



SURFACE VEHICLE RECOMMENDED PRACTICE

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Connected Intersections Implementation Guide - SPaT Guidance

RATIONALE

The Connected Intersections (CI) Implementation Guide was developed by engaging a broad community of stakeholders, including but not limited to infrastructure owners/operators, automobile original equipment manufacturers (OEMs) and their suppliers, roadside unit (RSU) manufacturers, and the end users of connected vehicle data and services. The guide was supported by the United States Department of Transportation (USDOT) Intelligent Transportation Systems (ITS) Joint Program Office (JPO). Several associations, such as the American Association of State Highway Transportation Officials (AASHTO), the Institute of Transportation Engineers (ITE), the National Electrical Manufacturers Association (NEMA), and SAE International, contributed to ensuring balanced and effective stakeholder representation and adherence to standards development processes as Standards Development Organizations (SDOs).

The CTI 4501 family of documents are recommended practices developed with the combined effort of stakeholders representing the industry at large, including Infrastructure Owner Operators (IOOs), OEMs, fleet and truck operators, safety advocacy groups, multimodal partners, and end users of data and services. Several associations, including AASHTO, IEEE 1609 Working Group, ITE, NEMA, and SAE International, are involved in ensuring balanced and effective stakeholder representation and adherence to a consensus-based standards development process.

Through collaboration with these stakeholders, the guide addresses ambiguities and gaps identified by early deployers, providing direction on how to generate consistent, interoperable messages for signalized intersections across the United States, especially for automated transportation systems. Building on the USDOT-sponsored Cooperative Automated Transportation Clarifications for Consistent Implementations (CCIs) for Connected Signalized Intersections, the CI Implementation Guide focuses on harmonizing the messages broadcasted by connected intersections.

This document focuses on requirements and design considerations related to generating and broadcasting Signal Phase and Timing (SPaT) messages at connected intersections, providing practical guidance for broadcasting SPaT messages at connected intersections leading to interoperability and consistent data exchange across different regions and deployments.

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1. SCOPE

CTI 4501 defines the key capabilities and interfaces a connected signalized intersection must support to ensure interoperability with vehicles, including production vehicles, for state and local IOOs. A connected intersection is defined as an infrastructure system that broadcasts SPaT, MAP, and optionally position correction data to vehicles.

The CTI 4501 family of documents define procurement and implementation guidance and the expectations leading to minimum performance requirements for a connected intersection. It is intended to be used by IOOs to provide guidance on how to implement an interoperable connected intersection. For OEMs and other application developers, these recommended practices provide an explanation on what data and connected vehicle messages are being provided from an interoperable connected intersection so safety applications can be developed for production vehicles, with an initial focus on the Red Light Violation Warning (RLVW) application. Although the focus is on the RLVW application, requirements for other V2X applications related to connected intersections, including requirements for traffic signal controllers to generate the SPaT information, are also addressed assuming the connected intersection configuration and messages can support them and no significant effort was needed. The Needs to Requirements Traceability Matrix (NRTM) in CTI 4501 6.2.3 provides the guidance to IOOs for the procurement of a connected intersection.

Recognizing that some stakeholders require more in-depth guidance on specific aspects of connected intersections, Version 2 of the CI Implementation Guide has been reorganized into a main document and several companion sub-documents. The main document establishes the overarching framework - following a Systems Engineering Process (SEP) - and includes a Concept of Operations (ConOps) and an NRTM for a connected intersection and the generic requirements, generic system design details, and an RTM for those generic requirements. These elements enable users to identify and procure connected intersection solutions that satisfy their specific needs.

The companion documents elaborate on specialized areas such as SPaT, MAP, security, and testing and validation, providing requirements and design details tailored for those subject areas. Figure 1 depicts the relationships among these sub-documents and other documents that support the implementation of a connected intersection. By separating out these focused topics, the guide more effectively supports IOOs, OEMs, suppliers, and application developers who need targeted information. Taken together, the main guide and the companion documents ensure that connected intersection deployments align with national standards and support a high level of interoperability, ultimately facilitating safer and more efficient automated transportation systems.

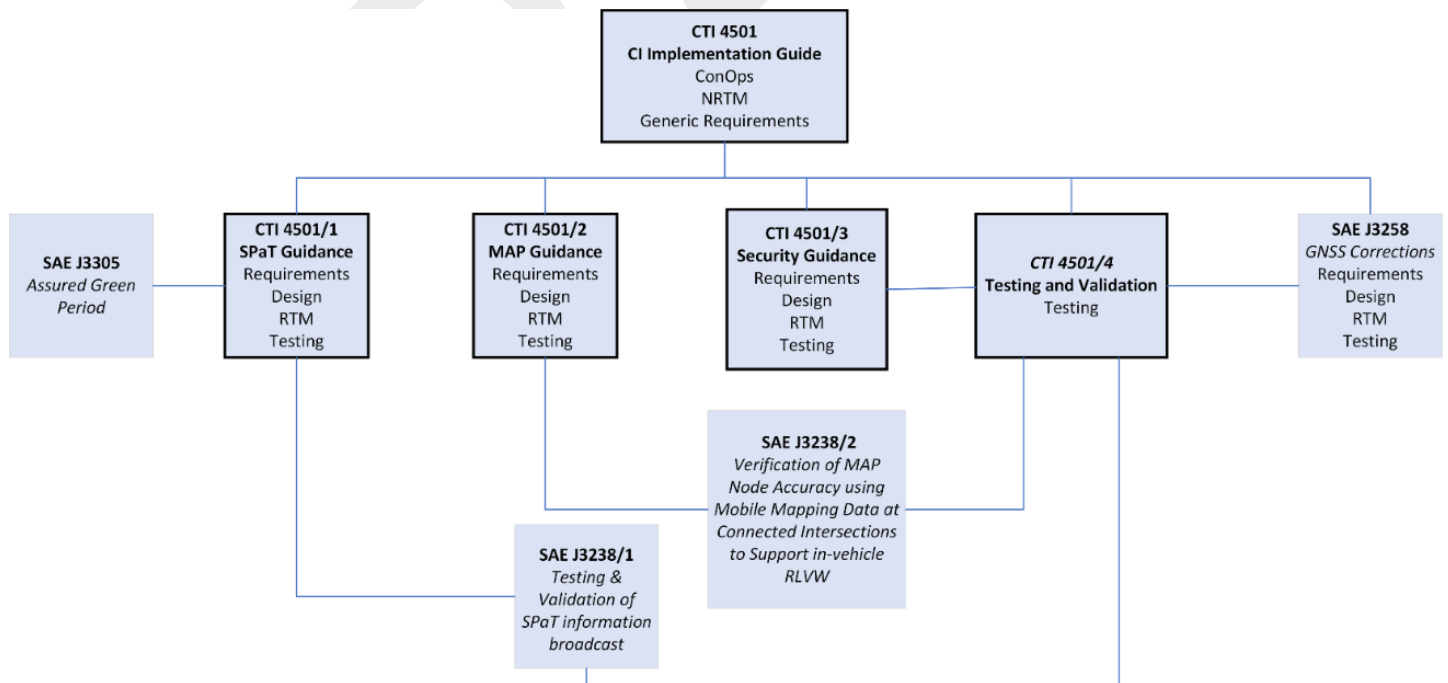


Figure 1 - Relationship with other documents

This document offers procurement and implementation guidance specific to SPaT messages in one focused resource while aligning with the overall structure and methodology of the main CTI 4501 document. It provides the requirements, design guidance, and testing considerations necessary to achieve minimum performance requirements for providing SPaT messages tailored for IOOs, OEMs, and application developers. This document allows stakeholders seeking detailed guidance on SPaT-related requirements and design considerations to access all relevant information in one focused resource while equipping practitioners with a comprehensive set of tools to design and deploy interoperable connected intersections.

For IOOs, this document provides actionable guidance on specifying and deploying SPaT-capable equipment to support interoperable connected intersections. For OEMs and developers, it explains which SPaT-related data and connected vehicle messages will be broadcast from compliant intersections, enabling the development of safety-critical applications such as RLVW.

2. REFERENCES

2.1 Applicable Documents

The following publications form a part of this specification to the extent specified herein. Unless otherwise indicated, the latest issue of SAE International and other publications shall apply.

2.1.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (U.S. and Canada only) or +1 724-776-4970 (outside U.S. and Canada), www.sae.org.

SAE J2735	V2X Communications Message Set Dictionary
SAE J2945/1	On-Board System Requirements for V2V Safety Communications
SAE J2945/9	Vulnerable Road User Safety Message Minimum Performance Requirements
SAE J3161	LTE Vehicle-to-Everything (LTE-V2X) Deployment Profiles and Radio Parameters for Single Radio Channel Multi-Service Coexistence
SAE J3161/1	Onboard System Requirements for LTE-V2X V2V Safety Communications
SAE J3224	V2X Sensor-Sharing for Cooperative and Automated Driving
SAE J3238/1	Testing and Validation SPaT information broadcast
SAE J3258	V2X Infrastructure Support for GNSS Corrections
SAE J3268	Listing of Provider Service Identifiers and Associated Application Technical Reports
SAE J3305	Assured Green Period to Support Red Light Violation Warning
SAE J3315	LTE-V2X Requirements and Deployment Profile for Aftermarket V2X Devices

2.1.2 Connected Transportation Interoperability (CTI) Publications

CTI documents are jointly developed by American Association of State Highway and Transportation Officials, Institute of Transportation Engineers, National Electrical Manufacturers Association, and SAE International. Available at: <https://www.ite.org/technical-resources/standards/rsu-standardization/>.

CTI 4001	Roadside Unit (RSU) Standard
CTI 4501	Connected Intersections (CI) Implementation Guide

- CTI 4501/2 Connected Intersections (CI) Implementation Guide - MAP Messages
- CTI 4501/3 Connected Intersections (CI) Implementation Guide - Security Guidance
- CTI 4501/4 Connected Intersections (CI) Implementation Guide - Testing and Validation

2.1.3 ETSI Publications

Available from European Telecommunications Standards Institute (ETSI), <https://www.etsi.org>.

- ETSI TS 136 213 Evolved Universal Terrestrial Radio Access (E-UTRA); Physical layer procedures, V14.2.0 (Release 14) [3GPP TS 36.213]
- ETSI TS 136 321 Evolved Universal Terrestrial Radio Access (E-UTRA); Medium Access Control (MAC) protocol specification, V14.2.1 (Release 14) [3GPP TS 36.321]
- ETSI TS 136 322 Evolved Universal Terrestrial Radio Access (E-UTRA); Radio Link Control (RLC) protocol specification, V14.1.0 (Release 14) [3GPP TS 36.322]

2.1.4 IEEE Publications

Available from IEEE Operations Center, 445 and 501 Hoes Lane, Piscataway, NJ 08854-4141, Tel: 732-981-0060, www.ieee.org.

Please note that this report incorporates certain IEEE specifications by reference. ESSENTIAL IPRs (Intellectual Property Rights) have been declared to IEEE. All information statements and licensing declarations of ESSENTIAL IPRs received by IEEE are publicly available via the IEEE IPR Online Database found at <https://standards.ieee.org/about/sasb/patcom/patents/>.

- IEEE Std 610.12 IEEE Standard Glossary of Software Engineering Terminology
- IEEE Std 802.11 IEEE Standard for Information technology - Telecommunications and information exchange between systems local and metropolitan area networks - Specific requirements - Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications (IEEE802dot11-MIB in Annex A.3)
- IEEE Std 1609.2 IEEE Standard for Wireless Access in Vehicular Environments - Security Services for Applications and Management Messages
- IEEE Std 1609.3 IEEE Standard for Wireless Access in Vehicular Environments (WAVE) - Networking Services

2.1.5 Internet Documents

Available from several repositories on the Internet or by “anonymous” File Transfer Protocol (FTP) with several hosts. Browse or FTP to <https://www.rfc-editor.org>.

- IETF RFC 4253 The Secure Shell (SSH) Transport Layer Protocol
- IETF RFC 8446 The Transport Layer Security (TLS) Protocol

2.1.6 ISO Publications

Copies of these documents are available online at www.iso.org/store.

- ISO/IEC/IEEE 24765 Systems and software engineering – Vocabulary

2.1.7 National Academy of Sciences Publications

Available at <https://www.trb.org>.

Signal Timing Manual

2.1.8 NIST Publications

Available from NIST, 100 Bureau Drive, Stop 1070, Gaithersburg, MD 20899-1070, Tel: 301-975-6478, www.nist.gov.

NIST FIPS 140-2 Security Requirements for Cryptographic Modules

2.1.9 NTCIP Standards

Available from NTCIP Coordinator, National Electrical Manufacturers Association, 1300 N. 17th Street, Suite 900, Rosslyn, Virginia 22209-3801, <https://www.ntcip.org>.

NTCIP 1202 National Transportation Communications for ITS Protocol Object Definitions for Actuated Signal Controllers (ASC) Interface

NTCIP 1218 National Transportation Communications for ITS Protocol Object Definitions for RoadSide Units (RSU)

2.1.10 RTCM Standards

Available from the Radio Technical Commission for Maritime Services, 2200 Wilson Blvd., Suite 102-109, Arlington, VA 22201, <https://www.rtc.org/publications>.

RTCM Standard 10410 Standard for Networked Transport of RTCM via Internet Protocol (NTRIP) - An application-level protocol that supports streaming Global Navigation Satellite System (GNSS) data over the Internet

2.1.11 U.S. Department of Transportation Publications

Available from U.S. Department of Transportation at <https://www.transportation.gov/>.

MUTCD Manual on Uniform Traffic Control Devices for Streets and Highways

V2I Hub ICD Integrated Vehicle-to-Infrastructure Prototype (IVP), V2I Hub Interface Control Document (ICD) - Final Report

2.2 Related Publications

The following publications are provided for information purposes only and are not a required part of this SAE Technical Report.

2.2.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (U.S. and Canada only) or +1 724-776-4970 (outside U.S. and Canada), www.sae.org.

SAE J2945 Dedicated Short Range Communication (DSRC) Systems Engineering Process Guidance for SAE J2945/X Documents and Common Design Concepts™

SAE J3161/2 LTE Vehicle-to-Everything (LTE-V2X) Deployment Profiles and Radio Parameters for PC5 Interface in 10 MHz Channel 180

SAE J3287 V2X Misbehavior Reporting

2.2.2 Crash Avoidance Metrics Partners (CAMP) Publications

Available from CAMP LLC at <https://www.campllc.org/publications/>.

Red Light Violation Warning (RLVW) Application Vehicle System, Concept of Operations, Version 2.4, CAMP LLC, V2I-4 Consortium, 1/18/2021.

Red Light Violation Warning (RLVW) Application Vehicle System, High-Level System Requirements, Version 1.10, CAMP LLC, V2I-4 Consortium, 1/12/21.

2.2.3 Connected Transportation Interoperability (CTI) Documents

CTI documents are jointly developed by American Association of State Highway and Transportation Officials, Institute of Transportation Engineers, National Electrical Manufacturers Association, and SAE International. Available at: <https://www.ite.org/technical-resources/standards/rsu-standardization/>.

CTI 4502 Connected Intersections Validation Report: Findings from the Connected Intersections (CI) Project Validation Phase

2.2.4 Connected Vehicle Pooled Fund Study Documents

Available at <https://engineering.virginia.edu/labs-groups/cvpfs>.

CVPFS Connected Intersection Guidance Document

CVPFS CIMMS Systems Requirements

CVPFS Guidance Document for MAP Message Preparation

2.2.5 IEEE Publications

Available from IEEE Operations Center, 445 and 501 Hoes Lane, Piscataway, NJ 08854-4141, Tel: 732-981-0060, <https://www.ieee.org>.

IEEE Std 829 IEEE Std 829 IEEE Standard for Software and System Test Documentation

IEEE Std 1362 IEEE Guide for Information Technology System Definition - Concept of Operations (ConOps) Document

2.2.6 Institute of Transportation Engineers Publications

Copies of these documents are available online at <https://www.ite.org/>.

Manual of Traffic Signal Design

Traffic Control Devices Handbook

2.2.7 ISO Publications

Copies of these documents are available online at www.iso.org/store.

ISO 26262 Road vehicles - Functional safety, International Standards Organization

ISO/PAS 21448 Road vehicles - Safety of the Intended Functionality

2.2.8 NEMA Standards

Available from National Electrical Manufacturers Association, 1812 N. Moore Street, Suite 2200, Arlington, VA 22209, Tel: 703-841-3200, www.makeitelectric.org.

NEMA TS 40001 Traffic Control Systems

NEMA TS 40002 Traffic Controller Assemblies with NTCIP Requirements

NEMA TS 40010 Connected Vehicle Infrastructure - Roadside Equipment

2.2.9 NTCIP Standards

Available from NTCIP Coordinator, National Electrical Manufacturers Association, 1300 N. 17th Street, Suite 900, Rosslyn, Virginia 22209-3801, <https://www.ntcip.org>.

NTCIP 8002 Annex B1 National Transportation Communications for ITS Protocol Content Outline for NTCIP 1200-Series Documents (for Standards Engineering Process (SEP) Content)

NTCIP 9001 The NTCIP Guide

2.2.10 SCMS Manager Publications.

Available from SCMS Manager at <https://www.scmsmanager.org/publications/>.

End-entity Security Requirements, Design Guidance, and Validation Approach

2.2.11 U.S. Department of Transportation Documents

Available from U.S. Department of Transportation at <https://www.transportation.gov/>.

RSU Specification 4.1 Dedicated Short-Range Communications Roadside Unit Specifications v4.1, USDOT, Saxton Transportation Operations Laboratory

Systems Engineering for ITS

2.2.12 Other Publications

CIS Controls Implementation Guide for Industrial Control Systems

Cooperative Automated Transportation Clarifications for Consistent Implementations (CCIs) To Ensure National Interoperability Connected Signalized Intersections

Enabling Connected Intersections Concept Paper - Working Draft to Support Discussions of the IOO/OEM Forum SPaT/RLVW Group

3. DEFINITIONS

For the purposes of this recommended practice, the following definitions shall apply.

APPROACH: All lanes of traffic moving towards an intersection or a midblock location from one direction, including any adjacent parking lane(s). An approach is typically identified by its general flow, i.e., “the east-bound approach.” In this document, an approach consists of one or more motor vehicle lanes of travel, as well as possible pedestrian lanes, parking lanes, barriers, and other types of lane objects some of which cross the path of the motor vehicle travel. Approach is also used in certain messages to specify where one or more lanes begin, regardless of whether the lane is ingress or egress.

Source: SAE J2735

APPROACH SPEED: The uninterrupted speed (or free-flow speed) of through movement vehicles used in the design of the timing parameters that control the operations of the traffic signal.

ASSURED GREEN END TIME (AGET): The UTC time denoting the end of a green signal indication for a movement. The AGET is set when the CI/TSC infrastructure determines when the through movement green interval will definitively end, unless there is preemption, failure, or something else outside of the CI/TSC infrastructure's control.

ASSURED GREEN PERIOD (AGP): When a connected vehicle is approaching a connected intersection in a through lane currently in a green signal state indication, the AGP is a fixed portion of green interval for the through movement that, when combined with the duration of the yellow change interval, decreases the likelihood that the vehicle will be in the connected intersection during a red signal state indication.

COMPONENT: An element of the CI System. The element may be a device or a logical process.

CONNECTED INTERSECTION (CI): An infrastructure system that creates and broadcasts signal, phase, and timing (SPaT), mapping information, and position correction data to On-Board Units (OBUs) and Mobile Units (MUs).

CONNECTED VEHICLE: A vehicle equipped with devices enabling interoperable direct short-range broadcast communication to convey and receive safety- and mobility-enhancing messages.

CONNECTION: In the context of a connected intersection, the link between an ingress lane and a downstream lane, which may be an egress lane out of the intersection or an ingress lane within the intersection (e.g., storage lane).

EXTENSIBLE PORTION: That portion of the green interval of an actuated phase following the initial portion that may be extended, for example, by traffic actuation. Source: NEMA TS2-2021.

EXTERNAL CONTROL LOCAL APPLICATION (ECLA): An application that asserts a higher-level control over the traffic signal controller.

FIRMWARE: Software tightly coupled to a specific piece of computing hardware. Typically used for control, configuration, and interface definition and rarely interacted with directly by the user. It may be necessary for firmware to be updated from time to time, for example, to ensure the continued correct operation of the hardware or expose or enable new features.

INITIAL PORTION: The first timed portion of the green interval in an actuated controller unit. Source: NEMA TS2-2021.

INTERCHANGEABILITY: The capability to exchange devices of the same type on the same communications channel and have those devices interact with other devices of the same type using standards-based functions. Source: NTCIP 9001

INTERFACE: A shared boundary across which information is passed. Source: IEEE Std 610.12

INTEROPERABILITY: The ability of two or more systems or components to exchange information and to use the information that has been exchanged. Source: IEEE Std 610.12

INTERSECTION OR INTERSECTION BOX: Where a stop line, yield line, or crosswalk is designated on the roadway on the intersection approach, the area within the crosswalk and/or beyond the designated stop line or yield line shall be part of the intersection. If there are no stop lines, then the intersection box is defined by the extension of the curb lines. Refer to MUTCD for additional definitions of an intersection.

LONG-TERM EVOLUTION-BASED VEHICLE-TO-EVERYTHING (LTE-V2X): Vehicle-to-everything (V2X) sidelink communications protocols specified by 3GPP (releases 14 and 15).

MOBILE UNIT (MU): A device used to wirelessly communicate with other devices for safety and mobility purposes carried by a pedestrian, bicyclist, work zone worker, or other traveler. Source: CTI 4001

MOVEMENT: A term used to describe the user (e.g., vehicle or pedestrian) action taken at an intersection (e.g., vehicle turning movement or pedestrian crossing). Two different types of movements include those that have the right-of-way (protected/exclusive) and those that must yield (permitted/permissive), consistent with the rules of the road or the Uniform Vehicle Code. Source: Signal Timing Manual

ON-BOARD UNITS (OBU): A device used to wirelessly communicate with other devices for safety and mobility purposes installed in a vehicle as original equipment or as aftermarket equipment (sometimes referred to as an “aftermarket V2X device (AVD).” Source: SAE J3315

PERMISSIVE MOVEMENT: A permitted movement that may conflict with protected movements and other permissive movements. Traffic making a permissive movement must yield to conflicting traffic, which may require the traveler to first come to a full stop.

PERMITTED MOVEMENT: A movement that is allowed to proceed if there are available gaps in the conflicting flow. Source: Signal Timing Manual

PREEMPTION: The transfer of the normal control of signals to a special signal control mode for the purpose of servicing railroad crossings, emergency vehicle passage, mass transit vehicle passage, and other special tasks, the control of which requires terminating normal traffic control to provide the higher priority needs of the special task. Source: NTCIP 1202

PROTECTED MOVEMENT: A permitted movement that has the right of way over other conflicting movements (including pedestrians) and is not required to yield to permissive movements. Traffic making a protected movement should be aware that conflicting traffic from other signal types (e.g., pedestrian signals) may need to clear the intersection before proceeding.

PROTECTED/PERMISSIVE MOVEMENT: A permitted movement at an intersection that, through the use of different signal indications, is protected (i.e., has the exclusive right-of-way over conflicting movements) during a defined portion of the signal operations and permissive (i.e., must yield the right-of-way to conflicting movements) during other portions of the signal operations.

PROVIDER SERVICE IDENTIFIER: An integer that identifies an application specification. Source: SAE J3268

RED LIGHT VIOLATION WARNING (RLVW) APPLICATION: An application that aims to reduce the potential for conflicts with other vehicles and pedestrians in the intersection. Source: RLVW Application Vehicle System, Concept of Operations

RLVW DETECTION ZONE (RDZ): The area on a through movement lane that is used to detect vehicles for the RLVW operation.

ROADSIDE UNIT (RSU): A transportation infrastructure communications device located on the roadside that provides V2X connectivity between OBUs/MUs and other parts of the transportation infrastructure, including traffic control devices, traffic management systems, and back-office systems.

NOTE: Devices that are not part of the transportation infrastructure, such as cellular base stations or satellites, are not RSUs.

Source: CTI 4001

ROBUSTNESS: Degree to which a system or component can function correctly in the presence of invalid inputs or stressful environmental conditions. Source: ISO/IEC/IEEE 24765

REVOCABLE LANE: A lane whose properties may be in effect or not. Lane properties in SAE J2735 are defined by the type of lane (e.g., a travel lane, a parking lane, a shoulder), the type of travelers that may use the lane (passenger vehicles, transit vehicles only, bicycles, pedestrians), and the direction of travel. A physical lane in the roadway may be defined by more than one lane identifier, each with a different set of lane properties, and a bit can be used to determine if that lane property is in effect or not. For example, a reversible lane may be defined by two lane identifiers, one for each direction of traffic, but only one (revocable) lane identifier is in effect.

SIGNAL GROUP: A logical grouping of one or more traffic movements that are controlled by the same traffic signal indication (e.g., green, yellow, red). Each signal group typically governs the right-of-way for a specific set of vehicle or pedestrian movements at an intersection and is the basis for how signal timing is communicated in connected vehicle systems. Signal groups enable coordination between the SPaT and MAP messages by identifying which movements receive which signal indications. See Movement above. Source: SAE J2735, section on DF_MovementState

SIGNAL GROUP ID: A numeric identifier assigned to a signal group within the Signal Phase and Timing (SPaT) message. It uniquely identifies which set of traffic movements is governed by a particular signal indication at a given intersection. This ID serves as the link between the SPaT message (which provides the signal state) and the MAP message (which defines the intersection's geometry and permitted movements). Source: SAE J2735, section on DF_MovementState

SIGNAL INDICATION: The illumination of a signal lens or equivalent device. Source: MUTCD

SIGNAL INTERVAL: The part of a signal cycle during which signal indications do not change. Source: MUTCD

SIGNAL MONITOR UNIT: Field equipment that monitors the functions within a traffic cabinet. Industry standard examples of a signal monitor unit include Malfunction Management Unit (MMU) and Cabinet Monitor Unit (CMU).

SIGNAL TIMING DATA: For the purpose of this document, signal timing data for a connected intersection is the movement state and information when a movement may end for each movement at an intersection.

SIGNAL TIMING STATUS: For the purpose of this document, signal timing status is the status of the signal controller, such as its mode of operation, and its failure state, if any.

SPaT INFORMATION: Signal phase and timing data, such as timing and movement state information for each movement through an intersection, which is sent from a traffic signal controller to another device. This document describes three methods to send SPaT information to RSUs.

