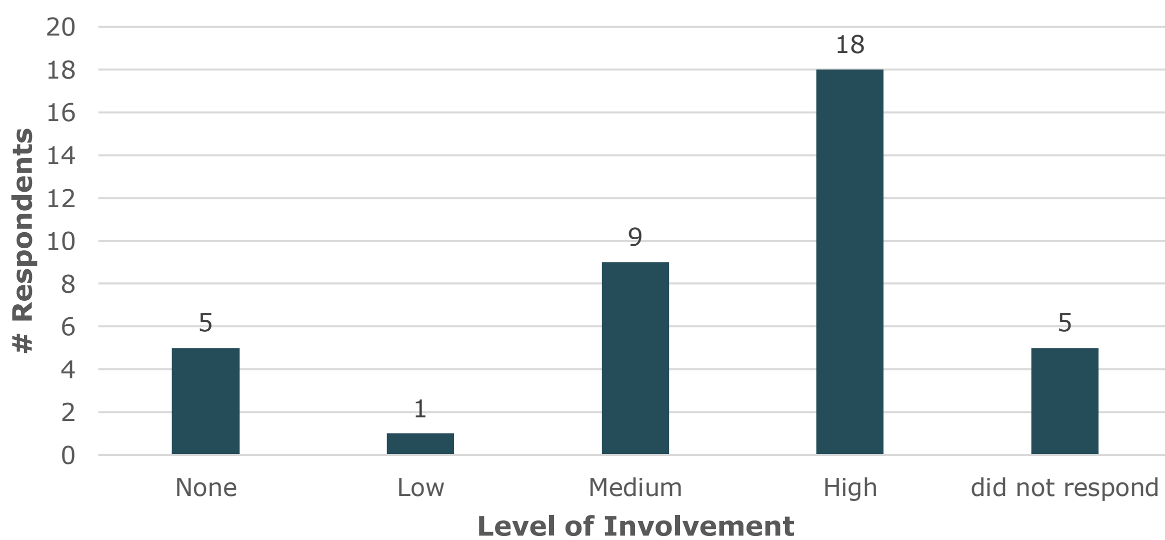
Appendix A. Questionnaire Results Summary

Q1) Please indicate the primary perspective you are representing in this questionnaire:

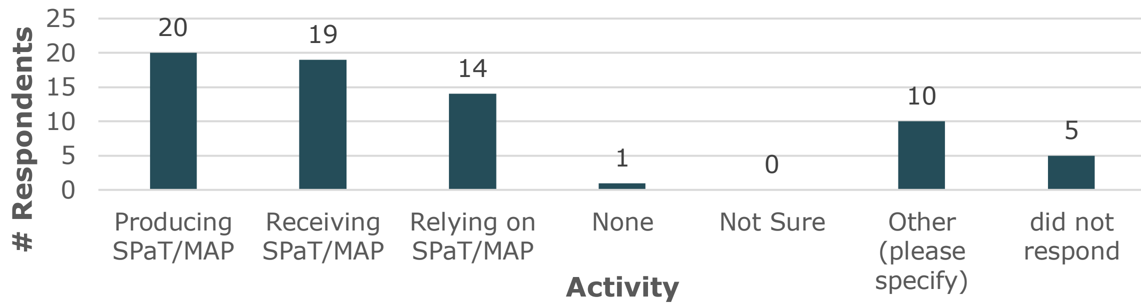


Other responses entered included: Standards (ISO, IEEE, SAE) but also architecture and cybersecurity | System Architect | Testing and Verification | OEM Technology Partner

Q2) What level of involvement do you currently have in verifying SPAT and MAP?

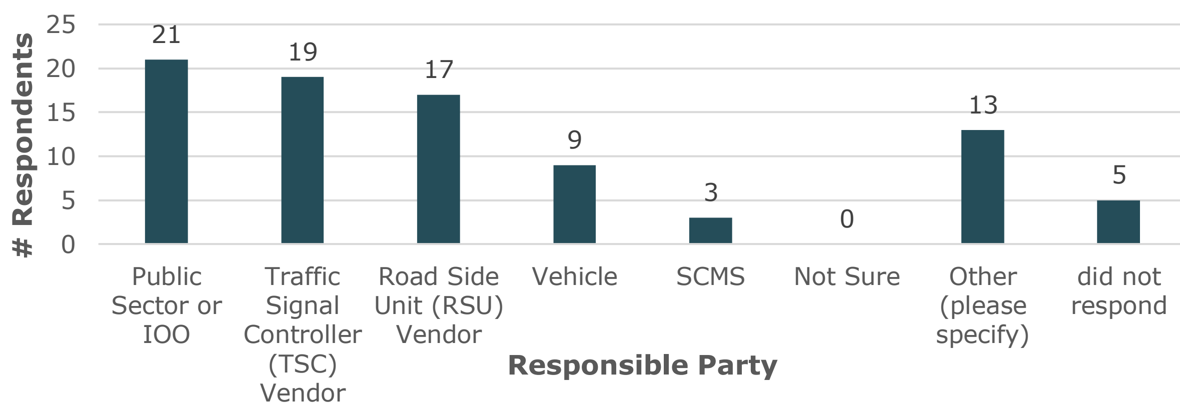


Q3) What activities are you involved with? (multi-response)