STATUTORY SPEED LIMIT: A speed limit established by legislative action (such as Federal or State law) that typically is applicable for a particular class of highways with specified design and functional, jurisdictional, and/or location characteristics and that is not necessarily displayed on Speed Limit signs. Source: MUTCD

THROUGH MOVEMENT: A movement of a vehicle or pedestrian at an intersection where the direction of travel is unaltered by a left turn, right turn, or U-turn.

TIME MARK: Used to relate a moment in UTC (Coordinated Universal Time)-based time (referenced from the top of the hour) when an event is predicted or expected to occur, such as a change in the signal indication). Time marks are expressed as the number of 1/10th of seconds from the beginning (or top) of the hour. Refer to SAE J2735.

TRANSPORTATION FIELD DEVICES: Devices and electronic systems that monitor and control traffic operations on a roadway. Examples include a traffic signal controller and a roadside unit.

TRAVEL LANE: The area of the roadway designated for the movement of a vehicle, pedestrian, bicycle, or designated user.

TSC INFRASTRUCTURE: The systems and components within the traffic cabinet that control the operations of the signal indications at a signalized intersection, including an external control local application (ECLA) that may assert a higher-level control over the traffic controller.

V2X: Vehicle-to-everything (V2X) communications are comprised of various connected devices including vehicles (V), infrastructure (I), and other devices (D). Subsets of V2X communications referenced in this document include vehicle to vehicle (V2V), vehicle-to-infrastructure (V2I), and infrastructure-to-vehicle (I2V). Source: SAE J3161

V2X VEHICLE: A vehicle equipped with devices enabling interoperable direct short-range broadcast communication using 3GPP-defined LTE-V2X Rel-14 PC5 mode to convey safety- and mobility-enhancing messages. The V2X vehicle defined and used in this document does not include networked communications or commercial connected vehicle applications. Source: SAE J3161 and SAE J3161/1

VULNERABLE ROAD USER (VRU): A road user, who is not occupying a vehicle such as a passenger car, motorcycle, public transit vehicle, or train. Pedestrians, cyclists, children, elderly, disabled people, and road workers are particularly vulnerable to serious injury or death when involved in a motor-vehicle-related collision. Source: SAE J2945/9

4. ABBREVIATIONS

Cited below are the abbreviations that are used in this report:

AASHTO	American Association of State Highway and Transportation Officials
AGET	Assured Green End Time
AGP	Assured Green Period
ARC-IT	Architecture Reference for Cooperative and Intelligent Transportation
ASN.1	Abstract Syntax Notation 1
BSM	Basic Safety Message
CAT	Cooperative Automated Transportation Coalition
CCI	Clarifications for Consistent Implementations (document)
CI	Connected Intersection
CMU	Cabinet Monitor Unit
ConOps	Concept of Operations
CRL	Certificate Revocation List
CTI	Connected Transportation Interoperability
CV	Connected Vehicle
CVPFS	Connected Vehicle Pooled Fund Study
DSRC	Dedicated Short Range Communication
DTLS	Datagram Transport Layer Security
ECLA	External Control Local Application
FHWA	Federal Highway Administration
GNSS	Global Navigation Satellite System
HSM	Hardware Security Module
IEEE	Institute of Electrical and Electronics Engineers
ICD	Interface Control Document
IFM	Immediate Forward Message
IOO	Infrastructure Owner/Operator

ITE	Institute of Transportation Engineers
JSON	Java Script Object Notation
LTE-V2X	Long-Term Evolution-Vehicle to Everything
MMU	Malfunction Management Unit
MPH	Miles per Hour
MTBF	Mean Time Between Failures
MU	Mobile Units
MUTCD	Manual of Uniform Traffic Control Devices
NEMA	National Electrical Manufacturers Association
NRTM	Needs to Requirements Traceability Matrix
NTRIP	Network Transport of RTCM via Internet Protocol
NTP	Network Time Protocol
O&M	Operations & Maintenance
OBU	On-Board Units
OEM	Original Equipment Manufacturers
PER	Packet Error Rate
PTP	Precise Time Protocol
PSID	Provider Service Identifier
PSM	Personal Safety Message
RAID	Road Authority Identifier
RLVW	Red Light Violation Warning
RSU	Roadside Unit
RTCM	Radio Technical Commission for Maritime Services
RTCTM	Requirements to Test Case Traceability Matrix
RTM	Requirements Traceability Matrix
SAE	SAE International
SCMS	Security Credential Management System
SDO	Standards Development Organization
SEP	Systems Engineering Process

SMU	Signal Monitor Unit
SPaT	Signal Phase and Timing
TLS	Transport Layer Security
TOD	Time of Day
TSC	Traffic Signal Controller
TSCBM	Traffic Signal Controller Broadcast Message
UPER	Unaligned Packed Encoding Rules
USDOT	United States Department of Transportation
V2I	Vehicle-to-Infrastructure
V2X	Vehicle-to-Everything
VRU	Vulnerable Road User
WSM	WAVE Short Message

5. CONCEPT OF OPERATIONS

Refer to CTI 4501, Section 5, Concept of Operations for the user needs, Needs to Requirements Traceability Matrix (NRTM), and operational scenarios.

6. FUNCTIONAL REQUIREMENTS

This section defines the functional requirements for SPaT messages based on the user needs identified in the Concept of Operations (refer to CTI 4501, Section 5, Concept of Operations). This section includes the following:

- a. A tutorial
- b. Requirements. These are requirements that collectively satisfy the user needs related to the generation of SPaT information and SPaT messages identified in CTI 4501, 5.4, Needs. These requirements provide the details so that a requirement can be fulfilled and validated.
- c. Needs to Requirements Traceability Matrix (NRTM). A functional requirement is a requirement of a given function and therefore is only required to be implemented if the associated functionality (e.g., user need) is selected through the use of the NRTM. The NRTM also indicates which of the items are mandatory, conditional, or optional. The NRTM can be used by procurement personnel to specify the desired features for a connected intersection or can be used by an implementation to document the features supported by their implementation. The NRTM can also be used to define which requirements are to be tested (by demonstrating which requirements are to be implemented). The NRTM is in CTI 4501, Table 5, Needs to Requirements Traceability Matrix.

Section 6 is intended for all readers, including the following:

- Transportation Managers
- Transportation Operators
- Transportation Engineers
- System Integrators
- Device Manufacturers
- Application Developers

For the first four categories of readers, Section 6 is useful in understanding the details of CTI 4501. For these readers, the NRTM is particularly useful in preparing procurement specifications and assists in mapping the various rows of this table to the more detailed text contained within the other sections.

For the next two categories of readers, this section is useful to fully understand what is required for conformance to CTI 4501. Table 5, Needs to Requirements Traceability Matrix in CTI 4501 may be used to document the capabilities of their implementations.

For application developers, this section is useful to understand the data provided by a connected intersection and what the data represents.

6.1 Tutorial [Informative]

This Functional Requirements section defines the formal requirements that are intended to satisfy the user needs identified in CTI 4501, 5.4, Needs. This is achieved through the development of an NRTM that traces each user need to one or more requirements defined in this section. The details of each requirement are then presented in 6.3, Requirements.

6.2 Needs to Requirements Traceability Matrix (NRTM)

Refer to CTI 4501, 6.2 for the Needs to Requirements Traceability Matrix.

6.3 Requirements

The requirements for CTI 4501/1 follow.

Some requirements are generic requirements for a CI system, and this section references those requirements in CTI 4501. Some requirements are not applicable to the generation or broadcast of SPaT messages but are included in this section so the numbering is consistent among CTI 4501 and the sister documents of CTI 4501/1 (e.g., CTI 4501/2).

6.3.1 Architectural Requirements

The requirements for wireless communications from a connected intersection to the applications on an OBU/MU follow.

6.3.1.1 LTE-V2X Traffic Class Settings

Refer to CTI 4501, 6.3.1.1, LTE-V2X Traffic Class Settings.

6.3.1.1.1 Traffic Class Requirements

When using LTE-V2X, each packet generated by the application layer is associated with a priority value, called ProSe Per Packet Priority (PPPP). PPPP can be used to determine the minimum PDB, Channel Occupancy Ratio (CR) limit, and Reference Signal Receive Power (RSRP) threshold for accessing the channel.

Refer to SAE J3161 for the definition of and background on SPS and one shot transmission, PPPP, and PDB.

6.3.1.1.1.1 ProSe Per Packet Priority – SPaT Message

A connected intersection shall broadcast SPaT messages using the SAE J3161 settings specified in Table 1.

Table 1 - SPaT LTE-V2X Settings

Parameter	Setting	Notes
Frequency Band	Refer to SAE J3161	SAE J3161 only defines a single frequency band.
Destination Layer 2 ID	Refer to SAE J3161	See section on Broadcast Addressing.
Traffic Family	Essential I2V	See section on Different Traffic Classes in SAE J3161.
ProSe per Packet Priority (PPPP) Value	5	This is the minimum value provided by SAE J3161.
Packet Delay Budget (PDB)	100 ms	This is the minimum value provided by SAE J3161.
Channel Occupancy Ratio (CR) Limit	Refer to SAE J3161	
Reference Signal Receive Power (RSRP)	Refer to SAE J3161	
Transmit Power Level	Refer to SAE J3161	<ul style="list-style-type: none"> SAE J3161 defines the maximum conducted power at the radio device's port to the antenna cable. If an implementation needs more power than this, it can do so via the use of a higher gain antenna if the max EIRP is within regulatory requirements. An implementation may use a lower power level than this as long as it can still meet the transmit range requirements specific to the implementation.

NOTE: These settings are the recommended traffic class settings in SAE J3161 for SPaT messages.

6.3.1.1.2 Transmit Radio Requirements

The transmit radio requirements for wireless communications using LTE-V2X from a connected intersection to the applications on an OBU/MU follow.

6.3.1.1.2.1 Transmit Radio - SPaT Message

A connected intersection shall follow the radio profile and parameters for transmitting SPaT messages as described in SAE J3161.

6.3.2 TSC Infrastructure to RSU Requirements

The requirements for a TSC infrastructure to provide signal timing information to an RSU, as depicted by the green arrow in Figure 2, follow.

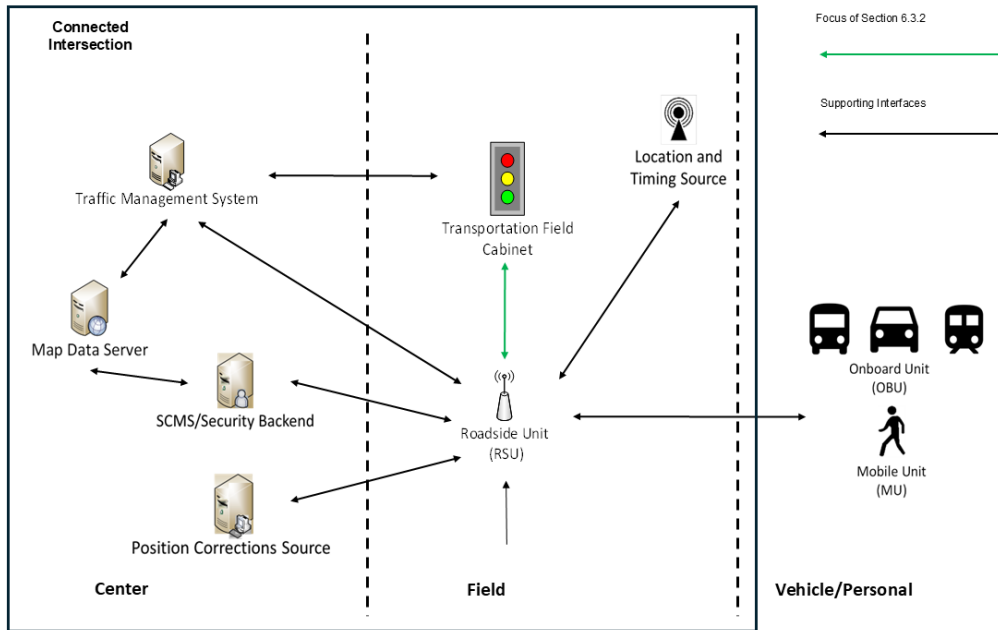


Figure 2 - Context for TSC infrastructure to RSU requirements

6.3.2.1 TSC Infrastructure Signal Timing Data Requirements

The requirements for a TSC infrastructure to provide signal phase and timing data to an RSU follow.

6.3.2.1.1 SPaT Information Requirements

The formats for a TSC infrastructure to provide “SPaT information” to an RSU follow. SPaT information contains the signal phase and timing data, such as the expected duration and movement state for each allowed movement through an intersection, necessary to generate an *SAE J2735* SPaT message. See the red arrow in Figure 3. It is assumed that the RSU will be signing the UPER *SAE J2735* SPaT message.



Figure 3 - SPaT information

6.3.2.1.1.1 NTCIP 1202 SPaT Information

A TSC infrastructure shall send SPaT information to an RSU in conformance with the applicable requirements in *NTCIP 1202*, 3.5.4.

6.3.2.1.1.2 TSCBM SPaT Information

A TSC infrastructure shall send SPaT information to an RSU in compliance with the Traffic Signal Controller Interface defined in Chapter 3 of the V2I Hub ICD. This information message is also known as the Traffic Signal Controller Broadcast Message (TSCBM).

NOTE: Use of the TSCBM is discouraged. Refer to Annex A.1, TSCBM & SPaT Data.

6.3.2.2.1 TSC Infrastructure Manual Control Indication

As part of the SPaT information, the TSC infrastructure shall indicate whether the intersection is operating under manual control.

NOTE: Manual control is a special operating mode where the advancement of signal indications is controlled by an external entity (such as a police officer at the traffic cabinet or an operator at a traffic management center) rather than the TSC.

6.3.2.2.2 TSC Infrastructure Stop Time Indication

As part of SPaT information, the TSC infrastructure shall indicate whether the intersection is operating under stop time control.

NOTE: The TSC is under stop time control when it receives a stop time input. Under stop time control, the TSC will stop counting/timings of all phases.

6.3.2.2.3 TSC Infrastructure Failure Flash (Exception Flash) Indication

As part of the SPaT information, the TSC infrastructure shall indicate whether the intersection is in a signal flash condition invoked outside of the TSC (e.g., a fault, toggle switch, police panel). Reasons why an intersection may be in a Failure Flash mode include the following:

- When the TSC detects an anomaly in the TSC infrastructure, such as a mismatch between its copy of the permissive channels and the SMU's copy of the permissive channel.
- A human-operator, such as a traffic signal technician or police officer, toggles a switch in the traffic cabinet to set the intersection in flash.

NOTE: Failure Flash is different than controller (or operational) flash. In failure flash, the TSC infrastructure is unaware of when flash operation will end. In controller flash, the TSC is responsible of invoking the flashing operation at the intersection as part of a timing plan, such as through a time-of-day operating plan or preemption. In controller flash, the TSC infrastructure is aware of when flash might end.

6.3.2.2.4 TSC Infrastructure Preemption Operation Indication

As part of the SPaT information, the TSC infrastructure shall indicate whether the intersection is in preemption operation.

NOTE: Preemption is a special operating mode at the intersection where the TSC interrupts its normal operation to provide an urgent request for preferential treatment to special classes of vehicles, such as a heavy-rail vehicle, light-rail transit vehicles, or emergency vehicles.

6.3.2.2.5 TSC Infrastructure Priority Operation Indication

As part of the SPaT information, the TSC infrastructure shall indicate whether the intersection is actively servicing a priority request.

NOTE 1: Priority is a special operating mode at an intersection where the TSC either extends or returns early to a phase to give preferential treatment to special classes of vehicles, such as a transit bus, an agency maintenance vehicle, or a commercial vehicle (i.e., truck). Priority differs from preemption in that the TSC attempts to accommodate the special vehicle without significantly altering the programmed timing plan.

NOTE 2: "Actively servicing a priority request" means that the TSC is in the process of altering the duration of the signal indications in response to a priority request. The TSC may not automatically or immediately respond to a priority request, depending on the circumstances at the intersection. A requesting vehicle should consult the Signal Status Message (SSM) to determine the status of individual priority requests.

6.3.2.2.6 TSC Infrastructure Fixed Time Control Indication

As part of the SPaT information, the TSC infrastructure shall indicate whether the intersection is operating under fixed time control.

NOTE: Fixed-time control is when the traffic signal indications for the entire intersection follow the same sequence and utilize the same duration each cycle, regardless of traffic demand. The TSC is operating under fixed time control if all phases in the active sequence are running with maximum vehicle recall, running a non-actuated split, or responding to a call to non-actuated input.

6.3.2.2.7 TSC Infrastructure Traffic Dependent Control

As part of the SPaT information, the TSC infrastructure shall indicate whether the intersection is operating in a mode where the TSC is responding to active demand. In this mode, the order and duration of one or more phases of the traffic signal may vary cycle-by-cycle in response to detector inputs.

NOTE: Traffic dependent control could refer to actuated signal control (including semi-actuation) or to some hybrid forms used in traffic responsive control or adaptive control. Demand need not be actively serviceable to be considered traffic dependent in the SPaT message. For example, a coordinator may omit a phase until its permissive window opens; however, SPaT is to consider this phase to have serviceable demand with the expectation of future opening of this permissive window.

6.3.2.2.8 TSC Infrastructure in Standby Mode

As part of the SPaT information, the TSC infrastructure shall indicate whether the intersection is in a standby mode. The intersection is in standby mode when the controller is partially switched off, waiting for input to begin operation (such as at a pedestrian hybrid beacon or HAWK signal or at a traffic signal installed near a fire station that flashes amber until activated by a fire truck), or during a TSC's initial start-up sequence (initializing control).

NOTE: The RSU may have its own "standby mode" where it does not transmit any message.

6.3.2.3 TSC Infrastructure RLVW Requirements

The requirements for a TSC infrastructure to provide support to the RLVW application follow.

6.3.2.3.1 TSC Infrastructure Assured Green End Time (AGET) Requirements

The requirements for a TSC infrastructure to provide support AGET follow.

6.3.2.3.1.1 AGET Known

The TSC infrastructure shall set both the minimum and maximum end times to the termination time of the green interval (Assured Green End Time, or AGET) when a future termination time has been determined by the TSC infrastructure. Equal minimum and maximum end times for a green interval indicate with high certainty the time the green interval will end. Only signal preemption or failure can override an AGET.

6.3.2.3.1.2 AGET Undefined

The TSC Infrastructure shall set the maximum end time to “undefined” under the following intersection operating states:

- Manual Control
- Stop Time Control
- Cabinet Flash
- Standby Mode

NOTE: In some operating modes, such as Manual, Stop Time, and Cabinet Flash, the TSC does not control when the green interval for a phase will end. In these operating states, the maximum end time is undefined.

6.3.2.3.2 TSC Infrastructure Assured Green Period (AGP) Requirements

The requirements for a TSC infrastructure to provide an AGP follow.

6.3.2.3.2.1 AGP Extension

The TSC infrastructure shall provide a configurable interval portion (Assured Green Period or AGP) that may be used to extend the green interval of a through movement to decrease the likelihood that a V2X vehicle will be in the intersection at the onset of red.

6.3.2.3.2.2 AGP Application

The TSC infrastructure shall extend a through movement using the AGP when:

- An AGET has not been set for the through movement
- The current time plus the AGP is greater than the minimum end time of the interval
- The current time plus the AGP is less than or equal to the maximum end time of the interval

6.3.2.3.2.3 AGP Limited to Traffic Dependent Control

The TSC infrastructure shall only apply an AGP when an intersection is operating in traffic dependent time control.

6.3.2.4 BSM Processing Requirements

The requirements for a TSC infrastructure to receive and filter Basic Safety Messages (BSM) follow.

The TSC infrastructure may use BSMs to support AGP/RLVW and other applications that may affect the signal phase and timing data (see 6.3.2.3, TSC Infrastructure RLVW Requirements).

6.3.2.4.1 Receive BSM Messages

The TSC infrastructure shall accept only authenticated UPER-encoded SAE J2735 BSM messages that conform to SAE J3161/1 from an RSU.

SAE J3161/1 describes the system and performance requirements for vehicles in classes 2, 3, 4, and 5 to BSMs over LTE-V2X sidelink, supporting V2V safety applications. In the United States, it is expected that BSMs transmitted by factory-installed OBUs in these vehicle classes will adhere to the specifications defined in SAE J3161/1.

Section 6.3.1 of SAE J3161/1 requires that all BSMs contain the BSM Part I content as specified by SAE J2735. Table 2 lists the data elements in Part I of the SAE J2735 BSM message available for use by the connected intersection.

Table 2 - Available data elements in SAE J2735 BSM (informative)

Data Element/Frame	Data element allowed to be set to unavailable, or represent an unknown value, as specified in SAE J2735	Corresponding section reference in SAE J3161/1
DE_DSRC_MessageID	No	6.3.6.1
DE_MsgCount	No	6.3.6.2
DE_TemporaryID	No	6.3.6.3
DE_DSecond	No	6.3.6.4
DE_Latitude	No	6.3.6.5
DE_Longitude	No	6.3.6.5
DE_Elevation	No	6.3.6.6
DF_PositionalAccuracy	No	6.3.6.7
DE_SemiMajorAxisAccuracy	No	6.3.6.7
DE_SemiMinorAxisAccuracy	No	6.3.6.7
DE_SemiMajorAxisOrientation	No	6.3.6.7
DE_Speed	No	6.3.6.8
DE_TransmissionState	Yes	6.3.6.9
DE_Heading	No	6.3.6.10
DE_SteeringWheelAngle	Yes	6.3.6.11
DF_AccelerationSet4Way		
DE_Acceleration (Longitudinal)	No	6.3.6.12
DE_Acceleration (Lateral)	Yes	6.3.6.12
DE_VerticalAcceleration	Yes	6.3.6.12
DE_YawRate	No	6.3.6.12
DF_BrakeSystemStatus	Yes ⁽¹⁾	6.3.6.13
DF_VehicleSize		
DE_VehicleWidth	No	6.3.6.14
DE_VehicleLength	No	6.3.6.14

⁽¹⁾ All parameters in DF_BrakeSystemStatus may be set to unavailable.

6.3.2.4.2 BSM Messages Filtered by Detection Zones

The TSC infrastructure shall process verified BSMs from V2X vehicles using virtual detection zones.

To enable the AGP/RLVW operation, a BSM from a V2X vehicle inside a RLVW Detection Zone (RDZ) has to be detected. This detection function can be performed by an RSU, an external device between the RSU and the TSC Infrastructure, or by the TSC Infrastructure. Refer to Annex D.4, RLVW Applications - Basic Safety Messages for AGP.

NOTE: The BSM filtering feature of an RSU is defined in 3.3.2.9.2.1 and 4.3.2.14.4 of CTI 4001. An RSU can be configured to geographically define CTI 4001 “zones” that correspond to the RDZs used for the AGP/RLVW operation of an intersection. Using the “ZoneEnter” event type, once a verified BSM is received from a vehicle inside one of the zones, the RSU will forward the BSM to the TSC infrastructure. No other BSMs will be forwarded for that vehicle until it leaves and reenters the Zone. Also, if all Zones are configured for an RSU using the ZoneEnter event type, no BSMs are forwarded to the TSC infrastructure except those that would apply to the AGP/RLVW operation. This significantly reduces the number of BSMs that the TSC must process. See 6.3.2.4.3, BSM Message Rate for AGP and RLVW and 7.3.2.3.2 for the design details.

6.3.2.4.3 BSM Message Rate for AGP and RLVW

The TSC infrastructure shall be able to process a minimum of 160 BSMs per second from a filtered detection zone on the RSU.

The minimum of 160 BSMs per second is based on the assumption that the TSC infrastructure is only receiving BSMs from the RSU from zones that are being used for the AGP/RLVW application. If BSM filtering is being performed by the TSC infrastructure instead of the RSU, it is estimated that the BSM message rate would be a minimum of 800 BSMs per second.

It may be desirable to perform BSM filtering in the TSC infrastructure in the future. In this case, the RSU forwards all verified BSMs to the TSC infrastructure. It is the responsibility of the TSC infrastructure to filter the BSMs and identify vehicles that enter the RDZs of the intersection. In this case, the TSC infrastructure would have to be able to receive and filter 800 BSMs per second. This rate is based on real-world test data from the USDOT. The rate is lower than might be expected due to the congestion mitigation functions of the OBU during high-density message traffic.

6.3.3 Message Requirements

The requirements for a connected intersection broadcasting messages to OBUs/MUs, as depicted by the red arrow in Figure 5, follow.

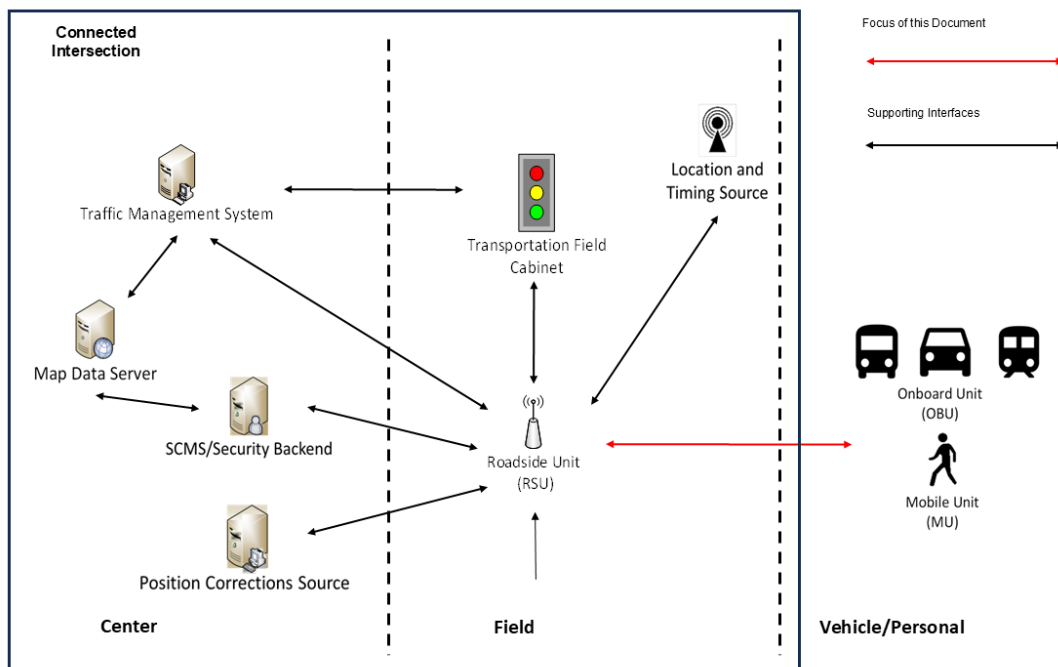


Figure 5 - Context for message requirements

6.3.3.1 Message Performance Requirements

The performance requirements for a connected intersection broadcasting messages to OBUs/MUs follow.

6.3.3.1.1 Uniform Message Requirements

The requirements to provide a consistent representation of the situation and operating conditions at a connected intersection follow.

6.3.3.1.1.1 SPaT Message - SAE J2735

A connected intersection shall send signal timing information using signal phase and timing (SPaT) messages that conform to SAE J2735 (MSG_SignalPhaseAndTiming Message).

NOTE: At the time of this publication, the most current version of SAE J2735 is SAE J2735_202409; that version or later shall be used.

6.3.3.1.1.2 SPaT Message - Mandatory Data Elements

A connected intersection shall provide those data elements in the SAE J2735 MSG_SignalPhaseAndTiming Message defined as mandatory.

6.3.3.1.1.3 SPaT Message - Required Data Elements

A connected intersection shall provide those data elements in the SAE J2735 MSG_SignalPhaseAndTiming Message defined as optional by SAE J2735 but necessary to fulfill the CI requirements, as indicated in the NRTM (refer to CTI 4501, Table 5, Needs to Requirements Traceability Matrix).

6.3.3.1.1.4 SPaT Message PSID

A connected intersection shall broadcast SPaT messages using a Provider Service Identifier (PSID) of 0x82 (0p80-02).

The IEEE PSID Public Listing can be found at <https://standards.ieee.org/products-programs/regauth/psid/public/>.

6.3.3.1.1.5 MAP Message - SAE J2735

Not applicable.

6.3.3.1.1.6 MAP Message - Mandatory Data Elements

Not applicable.

6.3.3.1.1.7 MAP Message - Required Data Elements

Not applicable.

6.3.3.1.1.8 MAP Message PSID

Not applicable.

6.3.3.1.1.9 RTCMcorrections Message - SAE J2735

Not applicable.

6.3.3.1.1.10 RTCMcorrections Message - Mandatory Data Elements

Not applicable.

6.3.3.1.1.11 RTCMcorrections Message - Required Data Elements

Not applicable.

6.3.3.1.1.12 RTCMcorrections Message PSID

Not applicable.

6.3.3.1.1.13 BSM Message - SAE J2735

A connected intersection shall receive vehicle data using BSMs that conform to SAE J2735 (MSG_BasicSafetyMessage). BSM data is used to support RLVW applications, such as the Assured Green Period (see 6.3.2.3, TSC Infrastructure RLVW Requirements).

SAE J3161/1 describes the standards profiles, functional requirements, and performance requirements related to transmitting and receiving SAE J2725-defined BSMs over a PC5 Sidelink V2X (mode 4) communications link as defined in ETSI Release 142.3.

6.3.3.1.1.14 BSM Message PSID

A connected intersection shall receive BSM messages with a Provider Service Identifier (PSID) of 0x20 (0p20).

The IEEE PSID Public Listing can be found at <https://standards.ieee.org/products-programs/regauth/psid/public/>.

6.3.3.1.2 Robustness Requirements

The requirements for a connected intersection to operate under different degraded conditions follow.

6.3.3.1.2.1 Broadcast SPaT Message

A connected intersection shall broadcast a SPaT message upon receipt of valid SPaT information from the TSC infrastructure. In this context, valid SPaT information from the TSC infrastructure is properly formatted and within the permitted data ranges, even if the noValidSPaTisAvailableAtThisTime bit in DE_IntersectionStatusObject is enabled (equal to 1).

6.3.3.1.2.2 Continuous Broadcast of SPaT Messages

A connected intersection shall always broadcast a SPaT message even if TSC infrastructure cannot produce valid SPaT information. If the TSC infrastructure cannot produce valid SPaT information, the connected intersection shall indicate in the SPaT message that no valid SPaT information is available at this time.

6.3.3.1.3 Concise Messages Requirements

The requirements to provide complete data describing the situation within the maximum message size supported by the communications stack follow.

6.3.3.1.3.1 Transport Message Size - WAVE

Refer to CTI 4501, 6.3.3.1.3.1, Transport Message Size - WAVE.

6.3.3.1.4 Advanced Notification Requirements

Refer to CTI 4501, 6.3.3.1.4, Advanced Notification Requirements.

6.3.3.1.5 Timeliness Requirements

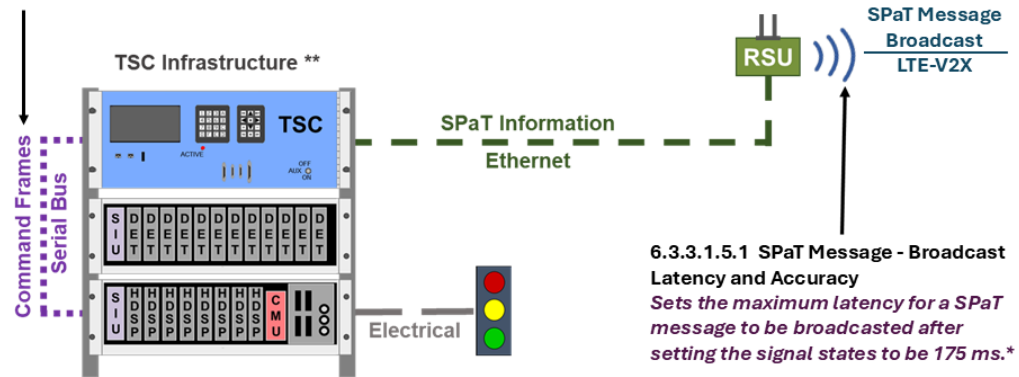
The requirements for indicating changes in the signal indication state and timing follow.

6.3.3.1.5.1 SPaT Message - Broadcast Latency and Accuracy

A connected intersection shall broadcast a SPaT message within 175 ms from the time the TSC infrastructure sets the corresponding signal indications on the traffic cabinet serial bus.

6.3.2.1.2 TSC Signal State Periodicity

*Sets the signal states over the serial bus at 100 ms +/- 25 ms intervals. **



6.3.3.1.5.1 SPaT Message - Broadcast Latency and Accuracy
*Sets the maximum latency for a SPaT message to be broadcasted after setting the signal states to be 175 ms.**

* See the section identified for the full requirement.

** The TSC Infrastructure may consist of many different components. This illustration is not intended to reflect a particular configuration.

Figure 6 - CI SPaT message broadcast latency and accuracy requirement

6.3.3.1.5.2 SPaT Message Broadcast - Periodicity

A connected intersection shall broadcast a SPaT message every 100 ms \pm 25 ms, where the duration of any ten consecutive SPaT messages is 1.0 second \pm 25 ms.

6.3.3.1.6 Quality Assurance Requirements

The requirements to provide quality information follow.

6.3.3.1.6.1 Completeness - SPaT Message

A connected intersection shall provide a SPaT message containing signal timing information for all movements controlled by the TSC infrastructure and included in the associated MAP message.

6.3.3.1.6.2 Completeness - MAP Message

Not applicable.

6.3.3.1.6.3 SPaT Message - Time Mark Accuracy

A connected intersection shall broadcast SPaT messages with time marks that are accurate to within 100 ms of setting the corresponding signal indications.

NOTE: Time marks are only accurate to a tenth of a second. Time rounding issues can occur between the TSC infrastructure and the RSU due to the latency in transmitting the SPaT information to the RSU and the conversion of ticks to UTC time. Consequently, the time marks for the signal indications can be off by up to 100 ms.

6.3.3.2 Generic Message Requirements

The requirements for a connected intersection transmitting data follow.

6.3.3.2.1 Time Accuracy

Refer to CTI 4501, 6.3.3.2.1, Time Accuracy.

6.3.3.2.2 Message Revision Requirements

The requirements for messages that have changed since the previous transmission follow.

6.3.3.2.2.1 SPaT Message - Revision Counter Increment

A connected intersection shall increment a revision counter to the next value whenever the value of any data element in the SPaT message, except for the time stamp, describing the signal phase and timing for that intersection changes.

NOTE: A SPaT message contains two counters: one counter for the overall SPaT message and one counter for the intersection. This requirement applies to the intersection counter.

6.3.3.2.2.2 SPaT Message - Revision Counter Not Increment

The message counter for a connected intersection shall remain the same if the value of no data element in the SPaT message, except for the time stamp, describing the signal phase and timing for that intersection changes. The connected intersection does not increment the sequence number if there is no change in the SPaT message content, other than the change in UTC time.

NOTE: A SPaT message contains two counters: one counter for the overall SPaT message and one counter for the intersection. This requirement applies to the intersection counter.

6.3.3.2.3 Time Stamp Requirements

The requirements for a time stamp in messages transmitted by a connected intersection follow.

6.3.3.2.3.1 SPaT Message - Message Time Stamp

A connected intersection shall provide a time stamp indicating the minute of the year when the SPaT message is created.

6.3.3.2.3.2 SPaT Message - Intersection Time Stamp

A connected intersection shall provide a time stamp indicating the milliseconds within the current minute when the SPaT information for the intersection within the SPaT message is generated.

NOTE: If SPaT information for more than one intersection is included within a single SPaT message, the time stamp may be different for each intersection.

6.3.3.3 Signal Timing Data Requirements

The requirements for signal timing data broadcasted by a connected intersection follow.

6.3.3.3.1 Intersection Identification Requirements

The requirements to provide a unique identifier for an intersection follow.

6.3.3.3.1.1 Intersection Signal Timing Information

A connected intersection shall be capable of providing signal timing information for one or more intersections. This requirement allows an RSU to broadcast signal timing information from one or more TSCs.

6.3.3.3.1.2 Intersection Identifier

As part of the signal phase and timing information, a connected intersection shall provide an intersection identifier unique to an organization. The identifier of the organization is called the Road Authority Identifier (RAID). See 6.3.3.3.1.3, Road Authority Identifier.

NOTE: This requirement is updated in CTI 4501 v02 to replace the road regulator identifier. The updated guidance is that the combination of the OpOrgID (Operator Organization Identifier), the intersection identifier, and optionally the road authority identifier (see 6.3.3.3.1.3, Road Authority Identifier) is a globally unique identifier for the connected intersection. Refer to CTI 4501, Annex A.1, Road Authority Identifier for a detailed description.

6.3.3.3.1.3 Road Authority Identifier

As part of the signal phase and timing information, a connected intersection shall provide a RAID. The RAID establishes an organization that either owns or operates a connected intersection. The RAID consists of the Operator Organization Identifier (OpOrgID) and, optionally, the relative Road Authority Identifier.

The OpOrgID is identified in the IEEE Std 1609.2 certificate used to sign the SPaT message. There is no data element in SAE J2735 to identify (or exchange) OpOrgId.

The Relative Road Authority Identifier is used to further partition the OpOrgID into an agency or division. If the organization that owns or operates the connected intersection is different than the OpOrgId, the Relative Road Authority Identifier is included in the SPaT message.

NOTE: This requirement is updated in CTI 4501 v02 to replace the road regulator identifier. The updated guidance is that the combination of the OpOrgID (Operator Organization Identifier) in the IEEE Std 1609.2 certificate, which identifies the organization that owns or requested the certificate, the intersection identifier, and optionally the relative road authority identifier, is a globally unique identifier for the connection intersection. Refer to CTI 4501, Annex A.1, Road Authority Identifier for a detailed description. SAE J2735_202211 added DE_RoadAuthorityID as a more extensible means of identifying IOOs.

6.3.3.3.2 Intersection Status Requirements

The requirements to provide the current operating status of a connected intersection follow.

6.3.3.3.2.1 Manual Control

A connected intersection shall indicate in the SPaT whether the TSC is operating under manual control. See 6.3.2.2.1.

6.3.3.3.2.2 Stop Time

A connected intersection shall indicate in the SPaT whether the TSC is operating under stop time control. See 6.3.2.2.2.

6.3.3.3.2.3 Failure Flash

A connected intersection shall indicate in the SPaT whether the TSC is in a signal flash condition invoked outside of the TSC (e.g., a fault, toggle switch). See 6.3.2.2.3.

6.3.3.3.2.4 Preemption

A connected intersection shall indicate in the SPaT whether the TSC is in preemption operation. See 6.3.2.2.4.

6.3.3.3.2.5 Priority

A connected intersection shall indicate in the SPaT whether the TSC is in priority operation. See 6.3.2.2.5.

6.3.3.3.2.6 Fixed Time

A connected intersection shall indicate in the SPaT whether the TSC is operating under fixed time control. See 6.3.2.2.6.

6.3.3.3.2.7 Traffic Dependent Mode

A connected intersection shall indicate in the SPaT whether the TSC is operating in a traffic dependent (non-fixed time) mode. See 6.3.2.2.7.

6.3.3.3.2.8 Standby Mode

A connected intersection shall indicate whether the TSC is in a standby mode. See 6.3.2.2.8.

6.3.3.3.2.9 Failure Mode

A connected intersection shall indicate whether the TSC infrastructure has a problem or failure in operation. This mode is different than 6.3.3.3.2.3, Failure Flash. The connected intersection uses the failure mode to indicate when the TSC is not operating properly or has failed if the TSC is able to. Examples of a TSC failure mode might include if the TSC detects a process is not operating properly, a memory data error, or an internal voltage failure.

6.3.3.3.2.10 Controller Off

A connected intersection shall indicate whether the TSC infrastructure is providing valid data.

6.3.3.3.2.11 Recent MAP Update

A connected intersection shall always indicate whether a recent MAP message update is available. This is done to ensure the OBU/MU always uses the most current intersection configuration.

6.3.3.3.2.12 New Lane IDs

A connected intersection shall always indicate whether a recent change in MAP assigned lane IDs or revocable lanes are currently enabled, except when the no valid MAP message status bit is set (see 6.3.3.3.2.13). This is done to ensure the OBU/MU always uses the most current intersection configuration.

6.3.3.3.2.13 No MAP Available

A connected intersection shall indicate whether a valid MAP is not available. Conditions when a valid MAP message is considered to be unavailable include the following:

- A connected intersection does not have a valid MAP message to broadcast.
- An authorized user indicates that the MAP message for the intersection is invalid because the signalized intersection is under test or because there is temporary work at the signalized intersection, such as lane closures, that may make the MAP message invalid.

6.3.3.3.2.14 No SPaT Available

A connected intersection shall indicate whether valid SPaT information is available. Conditions when a valid SPaT message is considered not available include:

- The connected intersection is not able to broadcast a valid MAP message.
- An RSU has not received any SPaT information from the TSC infrastructure for more than 300 ms.
- An authorized user commands the TSC infrastructure to indicate that the SPaT information is not valid, such as when the controller is under test.

NOTE: Section 4.3.2.14.2 in CTI 4001 states that the RSU shall set the "noValidSPaTisAvailableAtThisTime" Bit in the DE_IntersectionStatusObject if the RSU has not received any valid SPaT information from the TSC Infrastructure within the last 200 ms.

6.3.3.3.2.15 RTCM Corrections Available [Informative]

At the time of publication, the committee was considering a requirement, “A connected intersection shall indicate in the SPaT message whether Radio Technical Commission for Maritime Services (RTCM) corrections messages, per SAE J3258, are available to support position correction functions by V2X vehicles approaching the intersection.”

Conditions when a valid RTCMcorrections message is considered NOT available include:

- The connected intersection and surrounding connected intersections are not able to broadcast a valid RTCMcorrections message.
- An authorized user commands the TSC infrastructure to indicate that the RTCMcorrections information for the connected intersection is not valid.

The RTCMcorrections messages may be broadcasted by nearby RSUs - the RSU does not have to be located at the connected intersection the V2X vehicle is approaching.

This requirement is proposed to be fulfilled by setting bit 14 in the DE_IntersectionStatusObject field of the SPaT message. See 7.3.3.3.2.15 for more details.

NOTE: This requirement is included in this document for informational purposes only because the specific requirements and how to fulfill this requirement are still under discussion. In addition, the proposed change to bit 14 to the DE_IntersectionStatusObject in SAE J2735 to fulfill this requirement has not been published and is still subject to change.

6.3.3.3.2.16 Supports RLVW [Informative]

At the time of publication, the committee was considering a requirement, “A connected intersection shall indicate in the SPaT message whether it fulfills the minimum requirements to support a RLVW application.”

Minimally, the IOO must have successfully completed verification tests for all minimum requirements to claim this requirement is fulfilled. The minimum requirements are defined in CTI 4501, Table 5, Needs to Requirements Traceability Matrix.

This requirement is proposed to be fulfilled by setting bit 15 in the DE_IntersectionStatusObject field of the SPaT message. See 7.3.3.3.2.16 for more details.

NOTE: This requirement is included in this document for informational purposes only because the specific requirements and how to fulfill this requirement is still under discussion. In addition, the proposed change to bit 15 to the DE_IntersectionStatusObject in SAE J2735 to fulfill this requirement has not been published and is still subject to change.

6.3.3.3.3 Current Movement State Requirements

The requirements for the current movement state of a signal group follow.

6.3.3.3.3.1 Current Movement State for a Signal Group

A connected intersection shall provide the current movement state for each signal group identified in the MAP message. The valid values for the current movement state for a signal group are defined by DE_MovementPhaseState in SAE J2735.

6.3.3.3.3.2 Unknown Current Movement State for a Signal Group

If the TSC infrastructure does not provide a value for the current movement state for a signal group, a connected intersection shall use a value of unavailable, as defined by DE_MovementPhaseState in SAE J2735.

6.3.3.3.3 Flashing Yellow Arrow Permissive Movement

At an intersection that uses a flashing yellow arrow to control a permissive movement during stop and go operation, a connected intersection shall use the value of permissive-Movement-Allowed as the current movement state for the signal group when the flashing yellow arrow is active, as defined by DE_MovementPhaseState in SAE J2735.

6.3.3.3.4 Protected and Permissive Clearance

A connected intersection shall use the value of protected-clearance or permissive-clearance as the current movement state of a signal group to correspond with the protected or permissive condition of the allowed movement immediately preceding the current (clearance) interval, as defined by DE_MovementPhaseState in SAE J2735.

Examples of a protected clearance include:

- A yellow arrow following a green arrow
- A circular yellow following circular green for a through vehicle and bicycle movement
- A steady circular yellow following a flashing circular yellow for a through movement at a pedestrian hybrid beacon
- A flashing DON'T WALK

Examples of a permissive clearance include:

- A circular yellow for a turning vehicle and bicycle movement
- A yellow arrow following a flashing yellow arrow or flashing red arrow
- A steady circular yellow following a flashing circular yellow ending off-peak flashing operation
- A steady circular yellow following a flashing circular yellow for turning movement at a pedestrian hybrid beacon
- A steady yellow BICYCLE indication

6.3.3.3.5 Resolve Protected Versus Permissive Movement

When an allowed movement controlled by a signal group is sometimes protected and sometimes permissive, such as a protected/permissive left turn, a connected intersection shall determine whether the currently allowed movement is protected or permissive and use the corresponding current movement state (protected-Movement-Allowed, permissive-Movement-Allowed) for the signal group, as defined by DE_MovementPhaseState in SAE J2735.

6.3.3.3.6 Yield Causes Permissive

When an allowed movement must yield to other vehicle, pedestrian, or bicycle movements, a connected intersection shall use permissive-Movement-Allowed as the current movement state for the signal group associated with that movement, as defined by DE_MovementPhaseState in SAE J2735.

Examples include:

- A circular green for turning vehicle and bicycle movement
- A flashing yellow arrow
- A flashing circular yellow during off-peak flashing operation
- A dark indication for turning movement at a pedestrian hybrid beacon
- A dark pedestrian indication for pedestrians facing a flashing circular yellow during off-peak flashing operation
- A steady green BICYCLE for turning bicycle movements

6.3.3.3.3.7 Right-of-Way Causes Protected

When an allowed movement has the right-of-way, a connected intersection shall use protected-Movement-Allowed as the current movement state for the signal group associated with that movement, as defined by DE_MovementPhaseState in SAE J2735.

Examples include:

- A green arrow
- A circular green for a through movement
- A dark indication for a through movement at a pedestrian hybrid beacon
- A flashing circular yellow for a through movement at a pedestrian hybrid beacon
- A WALK indication
- A steady green BICYCLE indication for through bicycle movements

6.3.3.3.3.8 WALK State Enumeration

A connected intersection shall use protected-Movement-Allowed as the current movement state for an allowed pedestrian movement for the pedestrian WALK interval, as defined by DE_MovementPhaseState in SAE J2735.

6.3.3.3.3.9 Flashing DON'T WALK State Enumeration

A connected intersection shall use protected-clearance as the current movement state for the pedestrian Flashing DON'T WALK interval, as defined by DE_MovementPhaseState in SAE J2735, to correspond with the protected condition of the allowed WALK movement immediately preceding the current (clearance) interval.

6.3.3.3.3.10 Steady DON'T WALK State Enumeration

A connected intersection shall use stop-And-Remain as the current movement state for the pedestrian Steady DON'T WALK interval, as defined by DE_MovementPhaseState in SAE J2735.

6.3.3.3.3.11 Movement State for Signal Groups Identified

A connected intersection shall provide the current movement state for only signal groups identified in the MAP message for the same intersection. The connected intersection will not provide a movement state for any signal group not identified by the corresponding MAP message.

6.3.3.3.12 Dark Pedestrian Indications

At connected intersections that include movement states for pedestrians, a connected intersection shall use the current movement state of the corresponding vehicle indications facing the pedestrian movement if the pedestrian indications are dark. This is a common scenario during off-peak flashing operation.

Examples include:

- permissive-Movement-Allowed for pedestrians facing a flashing circular yellow indication for the vehicles
- stop-Then-Proceed for pedestrians facing a flashing red for the vehicles

6.3.3.3.13 Prohibited Movements

A connected intersection shall use the value of stop-And-Remain as the current movement state for the signal group when the movement is in a stop condition and is not allowed to proceed until the state changes.

Examples include:

- A steady circular red for a through vehicle and bicycle movement
- A steady circular red for a turning movement when a turn on red is not permitted
- A steady red arrow for a turning movement when a turn on red is not permitted
- A steady double circular red for a through movement at a pedestrian hybrid beacon
- A steady double circular red at a pedestrian hybrid beacon for a turning movement when a turn on red is not permitted
- A steady DON'T WALK indication
- A steady red BICYCLE indication

NOTE: The stop-And-Remain state for turns will be consistent with the indication of whether a turn on red is permitted or not permitted as part of the lane description in the MAP message.

6.3.3.3.14 Movements Allowed After a Stop

A connected intersection shall use the value of stop-Then-Proceed as the current movement state for the signal group when the movement requires a stop but allows subsequent movement yielding to conflicting traffic.

Examples include:

- A flashing red arrow
- A steady circular red for a turning movement when a turn on red is permitted
- A steady red arrow for a turning movement when a turn on red is permitted
- A flashing circular red during off-peak flashing operation
- A steady double circular red at a pedestrian hybrid beacon for a turning movement when a turn on red is permitted
- A flashing double circular red at a pedestrian hybrid beacon
- A dark pedestrian indication for pedestrians facing a flashing circular red

NOTE: The stop-Then-Proceed state for turns will be consistent with the indication of whether a turn on red is permitted or not permitted as part of the lane description in the MAP message.

6.3.3.3.4 Next Movement State Requirements

The requirements for the next movement state of a signal group follow.

6.3.3.3.4.1 Next Movement State

A connected intersection shall indicate the next (future) movement state to follow the current movement state for a signal group. The valid values for the next movement state for a signal group are defined by DE_MovementPhaseState in SAE J2735.

Examples include:

- A permissive interval following a protected interval for a leading protected, permissive signal indication
- A yellow change interval following a green interval

6.3.3.3.4.2 Unknown Next Movement State

In a situation when a connected intersection cannot determine the next movement state, a connected intersection shall use unavailable as the next movement state for a signal group, as defined by DE_MovementPhaseState in SAE J2735.

6.3.3.3.4.3 No Past State

A connected intersection shall not provide the state or timing for intervals that are already completed.

6.3.3.3.5 Time Change Details Requirements

The requirements for when the signal interval state for a signal group may change follow.

6.3.3.3.5.1 Time Change Details

A connected intersection shall provide SPaT time change details for each signal group identified in the MAP message for the same intersection.

6.3.3.3.5.2 Unknown Time Change Detail

If the TSC infrastructure does not provide a value for a mandatory time change detail element (e.g., minimum end time, maximum end time, etc.; refer to the requirements for User Need 5.4.3.3.5 in CTI 4501, Table 5), a connected intersection shall use a value of unknown, as defined by DE_TimeMark in SAE J2735.

NOTE: The value of DE_TimeMark indicating unknown changed from a value of 36001 in SAE J2735_201603 to a value of 36111 in SAE J2735_202007 to properly address leap seconds.

6.3.3.3.5.3 Minimum End Time

A connected intersection shall provide a time mark, in tenths of a second in the current or next hour, indicating the soonest time that the current and any future interval for a signal group could end in the absence of unpredicted events such as preemption. For intervals with a predetermined duration (such as the minimum green, yellow change, red clearance, pedestrian walk, and pedestrian clearance intervals), the minimum end time is set based on the duration of the predefined interval. For intervals that do not have a predetermined duration (such as in actuated control or volume-density control), the minimum end time is set based on the duration of the associated interval portion (i.e., the initial portion, the extensible portion, or the AGP used by the TSC in determining when to terminate the green interval).

For fixed time control and coordinated control (non-actuated), the minimum end time is set equal to the maximum duration of each interval in the phase.

In no case shall the minimum end time be less than 0.1 second.

6.3.3.3.5.4 Maximum End Time

A connected intersection shall provide a time mark, in tenths of a second in the current or next hour, indicating the latest time that the current and any future interval for a signal group could end in the absence of unpredictable events such as preemption.

For intervals that do have a predetermined end time (fixed time control), the maximum end time is equal to the minimum end time.

6.3.3.3.5.5 Unknown Maximum End Time

In a situation where a connected intersection cannot determine a latest end time, a connected intersection shall use a value of unknown, as defined by DE_TimeMark in SAE J2735.

NOTE: The value of DE_TimeMark indicating unknown changed from a value of 36001 in SAE J2735_201603 to a value of 36111 in SAE J2735_202007 to properly address leap seconds.

6.3.3.3.5.6 Current Movement State Start Time Unknown

A connected intersection shall provide a start time of unknown for the current movement state.