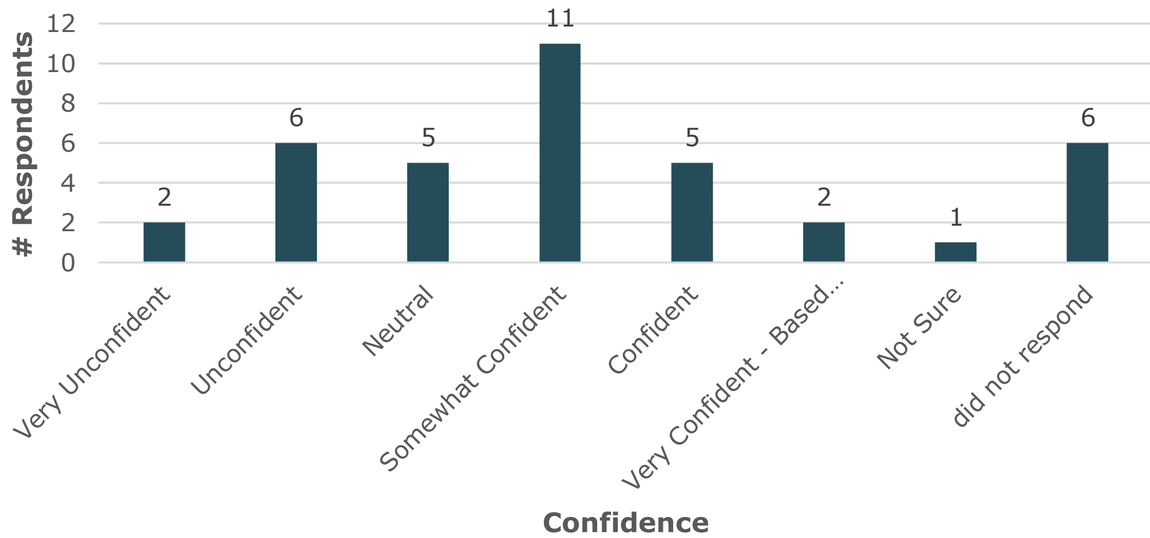
Other responses entered included: Developing standards to support mapping and signal phase and timing | Standardization | Previously some level of coordination with the three USDOT-funded CV pilots to coordinate their interfaces to be identical where practical, which included SPaT/MAP | Adding Regional elements to SPaT | Standards development | Verifying & Validating SPAT/MAP and its implementation | Focus on verification testing content and performance of SPaT/MAP messages| validating SPaT predictions | CI SPaT/Map Taskforce co-chair | Developing US and China C-V2X interface concepts and protocols to intersections - concepts, standards, guides.

Q4) Who do you believe is responsible for ensuring if SPaT and MAP messages are accurate/valid? (multi-response)