NOTE: A time mark for start time for a current state would be a past time and is not needed for RLVW. Including this data element with a value of unknown for currently timing intervals, rather than omitting it, allows the structure of the SPaT message to be the same for the current interval as for the next interval. The current state's position in the SPaT message removes any ambiguity as to which state is the current state and which state is the next state.

6.3.3.3.5.7 Next Movement State Start Time

A connected intersection shall provide the time mark, in tenths of a second in the current or next hour, of the estimated start time of the next (future) movement state that follows the current movement state for a signal group.

NOTE: This is a future time.

6.3.3.3.5.8 Next State Start Time Equals Current State Minimum End Time

A connected intersection shall provide a start time for the next (future) movement state that is the same as the soonest time the current movement state could end (i.e., the minimum end time).

6.3.3.3.6 Next Allowed Movement Requirements

The requirements for when a movement at an intersection is next allowed to proceed (e.g., green, flashing yellow) follow.

6.3.3.3.6.1 Time of Next Allowed Movement

A connected intersection shall provide the estimated time mark, in tenths of a second in the current or next hour, that the current movement will next be in the permissive-Movement-Allowed or protected-Movement-Allowed (green) state in the absence of unpredictable events such as preemption.

6.3.3.3.7 Enabled Lanes Indication

If the MAP message for the intersection includes lanes indicated as being revocable lanes, a connected intersection shall identify which revocable lanes are currently enabled.

6.3.3.3.8 SPaT Message - Accuracy

A connected intersection shall broadcast SPaT messages that accurately reflect the physical signal indications by the TSC infrastructure at the intersection. For example, the current movement state for each signal group ID matches the information in the SPaT message.

6.3.3.4 Roadway Geometry Data Requirements

The requirements to provide information about travel lanes follow.

6.3.3.4.1 Intersection Geometry Requirements

Not applicable.

6.3.3.4.2 Lane Attributes

Not applicable.

6.3.3.4.3 Lane Maneuvers

Not applicable.

6.3.3.4.4 Connections Between Lanes

Not applicable.

6.3.3.4.5 Speed Limit Information Requirements

Not applicable.

6.3.3.4.6 Revocable Lanes

Not applicable.

6.3.3.4.7 Signal Timing and Roadway Geometry Information Synchronization

The requirements to ensure that the roadway geometry information being broadcast reflects the current operating state used to generate the signal timing data follow.

6.3.3.4.7.1 Matching SPaT and MAP Version

The contents of the SPaT message broadcasted for an intersection shall be consistent/compatible with the MAP message broadcasted for the same intersection. For example, if the physical roadway geometry changes, the SPaT message may need to be updated to reflect those changes.

6.3.3.4.7.2 Matching Intersection Reference Identifiers

A connected intersection shall provide an intersection reference identifier for the SPaT message that matches the intersection reference identifier used in the MAP message for the same intersection. The intersection reference identifier consists of the intersection identifier (see 6.3.3.3.1.2, and refer to CTI 4501/2, 6.3.3.4.1.3), the OpOrgID, and, optionally, the relative road authority identifier (see Section 6.3.3.3.1.3 and refer to CTI 4501/2, 6.3.3.4.1.2). Refer to CTI 4501, Annex A.1, Road Authority Identifier for a detailed explanation and guidance on the intersection reference identifiers.

6.3.3.4.7.3 Complete List of Signal Group Identifiers

All signal group IDs identified in a SPaT message for a connected intersection shall be defined in the MAP message for the same intersection. For example, if a SPaT message contains movement information for signal group ID 1 (e.g., movement state and time change details), the MAP message for that same intersection must define the lane connection(s) for signal group ID 1.

6.3.3.4.7.4 Matching Signal Group Identifier Movements

The movement state for a signal group ID in the SPaT message for a connected intersection shall reflect the movement state for the same signal group ID defined in the MAP message for the same intersection. For example, if the movement state for signal group ID 7 is permissive-Movement-Allowed and signal group ID is for a permissive left turn, then the connection for signal group ID 7 defined in the MAP message must be a left turn.

6.3.3.5 Positioning Messages

Not applicable.

6.3.3.6 Vehicle Messages Requirements

The requirements for receiving vehicle data broadcasted by V2X vehicles surrounding the connected intersection follow.

6.3.3.6.1 Vehicle Position

A connected intersection shall receive information about the position of vehicles approaching the intersection.

6.3.3.6.2 Vehicle Kinematics

A connected intersection shall receive information about the kinematics of vehicles approaching the intersection.

6.3.4 Security Requirements

CTI 4501/3 contains the security requirements for a connected intersection.

Some of those security requirements are relevant to the generation and broadcast of SPaT messages, and this section references those requirements in CTI 4501/3.

Refer to CTI 4501/3, 6.3.4 for a definition of terms user for security requirements.

6.3.4.1 Data Trustworthiness: Sources and Processing

Refer to CTI 4501/3, 6.3.4.1, Data Trustworthiness: Sources and Processing.

NOTE: Several of these requirements point to the use of IEEE 1609.2 certificates. The security profile for BSM messages is defined in SAE J3161/1.

6.3.4.2 Data Communications Security

Refer to CTI 4501/3, 6.3.4.2, Data Communications Security.

NOTE: Several of these requirements point to the use of IEEE 1609.2 certificates. The security profile for SPaT message are found in Annex B.1.

6.3.4.3 Trustworthiness of TSC-Originating Information

Refer to CTI 4501/3, 6.3.4.3, Trustworthiness of TSC-originating Information.

6.3.4.4 Approaching Vehicle Information Trustworthiness: RSU

Refer to CTI 4501/3, 6.3.4.4, Approaching Vehicle Information Trustworthiness: RSU.

NOTE: Several of these requirements point to the use of IEEE 1609.2 certificates. The security profile for BSM messages is defined in SAE J3161/1.

6.3.4.5 Approaching Vehicle Information Trustworthiness and AGP: TSC

Refer to CTI 4501/3, 6.3.4.5, Approaching Vehicle Information Trustworthiness and AGP: TSC.

6.3.4.6 Time Source Trustworthiness

Refer to CTI 4501/3, 6.3.4.6, Time Source Trustworthiness.

6.3.4.7 SPaT Message Trustworthiness and Reliability

Refer to CTI 4501/3, 6.3.4.7, SPaT Message Trustworthiness and Reliability

6.3.4.8 MAP Message Contents Trustworthiness

Not applicable.

6.3.4.9 RTCM Message Contents Trustworthiness

Not applicable.

6.3.4.10 Consistency Between MAP and SPaT Messages

Refer to CTI 4501/3, 6.3.4.10, Consistency Between MAP and SPaT Messages.

6.3.4.11 Unavailability Indications

The requirements for unavailability indications for a connected intersection follow.

6.3.4.11.1 Correctness of SPaT Availability Indications

Refer to CTI 4501/3, 6.3.4.11.1, Correctness of SPaT Availability Indications.

6.3.4.11.2 Correctness of SPaT Unavailability Indications

Refer to CTI 4501/3, 6.3.4.11.2, Correctness of SPaT Unavailability Indications.

6.3.4.12 Intersection Identifier Trustworthiness

Refer to CTI 4501/3, 6.3.4.12, Intersection Identifier Trustworthiness.

6.3.4.13 System Management and Recovery

Not applicable.

6.3.4.14 Support Systems and Functions

Not applicable.

6.3.4.15 Updates and Update Planning

Not applicable.

6.3.4.16 System Operational Modes, Accesses, and Status

Not applicable.

6.3.4.17 V2X Message Transmission

Not applicable.

6.3.4.18 CI Security Verification Requirements

Refer to CTI 4501/3, 6.3.4.18, CI Security Verification Requirements.

6.3.5 Operations and Maintenance Requirements

Refer to CTI 4501, 6.3.5, Operations and Maintenance Requirements.

7. SYSTEM DESIGN

Section 7 defines the system design details based on the requirements identified in the Functional Requirements section (see Section 6). This section includes the following:

- A tutorial.
- A Requirements Traceability Matrix (RTM). The RTM links the requirements presented in 6.3 with the design details that describe how to fulfill each requirement. Using this table, each requirement can then be traced in a conformant way.
- Design Details. Contains the details, guidance, and examples on how to fulfill a requirement.

Section 7 is intended for the following readers:

- System integrators
- Device manufacturers/vendors
- Central system developers
- Conformance testers
- Other interested parties

For these readers, Section 7 is useful to understand how particular functions and information may be implemented to conform to CTI 4501/2.

7.1 Tutorial

The Requirements Traceability Matrix (RTM) in 7.2 identifies the design details that fulfill each of the requirements defined in 6.3. The design details that fulfill the requirements can be categorized as follows:

- Design details that do not require additional explanation. Some requirements do not require additional details on how to fulfill the requirement - those requirements are identified by "No Further Design Details" in the RTM.
- Design details that can be found in another reference.
- Design details that require additional guidance or explanation. These design details are found in 7.3.

7.2 Requirements Traceability Matrix

The Requirements Traceability Matrix (RTM) links the requirements in 6.3 with the corresponding design details on the same line. Using this table, each requirement in 6.3 can thus be traced in a conformant way. Each requirement either points to other sections of the recommended practice where the formal design details on how to fulfill the requirement is described, provides no additional design details because the requirement is self-explanatory, or points to a normative reference that fulfills the requirement. In the latter case, the design details necessary to fulfill the requirement is contained within the normative reference.

To conform to a requirement, a connected intersection shall implement the design details traced from that requirement.

7.2.1 Notation [Informative]

7.2.1.1 Functional Requirement Columns

The functional requirements are defined within 6.3, and the RTM is based upon the requirements within that section. The section number and the functional requirement name are indicated within these columns.

7.2.1.2 Design Details

The “Design Details” column either provides a hyperlinked reference to a section number where the design details are defined within 7.3, provides an external, normative reference that provides the details on how to fulfill the requirement, or indicates “No Further Design Details” because no additional design information is necessary (i.e., the requirement is self-explanatory).

7.2.1.3 Additional Specifications

The “Additional Specifications” column may (and should) be used to provide additional notes and requirements or may be used by an implementer to provide any additional details about the implementation.

7.2.2 Instructions for Completing the RTM [Informative]

To find the conformant design content for a functional requirement, search for the requirement identification (section) number or functional requirement under the appropriate column. Next to the functional requirements column are columns that define the conformant design details that fulfill the requirement. The “Additional Specifications” column provides additional notes or details about the design content.

Table 3 - Requirements traceability matrix

Requirements Traceability Matrix (RTM)			
FR ID	Functional Requirement	Design Detail	Additional Specification
6.3	Requirements		
6.3.1	Architectural Requirements	Refer to CTI 4501, Table 6, Requirements Traceability Matrix	
6.3.2	TSC Infrastructure to RSU Requirements		
6.3.2.1	TSC Infrastructure Signal Timing Data Requirements		
6.3.2.1.1	SPaT Information Requirements		
6.3.2.1.1.1	NTCIP 1202 SPaT Information	See 7.3.2.1.1.1, NTCIP 1202 SPaT Information Design Details	
6.3.2.1.1.2	TSCBM SPaT Information	See 7.3.2.1.1.2, TSCBM SPaT Information Design Details	
6.3.2.1.1.3	SPaT Message - Immediate Forward	See 7.3.2.1.1.3, SPaT Message Design Details	
6.3.2.1.2	TSC Signal State Periodicity	No Further Design Details	
6.3.2.1.3	TSC Signal Indication Phase State and SPaT Information Consistency	No Further Design Details	
6.3.2.2	Signal Status Requirements		
6.3.2.2.1	TSC Infrastructure Manual Control Indication	See 7.3.2.2.1, TSC Infrastructure Manual Control Indication Design Details	
6.3.2.2.2	TSC Infrastructure Stop Time Indication	See 7.3.2.2.2, TSC Infrastructure Stop Time Indication Design Details	
6.3.2.2.3	TSC Infrastructure Failure Flash (Exception Flash) Indication	See 7.3.2.2.3, TSC Infrastructure Failure Flash (Exception Flash) Indication Design Details	
6.3.2.2.4	TSC Infrastructure Preemption Operation Indication	See 7.3.2.2.4, TSC Infrastructure Preemption Operation Indication Design Details	
6.3.2.2.5	TSC Infrastructure Priority Operation Indication	See 7.3.2.2.5, TSC Infrastructure Priority Operation Indication Design Details	
6.3.2.2.6	TSC Infrastructure Fixed Time Control Indication	See 7.3.2.2.6, TSC Infrastructure Fixed Time Control Indication Design Details	
6.3.2.2.7	TSC Infrastructure Traffic Dependent Control	See 7.3.2.2.7, TSC Infrastructure Traffic Dependent Control Design Details	
6.3.2.2.8	TSC Infrastructure in Standby Mode	See 7.3.2.2.8, TSC Infrastructure in Standby Mode Design Details	
6.3.2.3	TSC Infrastructure RLWV Requirements		
6.3.2.3.1	TSC Infrastructure Assured Green End Time (AGET) Requirements		
6.3.2.3.1.1	AGET Known	See 7.3.2.3.1.1, AGET Known Design Details	
6.3.2.3.1.2	AGET Undefined	No Further Design Details	

Requirements Traceability Matrix (RTM)			
FR ID	Functional Requirement	Design Detail	Additional Specification
6.3.2.3.2	TSC Infrastructure Assured Green Period (AGP) Requirements		
6.3.2.3.2.1	AGP Extension	See 7.3.2.3.2, TSC Infrastructure AGP Extension Method Design Details	
6.3.2.3.2.2	AGP Application	No Further Design Details	
6.3.2.3.2.3	AGP Limited to Traffic Dependent Control	No Further Design Details	
6.3.2.4	BSM Processing Requirements		
6.3.2.4.1	Receive BSM Messages	No Further Design Details	
6.3.2.4.2	BSM Messages Filtered by Detection Zones	No Further Design Details	
6.3.2.4.3	BSM Message Rate for AGP and RLVW	No Further Design Details	
6.3.3	Message Requirements		
6.3.3.1	Message Performance Requirements		
6.3.3.1.1	Uniform Message Requirements		
6.3.3.1.1.1	SPaT Message - SAE J2735	See 7.3.3.1.1.1, SPaT Message - SAE J2735 Design Details	
6.3.3.1.1.2	SPaT Message - Mandatory Data Elements	See 7.3.3.1.1.2, SPaT Message - Mandatory Data Elements Design Details	
6.3.3.1.1.3	SPaT Message - Required Data Elements	See 7.3.3.1.1.3, SPaT Message - Required Data Element Design Details	
6.3.3.1.1.4	SPaT Message PSID	See 7.3.3.1.1.4, SPaT Message PSID	
6.3.3.1.1.5	MAP Message - SAE J2735	Not applicable	
6.3.3.1.1.6	MAP Message - Mandatory Data Elements	Not applicable	
6.3.3.1.1.7	MAP Message - Required Data Elements	Not applicable	
6.3.3.1.1.8	MAP Message PSID	Not applicable	
6.3.3.1.1.9	RTCMcorrections Message - SAE J2735	Not applicable	
6.3.3.1.1.10	RTCMcorrections Message - Mandatory Data Elements	Not applicable	
6.3.3.1.1.11	RTCMcorrections Message - Required Data Elements	Not applicable	
6.3.3.1.1.12	RTCMcorrections Message PSID	Not applicable	
6.3.3.1.1.13	BSM Message - SAE J2735	See 7.3.3.1.1.13, Basic Safety Message - SAE J2735	
6.3.3.1.1.14	BSM Message PSID	See 7.3.3.1.1.14, Basic Safety Message PSID	

Requirements Traceability Matrix (RTM)			
FR ID	Functional Requirement	Design Detail	Additional Specification
6.3.3.1.2	Robustness Requirements		
6.3.3.1.2.1	Broadcast SPaT Message	See 7.3.3.1.2.1, Broadcast SPaT Message Design Details	
6.3.3.1.2.2	Continuous Broadcast of SPaT Messages	See 7.3.3.1.2.2, Continuous Broadcast of SPaT Messages Design Details	
6.3.3.1.3	Concise Messages Requirements		
6.3.3.1.3.1	Transport Message Size - WAVE	Refer to CTI 4501, Table 6, Requirements Traceability Matrix	
6.3.3.1.4	Advanced Notification Requirements	Refer to CTI 4501, Table 6, Requirements Traceability Matrix	
6.3.3.1.5	Timeliness Requirements		
6.3.3.1.5.1	SPaT Message - Broadcast Latency and Accuracy	See 7.3.3.1.5.1, SPaT Message - Broadcast Latency and Accuracy Design Details	
6.3.3.1.6	Quality Assurance Requirements		
6.3.3.1.6.1	Completeness - SPaT Message	See 7.3.3.1.6.1, Completeness - SPaT Message Design Details	
6.3.3.1.6.2	Completeness - MAP Message	Not applicable	
6.3.3.1.6.3	SPaT Message - Time Mark Accuracy	No Further Design Details	
6.3.3.2	Generic Message Requirements		
6.3.3.2.1	Time Accuracy	Refer to CTI 4501, Table 6, Requirements Traceability Matrix	
6.3.3.2.2	Message Revision Requirements		
6.3.3.2.2.1	SPaT Message - Revision Counter Increment	See 7.3.3.2.2.1, SPaT Message - Revision Counter Increment Design Details	
6.3.3.2.2.2	SPaT Message - Revision Counter Not Increment	See 7.3.3.2.2.2, SPaT Message - Revision Counter Not Increment Design Details	
6.3.3.2.3	Timestamp Requirements		
6.3.3.2.3.1	SPaT Message - Message Time Stamp	See 7.3.3.2.3.1, SPaT Message - Message Time Stamp Design Details	
6.3.3.2.3.2	SPaT Message - Intersection Time Stamp	See 7.3.3.2.3.2, SPaT Message - Intersection Time Stamp Design Details	
6.3.3.3	Signal Timing Data Requirements		
6.3.3.3.1	Intersection Identification Requirements		
6.3.3.3.1.1	Intersection Signal Timing Information	See 7.3.3.3.1.1, Intersection Signal Timing Information Design Details	
6.3.3.3.1.2	Intersection Identifier	See 7.3.3.3.1.2, Intersection Identifier Design Details	
6.3.3.3.1.3	Road Authority Identifier	See 7.3.3.3.1.3, Road Authority Identifier Design Details	
6.3.3.3.2	Intersection Status Requirements		
6.3.3.3.2.1	Manual Control	See 7.3.3.3.2.1, Manual Control Design Details	
6.3.3.3.2.2	Stop Time	See 7.3.3.3.2.2, Stop Time Design Details	
6.3.3.3.2.3	Failure Flash	See 7.3.3.3.2.3, Failure Flash Design Details	
6.3.3.3.2.4	Preemption	See 7.3.3.3.2.4, Preemption Design Details	

Requirements Traceability Matrix (RTM)			
FR ID	Functional Requirement	Design Detail	Additional Specification
6.3.3.3.2.5	Priority	See 7.3.3.3.2.5, Priority Design Details	
6.3.3.3.2.6	Fixed Time	See 7.3.3.3.2.6, Fixed Time Design Details	
6.3.3.3.2.7	Traffic Dependent Mode	See 7.3.3.3.2.7, Traffic Dependent Mode Design Details	
6.3.3.3.2.8	Standby Mode	See 7.3.3.3.2.8, Standby Mode Design Details	
6.3.3.3.2.9	Failure Mode	See 7.3.3.3.2.9, Failure Mode Design Details	
6.3.3.3.2.10	Controller Off	See 7.3.3.3.2.10, Controller Off Design Details	
6.3.3.3.2.11	Recent MAP Update	See 7.3.3.3.2.11, Recent MAP Update Design Details	
6.3.3.3.2.12	New Lane IDs	See 7.3.3.3.2.12, New Lane IDs Design Details	
6.3.3.3.2.13	No MAP Available	See 7.3.3.3.2.13, No MAP Available	
6.3.3.3.2.14	No SPaT Available	See 7.3.3.3.2.14, No SPaT Available Design Details	
6.3.3.3.2.15	RTCM Corrections Available [Informative]	See 7.3.3.3.2.15, RTCM Services Available Details [Informative]	
6.3.3.3.2.16	Supports RLVW [Informative]	See 7.3.3.3.2.16, Supports RLVW Details [Informative]	
6.3.3.3.3	Current Movement State Requirements		
6.3.3.3.3.1	Current Movement State for a Signal Group	See 7.3.3.3.3.1, Current Movement State for a Signal Group	
6.3.3.3.3.2	Unknown Current Movement State for a Signal Group	See 7.3.3.3.3.2, Unknown Current Movement State for a Signal Group	
6.3.3.3.3.3	Flashing Yellow Arrow Permissive Movement	See 7.3.3.3.3.3, Flashing Yellow Arrow Permissive Movement	
6.3.3.3.3.4	Protected and Permissive Clearance	See 7.3.3.3.3.4, Protected and Permissive Clearance	
6.3.3.3.3.5	Resolve Protected Versus Permissive Movement	See 7.3.3.3.3.5, Resolve Protected Versus Permissive Movement	
6.3.3.3.3.6	Yield Causes Permissive	See 7.3.3.3.3.6, Yield Causes Permissive	
6.3.3.3.3.7	Right-of-Way Causes Protected	See 7.3.3.3.3.7, Right-of-Way Causes Protected	
6.3.3.3.3.8	WALK State Enumeration	See 7.3.3.3.3.8, WALK State Enumeration	
6.3.3.3.3.9	Flashing DON'T WALK State Enumeration	See 7.3.3.3.3.9, Flashing DON'T WALK State Enumeration	
6.3.3.3.3.10	Steady DON'T WALK State Enumeration	See 7.3.3.3.3.10, Steady DON'T WALK State Enumeration	
6.3.3.3.3.11	Movement State for Signal Groups Identified	No Further Design Details	
6.3.3.3.3.12	Dark Pedestrian Indications	See 7.3.3.3.3.12, Dark Pedestrian Indications	
6.3.3.3.3.13	Prohibited Movements	See 7.3.3.3.3.13, Prohibited Movements	
6.3.3.3.3.14	Movements Allowed After a Stop	See 7.3.3.3.3.14, Movements Allowed After a Stop	
6.3.3.3.4	Next Movement State Requirements		

Requirements Traceability Matrix (RTM)			
FR ID	Functional Requirement	Design Detail	Additional Specification
6.3.3.3.4.1	Next Movement State	See 7.3.3.3.4.1, Next Movement State	
6.3.3.3.4.2	Unknown Next Movement State	See 7.3.3.3.4.2, Unknown Next Movement State	
6.3.3.3.4.3	No Past State	No Further Design Details	
6.3.3.3.5	Time Change Details Requirements		
6.3.3.3.5.1	Time Change Details	See 7.3.3.3.5.1, Time Change Details	
6.3.3.3.5.2	Unknown Time Change Detail	See 7.3.3.3.5.2, Unknown Time Change Detail	
6.3.3.3.5.3	Minimum End Time	See 7.3.3.3.5.3, Minimum End Time	
6.3.3.3.5.4	Maximum End Time	See 7.3.3.3.5.4, Maximum End Time	
6.3.3.3.5.5	Unknown Maximum End Time	See 7.3.3.3.5.2, Unknown Time Change Detail	
6.3.3.3.5.6	Current Movement State Start Time	No Further Design Details	
6.3.3.3.5.7	Next Movement State Start Time	See 7.3.3.3.5.7, Next Movement State Start Time	
6.3.3.3.5.8	Next State Start Time Equals Current State Minimum End Time	See 7.3.3.3.5.8, Next State Time Start Equals Current State Minimum End Time	
6.3.3.3.6	Next Allowed Movement Requirements		
6.3.3.3.6.1	Time of Next Allowed Movement	See 7.3.3.3.6.1, Time of Next Allowed Movement	
6.3.3.3.7	Enabled Lanes Indication	See 7.3.3.3.7, Enabled Lanes Indication	
6.3.3.3.8	SPaT Message - Accuracy	No Further Design Details	
6.3.3.4	Roadway Geometry Data Requirements	Not applicable	
6.3.3.4.1	Intersection Geometry Requirements	Not Applicable	
6.3.3.4.2	Lane Attributes	Not Applicable	
6.3.3.4.3	Lane Maneuvers	Not Applicable	
6.3.3.4.4	Connection Between Lanes	Not Applicable	
6.3.3.4.5	Speed Limit Information Requirements	Not Applicable	
6.3.3.4.6	Revocable Lanes	Not Applicable	
6.3.3.4.7	Signal Timing and Roadway Geometry Information Synchronization		
6.3.3.4.7.1	Matching SPaT and MAP Version	See 7.3.3.4.7.1, Matching SPaT and MAP Version Design Details	
6.3.3.4.7.2	Matching Intersection Reference Identifiers	See 7.3.3.4.7.2, Matching Intersection Reference Identifier Design Details	
6.3.3.4.7.3	Complete List of Signal Group Identifiers	See 7.3.3.4.7.3, Complete List of Signal Group Identifiers Design Details	
6.3.3.4.7.4	Matching Signal Group Identifier Movements	See 7.3.3.4.7.4, Matching Signal Group Identifier Movements Design Details	
6.3.3.5	Positioning Messages	Not Applicable	
6.3.3.6	Vehicle Messages Requirements		
6.3.3.6.1	Vehicle Position	See 7.3.3.6.1, Vehicle Position	

Requirements Traceability Matrix (RTM)			
FR ID	Functional Requirement	Design Detail	Additional Specification
6.3.3.6.2	Vehicle Kinematics	See 7.3.3.6.2, Vehicle Kinematics	
6.3.4	Security Requirements		
6.3.4.1	Data Trustworthiness: Sources and Processing	Refer to CTI 4501/3, Table 1, Requirements Traceability Matrix	
6.3.4.2	Data Communications Security	Refer to CTI 4501/3, Table 1, Requirements Traceability Matrix	
6.3.4.3	Trustworthiness of TSC-Originating Information	Refer to CTI 4501/3, Table 1, Requirements Traceability Matrix	
6.3.4.4	Approaching Vehicle Information Trustworthiness: RSU	Refer to CTI 4501/3, Table 1, Requirements Traceability Matrix	
6.3.4.5	Approaching Vehicle Information Trustworthiness and AGP: TSC	Refer to CTI 4501/3, Table 1, Requirements Traceability Matrix	
6.3.4.6	Time Source Trustworthiness	Refer to CTI 4501/3, Table 1, Requirements Traceability Matrix	
6.3.4.7	SPaT Message Trustworthiness and Reliability	Refer to CTI 4501/3, Table 1, Requirements Traceability Matrix	
6.3.4.8	MAP Message Contents Trustworthiness	Not Applicable	
6.3.4.9	RTCM Message Contents Trustworthiness	Not Applicable	
6.3.4.10	Consistency Between MAP and SPaT Messages	Refer to CTI 4501/3, Table 1, Requirements Traceability Matrix	
6.3.4.11	Unavailability Indications		
6.3.4.11.1	Correctness of SPaT Availability Indications	Refer to CTI 4501/3, Table 1, Requirements Traceability Matrix	
6.3.4.11.2	Correctness of SPaT Unavailability Indications	Refer to CTI 4501/3, Table 1, Requirements Traceability Matrix	
6.3.4.12	Intersection Identifier Trustworthiness	Refer to CTI 4501/3, Table 1, Requirements Traceability Matrix	
6.3.4.13	System Management and Recovery	Not Applicable	
6.3.4.14	Support Systems and Functions	Not Applicable	
6.3.4.15	Updates and Update Planning	Not Applicable	
6.3.4.16	System Operational Modes, Accesses, and Status	Not Applicable	
6.3.4.17	V2X Message Transmission	Not Applicable	
6.3.4.18	CI Security Verification Requirements	Refer to CTI 4501/3, Table 1, Requirements Traceability Matrix	
6.3.5	Operations and Maintenance Requirements	Refer to CTI 4501, Table 6, Requirements Traceability Matrix	

7.3 Design Details

The design details to fulfill the requirements defined in 6.3 follow.

7.3.1 Architectural Design Details

Refer to CTI 4501, Table 6, Requirements Traceability Matrix for the design guidance to fulfill the Architectural Requirements.

7.3.2 TSC Infrastructure to RSU Design Details

The design details to fulfill the requirements for a TSC infrastructure to provide signal timing information to an RSU follow. These requirements are defined in 6.3.2.

7.3.2.1 TSC Infrastructure Signal Timing Data Design Details

The design details to fulfill the requirements for a TSC infrastructure to provide signal phase and timing data to an RSU follow. These requirements are defined in 6.3.2.1.

7.3.2.1.1 SPaT Information Design Details

The design details to fulfill the requirements defined in 6.3.2.1.1 follow.

The SAE J2735 SPaT message transmitted by a connected intersection uses SPaT information sent from the TSC infrastructure to the RSU (see the red arrow in Figure 7). Three formats in which SPaT information may be sent to the RSU are:

- Using the NTCIP 1202 Standard (v03B or later)
- Using the V2I Hub ICD TSCBM
- Using the MSG_SignalPhaseAndTiming Message (SPaT) message defined in SAE J2735



Figure 7 - SPaT information

7.3.2.1.1.1 NTCIP 1202 SPaT Information Design Details

The design details to use NTCIP 1202 to transmit SPaT information are as follows.

NTCIP 1202 defines data objects that provide the information needed by the SPaT message generation process to generate an UPER-encoded SPaT message. A deployer/developer can find the requirements for generating the SPaT message in 3.5.4 of NTCIP 1202. The design details to fulfill each of those requirements are found in NTCIP 1202, Annex A.3, Requirements Traceability Matrix.

The SPaT message generation process, which is part of the CV Application Process (see D.2.1.3), then uses this information to generate an UPER-encoded SAE J2735 SPaT message.

Notes:

- A connected intersection uses UTC time (see 6.3.3.2.1, Time Accuracy); however, not all TSC infrastructure uses UTC time. Thus, an SPaT message generation process must convert the timepoints (or ticks) provided by the TSC infrastructure into UTC time to properly generate a SPaT message.
- See D.3.2, Profile 1: SPaT Information between the TSC Process and the CV Application Process for additional design details.

7.3.2.1.1.2 TSCBM SPaT Information Design Details

The design details to transmit SPaT information using the TSCBM is described in the section titled “Traffic Signal Controller Interface” in Chapter 3 of the V2I Hub ICD and consists of the data objects that are exchanged between the TSC infrastructure and the RSU. These data objects consist of NTCIP 1202 v02 data objects, as described in Table 3-2, NTCIP 1202 Interface SNMP Data Objects, of the V2I Hub ICD and additional data objects, listed in Table 3-3, Extended SNMP Data Objects, of the V2I Hub ICD. The additional, or extended, data objects along with several NTCIP data objects are sent in a single message, also known as the Traffic Signal Controller Broadcast Message (TSCBM). The structure of the TSCBM is described in Table 3-4 of the V2I Hub ICD. See Annex A.1, TSCBM & SPaT Data.

The SPaT message generation process, which is part of the CV Application Process (see D.2.1.3), then uses this information to generate an UPER-encoded SAE J2735 SPaT message. The SPaT message generation process can reside either in the RSU, an external device between the TSC and the RSU, or in the TSC. See Annex D for additional details.

Notes:

- Unlike the SAE J2735 SPaT message, times provided in the TSCBM are time to change. Thus, the SPaT message generation process must convert the time to change information into a time mark to properly generate a SPaT message.
- The TSCBM does not assign a signal group identifier. Thus, an SPaT message generation process has to have a translation table to convert the phases/overlaps to a signal group identifier to generate a SPaT message.
- The TSCBM does not indicate if a movement/phase is a protected or permissive movement. Thus, an SPaT message generation process has to have a table to indicate if a phase/overlap is a protected or permissive movement/clearance.
- Some information required for the SPaT information is not provided by the TSC infrastructure and must be provided by the RSU, such as intersection ID and enabled lanes.
- The SPaT message generation process may have to convert the spatTimestamp in the TSCBM into UTC time. The spatTimestamp may be based on the clock that the controller is using, which may be different than UTC time.

7.3.2.1.1.3 SPaT Message Design Details

Some TSC infrastructure systems are capable of generating an UPER-encoded SAE J2735 SPaT message directly. If the TSC infrastructure system can generate a complete UPER-encoded SAE J2735 SPaT message, the TSC infrastructure system should transmit the SPaT message to the RSU and store it in the Immediate Forward Message (IFM) table of the RSU. The IFM table is called rsuIFMStatusTable in NTCIP 1218, and CTI 4001, which references NTCIP 1218.

If the RSU is using NTCIP 1218, upon receiving the UPER-encoded SPaT message, the appropriate entry in the IFM table will determine what security processing is to be performed before the SPaT message is broadcasted.

Notes:

- A connected intersection uses UTC time (see 6.3.3.2.1, Time Accuracy); however, not all TSC infrastructure uses UTC time. Thus, an SPaT message generation process must convert the timepoints (or ticks) provided by the TSC infrastructure into UTC time to properly generate a SPaT message.
- See D.3.3, Profile 2: SPaT Information between the CV Application Process to the Message Handling Process for additional design details.

7.3.2.1.2 TSC Signal State Periodicity

No design details provided at this time.

7.3.2.1.3 TSC Signal Indication Phase State and SPaT Information Consistency

No design details provided at this time.

7.3.2.2 Signal Timing Status Design Details

The design details to fulfill the requirements for a TSC infrastructure to provide signal timing status to an RSU follow. These requirements are defined in 6.3.2.2.

7.3.2.2.1 TSC Infrastructure Manual Control Indication Design Details

See 7.3.3.3.2.1, Manual Control Design Details and NTCIP 1202, Annex F.3.3.4.1, Manual Control for a description of Manual Control.

The method that the TSC infrastructure uses to indicate when it is operating in Manual Control depends on the format used to send SPaT information from the TSC infrastructure to the RSU.

7.3.2.2.1.1 TSC Infrastructure Manual Control Indication (NTCIP 1202)

When sending NTCIP 1202 data, NTCIP Object spatStatus2 Bit 0 is enabled (1) when NTCIP Object unitControlStatus is set to remoteManualControl (9) or localManualControl (10). Otherwise, NTCIP Object spatStatus2 Bit 0 is disabled (0).

NOTE: This design detail is updated in CTI 4501 v02 to reference NTCIP 1202 v03B and later. CTI 4501 v01 referenced NTCIP 1202 v03A.

7.3.2.2.1.2 TSC Infrastructure Manual Control Indication (TSCBM)

When sending TSCBMs, TSCBM Byte 232 Bit 0 is set to 1 when NTCIP Object unitControlStatus is set to remoteManualControl (9) or localManualControl (10). Otherwise, TSCBM Byte 232 Bit 0 is set to 0.

7.3.2.2.1.3 TSC Infrastructure Manual Control Indication (SAE J2735)

When sending SAE J2735 SPaT messages, DE_IntersectionStatusObject Bit 0 is set to 1 when NTCIP Object unitControlStatus is set to remoteManualControl (9) or localManualControl (10). Otherwise, DE_IntersectionStatusObject Bit 0 is set to 0.

7.3.2.2.2 TSC Infrastructure Stop Time Indication Design Details

See 7.3.3.3.2.2, Stop Time Design Details and NTCIP 1202, Annex F.3.3.4.2, Stop Time for a description of Stop Time.

The design for the TSC Infrastructure Stop Time Indication depends on what format is used to send SPaT information from the TSC infrastructure to the RSU.

7.3.2.2.2.1 TSC Infrastructure Stop Time Indication (NTCIP 1202)

When sending NTCIP 1202 data, NTCIP Object spatStatus2 Bit 1 is enabled (1) when NTCIP Object unitAlarmStatus2 Bit 4 is True (1). Otherwise, NTCIP Object spatStatus2 Bit 1 is disabled (0).

NOTE: This design detail is updated to reference NTCIP 1202 v03B and later. CTI 4501 v01 referenced NTCIP 1202 v03A.

7.3.2.2.2.2 TSC Infrastructure Stop Time Indication (TSCBM)

When sending TSCBMs, TSCBM Byte 232 Bit 1 is set to 1 when NTCIP Object unitAlarmStatus2 Bit 4 is True (1). Otherwise, TSCBM Byte 232 Bit 1 is set to 0.

7.3.2.2.2.3 TSC Infrastructure Stop Time Indication (SAE J2735)

When sending SAE J2735 SPaT messages, DE_IntersectionStatusObject Bit 1 is set to 1 when NTCIP Object unitAlarmStatus2 Bit 4 is True (1). Otherwise, DE_IntersectionStatusObject Bit 1 is set to 0.

7.3.2.2.3 TSC Infrastructure Failure Flash (Exception Flash) Indication Design Details

Cabinet Flash is any type of flash that is initiated and terminated by sources external to the controller. There are two types of Cabinet Flash:

- "Monitor Flash" is Cabinet Flash controlled by the monitor in the following two scenarios:
 - When resuming operation after a power loss or interruption, the monitor keeps the Flash Bus energized for a minimum of 6 seconds before energizing the Signal Bus and transferring control to the controller.
 - When a fault is detected by the monitor, it energizes the Flash Bus until either the fault is cleared by pressing the Reset button on the monitor (latching fault) or, with certain types of faults, when the condition that caused the fault is no longer present (non-latching fault).
- "Local Flash" is Cabinet Flash controlled by human-operated switches in the traffic cabinet, typically labeled "AUTO/FLASH," that are used by technicians to flash the signals when performing maintenance on the controller (Tech Flash) or by police during unusual traffic conditions or situations (Police Flash).

The end of Cabinet Flash is indeterminate because the controller does not know when the monitor is going to be reset or when the flash switch is going to be moved from "FLASH" to "AUTO." Therefore, time change details during Cabinet Flash cannot be supplied.

During Cabinet Flash, signal indications are determined by traffic cabinet wiring (jumpers or flash program blocks) rather than controller software, so the TSC does not have intrinsic knowledge of the signal indications during Cabinet Flash. A workaround for this may be provided in future versions of this document, perhaps using new NTCIP objects (per-channel entry of Yellow, Red, or Dark to match physical wiring) or real-time voltage and current measurements (where supported by serial cabinet architectures).

Certain traffic cabinet architectures such as NEMA TS 1 do not define Flash Sense inputs to the TSC. IOOs using these cabinets are cautioned that without special accommodations, TSCs running in these traffic cabinets do not know that Cabinet Flash is active and may continue to cycle normally and erroneously provide normal time change details and movement states to OBUs/MUs during Cabinet Flash. Signalized intersections where the TSC do not know when Cabinet Flash is active are PROHIBITED from broadcasting SPaT messages.

See 7.3.3.3.2.3, Failure Flash Design Details and NTCIP 1202, Annex F.3.3.4.3, Failure Flash for additional descriptions of Failure Flash.

The design for the TSC Infrastructure Failure Flash (Exception Flash) Indication depends on what format is used to send SPaT information from the TSC infrastructure to the RSU. Failure flash is also known as cabinet flash.

7.3.2.2.3.1 TSC Infrastructure Cabinet Flash (Exception Flash) Indication (NTCIP 1202)

When sending NTCIP 1202 data, NTCIP Object spatStatus2 Bit 2 is enabled (1) when NTCIP Object unitFlashStatus is other (1), localManual (4), or mmu (6). Otherwise, NTCIP Object spatStatus2 Bit 2 is disabled (0).

TSC Infrastructure can be in either Cabinet Flash or Controller Flash but not both. Therefore, NTCIP Object spatStatus2 Bit 2 and Bit 7 shall not simultaneously equal 1.

NOTE: This design detail is updated to reference NTCIP 1202 v03B or later. CTI 4501 v01 referenced NTCIP 1202 v03A.

7.3.2.2.3.2 TSC Infrastructure Cabinet Flash (Exception Flash) Indication (TSCBM)

When sending TSCBM, TSCBM Byte 232 Bit 2 is set to 1 when NTCIP Object unitFlashStatus is other (1), localManual (4), or mmu (6). Otherwise, TSCBM Byte 232 Bit 2 is set to 0.

TSC Infrastructure can be in either Cabinet Flash or Controller Flash but not both. Therefore, TSCBM Byte 232 Bit 2 and Bit 7 shall not simultaneously equal 1.

7.3.2.2.3.3 TSC Infrastructure Cabinet Flash (Exception Flash) Indication (SAE J2735)

When sending SAE J2735 SPaT messages, DE_IntersectionStatusObject Bit 2 is set to 1 when NTCIP Object unitFlashStatus Bit 2 is enabled (1) when NTCIP Object unitFlashStatus is other (1), localManual (4), or mmu (6). Otherwise, DE_IntersectionStatusObject Bit 2 is set to 0. See 7.3.3.3.2.3.

TSC Infrastructure can be in either Cabinet Flash or Controller Flash but not both. Therefore, DE_IntersectionStatusObject Bit 2 and Bit 7 shall not simultaneously equal 1.

7.3.2.2.4 TSC Infrastructure Preemption Operation Indication Design Details

NTCIP 1202 defines preemption as “the transfer of the normal control (operation) of traffic signals to a special signal control mode for the purposes of servicing railroad crossings, emergency vehicle passage, mass transit vehicle passage, and other special tasks, the control of which requires terminating normal traffic control to provide the service needs of the special task.” Under preemption, the normal operations of the TSC are immediately interrupted to provide preferential treatment to specific classes of vehicles, such as trains or emergency vehicles, which have an urgent need for the right-of-way, regardless of the signal state. Due to the urgency to change the right-of-way, preemption can disrupt coordination, pedestrian services, and phasing patterns. The severity of the impacts depends on several factors, including timing parameters, intersection spacing, transition algorithm, level of saturation, duration of preemption, and the amount of slack time available in the intersection cycle.

Most TSCs have multiple preemptions that allow agencies to assign precedence to the order in which requests for preemption are serviced. Higher levels of preemption have precedence over lower levels of preemption. That means if the TSC receives a request for preemption of higher precedence while servicing a lower level of preemption, it will immediately terminate the lower level of preemption to service the one with the higher precedence. However, if the request is for a lower level of preemption, the TSC will continue to service the higher preemption request until it has been satisfied and then service the lower-level preemption (if the request for service still exists). As a result, most IOOs reserve the highest level of preemption for the most critical vehicles using the intersection (e.g., trains over emergency services over police over transit).

Preemption is comprised of four distinct stages:

- Transition Preparation Stage - The TSC begins this stage immediately upon receiving a preemption request. During this stage, the TSC transfers the right-of-way from the movements that are currently active to the movements requiring preferential treatment at the intersection. Depending upon which movements the TSC is presently servicing, transferring the right-of-way may require the TSC to terminate existing signal indications as quickly and safely as possible. Depending on the level of precedence of the request, IOOs may be permitted to truncate the duration of some intervals (such as pedestrian clearance intervals) to ensure the quick transfer of the intersection right-of-way to the preferential movement.

NOTE: For railroad preemption, this stage is often referred to as the right-of-way transfer period.

- Transition Stage - This stage occurs after the TSC has transferred the right-of-way to the movement request preferential treatment. During this stage, the TSC provides a green indication to the movement requesting preferential treatment to clear queued vehicles in advance of the arrival of the requesting vehicle. (For railroad preemption, this is commonly referred to as the track clearance phase.)
- Dwell Stage - In this stage, the TSC is actively servicing the preferential vehicle. Once the TSC completes its transition, it will remain in this stage until the preempt call for service is removed (i.e., the preempt call is deactivated). How the signal operates during this stage depends on what type of preferential treatment is being provided. If the preemption is used to service transit and emergency vehicles, the TSC will be programmed to remain in green until the vehicle has cleared the intersection (or the preempt times out). For railroad preemption, the TSC may operate using one of the following during the dwell stage:
 - Red flash for all phases except those in conflict with the railroad crossing.
 - Flashing yellow for major allowable movements and flashing red for allowable minor movements.
 - Steady red or all-way stop.
 - Limited service, in which the TSC services and cycles through the allowable phases not in conflict with the preempted movements.
 - Rest in green for movements parallel to the railroad track.
- Recovery (or Exit) Stage - This stage occurs after the requesting vehicle has left the intersection. The IOO programs the sequencing and durations of the signal indications used in the recovery stage - usually, those movements most adversely impacted by the preemption operation. Once the recovery phases have been serviced, the TSC reverts to normal operations through firmware-specific predetermined logic. If normal operation requires the TSC to be in coordination with other intersections, the TSC may require anywhere between one to five cycles of transition before it can regain synchronization with other intersections.

The design for the TSC Infrastructure Preemption Operation Indication depends on what format is used to send SPaT information from the TSC infrastructure to the RSU.

7.3.2.2.4.1 TSC Infrastructure Preemption Operation Indication (NTCIP 1202)

When sending NTCIP 1202 data, NTCIP Object spatStatus2 Bit 3 is enabled (1) when NTCIP Object preemptState is any value other than other (1), notActive (2), or notActiveWithCall (3). Otherwise, NTCIP Object spatStatus2 Bit 3 is disabled (0).

NOTE: This design detail is updated to reference NTCIP 1202 v03B or later. CTI 4501 v01 referenced NTCIP 1202 v03A.

7.3.2.2.4.2 TSC Infrastructure Preemption Operation Indication (TSCBM)

When sending TSCBMs, TSCBM Byte 232 Bit 3 is set to 1 when NTCIP Object preemptState is any value other than other (1), notActive (2), or notActiveWithCall (3). Otherwise, TSCBM Byte 232 Bit 3 is set to 0.

7.3.2.2.4.3 TSC Infrastructure Preemption Operation Indication (SAE J2735)

When sending SAE J2735 SPaT messages, DE_IntersectionStatusObject Bit 3 is set to 1 when NTCIP Object preemptState is any value other than other (1), notActive (2), or notActiveWithCall (3). Otherwise, DE_IntersectionStatusObject Bit 3 is set to 0.

7.3.2.2.5 TSC Infrastructure Priority Operation Indication Design Details

Like preemption, priority is a special operating mode of the TSC that provides preferential treatment to specific user classes (transit vehicles, commercial fleet trucks, etc.) at a signalized intersection. However, unlike preemption, during priority the TSC attempts to provide this preferential treatment without disrupting the background timing plan and causing the TSC to drop out of coordination with other intersections. Under priority, the TSC will either extend or shorten individual phases to either extend a green indication past its normal termination point or return early to a green indication to service the vehicle requesting preferential treatment. Like preemption, authorized special vehicles need to request priority from the TSC. Unlike preemption, the TSC may or may not respond immediately to the request by altering the timing and sequencing of the signal indications, depending upon the estimated arrival time of the vehicle at the intersection. In some circumstances, no change in the phase duration or phase sequence may be needed to serve a priority request, while in other circumstances, a TSC may need to extend the operation of a phase past a previously broadcast maximum end time to service the priority request.

The design for the TSC Infrastructure Priority Operation Indication depends on what format is used to send SPaT information from the TSC infrastructure to the RSU.

7.3.2.2.5.1 TSC Infrastructure Priority Operation Indication (NTCIP 1202)

When sending NTCIP 1202 data, NTCIP Object spatStatus2 Bit 4 is enabled (1) when the TSC infrastructure needs to alter the signal timing to service a priority request. This does not include any time to transition. Otherwise, NTCIP Object spatStatus2 Bit 4 is disabled (0).

The purpose here is to indicate to OBUs/MUs when TSC infrastructure timing might be affected. If a request for service can be fulfilled without changes to the current signal timing, then this bit would remain disabled.

NOTE: This design detail is updated to reference NTCIP 1202 v03B and later. CTI 4501 v01 referenced NTCIP 1202 v03A.

7.3.2.2.5.2 TSC Infrastructure Priority Operation Indication (TSCBM)

When sending TSCBMs, TSCBM Byte 232 Bit 4 is set to 1 when the TSC infrastructure is servicing a priority request. Otherwise, TSCBM Byte 232 Bit 4 is set to 0.

7.3.2.2.5.3 TSC Infrastructure Priority Operation Indication (SAE J2735)

When sending SAE J2735 SPaT messages, DE_IntersectionStatusObject Bit 4 is set to 1 when the TSC infrastructure is servicing a priority request. This does not include any time to transition. Otherwise, DE_IntersectionStatusObject Bit 4 is set to 0. See 7.3.3.3.2.5.

The purpose here is to indicate to OBUs/MUs when TSC timing might be affected. If a request for service can be fulfilled without changes to the current signal timing, then this bit would remain 0.

7.3.2.2.6 TSC Infrastructure Fixed Time Control Indication Design Details

An intersection operates in a "Fixed Time" mode when the sequence (order) and duration of each phase is the same cycle-to-cycle, regardless of traffic demand. Under fixed time control, the TSC's ability to adjust the sequence and duration of individual movements based on detector inputs has been disabled, and the TSC follows a consistent pattern regardless of the demand. Agencies will frequently operate traffic signals downtown, urban cores under fixed time control.

See 7.3.3.3.2.6, Fixed Time Design Details for additional information on Fixed Time.

The design for the TSC Infrastructure Fixed Time Control Indication depends on what format is used to send SPaT information from the TSC infrastructure to the RSU.

7.3.2.2.6.1 TSC Infrastructure Fixed Time Indication (NTCIP 1202)

When sending NTCIP 1202 data, NTCIP Object spatStatus2 Bit 5 is enabled (1) when the TSC infrastructure is operating in fixed time control. Otherwise, NTCIP Object spatStatus2 Bit 5 is disabled (0).

One of NTCIP Object spatStatus2 Bit 5 and Bit 6 is always enabled and the bits are mutually exclusive.

NTCIP Object spatStatus2 Bit 5 and Bit 6 represent the general programming of the TSC infrastructure. These bits are not dynamic, changing cycle by cycle or by a preemption operation.

NOTE: This design detail is updated to reference NTCIP 1202 v03B or later. CTI 4501 v01 referenced NTCIP 1202 v03A.

7.3.2.2.6.2 TSC Infrastructure Fixed Time Indication (TSCBM)

There is no TSCBM element for a fixed time indication.

7.3.2.2.6.3 TSC Infrastructure Fixed Time Indication (SAE J2735)

When sending SAE J2735 SPaT messages, DE_IntersectionStatusObject Bit 5 is set to 1 when the TSC infrastructure is operating in fixed time control. Otherwise, DE_IntersectionStatusObject Bit 1 is set to 0. See 7.3.3.3.2.6.

One of DE_IntersectionStatusObject Bit 5 and Bit 6 is always 1 and the bits are mutually exclusive.

DE_IntersectionStatusObject Bit 5 and Bit 6 represent the general programming of the TSC infrastructure. These bits are not dynamic changing cycle by cycle or by a preemption operation.

7.3.2.2.7 TSC Infrastructure Traffic Dependent Control Design Details

The design for the TSC Infrastructure Traffic Dependent Control Indication depends on what format is used to send SPaT information from the TSC infrastructure to the RSU. Semi-actuated control, which is a legacy term, is considered traffic dependent.

7.3.2.2.7.1 TSC Infrastructure Traffic Dependent Indication (NTCIP 1202)

When sending NTCIP 1202 data, NTCIP Object spatStatus2 Bit 6 is enabled (1) when the TSC infrastructure is operating in traffic dependent control. Otherwise, NTCIP Object spatStatus2 Bit 6 is disabled (0).

One of NTCIP Object spatStatus2 Bit 5 and Bit 6 is always enabled and the bits are mutually exclusive.

NTCIP Object spatStatus2 Bit 5 and Bit 6 represent the general programming of the TSC infrastructure. These bits are not dynamic changing cycle by cycle or by a preemption operation.

NOTE: This design detail is updated to reference NTCIP 1202 v03B or later. CTI 4501 v01 referenced NTCIP 1202 v03A.

7.3.2.2.7.2 TSC Infrastructure Traffic Dependent Indication (TSCBM)

There is no TSCBM element for a traffic dependent indication.

7.3.2.2.7.3 TSC Infrastructure Traffic Dependent Indication (SAE J2735)

When sending SAE J2735 SPaT messages, DE_IntersectionStatusObject Bit 6 is set to 1 when the TSC infrastructure is operating in traffic dependent control. Otherwise, DE_IntersectionStatusObject Bit 6 is set to 0. See 7.3.3.3.2.7.

One of DE_IntersectionStatusObject Bit 5 and Bit 6 is always 1 and the bits are mutually exclusive.

7.3.2.2.8 TSC Infrastructure in Standby Mode Design Details

See 7.3.3.3.2.8, Standby Mode Design Details for additional descriptions of Standby Mode.

The design for the TSC Infrastructure in Standby mode depends on what format is used to send SPaT information from the TSC infrastructure to the RSU.

7.3.2.2.8.1 TSC Infrastructure in Standby Mode (NTCIP 1202)

When sending NTCIP 1202 data, NTCIP Object spatStatus2 Bit 7 is enabled (1) when the TSC infrastructure is operating in standby mode. Otherwise, NTCIP Object spatStatus2 Bit 7 is disabled (0).

NOTE: This design detail is updated to reference NTCIP 1202 v03B or later. CTI 4501 v01 referenced NTCIP 1202 v03A.