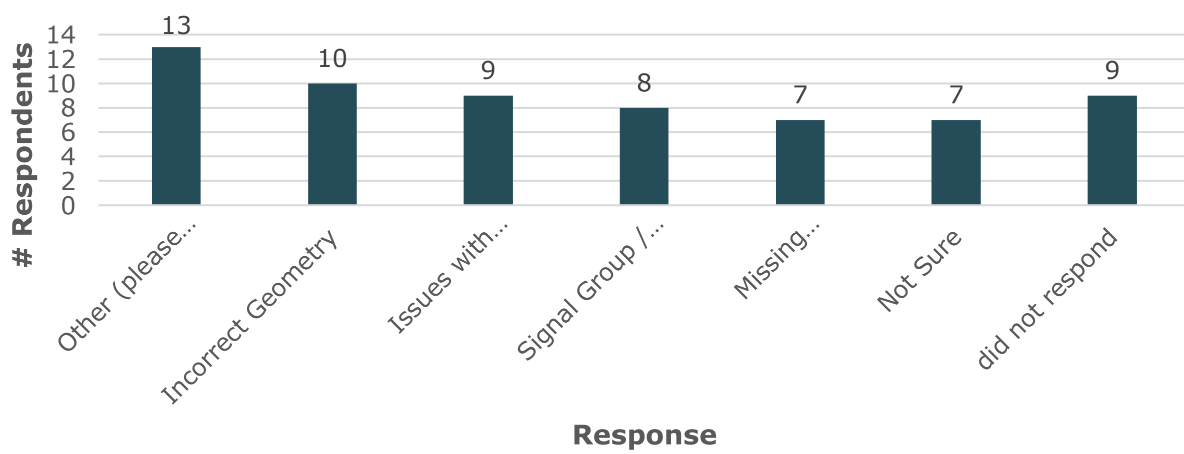


Other responses entered included: MAP message could be created by other 3rd party such as System Integrator | For controllers without SPaT module, application developer (RSU vendor or other) | Accurate and valid are two different things. Whoever produces the SPaT/MAP should be responsible for producing something that is accurate. This currently varies between the TSC and the RSU as well as some central systems. | an entity that is equipped to perform the MAP/SPAT validation work. | All parts need to do what they can to validate the accuracy and authenticity of SPaT/MAP messages. | The stack provider and the contractor working with end user | the owner of the device that signs the SPaT and MAP messages. If the RSU signs, then the RSU owner is responsible. | A central entity that establishes best practices. | For SPAT, whoever is responsible for producing the SPaT should be responsible for ensure the SPaT is valid. For example, if the SPaT is produced by the TSC, then the TSC must make sure it is correct. If an external entity produces the SPaT they are should be responsible for ensure the SPaT. Because the IOO is ultimately responsible for the signal indication, they should be responsible for ensuring the content of the SPaT agrees with the signal indications displayed to motorist. I believe the TSC is responsible ensure that the MAP agrees with the signal timing that is operational at the intersection (in case of TOD turn restrictions). | Test engineers | Tier 1 supplier | Map: IOO, SPaT: IOO and TSC Vendor | OmniAir Consortium (US, Korea)

Q5) How confident are you that SPaT or MAP messages being broadcast are accurate/valid?

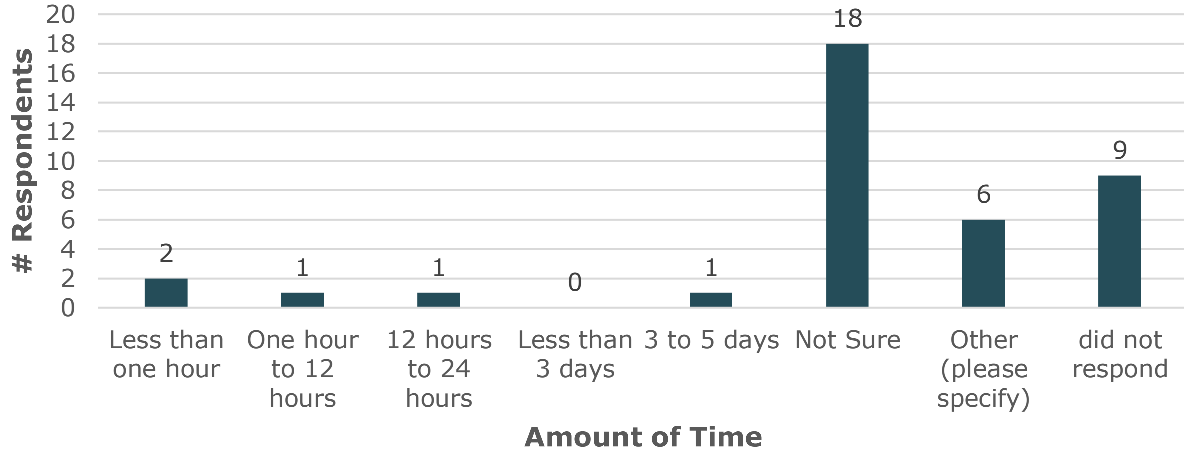


Q6) Have you ever found a SPaT or MAP message to be inaccurate after thinking that they were correct? (multi-response)



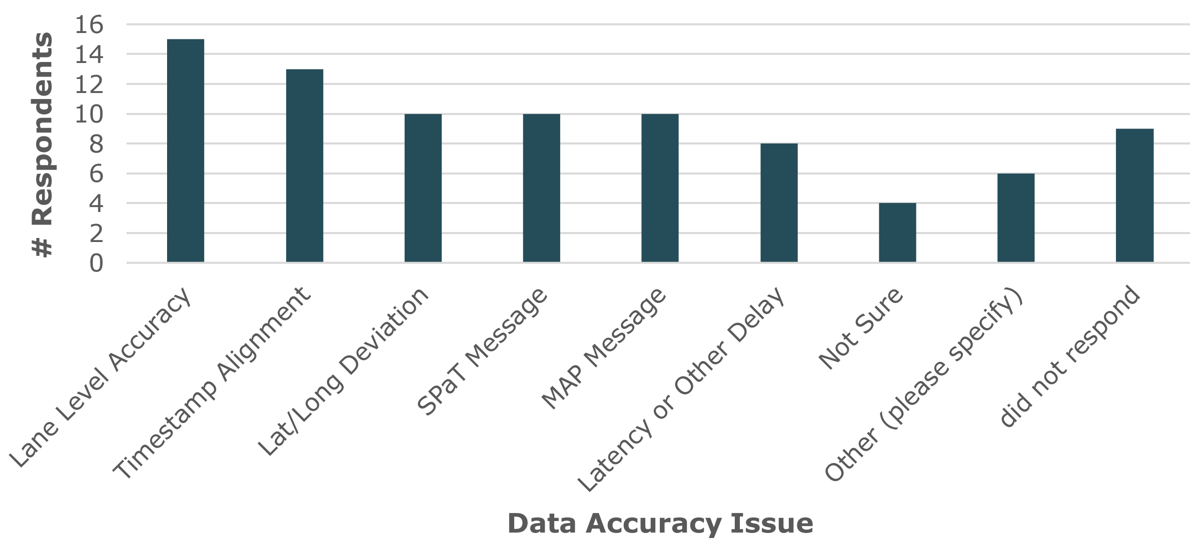
Other responses entered included: MAP geometry needs onsite measurements to be fully accurate | OEM field tests have shown incorrect geometry and mismatched SPaT | Signal dark but SPaT is still sending phase/timing information | SPaT: Issues with signal timing (time to change phase); MAP: lane points positioning accuracy | Jumpy values (e.g. LikelyTimeToChange) | I personally do not have details, we would need our team to respond | Phase change timing | Phase timing off between signal controller and what vehicle receives. | Tools used to generate MAPs don't same datum as vehicles. | all of the above | I assume they are incorrect unless proven otherwise. | additional phases/overlaps added | Implementations non-uniform

Q7) When you find an inaccuracy in a SPaT or MAP message, approximately how long had the inaccuracy been present in the message before you found out, or it was brought to your attention?



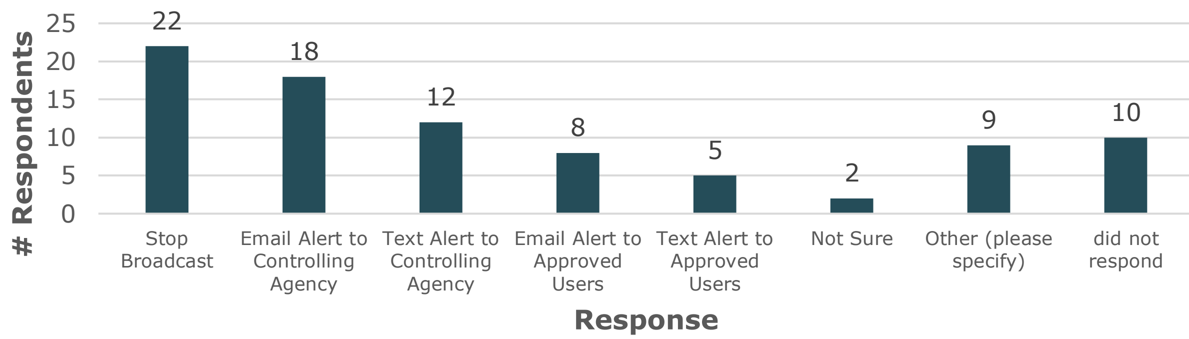
Other responses entered included: Variable from one deployment to another (mostly a few days) | Forever. | Don't know how to answer this. These are not periodic errors but systemic errors. They make take days to testing and trial and error to determine that their is an issues. We had to look at vehicle traces in lanes to discover many of these errors. | It had been incorrect since the system was put into operation. | Up to several weeks in one case | Depends

Q8) Based on your experience, what are the issues you have encountered with data accuracy in SPaT and/or MAP messages? (multi-response)



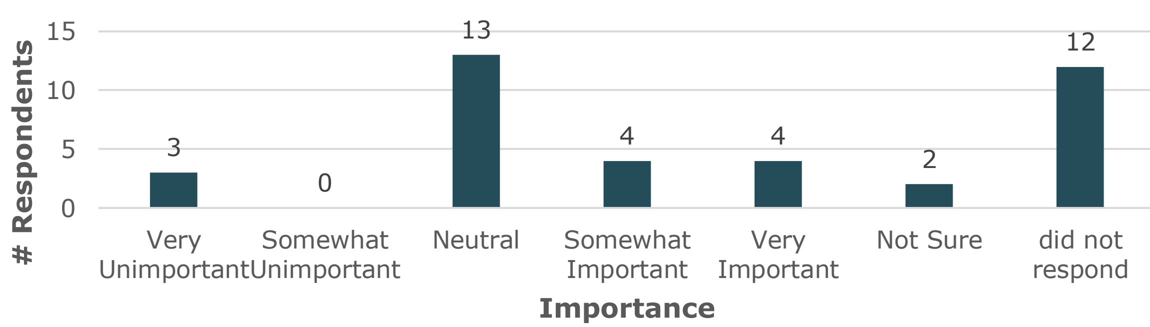
Other responses entered included: Wrong TLC system time causes timestamp misalignment in SPaT. They must be time synced | SPaT: Inaccuracies with signal timing (time to change phase); Miscorrelations between phase number (SPaT) and physical lane (MAP) | missing critical information like confidence | all are important parameters to be address | Currently there is no assured green time, and SPaT still broadcast when in flash. | Alignment between lane and corresponding signal head