7.3.2.2.8.2 TSC Infrastructure in Standby Mode (TSCBM)

There is no TSCBM element for a standby indication.

7.3.2.2.8.3 TSC Infrastructure in Standby Mode (SAE J2735)

When sending SAE J2735 SPaT messages, DE_IntersectionStatusObject Bit 7 is set to 1 when the TSC infrastructure is operating in standby mode. Otherwise, DE_IntersectionStatusObject Bit 7 is set to 0. See 7.3.3.3.2.8, Standby Mode Design Details.

7.3.2.3 TSC Infrastructure RLVW Design Details

The design details to fulfill the requirements for a TSC infrastructure to provide support for the RLVW application follow. These requirements are defined in 6.3.2.3. The scenario describing the operational scenario is in CTI 4501, 5.6.1, Red Light Violation Warning (RLVW) Application.

7.3.2.3.1 TSC Infrastructure Assured Green End Time (AGET) Design Details

The design details to provide an AGET follow.

7.3.2.3.1.1 AGET Known Design Details

If the AGET is a known value, the design details to provide an AGET follow.

7.3.2.3.1.1.1 TSC Infrastructure AGET (NTCIP 1202)

When sending NTCIP 1202 data, if the TSC infrastructure has determined a specific termination time for a green signal indication for a channel representing a through traffic movement, the TSC infrastructure shall set the NTCIP 1202 SignalStatusEntry2 objects signalStateMinEndTick2 and signalStateMaxEndTick2 for the channel to the termination time. The termination time shall be equal to or greater than the original signalStateMinEndTick2. Signal status information is arranged by signal group in NTCIP 1202.

NOTE: This design detail is updated to reference NTCIP 1202 v03B or later. CTI 4501 v01 referenced NTCIP 1202 v03A.

7.3.2.3.1.1.2 TSC Infrastructure AGET (TSCBM)

When sending TSCBMs, if the TSC infrastructure has determined a specific termination time for a green signal indication for a channel representing a through traffic movement, the TSC infrastructure shall set the TSCBM elements spatVehMinTimeToChange and spatVehMaxTimeToChange for the associated phase to the duration of time until the termination time. This duration shall be equal to or greater than the original spatVehMinTimeToChange.

NOTE: The TSCBM provides signal indication end times organized by phases in Bytes 2-209 and provides time-to-change values instead of the time-of-change values used by NTCIP 1202 and SAE J2735 SPaT messages. The SPaT message generation process is required to convert these to time-of-change.

7.3.2.3.1.1.3 TSC Infrastructure AGET (SAE J2735)

When sending SAE J2735 SPaT messages, if the TSC infrastructure has determined a specific termination time for a green signal indication for a channel representing a through traffic movement, the TSC infrastructure shall set the SAE J2735 DF_TimeChangeDetails elements MinEndTime and MaxEndTime for the movement to the termination time. The termination time shall be equal to or greater than the original MinEndTime.

NOTE: Time change details are arranged by movements in SAE J2735.

7.3.2.3.2 TSC Infrastructure AGP Extension Method Design Details

The section provides the design details for the TSC infrastructure to support the RLVW application using the AGP extension method. All values used to calculate the Assured Green Period, such as the yellow change interval duration and stopping distance, should be based using engineering practices described in ITE’s Traffic Control Devices Handbook and in ITE’s Manual of Traffic Signal Design. SAE J3305 contains examples of using the calculations.

The distance, size, position, and time elements in Figure 8 and the calculations used in the AGP extension method follow. The speed of the vehicle, as identified in a BSM, is used to determine the time the AGP should be applied. The AGP is calculated using the design speed of the approach and configured in the signal program as a fixed duration by a user.

NOTE 1: In the future, the AGP may be computed in real-time using the speed of the vehicle. The AGP would vary in this case. The current approach is being used to simplify implementation so that this support to the RLVW application can be evaluated.

NOTE 2: Figure 8 provides an approximate depiction of the constants used for the AGP extension calculation.

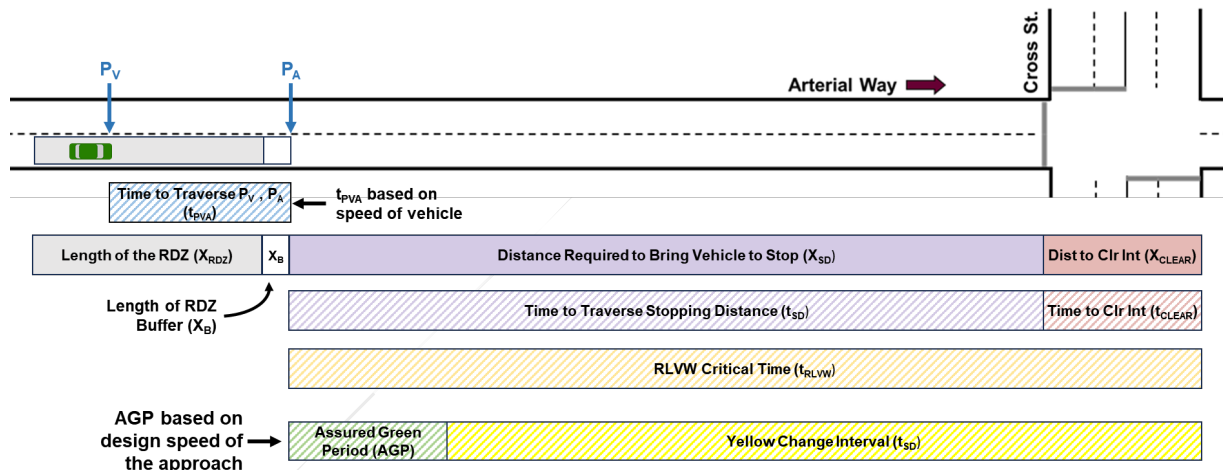


Figure 8 - Distance, size, position, and time elements for the AGP extension

Variables and constants used in the calculations for the AGP extension method are identified below. A lower case “t” is used to indicate a duration of time.

- $V_{Approach}$ is the signal timing design speed of the approach.
- t_{RDZ} is the duration required to detect a vehicle in the RDZ. The value is 1.3 seconds (1200 ms maximum time for detection plus 90 ms for the variance in channel access delay on the OBU).
- X_{RDZ} is the length of the RLVW Detection Zone which equals the time to detect vehicles (t_{RDZ}) multiplied by the signal timing design speed of the approach ($V_{Approach}$). An IOO will use the BSM filtering capabilities of the RSU to configure virtual detection zones for each RDZ of the intersection. An RSU will only send a single BSM to the TSC Infrastructure for a vehicle that enters a zone. See 6.3.2.4.2.

- **X_B** is the length of the RDZ buffer that is used to ensure that there is a small additional time to apply the AGP if a BSM comes in at the downstream edge of the RDZ. The value is 150 ms multiplied by the signal timing design speed ($V_{Approach}$) (the buffer compensates for the maximum channel access delay when the BSM is sent from the OBU).
- **X_{SD}** is the distance required to bring the vehicle to a stop based on the design speed.
- **X_{Clear}** is the distance to clear the intersection.
- **l** (small L) is the assumed typical vehicle length for vehicles using the intersection.
- **t_B** is the duration to traverse the RDZ buffer (XB) using the speed of the vehicle (V_{Speed}).
- **t_{SD}** is the duration to traverse the stopping distance using the assumed speed of the vehicle ($V_{Approach}$).
- **t_{Clear}** is the duration to traverse the length of the intersection using the assumed speed of the vehicle ($V_{Approach}$).
- **t_{Yellow}** is the duration of the yellow change interval.
- **t_{P/R}** is the duration of the perception/reaction time (1.0 second is used).
- **G** is the acceleration due to gravity which is 32.2 ft/s² or 9.81 m/s².
- **g** is the grade, which is feet per feet or meters per meters, where g is positive for an uphill grade approaching the signal, which allows faster deceleration.
- **a** is ITE's deceleration constant of 10 ft/s² or 3.01 m/s².
- **P_V** refers to the vehicle position (lat/long), speed, heading, and time (for which the data is valid, T_{PV}) as reported in a BSM for a vehicle in the RDZ.

NOTE: P_V elevation could be used in the future.

- **P_A** refers to a position (lat/long) along the edge of stopping distance used to compute the time when the AGP is to be applied to the green interval (T_{AGP}). It is suggested that a position be set midway between the combined width of the through lanes.

NOTE: Using an assumed position where the vehicle crosses the edge of the stopping distance is a simple calculation and has sufficient accuracy for this purpose of the AGP extension method. P_A elevation could be used in the future, while P_A speed and heading are not necessary.

- **T_{PV}** is the time the data is valid for the BSM that is received for a vehicle in the RDZ.
- **t_{PVA}** is the duration to traverse the distance between positions P_V and P_A.
- **T_{AGP}** is the time to apply the AGP to the green interval.
- **T_{MinEndTime}** represents the minimum end time of the interval currently being timed. This is an internal variable within the signal program. Implementers may use other names for this variable. It is used to set the minEndTime in the SPaT information sent to the RSU.

NOTE: This is not the phaseMinimumGreen object in NTCIP 1202.

- **T_{MaxEndTime}** is the maximum end time of the interval currently being timed. This is an internal variable within the signal program. Implementers may use other names for this variable. It is used to set the minEndTime in the SPaT information sent to the RSU.

NOTE: This is not the phaseMaximum1 object in NTCIP 1202.

The RLWV calculations are as follows:

- a. Length of the RLWV Detection Zone (RDZ)

$$X_{RDZ} = t_{RDZ} * V_{Approach}$$

- b. Stopping Distance (Basic Kinematic Equation)

$$X_{SD} = V_{Approach} t_{P/R} + \frac{V_{Approach}^2}{2(a \pm Gg)}$$

- c. Time to Clear Intersection at speed

$$t_{Clear} = \frac{X_{Clear} + l}{V_{Approach}}$$

- d. Time to Travel Through Stopping Distance at Approach Speed

$$t_{SD} = \frac{X_{SD}}{V_{Approach}}$$

- e. Red Light Violation Warning Critical Time

$$t_{RLVW} = t_{SD} + t_{Clear}$$

- f. Assured Green Period (AGP)

$$AGP = t_{RLVW} + t_{DC} - t_{yellow}$$

- g. Time to traverse the detected position of the vehicle to the projected position in which to apply the AGP (upstream edge of the stopping distance)

$$t_{PVA} = \frac{Distance(P_V, P_A)}{V_{Speed}}$$

- h. Time to apply the AGP to the green interval

$$T_{AGP} = T_{PV} + t_{PVA}$$

The design scenario is as follows:

- a. Using the calculations for the RDZ length and position, and the width of the RDZ based the combined width of the through lanes, the user configures corresponding zones within the RSU for each through movement of the intersection. The zones will use the event type "ZoneEnter." This means that the RSU only sends a single verified BSM to the TSC infrastructure for a CV that enters the zone. Refer to CTI 4001, 4.3.2.14.4.

NOTE: Within the context of the AGP extension method, the term "RDZ" is used. In CTI 4001, the term "zone" is used.

- b. Vehicle detection zones are configured in the controller to determine the presence and heading of vehicles heading toward the intersection.
- c. When the TSC infrastructure receives a BSM from the RSU on the port representing the particular RDZ, it uses the heading in the BSM to confirm the CV is moving toward the intersection. Otherwise, no further processing is performed and no AGP is applied.

- d. Using the V2X vehicle's position and speed from the BSM and the position, the time to apply the AGP (T_{AGP}) is computed. See the computation of T_{AGP} in items 7.3.2.3.2.g and 7.3.2.3.2.h in the RLVW calculations above.
- e. When the time reaches T_{AGP} , the TSC infrastructure will set the AGP timer (similar to an extension timer) to a defined AGP duration for the through movement phase if all of the following are true:
 1. The phase is in green (refer to NTCIP 1202 phaseStatusGroupGreens).
 2. The TSC infrastructure has not committed to a time to terminate the phase (i.e., an AGET has not been set, $T_{MinEndTime} \neq T_{MaxEndTime}$).
 3. The current time plus the AGP is greater than the minimum green end time ($T_{MinEndTime}$).
 4. The current time plus the AGP is less than or equal to the maximum green end time ($T_{MaxEndTime}$).

The TSC infrastructure may terminate a green interval for a through movement as part of the processing loop of its signal program, provided no AGP for the movement is being timed. V2X vehicles in or downstream of the RDZ will have received an AGP to help them clear the intersection before the beginning of red.

7.3.3 Message Design Details

The design details to fulfill the requirements for a connected intersection broadcasting messages to OBUs/MUs follow. These requirements are defined in 6.3.3.

7.3.3.1 Message Performance Design Details

The design details to fulfill the performance requirements for a connected intersection broadcasting messages to OBUs/MUs follow. These requirements are defined in 6.3.3.1.

7.3.3.1.1 Uniform Message Design Details

The design details to fulfill requirements to provide a consistent representation of the situation and operating conditions at a connected intersection follow. These requirements are defined in 6.3.3.1.1.

7.3.3.1.1.1 SPaT Message - SAE J2735 Design Details

See MSG_SignalPhaseAndTiming Message (SPaT) in SAE J2735.

NOTE: There are some differences between the SAE J2735_201603 version and later versions of SAE J2735. Implementers should be aware of the changes, such as the change in definition for DE_TimeMark.

7.3.3.1.1.2 SPaT Message - Mandatory Data Elements Design Details

See MSG_SignalPhaseAndTiming Message (SPaT) in SAE J2735.

7.3.3.1.1.3 SPaT Message - Required Data Element Design Details

Table 4 lists the data frames (begins with DF_) and the data elements (begins with DE_) in the MSG_SignalPhaseAndTiming Message (SPaT) message of SAE J2735 that are mandatory to be supported by a connected intersection to conform to CTI 4501. The data frames and data elements are listed in the order it appears in the SPaT message. Note that all data frames and data elements listed in Table 4 shall be supported by a connected intersection; however, several data frames and data elements do not have to be included in every broadcasted message under certain conditions.

The "SAE J2735 Mandatory" column indicates if the data frame or data element is mandatory to describe signal phase and timing data as defined in SAE J2735. A value of M indicates that the data frame or data element is mandatory to be supported, while a value of O indicates that the data frame or data element is optional.

The "CI Implementation" column indicates if the data frame or data element is mandatory to be included in every broadcast SPaT message as defined by CTI 4501. A value of M indicates the data frame or data element must be included in every SPaT message broadcasted. A value of C indicates the data frame or data element is conditionally mandatory, meaning that the data frame or data element shall be broadcasted if certain conditions are met. Those conditions can be found in the referenced section in parentheses.

For example, if there are no revocable lanes associated with an intersection, the data frame DF_EnabledLaneList is never transmitted in the SPaT message for that intersection. However, if a revocable lane is associated with that intersection (as defined in the MAP message for that intersection) and the revocable lane is active ("enabled"), then the data frame DF_EnabledLaneList shall be included in the SPaT message. These conditions are found in 7.3.3.3.7.

Similarly, if the TSC infrastructure provides a startTime for a signalGroupID, then startTime (DE_TimeMark) shall be included in the SPaT message. If the TSC infrastructure does not provide a startTime for a signalGroup, then startTime (DE_TimeMark) is a value of unknown in the SPaT message. These conditions are found in 7.3.3.3.5.7 and 7.3.3.3.5.8.

Note that the value in the "CI Implementation" column is different from the "Conformance" column in the NRTM (refer to CTI 4501, Table 5, Needs to Requirements Traceability Matrix) - the Conformance column defines if the implementation must support that requirement - it does not mean the data has to be sent in the SPaT message.

For example, to conform to CTI 4501, the implementation is required to support enabled lanes in the SPaT message, as indicated by the "M" in the Conformance column for requirement 6.3.3.3.7 in the NRTM. However, it is not required that the data element indicating an enabled lane is active (enabledLanes=DF_EnabledLaneList=1 to 16 x DE_LaneID under the "SAE J2735 Data Frames and Data Element" column) be included in the SPaT message that is broadcasted, as indicated by the "C" in the CI Implementation column.

Table 4 - SPaT message - required elements

SAE J2735 Data Frames and Data Elements	SAE J2735 Mandatory	CTI 4501 Implementation
messageId=DE_DSRC MessageID=19 (SPaT UPER)	M	M
timeStamp=DE_MinuteOfTheYear	O	M
intersections=DF_IntersectionStateList	M	M
id=DF_IntersectionReferenceID	M	M
region=DE_RoadRegulatorID	O	Not included
id=DE_IntersectionID	M	M
revision=DE_MsgCount	M	M
status=DE_IntersectionStatusObject	M	M
timeStamp=DE_Dsecond	O	M
enabledLanes=DF_EnabledLaneList=1 to 16 x DE_LaneID	O	C (if a revocable lane is active ("enabled") - see 7.3.3.3.7)
states=DF_MovementList=1 to 255 x DF_MovementState	M	M
signalGroup=DE_SignalGroupID	M	M
state-time-speed=DF_MovementEventList	M	M
eventState=DE_MovementPhaseState	M	M
timing=DF_TimeChangeDetails	O	M
startTime=DE_TimeMark	O	M
minEndTime=DE_TimeMark	M	M
maxEndTime=DE_TimeMark	O	M
nextTime=DE_TimeMark	O	M
roadAuthorityID=DF_RoadAuthorityID ⁽¹⁾	O	M
relRdAuthID=DE_RelativeRoadAuthorityID	O	C (if RelativeRoadAuthorityID is any value other than NULL. See 7.3.3.3.1.3, Road Authority Identifier Design Details).

* DE = Data Element, DF = Data Frame

(1) Added in CTI 4501 v02

The source for each of the data frames and data elements that comprise the SPaT message broadcasted by the RSU will vary based on how the connected intersection is configured and also what SPaT information format is used between the TSC infrastructure and the RSU. Table 5 contains links to the specific sections in CTI 4501 with the design details for generating that data element value, based on SPaT information format used between the TSC infrastructure and the RSU; whether it is the UPER-encoded SPaT Message or NTCIP 1202. Table 13 shows how a TSCBM may be used to generate a SPaT Message.

Table 5 - SPaT message data sources

SAE J2735 Data Element	SAE J2735 SPaT Message	NTCIP 1202 Object Definition
timeStamp (DE_MinuteOfTheYear)	See 7.3.3.2.3.2	Provided by the SPaT message generation process
id=DF_IntersectionReferenceID		
id=DE_IntersectionID	See 7.3.3.3.1.2	signalGroupIntersection
revision=DE_MsgCount	See 7.3.3.2.2.1	Provided by the SPaT message generation process
status=DE_IntersectionStatusObject	See 7.3.3.3.2	spatStatus2
timeStamp=DE_Dsecond	See 7.3.3.2.3.2	Provided by the SPaT message generation process
enabledLanes=DF_EnabledLaneList	See 7.3.3.3.7	spatEnabledLanesStatus
states=DF_MovementList	See 7.3.3.3.3	
signalGroup=DE_SignalGroupID	See 7.3.3.3.3.1	signalGroupID
state-time-speed=DF_MovementEventList		
eventState=DE_MovementPhaseState (Current Movement)	See 7.3.3.3.3	signalState2
eventState=DE_MovementPhaseState (Next Movement)	See 7.3.3.3.4	signalState2
timing=DF_TimeChangeDetails	See 7.3.3.3.5	
startTime=DE_TimeMark	See 7.3.3.3.5.7, 7.3.3.3.5.8	signalStateStartTick. Provided as ticks to the RSU
minEndTime=DE_TimeMark	See 7.3.3.3.5.3	signalStateMinEndTick2. Provided as ticks to the RSU
maxEndTime=DE_TimeMark	See 7.3.3.3.5.4	signalStateMaxEndTick2. Provided as ticks to the RSU
nextTime=DE_TimeMark	See 7.3.3.3.6.1	signalStateNextTick2. Provided as ticks to the RSU
roadAuthorityID=DF_RoadAuthorityID ⁽¹⁾	See 7.3.3.3.1.3	spatRoadAuthorityID

⁽¹⁾ Added in CTI 4501 v02.

7.3.3.1.1.4 SPaT Message PSID

The PSID for the SPaT message is defined in 6.3.3.1.1.4. The PSID is used for the destination address in broadcast WSM and in the app Permissions Field in the SPaT signing certificate.

See <https://standards.ieee.org/products-programs/regauth/psid/public/>.

7.3.3.1.1.5 MAP Message - SAE J2735

Not applicable.

7.3.3.1.1.6 MAP Message - Mandatory Data Elements

Not applicable.

7.3.3.1.1.7 MAP Message - Required Data Elements

Not applicable.

7.3.3.1.1.8 MAP Message PSID

Not applicable.

7.3.3.1.1.9 RTCMcorrections Message - SAE J2735

Not applicable.

7.3.3.1.1.10 RTCMcorrections Message - Mandatory Data Elements

Not applicable.

7.3.3.1.1.11 RTCMcorrections Message - Required Data Elements

Not applicable.

7.3.3.1.1.12 RTCMcorrections Message PSID

Not applicable.

7.3.3.1.1.13 Basic Safety Message - SAE J2735

Refer to MSG_BasicSafetyMessage (BSM) in SAE J2735.

7.3.3.1.1.14 Basic Safety Message PSID

The PSID for the BSM message is defined in 6.3.3.1.1.14. The PSID is used for the destination address in broadcast WSM and in the app Permissions Field in the BSM signing certificate.

See <https://standards.ieee.org/products-programs/regauth/psid/public/>.

7.3.3.1.2 Robustness Design Details

The design details to fulfill the requirements for a connected intersection to operate under different degraded conditions follow. These requirements are defined in 6.3.3.1.2.

7.3.3.1.2.1 Broadcast SPaT Message Design Details

Multiple elements in the SPaT message are mandatory to be broadcasted according to SAE J2735 and to conform to CTI 4501. Table 4 indicates which data frames and elements are mandatory to be included in the SPaT message. If a complete SPaT message can be generated (see 7.3.3.1.6.1, Completeness - SPaT Message Design Details), the connected intersection shall broadcast a SPaT message.

7.3.3.1.2.2 Continuous Broadcast of SPaT Messages Design Details

A connected intersection shall always attempt to broadcast a SPaT message nominally every 100 ms with bit 13 (noValidSPaTisAvailableAtThisTime) in the DE_IntersectionStatusObject enabled (set to 1), even if the TSC infrastructure cannot produce valid SPaT information.

If the SPaT message generation process does not receive valid SPaT information from the TSC infrastructure within 100 ms ± 25 ms (see 6.3.2.1.2, TSC Signal State Periodicity), the RSU is expected to still generate a SPaT message with Bit 9 in the DE_IntersectionStatusObject enabled (set to 1) and attempt to broadcast the SPaT message every 100 ms nominally, allowing that the message may actually not be broadcasted due to congestion over-the-air on the communications channel or other environmental factors.

7.3.3.1.3 Concise Messages Design Details

The design details to fulfill the requirements to provide complete data describing the situation within the maximum message size supported by the communications stack follow. The requirements are defined in 6.3.3.1.3.

7.3.3.1.3.1 Transport Message Size - WAVE

Refer to CTI 4501, Table 6, Requirements Traceability Matrix for the design guidance to fulfill the Transport Message Size - WAVE Requirements.

7.3.3.1.4 Advanced Notification Design Details

Refer to CTI 4501, Table 6, Requirements Traceability Matrix for the design guidance to fulfill the Advanced Notification Requirements.

7.3.3.1.5 Timeliness Design Details

The design details to fulfill the requirements for indicating changes in state, timing, and physical indications follow. The requirements are defined in 6.3.3.1.5.

7.3.3.1.5.1 SPaT Message - Broadcast Latency and Accuracy Design Details

This is a latency and accuracy requirement that helps to ensure the utility of the SPaT data to application programs such as RLWV. The budget includes the time for the following to occur:

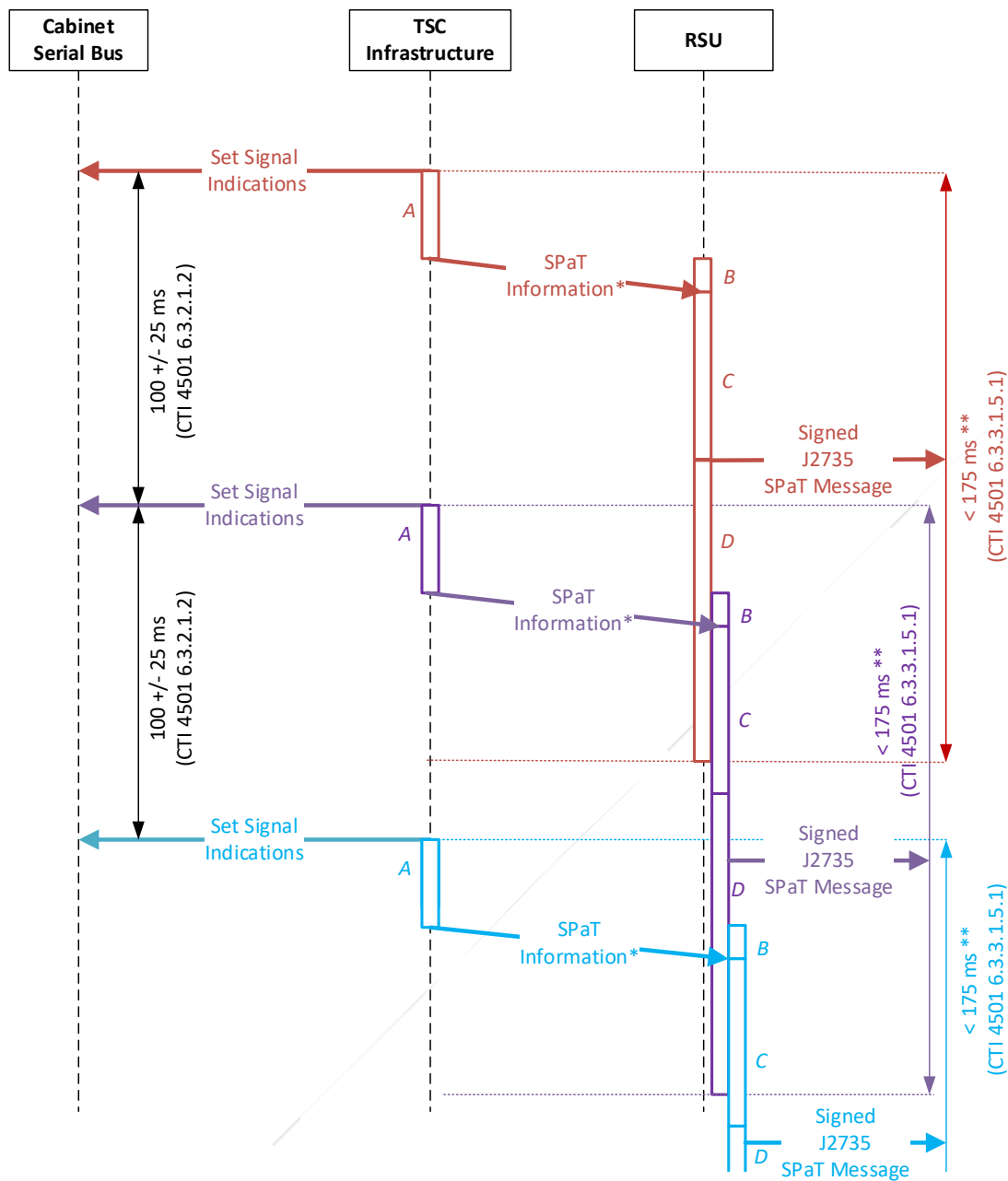
- The TSC infrastructure to send the SPaT information to the SPaT message generation process.
- The SPaT message generation process to convert the SPaT information into a properly formatted SAE J2735 SPaT message, attach the necessary security certificates, and place the SPaT in the broadcast buffer.
- The RSU to broadcast the SPaT message the over-the-air.