Q9) What should happen when it is determined that a SPaT or MAP message is not accurate/valid? And who should be informed? (multi-response)



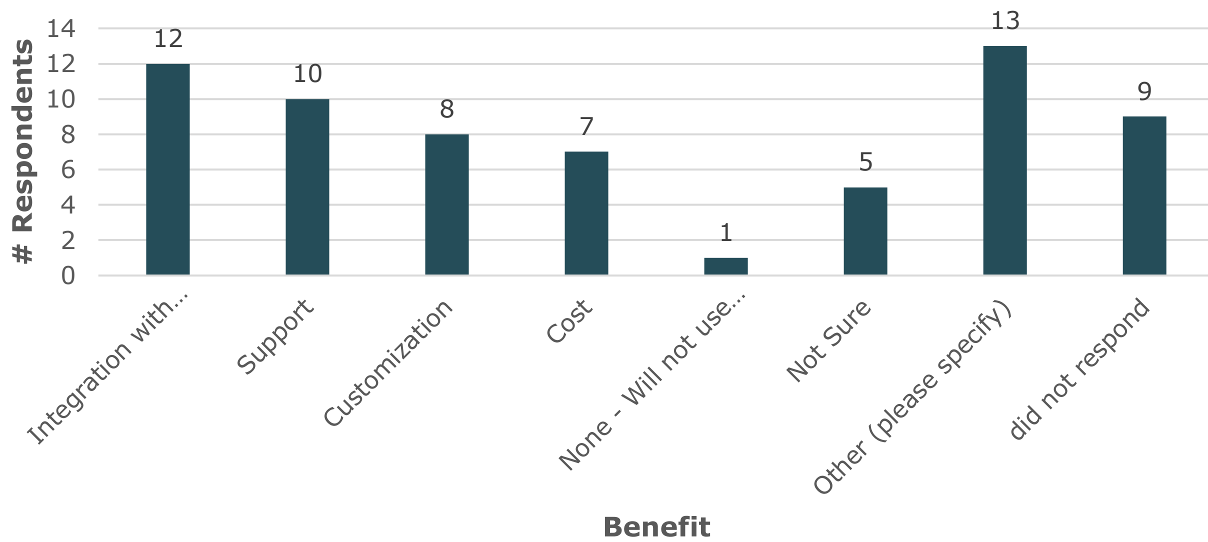
Other responses entered included: This is a technical challenge from the intersection equipment. Need to discuss one on one. | Our Central Software if installed will notify all authorized parties. | in certain situations - notification to SCMS MGR | Much more detail on the use case is required. One message is wrong and you're going to shut down the intersection broadcast? On who's authority? A more detailed selection of use cases need to be put forth. If however you can build a system that can identify these errors and the parameters are acceptable to contributing agencies, then any alert to cancel broadcasts needs to come through a secure channel signed as per IEEE 1609.2. | Depends on the issue and what applications are running at the intersection. I think the best approach is to change the intersection status object to say that SPaT and MAP are unavailable. You need to make a positive affirmation that the data is not available. That using the intersection status object in the SPaT alerts users that something is wrong (I don't know "approved" users are -- how do you know a user is approved?) The devices that noticed the needs to issue an alert to the controlling agency -- just like we do when signal goes into flash. I'm not sure email or text is appropriate though. Should be an error state in intersection management software. | Alert through the existing central signal system alarm process. | Evaluate issue and determine next step | Generate log entry for inclusion in future reports | backend reporting

Q10) How important is it that the proposed system is open source?



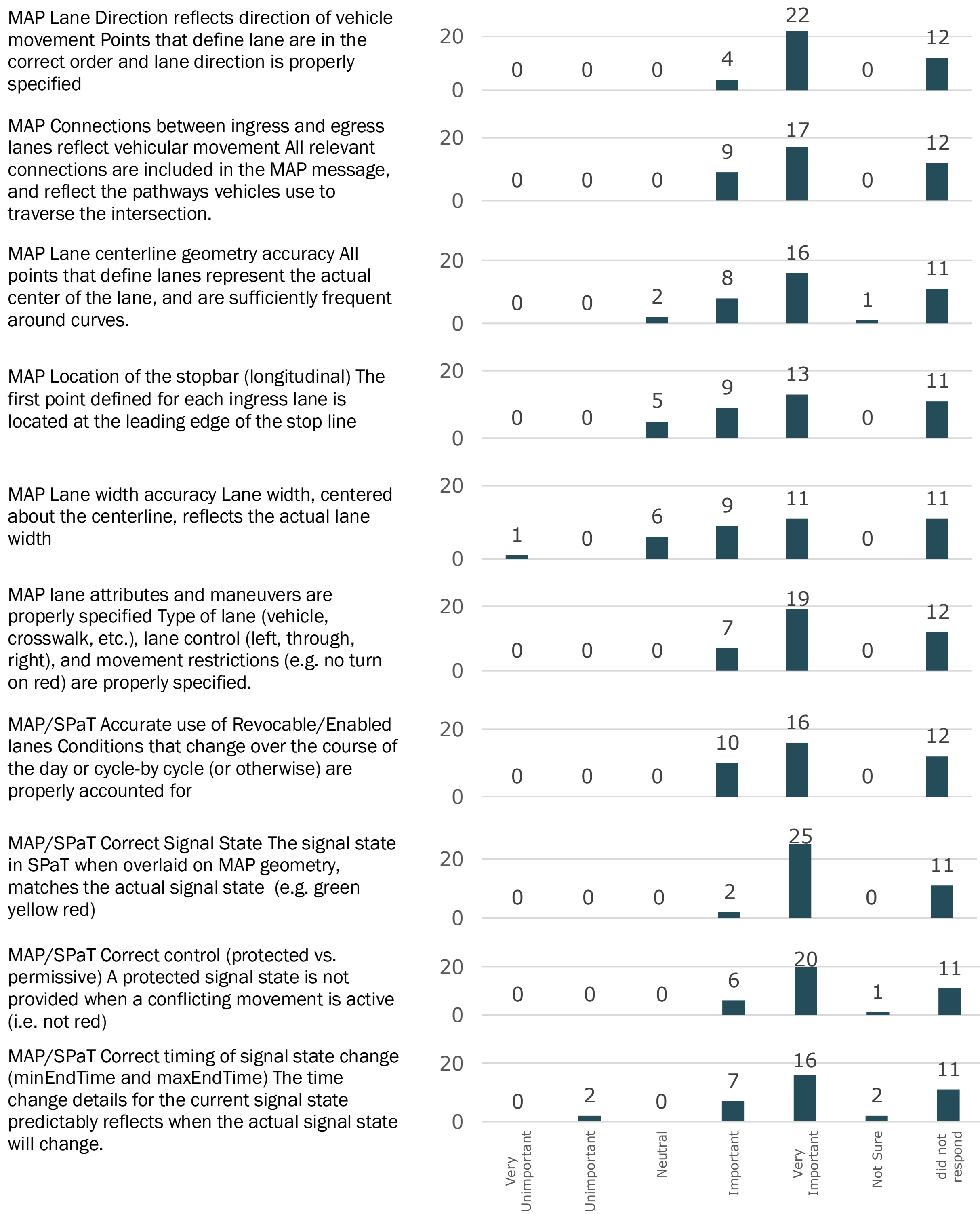
Other responses entered included: System itself is not important to be open source but it's interface should be open (API/SDK) | Who will be the responsible organization to manage and maintain the open source system? | Open Source may get the IOO started but takes time to understand and use the tools typically. Pay Services should allow quicker turn around and enhanced service offerings. | It is more important that it be trusted. | Error reporting and error check should be have standardized message objects and detection methodology. The source code to do the reporting, etc. will depend on where it resides | Common infrastructure approach so vehicles (OBUs) knows how to response. | The initial system development should be open-source in that it should be open for all users and integrators. Future integration efforts to improve / keep up to date might be performed by vendors acting under their own development funds. Those enhancements would therefore not be open source. | Open source is not a panacea -- and keeps some entities from participating. It should be in standards. This is a different concept but is essential to broad and growing deployment.

Q11) Which benefits of an open-source solution are important to include in the development of the new system? (multi-response)