Table 6 shows the maximum time budget for producing a valid SPaT message, regardless of the TSC infrastructure and RSU architecture. Figure 9 shows the time budgets in a SPaT message sequence diagram. See Annex A.2, Latency and Timing Error Analysis for Connected Intersections, for additional details and analysis.

Table 6 - SPaT message time budget allocations

Description	Time (ms)
TSC Infrastructure Sending of SPaT Information to RSU	
Maximum delay to send the SPaT information corresponding to setting the signal states	25
Ethernet communication of SPaT information	10
SPaT Message Processing	
Generate UPER encoded SPaT message per SAE J2735 and process SPaT message for the appropriate SCMS security for message broadcast	50
RSU Over-the-Air Message Broadcast	
Maximum channel access delay	90 ⁽¹⁾
Total	175

⁽¹⁾ Per SAE J3161 and SAE J3161/1, the LTE-V2X packet delay budget (PDB) setting for SPaT is 100 ms, which results in a maximum channel access delay of 90 ms. However, the actual maximum channel access delay is dependent on the channel busy ratio (CBR) during operation. When the channel is less than 10% loaded (CBR < .1), maximum channel access delay is reduced to 20 ms, and when the channel is between 10 and 75% loaded (.1 < CBR < .75), it is reduced to 50 ms. Only when the channel is more than 75% loaded (CBR > .75) will the maximum channel access delay be 90 ms.



*contains the signal phase and timing data necessary to generate a SAE J2735 SPaT message. See Section 6.3.2.1.1.

**This represents the maximum SPaT message latency. See Table 5 for details.

A. Maximum delay to send the SPaT information corresponding to setting the signal states (Not to exceed 25 ms. See Table 5 for details)

B. Ethernet communication of SPaT information. (Not to exceed 10 ms. See Table 5 for details)

C. Generate UPER encoded SPaT message per SAE J2735 and process SPaT message for the appropriate SCMS security for message broadcast. (not to exceed 50 ms. See Table 5 for details.)

D. Maximum channel access delay (not to exceed 90 ms. See Table 5 for details).

Figure 1 - SPaT message sequence diagram

NOTE: On rare occasions, SPaT messages that fulfill these requirements could be broadcast out of order. In this case, an OBU typically discards the older messages.

7.3.3.1.6 Quality Assurance Design Details

The design details to fulfill the requirements to provide quality information follow. These requirements are defined in 6.3.3.1.6, Quality Assurance Requirements.

7.3.3.1.6.1 Completeness - SPaT Message Design Details

Multiple elements in the SPaT message must be broadcast according to SAE J2735 and conform to CTI 4501. Table 4 indicates which data frames and elements are mandatory.

A SPaT message shall be broadcast for an intersection if ALL the following conditions are met:

- The SPaT message contains a valid Intersection reference identifier (DE_intersectionID + DE_RelativeRoadAuthorityID (if not NULL)).
- The SPaT message contains a valid revision object (DE_MsgCount).
- The SPaT message contains a valid intersection status object (DE_IntersectionStatusObject).
- The SPaT message contains a valid timeStamp (DE_Dsecond and DE_MinuteOfTheYear).
- The SPaT message is protected based on the IEEE Std 1609.2 security profile for SPaT messages (see Annex B).
- The requirements for 6.3.3.4.7, Signal Timing and Roadway Geometry Information Synchronization are fulfilled.
- All other data elements required to be included in the SPaT message by CTI 4501 may use a value of unavailable, unknown, or not known as appropriate.

A SPaT message is defined to be complete when all the mandatory data elements listed in Table 4 are represented in the SPaT movement for every movement controlled by the TSC infrastructure and included in the associated MAP message. Every allowed movement, including pedestrian movements, bicycle movements, and tracked vehicle movements, of every ingress lane (signalized and unsignalized) into the intersection shall be represented in the SPaT. Each movement may have one or more movement state, as represented by DE_MovementPhaseState. Each movement state should reflect the relative right-of-way of the movement compared to other movements at the intersection. The SPaT shall also include time change details for each movement controlled by traffic signal indications, including the start time, the minimum end time, and the maximum end time, for both current and next movement state. Each time a change detail is made, there shall be an appropriate time entry reflecting both the current and future state of each signal group. SPaT messages with missing or with entry values outside specified ranges shall be deemed “incomplete.”

See 7.3.3.3.2, Intersection Status Design Details for guidance on the content of the SPaT message under different intersection operating states.

See 7.3.3.3.3, Current Movement State Design Details and 7.3.3.3.4, Next Movement State Design Details for guidance on how to define current and future movement states in the SPaT message.

See 7.3.3.3.5, Time Change Details Design Details for guidance relating to communicating time change details through the SPaT message.

The completeness of the SPaT message can be verified by inspection.

7.3.3.2 Generic Message Design Details

The design details to fulfill requirements for a connected intersection transmitting data follow. These requirements are defined in 6.3.3.2.

7.3.3.2.1 Time Accuracy

Refer to CTI 4501, Table 6, Requirements Traceability Matrix for the design guidance to fulfill the Time Accuracy Requirement.

7.3.3.2.2 Message Revision Counter Design Details

The design details to fulfill the requirements to see if the data transmitted by a connected intersection is new follow. These requirements are defined in 6.3.3.2.2, Message Revision Requirements.

7.3.3.2.2.1 SPaT Message - Revision Counter Increment Design Details

The revision counter for a connected intersection in a SPaT message is represented by revision (DE_MsgCount) and found under the data frame DF_IntersectionState in MSG_SignalPhaseAndTiming Message in SAE J2735.

This requirement is verified by inspection.

7.3.3.2.2.2 SPaT Message - Revision Counter Not Increment Design Details

The revision counter for a connected intersection in a SPaT message shall remain the same during a stream of messages when the content within each message for that connected intersection has not changed except the time stamp from the prior message sent. The OBU/MU may ignore processing a new message in the stream if the revision count has not changed from the prior message.

This requirement is tested by inspection.

7.3.3.2.3 Time Stamp Design Details

The design details to fulfill the requirements for a time stamp in messages transmitted by a connected intersection follow. These requirements are defined in 6.3.3.2.3, Time Stamp Requirements.

7.3.3.2.3.1 SPaT Message - Message Time Stamp Design Details

The time stamp indicating the minute of the year when the SPaT message is created is represented by time stamp (DE_MinuteOfTheYear) and found in the MSG_SignalPhaseAndTiming Message in SAE J2735.

7.3.3.2.3.2 SPaT Message - Intersection Time Stamp Design Details

The time stamp indicating the milliseconds within the current minute when the SPaT information for the intersection is generated is represented by time stamp (DE_DSecond) and found under the data frame DF_IntersectionState in the MSG_SignalPhaseAndTiming Message in SAE J2735.

The design for the Intersection Time Stamp depends on what format is used to send SPaT information from the TSC infrastructure to the RSU.

7.3.3.2.3.2.1 Intersection Time Stamp (NTCIP 1202)

When sending NTCIP 1202 data, NTCIP object ascCurrentTick2 is used to define the current time point in tenths of a second from the top of the hour. Note that the TSC may not be providing the time point in UTC time, thus the SPaT message generation process may have to translate this timepoint to UTC time.

7.3.3.2.3.2.2 Intersection Time Stamp (TSCBM)

When sending TSCBMs, TSCBM Bytes 236-240 is spatTimeStamp and describes the time within the day when the TSCBM is generated. spatTimeStamp is 5 bytes: Byte 236 = hours, Byte 237 = minutes, Byte 238 = seconds, and Bytes 239-240 = milliseconds. Note that the TSC may not be providing the time stamp in UTC time, thus the SPaT message generation process may have to translate this time stamp to UTC time.

7.3.3.2.3.3 Intersection Time Stamp (SAE J2735)

When sending SAE J2735 SPaT messages, the time stamp indicating the milliseconds within the current minute when the SPaT information for the intersection is generated is represented by time stamp (DE_DSecond) and found under the data frame DF_IntersectionState in the MSG_SignalPhaseAndTiming Message in SAE J2735. It is expected that the TSC infrastructure is using a time source that provides UTC time.

7.3.3.3 Signal Timing Data Design Details

The design details to fulfill the requirements for signal timing data broadcasted by a connected intersection follow. The requirements are defined in 6.3.3.3, Signal Timing Data Requirements.

7.3.3.3.1 Intersection Identification Design Details

The design to provide a unique identifier for an intersection follow. These requirements are defined in 6.3.3.3.1, Intersection Identification Requirements.

7.3.3.3.1.1 Intersection Signal Timing Information Design Details

Signal phase and timing information for an intersection is represented by intersections (DF_IntersectionStateList) in the MSG_SignalPhaseAndTiming Message in SAE J2735.

7.3.3.3.1.2 Intersection Identifier Design Details

The intersection identifier is represented as id (DE_IntersectionID) and found under the data frame DF_IntersectionReferenceID in MSG_SignalPhaseAndTiming Message in SAE J2735.

The intersection identifier is assigned by the IOO represented by the RAID.

NOTE: This requirement is updated in CTI 4501 v02 to replace the road regulator identifier. The updated guidance is that the combination of the OpOrgID (Operator Organization Identifier), the intersection identifier, and, optionally, the relative road authority identifier (see 6.3.3.3.1.3) is a globally unique identifier for the connected intersection. Refer to CTI 4501, Annex A.1, Road Authority Identifier for a detailed description.

7.3.3.3.1.3 Road Authority Identifier Design Details

The relative road authority identifier is represented as a choice between a full object identifier (OID) reference or a relative OID (DF_RoadAuthorityID) and is found under the data frame DF_IntersectionState in MSG_SignalPhaseAndTiming Message in SAE J2735. If a relative road authority identifier is needed, only the relative OID is used (DE_RelativeRoadAuthorityID).

NOTE: This requirement is updated in CTI 4501 v02 to replace the road regulator identifier. The updated guidance is that the combination of the OpOrgID (Operator Organization Identifier), the intersection identifier, and, optionally, the road authority identifier (see 6.3.3.3.1.3) is a globally unique identifier for the connected intersection. Refer to CTI 4501, Annex A.1, Road Authority Identifier for a detailed description.

7.3.3.3.2 Intersection Status Design Details

The design details to fulfill the requirements to provide the status of a connected intersection follow. These requirements are defined in 6.3.3.3.2, Intersection Status Requirements.

Annex C contains a table that summarizes the status of a connected intersection based on the mode of operation of the TSC.

7.3.3.3.2.1 Manual Control Design Details

Annex F.3.3.4.1 of NTCIP 1202 specifies that the connected intersection shall define the intersection as operating under "Manual Control" when the advancement of signal indications is controlled by an external entity, such as a police officer at the traffic cabinet or an operator at a traffic management center, rather than the TSC. While, under certain conditions, the TSC may know the sequence of the phases and the duration of some intervals (e.g., the yellow change interval), the duration of the signal groups (specifically, the green intervals) is not controlled by the TSC. As a result, the signal groups may terminate early or the interval may dwell for a longer period of time than its the programmed time.

7.3.3.3.2.1.1 Manual Control - Intersection Status

The SPaT message uses Bit 0 in the DE_IntersectionStatusObject under the DF_IntersectionState data to indicate whether the intersection is operating under manual control. The connected intersection shall set Bit 0 in the DE_IntersectionStatusObject to a value of 1 to indicate that the intersection is operating under manual control (see 7.3.2.2.1, TSC Infrastructure Manual Control Indication). This value indicates to the receiver that the TSC is "not in control," thus the TSC generally does not know when the movement phase state will change. A value of zero (0) in Bit 0 of the DE_IntersectionStatusObject indicates when the intersection is not operating under manual control.

7.3.3.3.2.1.2 Manual Control - Movement States

Because the TSC will service each phase in sequence under Manual Control according to its programmed pattern, it knows the order in which signal groups will be serviced. Therefore, the SPaT message should reflect each signal group's current and next movement state.

7.3.3.3.2.1.3 Manual Control - Time Change Details

NTCIP 1202 provides the following guidance to deployers for establishing minimum and maximum end times when the intersection is operating under Manual Control:

- When manual control is "active" and the TSC controller is in a green interval:
 - The minimum time of change will be equal to the greater of the current time plus the minimum green time remaining (if in effect).
 - While the TSC is in a green dwell interval, the minimum time of change will not be less than 0.1 second from the current time mark.
 - The value for maximum time of change will be unknown.
- When manual control is "active" and the TSC is in a vehicle/pedestrian change or clearance interval that is not timed:
 - The minimum end will not be less than 0.1 second from the current time mark.
 - The value for maximum time of change will be unknown.
- When manual control is "active," and the TSC is in a vehicle/pedestrian change or clearance interval, and the interval durations (such as yellows) are timed, then the TSC will provide the known TimeChangeDetails values.

7.3.3.3.2.2 Stop Time Design Details

Under stop time control, the TSC suspends the countdown of all active timers, essentially "freezing" the intersection in its current state until the stop time command is lifted. Once the stop time command is lifted, the TSC will resume the countdown of the timers, picking up with the countdown of the timing remaining in the timing plan from the point where the timers stopped.

7.3.3.3.2.2.1 Stop Time - Intersection Status

The SPaT message uses Bit 1 in the DE_IntersectionStatusObject under the DF_IntersectionState data to indicate whether the TSC has suspended the timing of all signal groups at the intersection. When the TSC reports that it has received a command to suspend the timing for the entire intersection (see 7.3.2.2.2, TSC Infrastructure Stop Time Indication Design Details), the connected intersection sets Bit 1 in the DE_IntersectionStatusObject to a value of 1. The value of this bit remains at 1 until the stop time command is removed. A value of zero (0) in Bit 1 of the DE_IntersectionStatusObject indicates that the TSC has resumed normal operations.

7.3.3.3.2.2.2 Stop Time - Movement States

When the TSC receives a stop time input, the active (frozen) controller state on the affected (stopped) ring shall remain as the basis for generating the movement phase state. Even if the stop time duration is unknown, the movement state for each signal group will remain in its current state until the stop time command is lifted and the TSC resumes counting down the active phases.

7.3.3.3.2.2.3 Stop Time - Time Change Details

If the form of stop time input allows continuation of countdown timers for clearance intervals or other timers, the connected intersection shall adjust the TimeChangeDetails accordingly; otherwise, the values for TimeChangeDetails will be set to “unknown” (36111) for all signal groups for the entire duration that the stop time command is active. Once the stop time command is removed, the TSC will pick up counting down to time remaining in each signal group, at which time new minimum and maximum end times can be computed.

7.3.3.3.2.3 Failure Flash Design Details

Failure flash occurs when either (1) a monitor in the TSC infrastructure detects an error or anomaly in the operation of the TSC or (2) a human-operated switch in the traffic cabinet has been activated. When in a failure flash mode, the TSC is no longer in control of the intersection and the signal indications are determined by how the traffic cabinet is wired (jumpers or flash program blocks) rather than TSC software. Therefore, the TSC must detect when a Failure flash is triggered in the traffic cabinet. Failure flash is also known as cabinet flash.

7.3.3.3.2.3.1 Failure Flash - Intersection Status

The connected intersection uses Bit 2 in the DE_IntersectionStatusObject under the DF_IntersectionState data to indicate when the intersection is operating in a Failure Flash mode. When the TSC reports that it is in a Failure Flash State (see 7.3.2.2.3, TSC Infrastructure Failure Flash (Exception Flash) Indication Design Details), the connected intersection shall set Bit 2 in the DE_IntersectionStatusObject to a value of 1. The value of this bit remains at 1 until the TSC is returned to normal operation. A value of zero (0) in Bit 2 of the DE_IntersectionStatusObject indicates the TSC has resumed normal operations.

NOTE: Some transportation agencies, as part of their operational policy or local laws or regulations, may not allow the IOO to broadcast that an intersection is in failure flash. As noted in NTCIP 1202, Section 2.7, Operational Policies, Rules, and Regulations take precedence. If a transportation agency does not permit broadcast of Failure Flash, then the agency shall enable Bit 13 NoSPaTIsAvailableAtThisTime in DE_IntersectionStatusObject and set movement states and time change details for all signal groups to “Unknown” until the intersection is returned to service.

7.3.3.3.2.3.2 Failure Flash - Movement States

During Failure Flash operations, traffic cabinet wiring (jumpers or flash program blocks) rather than controller software determines the state of the signal indications. As a result, the TSC may not have any intrinsic knowledge of the state of the signal indications for each signal group, unless the TSC can monitor the real-time voltage and current of each signal group. In those cases where the TSC is unable to monitor the real-time voltage and current of each signal group, the SPaT message shall indicate a value of “Unavailable (1)” in DE_MovementPhaseState data element for each signal group.

However, some traffic cabinet architectures allow the controller to monitor the real-time voltage and current measurements. Under these circumstances, the TSC can determine the state of the signal (Yellow, Red, or Dark) of the signal indications during Failure Flash, then the TSC can provide the values of the DE_MovementPhaseState data element.

- If the signal group indication is a flashing red, the DE_MovementPhaseState shall report a value “stop-then-Proceed (2).”
- If the signal group indication is flashing yellow, the DE_MovementPhaseState shall report a value “caution-Conflicting-Traffic (9).”
- If the signal group indication is dark (i.e., not illuminated), the DE_MovementPhaseState shall indicate a value of “Dark (1)”. In this situation, the driver is expected the defined “rules of the road” for dark signal indications for the local jurisdiction.

7.3.3.3.2.3.3 Failure Flash - Time Change Details

Because the TSC does not know when the intersection when the monitor or the flash switch is going to be reset to allow normal operations, it cannot provide end times for the signal groups. Therefore, while the intersection is in a Flash Failure state, the connected intersection shall report all time change details as unknown using the values of “36111.”

7.3.3.3.2.4 Preemption Design Details

NTCIP 1202 defines preemption as “the transfer of the normal control (operation) of traffic signals to a special signal control mode for the purposes of servicing railroad crossings, emergency vehicle passage, mass transit vehicle passage, and other special tasks, the control of which requires terminating normal traffic control to provide the service needs of the special task.” Under preemption, the normal operations of the TSC are immediately interrupted to provide preferential treatment to specific classes of vehicles, such as trains or emergency vehicles, which have an urgent need for the right-of-way, regardless of the signal state. Due to the urgency to change the right-of-way, preemption can disrupt coordination, pedestrian services, and phasing patterns.

7.3.3.3.2.4.1 Preemption Intersection Status

The connected intersection shall enable Bit 3 of the DE_IntersectionStatusObject in the SPaT Message to indicate when the intersection is operating in preemption. The TSC reports that it is in a preemption state (see 7.3.2.2.4, TSC Infrastructure Preemption Operation Indication Design Details), and the connected intersection shall set Bit 3 in the DE_IntersectionStatusObject to a value of 1. The value of this bit remains at 1 until the TSC has fully recovered to normal operation after the preemption request has been dropped and the intersection has completed its recovery stage. A value of zero (0) in Bit 3 of the DE_IntersectionStatusObject indicates the TSC is not operating in preemption mode.

7.3.3.3.2.4.2 Preemption - Movement States

During preemption, the movement states should reflect the current state of each signal group during each stage of the preemption sequence. For example, during the dwell stage, the movement state will depend upon the how the IOO has programmed the TSC:

- If all the signal indications are flashing red, then DE_MovementPhaseState shall indicate a value of *stop-then Proceed (2)* for each signal group. V2X vehicles should treat this intersection as an all-way stop.
- If the TSC uses flashing yellow for major allowable movements and flashing red for allowable minor movements, DE_MovementPhaseState shall use *caution-Conflicting-Traffic (9)* as the movement state for those signal groups receiving the flashing yellow indications and *stop-Then-Proceed (3)* for those signal groups displaying flashing red signal indications. Travelers receiving *caution-Conflicting-Traffic (9)* may proceed with caution through the intersection as long as there is no conflicting traffic in the conflict area. Travelers receiving a *stop-Then-Proceed (3)* movement state shall stop at the stop line and then proceed through the intersection conflict area when safe to do so.

- If the TSC is using a steady red indication for a signal group, then the SPaT shall indicate *stop-And-Remain (3)* in DE_MovementPhaseState. This would require the V2X vehicles to stop and remain at the stop line until receiving a new movement state.
- The DE_MovementPhaseState for those signal groups that receive a green indication during preemption should be set to *permissive-Movement-Allowed (5)* in the SPaT message. With this state, V2X vehicles would know that they would be permitted to enter the intersection to clear a path for the preferential vehicle approaching the intersection. If the TSC is allowed to provide limited service during the dwell stage, the SPaT message should reflect the state of each signal group as it cycles through the allowable phases.

7.3.3.3.2.4.3 Preemption - Time Change Details

The TimeChangeDetails for the intersection during the preempt clearance phases while the TSC is servicing the preemption request are known and should be reflected in the SPaT message. During the transition preparation stage, the TimeChangeDetails for the intersection may change suddenly as the TSC transitions from normal operations to servicing a preemption request. As noted above, some signal groups may need to end earlier, as previously reported in the SPaT message, as the TSC prepares to transition to the requested movement. TSC should use the preempt programmed values to calculate the TimeChangeDetails values, such as preemptMinimumGreen or preemptEnterPedClear. The time change details should be as follows:

- The minimum time of change will be equal to the current time plus the minimum green time (if applicable) or the minimum dwell time remaining.
- Once the minimum duration times for the dwell phase are satisfied, the minimum time of change will not be less than 0.1 second unless the TSC commands a green termination and a change to the field outputs is imminent.
- The value for the maximum time of change will be the maximum dwell time (if available) or an appropriate value as timed by the TSC until the TSC determines when it will exit the dwell phase.

The TimeChangeDetails for the intersection during the exit phases while the TSC is servicing the preemption request are known and should be reflected in the SPaT data provided.

7.3.3.3.2.5 Priority Design Details

Like preemption, priority is a special operating mode of the TSC that provides preferential treatment to specific user classes (transit vehicles, commercial fleet trucks, etc.) at a signalized intersection. However, unlike preemption, during priority the TSC attempts to provide this preferential treatment without disrupting the background timing plan and causing the TSC to drop out of coordination with other intersections. Under priority, the TSC will either extend or shorten individual phases to either extend a green indication past its normal termination point or return early to a green indication to service the vehicle requesting preferential treatment. Like preemption, authorized special vehicles need to request priority from the TSC. Unlike preemption, the TSC may or may not respond immediately to the request by altering the timing and sequencing of the signal indications, depending upon the estimated arrival time of the vehicle at the intersection. In some circumstances, no change in the phase duration or phase sequence may be needed to serve a priority request, while in other circumstances, a TSC may need to extend the operation of a phase past a previously broadcast maximum end time to service the priority request.

7.3.3.3.2.5.1 Priority - Intersection Status

The connected intersection shall indicate when the TSC is actively servicing a priority request by enabling Bit 4 in the DE_IntersectionStatusObject under the data frame DF_IntersectionState in MSG_SignalPhaseAndTiming Message in SAE J2735. The connected intersection shall set Bit 4 in the DE_IntersectionStatusObject to a value of 1 only after it has determined that it needs to alter the signal timing to service the priority request (see 7.3.2.2.5). The connected intersection shall remain at 1 until the priority request is dropped. A value of zero (0) in Bit 4 of the DE_IntersectionStatusObject indicates the TSC is not servicing a priority request.

If the TSC determines that the priority request can be accommodated without altering the timing plan or that it cannot service the priority request (due to a lockout period between requests), then Bit 4 should remain in its current state.

NOTE: The Intersection Status object should not be used to convey the status of a request to the requesting vehicle. This should be done using the Signal Status Message (SSM). The Intersection Status Object in the SPaT message is intended to notify other V2X vehicles at the intersection is altering the durations (and maybe sequencing) of signal phases to service a priority request.

7.3.3.3.2.5.2 Priority - Movement States

Under priority control, the TSC will normally follow the programmed sequencing of phases. Therefore, the current movement states should reflect the current state of the signal indications at the intersection. For those cases where phase insertions or phase-skipping strategies are used, the TSC should use the next movement state to reflect the estimated time these phases will be active in the priority scheme.

Consult 7.3.3.3.3, Current Movement State Design Details and 7.3.3.3.4, Next Movement State Design Details for more information on how to set current and next movement states in the SPaT message.

7.3.3.3.2.5.3 Priority - Time Change Details

One common strategy for providing priority to preferential vehicles is to return as early as possible (within programmed constraints) to the priority phase. To return early to the priority vehicle phase, the TSC will need to shorten all the phases preceding the priority phase. Generally, an IOO will program into the TSC the amount of time that individual phases can be shortened (subject to minimum duration requirements) to return early to the priority phase. The TSC should modify the minimum and maximum end times to accurately reflect the phase durations that the TSC will use to return early to the priority phase.