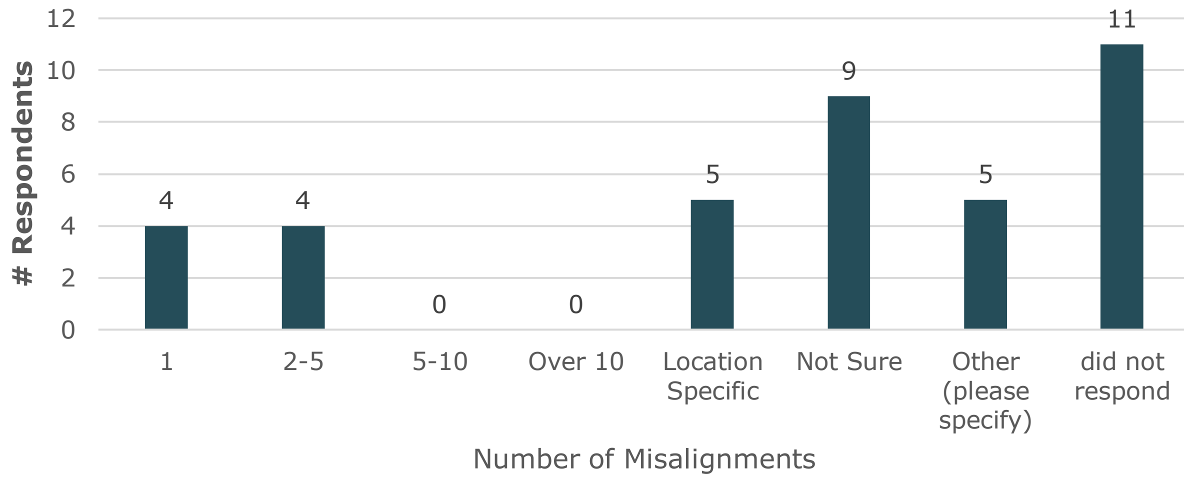


Other responses entered included: Customization for different vendors' current implementation (TLC, RSU) | Tools need to be available for public use. OSS can be used but there is a lot to be discussed here in planning for it. | peer review of logic | greater chance of learning about bugs | open-ness and transparency | An open design approach would best serve this situation. | Not sure it is appropriate for me to respond. It is important what we use standardized detection methodologies and responses/actions that devices take when errors occur. | Understand how such a system may work. | Interoperability and trusted common process | Base set of operational requirements and functionality | I think standardizing on configuration/system architecture and interfaces is more important than open source. | Easier integration with new systems | Per previous answer, not beneficial.

Q12) Indicate how important it is for each of the following aspects of SPaT and MAP messages to be consistently correct in order to be trustworthy.

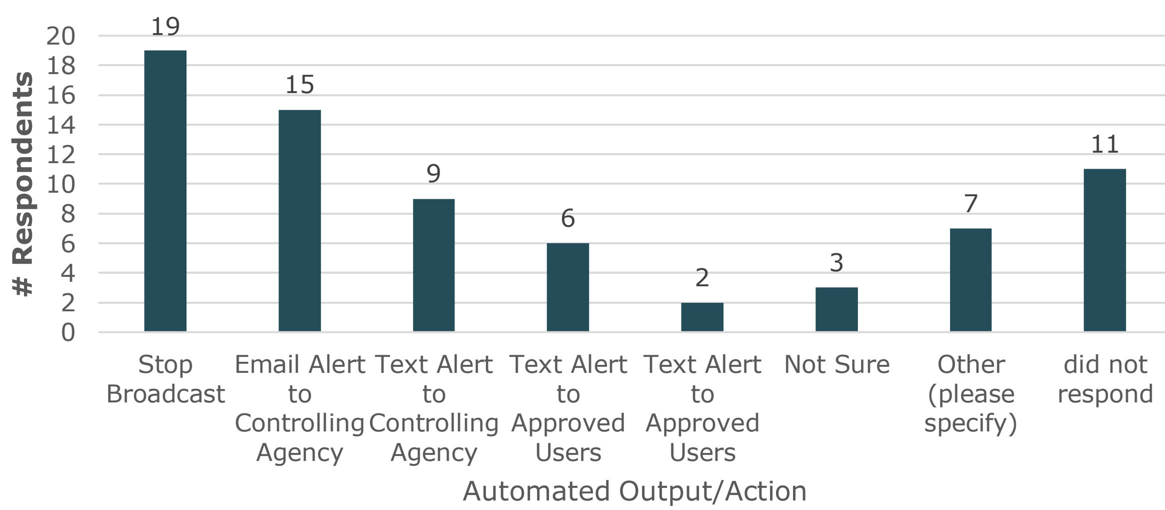


Q13) How many misalignments of the BSM vs SPaT/MAP messages should be required to trigger an alert?



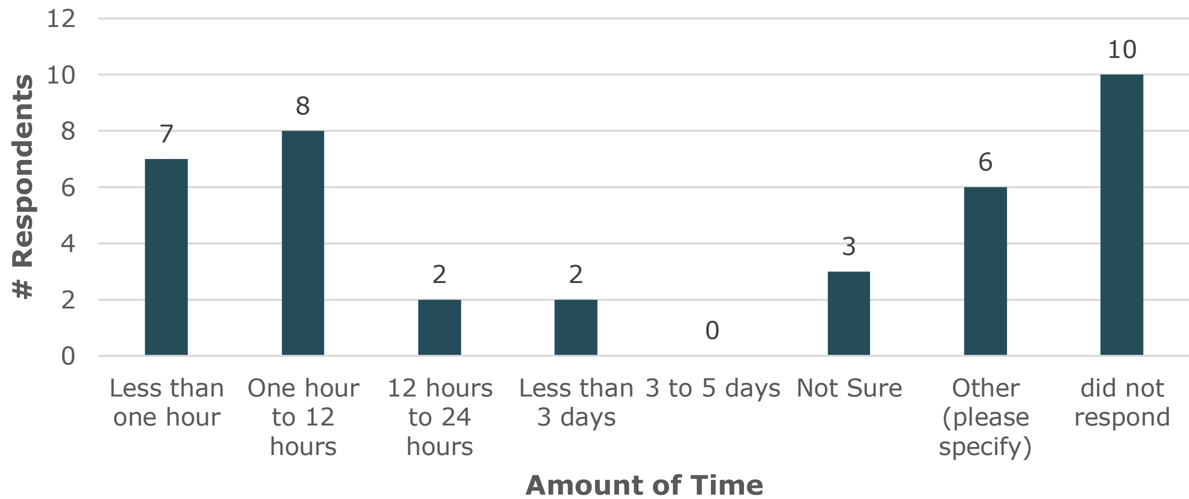
Other responses entered included: What is meant by misalignment between SPaT and BSM? Point of the question not clear | BSMs have their own issues, and BSMs produced by different manufacturers may perform better than others, and circumstances may drive this too. Probably more than 1, possibly more than 5 but definitely requires some research to understand just how good (or bad) BSMs are at leading to detection in SPaT/MAP. | I think this depends on the application. For example, RLVW might need very tight longitudinal accuracy, and not so much lateral accuracy. Other applications, such as IMA, might need both. | Location specific, but it's also a function of the type of misalignment and over a specified period of time. | Location Specific, within a specified time interval

Q14) What should the automated output/action be? (multi-response)



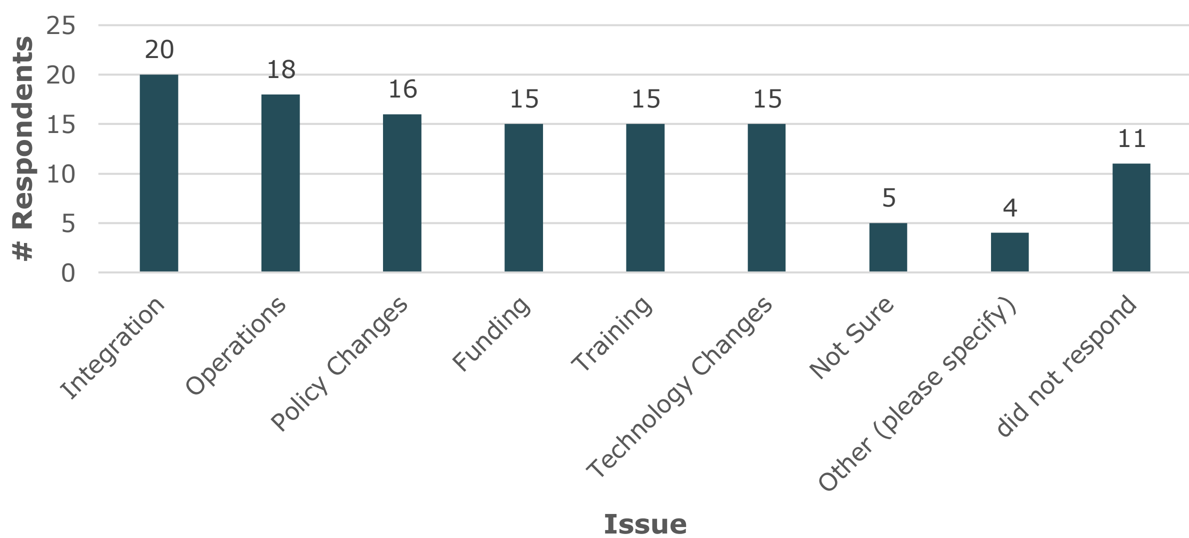
Other responses entered included: Automated output for what? | email alert to approved users | secure channel message to owner of the RSU/controlling agency. | Answered this already. Depends on application and what error is. The most important thing is that how errors are handle needs to be consistent between entities; therefore, responses need to be standardized by user community. | Send alert through existing central signal system alarms mechanism. | Email Alert to Approved Users | Consider revoking certificate asap |

Q15) How quickly would you expect the controlling agency to respond to an alert?



Other responses entered included: depends on what RSU actions are taken and what agency actions are required | Ideally there are multiple levels of response. There may be a protocol for automated response, with manual followup. Whether it is wise to stop broadcasts depends on the parameters used to generate the alert, as well as local conditions. | Depends on what error/issues is and what applications it impacts. Just like detection, in some cases, need to do risk assessment to determine impact of response. OEM do a safety analysis of applications, IOOs need something similar for infrastructure failures. | Need to respond very quickly to stop incorrect transmissions. Can take as long as necessary to get it started again correctly. | Depends | agency should confirm status of broadcast being off

Q16) What are the potential issues that a message monitoring system could experience? (multi-response)



Other responses entered included: Not clear on the question. | Accuracy | All of the above really, but I hit the biggest you listed. Bigger than all of those is establishing the institutional arrangements, assigning responsibilities and gaining trust. | Not enough BSMs available to function.