Another common strategy for providing priority at a signalized intersection is to extend the priority phase past its normal termination point. Usually, an IOO will set a maximum duration for which the traffic signal can extend a phase past its normal termination point to allow the transit to proceed without stopping. The requesting vehicle has until the maximum allowable extension to proceed through the intersection. If the requesting vehicle clears the intersection before the TSC reaches this maximum extension, the TSC will terminate the phase once the vehicle clears. If the requesting vehicle does not enter the intersection before the extension period ends, the TSC will terminate the phase, and the requesting vehicle will have to wait until the phase is reactivated in the next cycle. If the priority phase is active when TSC receives the priority request, the TSC should immediately increase the maximum end time to include the maximum allowable extension time programmed for the priority phase, even if the priority vehicle may not need the extra time to clear the intersection (instead of waiting until the phase reaches its previous maximum end time and then setting a new maximum end time). This will let other V2X vehicles approaching the intersection know the green phase may extend longer than previously broadcast maximum end times for the priority phase and prevent confusion with a phase extending past the normal termination point. After the priority vehicle has cleared the intersection, the TSC may then shorten subsequent phases to allow the TSC to maintain coordination with other intersections. The time change details should also reflect the shortened phase durations as the intersection recovers from providing priority.

If the TSC supports other priority strategies (such as phase insertion or phase skipping), the time change details should be modified to reflect the appropriate duration and phase sequencing programmed by the IOO into the TSC.

7.3.3.3.2.6 Fixed Time Design Details

An intersection operates in a "Fixed Time" mode when the sequence (order) and duration of each phase is the same cycle-to-cycle regardless of traffic demand. Under fixed time control, the TSC's ability to adjust the sequence and duration of individual movements based on detector inputs has been disabled, and the TSC follows a consistent pattern regardless of the demand. Agencies will frequently operate traffic signals downtown, urban cores under fixed time control.

NOTE 1: For a traffic signal operation to be classified as "fixed time," all of the phases in a pattern must operate with fixed duration. While some intersections may have individual phases that operate with fixed durations, the intersection status is not fixed unless all phases at the intersection are fixed.

NOTE 2: In many cases, intersections operating in coordination with other intersections frequently use a timing plan that results in fixed operations but not always. Some agencies prefer to operate some intersections in actuated-coordinated mode. The intersection status of those intersections that have been programmed to operate in an actuated-coordinated mode should be defined "Traffic Dependent" and not "Fixed Time."

7.3.3.3.2.6.1 Fixed Time - Intersection Status

The connected intersection shall enable Bit 5 (set to a value of 1) in the DE_IntersectionStatusObject under the data frame DF_IntersectionState in MSG_SignalPhaseAndTiming Message in SAE J2735 to indicate when the intersection is operating in fixed time (see 7.3.2.2.6). A value of zero (0) in Bit 5 of the DE_IntersectionStatusObject indicates the TSC is not in fixed time operation. If the TSC is in Manual Control, Stop Time or in Standby Operation, then Fixed Time Operation should be disabled.

7.3.3.3.2.6.2 Fixed Time - Movement States

Under Fixed Time control, current and future movement states are well known and can be obtained directly from the TSC's timings and phasing patterns.

Consult 7.3.3.3.3, Current Movement State Design Details for more information on how to determine the movement state for the different types of signal indications used at signalized intersections.

7.3.3.3.2.6.3 Fixed Time - Time Change Details

The TimeChangeDetails for the intersection while the TSC is in fixed-time operation are generally known and should be reflected in the SPaT message. Because the duration of each phase is fixed, the TimeMark when each movement state will change is also known. The DE_minEndTime and DE_maxEndTime should be equal. The TimeMark of the change in the next Movement State is also known and can be reflected in the SPaT message.

Consult 7.3.3.3.5, Time Change Details Design Details for more information on determining the time change details for individual signal groups.

7.3.3.3.2.7 Traffic Dependent Mode Design Details

An intersection where an agency has programmed one or more phases in the TSC to respond to detection inputs. Therefore, in traffic-dependent operations, the duration and/or sequencing of the signal indications can vary from cycle to cycle.

NOTE: An intersection running "Free" may or may not operate in a traffic dependent mode. "Free" refers to a controller that is not operating under the constraints of coordination. An intersection may be "free" and operating in a traffic dependent or fixed-time control.

7.3.3.3.2.7.1 Traffic Dependent - Intersection Status

When a signalized intersection operating in a traffic dependent mode (see 7.3.2.2.7) is represented by Bit 6 in the DE_IntersectionStatusObject and found under the data frame DF_IntersectionState in the MSG_SignalPhaseAndTiming Message in SAE J2735. The connected intersection shall set Bit 6 in the DE_IntersectionStatusObject to a value of 1 if it is operating in traffic dependent mode. The connected intersection shall remain at 1 until the TSC is no longer responding to traffic detector inputs. A value of zero (0) in Bit 6 of the DE_IntersectionStatusObject indicates the TSC is not operating in a traffic dependent mode. The TSC is not in traffic dependent operation if the TSC is in Manual Control, Stop Time or in StandbyOperation.

Note that the TSC cannot operate in Traffic Dependent Mode and Fixed Time (see 7.3.3.3.2.6) at the same time.

7.3.3.3.2.7.2 Traffic Dependent - Movement States

In this mode of operation, the movement states need to reflect the current state of the traffic signal indications for each signal group. Consult 7.3.3.3.3, Current Movement State Design Details for more information on how to determine the movement state for the different types of signal indications used at signalized intersections.

7.3.3.3.2.7.3 Traffic Dependent - Time Change Details

Because the TSC has been programmed to respond to the presence (or absence) of traffic demand (as measured by the detection system), the duration of each signal indication is not known definitely; therefore, the time change details should reflect the minimum and maximum time until a change in the current movement state can occur. The minimum end time should reflect the absolute minimum duration that a signal group will remain in its current movement phase state until a change is possible, while the maximum end time reflects the maximum duration that a signal group can remain in its current state, given the current detection inputs in the controller. As the detection inputs change at an intersection, the time change details should also update to reflect the current estimated phase durations based on traffic demands. Consult 7.3.3.3.5, Time Change Details Design Details for more information on determining the time change details for individual signal groups.

7.3.3.3.2.8 Standby Mode Design Details

The intersection is in standby mode when the controller is partially switched off, waiting for input to begin operation (such as at a pedestrian hybrid beacon or HAWK signal or at a traffic signal installed near a first station that flashes amber until activated by a fire truck) or during a signal's initial start-up sequence (initializing control).

7.3.3.3.2.8.1 Standby - Intersection Status

The connected intersection shall enable Bit 7 in the DE_IntersectionStatusObject under the data frame DF_IntersectionState in MSG_SignalPhaseAndTiming Message in SAE J2735 to indicate when the TSC at the connected intersection is in a standby mode (see 7.3.3.3.2.8). The connected intersection shall set Bit 7 in the DE_IntersectionStatusObject to a value of 1 if it is in standby mode. A value of zero (0) in Bit 6 of the DE_IntersectionStatusObject indicates the TSC is not in a standby mode.

7.3.3.3.2.8.2 Standby - Movement State

At pedestrian hybrid beacons, the signal indications governing vehicle movements at the intersection are dark when the intersection is in standby mode, waiting for pedestrian demand to activate the signal. Normally, the movement state for dark signal indications would be to "stop and proceed (2);" however, for pedestrian hybrid beacons, the connected intersection should set the movement phase state to "permissive-Movement-Allowed (5)." This movement state allows V2X vehicles to travel through the dark signal indications without first coming to a stop.

7.3.3.3.2.8.3 Standby - Time Change Details

If the TSC can determine how long it will remain in standby mode (such as signal start-up), the SPAT message should contain appropriate time change detections for each signal group. However, if the TSC cannot determine how long it might be in standby mode (such as at a pedestrian hybrid beacon waiting for a pedestrian detection input), the time change details should reflect this unknown state. In the case where TSC cannot determine the duration of the standby mode, the connected intersection should report both the minimum and maximum end times to be unknown (a value of 36111).

"Startup Flash" is a transitory interval timed immediately after the monitor transfers control to the controller. The duration of Startup Flash is controlled by the NTCIP 1202 unitStartupFlash object, thus the minEndTime shall be based on unitStartupFlash.

7.3.3.3.2.9 Failure Mode Design Details

This state is intended to indicate when the TSC infrastructure has a problem or failure in operation. Examples of a TSC failure mode might include if the TSC detects a process is not operating properly, a memory data error, or an internal voltage failure. This state indicates that a failure has occurred that could impact the SPAT message.

7.3.3.3.2.9.1 Failure Mode - Intersection Status

Whether a signalized intersection is in a failure mode is represented by Bit 8 in the DE_IntersectionStatusObject and found under the data frame DF_IntersectionState in MSG_SignalPhaseAndTiming Message in SAE J2735. A value of 1 for Bit 8 indicates that the TSC infrastructure is in failure mode.

7.3.3.3.2.9.2 Failure Mode - Movement State

When the connected intersection reports the intersection status to be in a Failure Mode, the connected intersection shall also indicate that the movement state for each signal group is "unavailable (0)."

7.3.3.3.2.9.3 Failure Mode - Time Change Details

When the connected intersection reports the Intersection Status to be in a Failure Mode, the connected intersection shall use a value of unknown (36111) for all time change details for all movement states. The connected intersection shall continue to report these time change details until the failure has been cleared and normal operation has been restored.

7.3.3.3.2.10 Controller Off Design Details

This state is intended to reflect when a communication issue between the TSC Infrastructure and the RSU prevents the SPaT message generation process from receiving the SPaT information. However, the connected intersection is still expected to generate and broadcast a SPaT message (see 7.3.3.1.2.2, Continuous Broadcast of SPaT Messages Design Details). When this occurs, the connected intersection indicates that a failure has occurred that could impact the SPaT message.

NOTE: If the TSC infrastructure generates the UPER-encoded SAE J2735 SPaT message and the controller is off, no SPaT message will be generated. Similarly, CTI 4001 v01.01, 4.3.2.14.2 describes how the RSU sets status bits in the SPaT status data element if data is not received from the TSC Infrastructure.

7.3.3.3.2.10.1 Controller Off - Intersection Status

If an RSU stops receiving valid data from the TSC infrastructure, the SPaT message generation process uses Bit 9 in the DE_IntersectionStatusObject and found under the data frame DF_IntersectionState in MSG_SignalPhaseAndTiming Message in SAE J2735 to indicate that the RSU has stopped receiving SPaT information from the TSC Infrastructure. Bit 13 in the DE_IntersectionStatusObject should also be set to 1 to indicate that no valid SPaT is available at this time. For more information on using Bit 13, see 7.3.3.3.2.14, No SPaT Available Design Details.

7.3.3.3.2.10.2 Controller Off - Movement State

If the connected intersection reports via the DE_IntersectionStatusObject that the controller is off (Bit 9 set to a value of 1), the connected intersection shall also indicate that the movement state for each signal group is "unavailable (0)." The connected intersection shall continue to report the movement states as unavailable until the IOO has confirmed that the controller is operational and capable of broadcasting appropriate movement states.

7.3.3.3.2.10.3 Controller Off - Time Change Details

If the connected intersection reports via the DE_IntersectionStatusObject that the controller is off (Bit 9 set to a value of 1), the connected intersection shall use a value of unknown (36111) for all time change details for all signal groups. The connected intersection shall continue to report these time change details until the IOO has confirmed that the controller is operational and capable of broadcasting appropriate time change details.

7.3.3.3.2.11 Recent MAP Update Design Details

The original intent of this intersection status bit was to tell V2X vehicles approaching a connected intersection that something in the MAP message changed that requires the V2X vehicle to process the entire MAP message. However, because of the importance of the MAP message as it relates to the SPaT message, the technical committee recommends that the V2X vehicles continuously check the MAP to ensure it is always working with the latest MAP version.

NOTE: This intersection status bit is not mutually exclusive with the other intersection status bits. The SPaT can indicate that a MAP update is available for an intersection while the connected intersection operates in any of the other states (DE_IntersectionStatusObject Bits 0-9 enabled).

7.3.3.3.2.11.1 Recent MAP Update - Intersection Status

The connected intersection uses Bit 10 in the DE_IntersectionStatusObject and is found under the data frame DF_IntersectionState in MSG_SignalPhaseAndTiming Message in SAE J2735 to indicate that the MAP message has been updated. A value of 1 for Bit 10 indicates that the MAP message transmitted by the RSU has recently been updated. However, in practice, this IntersectionStatusObject (Bit 10) shall always be set to 1 for CI deployments, even if no change in the intersection configuration has occurred. Setting this bit 10 to 1 will require each vehicle to process each map message it receives to determine if a change to the intersection configuration has occurred.

NOTE: A connected intersection can broadcast a MAP message without a SPaT message, but a SPaT message must be accompanied by a valid MAP message for the same intersection. If the connected intersection receives a SPaT message without a valid MAP message, the OBU may ignore the SPaT message and assume no valid SPaT information is available at this time.

7.3.3.3.2.11.2 Recent MAP Update - Movement State

Because this operating state is not mutually exclusive with the other operating states, the connected intersection should use the other operating states to define the content of the movement states in the SPaT Message. The user should consult 7.3.3.3.2.1 through 7.3.3.3.2.10 to determine the appropriate content of the movement states for these other operating modes.

If no other Intersection Status bit is set, the connected intersection should indicate that the movement state for each signal group is "unavailable" (0). The connected intersection shall continue to broadcast that the movement states for each signal group are unavailable until the TSC Infrastructure can determine the operating state of the intersection.

7.3.3.3.2.11.3 Recent MAP Update - Time Change Details

Because this operating state is not mutually exclusive with the other operating states, the connected intersection should use the other operating states to define the content of the time change details in the SPaT Message. The user should consult 7.3.3.3.2.1 through 7.3.3.3.2.10 to determine the appropriate content of the time change details for these other operating modes.

If no other Intersection Status bit is set, the connected intersection should indicate that the time change details for each signal group is "unknown" (36111). The connected intersection shall continue to broadcast that the time change details for each signal group are unavailable until the TSC Infrastructure can determine the operating state of the intersection.

7.3.3.3.2.12 New Lane IDs Design Details

The original intent of this intersection status was to notify V2X vehicles about a change in the movements allowed at an intersection; otherwise, the V2X vehicle could assume that no change occurred in the allowable movements between SPaT updates. However, some use cases exist where movements at an intersection are dynamically enabled and disabled depending on the circumstances. For example, an IOO may want to prohibit right turns across a railroad train from a shared right-through lane during preemption or prohibit right-turn-on-red during portions of a signal cycle but allow right-turn-on-red during other portions of the cycle. Because these movement restrictions may change dynamically, the technical committee recommends that the V2X vehicles always check which movements are allowed with each SPaT update.

NOTE: This intersection status bit is not mutually exclusive with the other intersection status bits. The SPaT can indicate that new lanes have been enabled while the connected intersection operates in any of the other states (DE_IntersectionStatusObject Bits 0-9 enabled).

7.3.3.3.2.12.1 New Lane IDs - Intersection Status

Whether an RSU is broadcasting a MAP message with changes in lane assignments or which lanes are enabled in the SPaT message is represented by Bit 11 in the DE_IntersectionStatusObject, which is found under the data frame DF_IntersectionState in MSG_SignalPhaseAndTiming Message in SAE J2735.

A value of 1 for Bit 11 indicates that the lane definitions in the MAP message or the enabled lanes in the SPaT message transmitted by the RSU have recently been updated. However, in practice, this bit is not expected to be used by RLVW applications on OBUs. RLVW applications are expected to use the revision counter in the SPaT and MAP message to determine if there are changes in either message. Thus, Bit 11 shall always have a value of 1.

7.3.3.3.2.12.2 New Lane IDs - Movement State

Because this operating state is not mutually exclusive with the other operating states, the connected intersection should use the other operating states to define the content of the movement phase states in the SPaT Message. The user should consult 7.3.3.3.2.1 through 7.3.3.3.2.10 to determine the appropriate content of the movement states for these other operating modes.

If no other intersection status bit is set, the connected intersection should indicate that the movement state for each signal group is "unavailable (0)." The connected intersection shall continue to broadcast that the movement states for each signal group are unavailable until the TSC Infrastructure can determine the operating state of the intersection.

7.3.3.3.2.12.3 New Lane IDs - Time Change Details

Because this operating state is not mutually exclusive with the other operating states, the connected intersection should use the other operating states to define the content of the time change details in the SPaT Message. The user should consult 7.3.3.3.2.1 through 7.3.3.3.2.10 to determine the appropriate content of the time change details for these other operating modes.

If no other intersection status bit is set, the connected intersection should indicate that the time change details for each signal group is "unknown (36111)." The connected intersection shall continue to broadcast that the time change details for each signal group are "unavailable" until the TSC Infrastructure can determine the operating state of the intersection.

7.3.3.3.2.13 No MAP Available

A connected intersection is required to broadcast a MAP message once every second. A MAP message can be broadcast without a SPaT message, but the SPaT message must be sent with a valid MAP message describing the intersection associated with the SPaT message. However, there are scenarios when the IOO may decide (for operational or maintenance purposes) to mark a broadcasted MAP message as invalid or the MAP message doesn't have a valid IEEE Std 1609.2 certificate, even if the intersection is operating properly. Situations when a MAP may be invalid include temporary lane closures caused by a vehicle crash or when a contractor fails to notify or delays notifying an IOO of lane closure. Other examples include when a contractor is setting up cones/barrels for lane closures, when flaggers are present, etc.

NOTE: A connected intersection can broadcast a MAP message without a SPaT message, but a SPaT message must be accompanied by a valid MAP message. If the OBU receives a SPaT message without a valid MAP message, the OBU should ignore the SPaT message and assume no valid SPaT information is available at this time.

7.3.3.3.2.13.1 No MAP Available - Intersection Status

The connected intersection shall use Bit 12 in the DE_IntersectionStatusObject found under the data frame DF_IntersectionState in MSG_SignalPhaseAndTiming Message in SAE J2735 to indicate whether an RSU is broadcasting a valid MAP. A value of 0 for Bit 12 indicates that the RSU is broadcasting a properly formatted MAP message with a PSID as defined in 0 and a valid IEEE Std 1609.2 certificate. A value of 1 in Bit 12 indicates the MAP message is unavailable or invalid.

The connected intersection shall continue to broadcast that no valid MAP is available until the IOO has verified that a valid MAP is available. For example, when the MAP message represents the appropriate intersection configuration and/or any temporary lane closures have been removed by the contractor for lane closure or time lags. This applies when the contractor is setting up cones/barrels for lane closures, presence of flaggers, etc.

A MAP message can be broadcasted without a SPaT message, but the SPaT message must be sent with a valid MAP message describing the intersection associated with the SPaT message. However, there are scenarios when the intersection is operating properly, but the IOO decides not to generate a MAP message, maybe for operational or maintenance purposes or the MAP message doesn't have a valid IEEE Std 1609.2 certificate.

NOTE: If the UPER-encoded SAE J2735 SPaT message is generated by the TSC infrastructure and the MAP message is generated elsewhere, the TSC infrastructure must be informed if the RSU is broadcasting a MAP message to set Bit 12 properly. Note CTI 4501 does not define a requirement for the TSC infrastructure to be informed if a new MAP message is being broadcast.

7.3.3.3.2.13.2 No MAP Available - Movement State

When the connected intersection indicates via the intersection status bit that no MAP is available, it shall also indicate that the movement state for each signal group is "unavailable (0)." The connected intersection shall continue to broadcast that the movement phase states for each signal group are unavailable until the IOO has verified that the MAP message represents the appropriate intersection configuration and/or any temporary lane closures have been removed.

7.3.3.3.2.13.3 No MAP Available - Time Change Details

When the connected intersection indicates via the intersection status that no MAP is available, it shall use a value of unknown (36111) for all time change details for all movement states. The connected intersection shall continue to report these time change details until a valid and appropriate MAP message becomes available. The connected intersection shall continue to indicate that the time change details for all signal groups are unknown until the IOO has verified that the MAP message represents the appropriate intersection configuration and/or any temporary lane closures have been removed.

7.3.3.3.2.14 No SPaT Available Design Details

This intersection status bit indicates that the broadcasted SPaT message may not be valid, and thus the contents of the SPaT message might not be trusted.

NOTE: A connected intersection can broadcast a MAP message without a SPaT message, but a SPaT message must be accompanied by a valid MAP message. If the connected intersection receives a SPaT message without a valid MAP message for the same intersection, the OBU should ignore the SPaT message and assume no valid SPaT information is available at this time.

7.3.3.3.2.14.1 No SPaT Available - Intersection Status

The connected intersection shall use Bit 13 in the DE_IntersectionStatusObject found under the data frame DF_IntersectionState in MSG_SignalPhaseAndTiming Message in SAE J2735 to indicate when the TSC Information is capable of producing valid SPaT messages. The connected intersection shall set Bit 13 to a value of one (1) to indicate that it determines that the TSC Infrastructure is not capable of producing valid SPaT messages; otherwise, Bit 13 shall be set to zero (0), indicating that the TSC infrastructure is producing valid SPaT messages. If the connected intersection determines that the TSC infrastructure is not capable of producing valid SPaT messages at this time, it shall remain in this state until an IOO has verified that the connected intersection can produce valid and appropriate SPaT messages.

7.3.3.3.2.14.2 No SPaT Available - Movement State

When the connected intersection indicates via the intersection status bit that no SPaT is available, it shall also indicate that the movement state for each signal group is also "unavailable (0)." The connected intersection shall continue to broadcast that the movement states for each signal group is unavailable until the IOO has verified that the connected intersection can produce valid and appropriate SPaT messages.

7.3.3.3.2.14.3 No SPaT Available - Time Change Details

When the connected intersection indicates via the intersection status that no SPaT is available, it shall use a value of unknown (36111) for all time change details for all signal groups. The connected intersection shall continue to report the time change details as unknown until the IOO can verify that the connected intersection can produce valid and appropriate SPaT messages.

7.3.3.3.2.15 RTCM Services Available Details [Informative]

At the time of publication, the committee was considering a requirement, "A connected intersection shall indicate in the SPaT message whether Radio Technical Commission for Maritime Services (RTCM) corrections messages, per SAE J3258, are available to support position correction functions by V2X vehicles approaching the intersection."

This intersection status bit indicates whether RTCM corrections messages that the OBU can use to improve the vehicle's position when approaching this intersection. The OBU applies the information in the RTCM corrections message to improve the latitude, longitude, and elevation of the vehicle. The RTCM corrections message may be broadcasted from an RSU not at that intersection (e.g., it can be broadcasted by an adjacent intersection). For more information on the use of RTCM corrections, refer to SAE J3258.

7.3.3.3.2.15.1 RTCM Services Available - Intersection Status

The connected intersection shall use Bit 14 in the DE_IntersectionStatusObject found under the data frame DF_IntersectionState in MSG_SignalPhaseAndTiming Message in SAE J2735 to indicate whether the RTCM services, as defined in SAE J3258, are available at the intersection to support position correction applications. The connected intersection shall set Bit 14 to a value of one (1) to indicate that RTCM services are available; otherwise, Bit 14 shall be set to zero (0), indicating that the no RTCM services are available for this intersection.

NOTE: This operating state is not mutually exclusive from any other intersection operating state described above. Therefore, this bit is set independently from any other intersection status bit. The default value for this bit shall be zero (0), indicating that that no RTCM services are available for this intersection.

7.3.3.3.2.15.2 RTCM Services Available – Movement State

Because this operating state is not mutually exclusive with the other operating states, the connected intersection should use the other operating states to define the content of the movement phase states in the SPaT Message. The user should consult 7.3.3.3.2.1 through 7.3.3.3.2.10 to determine the appropriate content of the movement states for these other operating modes.

7.3.3.3.2.15.3 RTCM Services Available - Time Change Details

Because this operating state is not mutually exclusive with the other operating states, the connected intersection should use the other operating states to define the content of the time change details in the SPaT Message. The user should consult 7.3.3.3.2.1 through 7.3.3.3.2.10 to determine the appropriate content of the time change details for these other operating modes.

7.3.3.3.2.16 Supports RLVW Details [Informative]

At the time of publication, the committee was considering a requirement, "A connected intersection shall indicate in the SPaT message whether it fulfills the minimum requirements to support a RLVW application."

This intersection status bit indicates whether the connected intersection fulfills all the minimum requirements for a connected intersection, as defined by CTI 4501.

7.3.3.3.2.16.1 Supports RLVW - Intersection Status

The connected intersection shall use Bit 15 in the DE_IntersectionStatusObject found under the data frame DF_IntersectionState in MSG_SignalPhaseAndTiming Message in SAE J2735 to indicate whether the connected intersection fulfills the minimum requirements, as defined in CTI 4501, to support a RLVW application. The connected intersection shall set Bit 15 to a value of one (1) to indicate that the connected intersections fulfills the minimum requirements; otherwise, Bit 15 shall be set to zero (0), indicating that the intersection does not fulfill the minimum requirements or the status is unknown.

NOTE: This operating state is not mutually exclusive from any other intersection operating state described above. Therefore, this bit is set independently from any other intersection status bit. The default value for this bit shall be zero (0), indicating that that the connected intersection does not fulfill the minimum requirements, or it's unknown.

7.3.3.3.2.16.2 Supports RLVW - Movement State

Because this operating state is not mutually exclusive with the other operating states, the connected intersection should use the other operating states to define the content of the movement phase states in the SPaT Message. The user should consult 7.3.3.3.2.1 through 7.3.3.3.2.10 to determine the appropriate content of the movement states for these other operating modes.

7.3.3.3.2.16.3 Supports RLVW - Time Change Details

Because this operating state is not mutually exclusive with the other operating states, the connected intersection should use the other operating states to define the content of the time change details in the SPaT Message. The user should consult 7.3.3.3.2.1 through 7.3.3.3.2.10 to determine the appropriate content of the time change details for these other operating modes.

7.3.3.3.3 Current Movement State Design Details

The design details to fulfill the requirements for the current movement state of a signal group follow. These requirements are defined in 6.3.3.3.3, Current Movement State Requirements.

Annex C contains a table that summarizes the values for the current movement state based on the mode of operation of the TSC.

7.3.3.3.3.1 Current Movement State for a Signal Group

The state of a movement through an intersection is represented as eventState (DE_MovementPhaseState) and found under data frame DF_MovementEvent in MSG_SignalPhaseAndTiming Message in SAE J2735.

Each movement is tied to an identifier called the signalGroup (DE_SignalGroupID), which represents a collection of movements of a common type through the intersection.

If the signal group does not correspond to an actual signal head and therefore is not in the MAP message, then sending information about that fictitious signal group is prohibited.

If the signal group does correspond to an actual signal head and is in the MAP message, then the current movement state has to be sent, even if the current movement state is dark (1). An application will be expecting a state for signal group since it is in the MAP message.

7.3.3.3.3.2 Unknown Current Movement State for a Signal Group

If the current state of a movement through an intersection is unknown, it is represented by a value of unavailable (0) for the eventState (DE_MovementPhaseState), found under data frame DF_MovementEvent in MSG_SignalPhaseAndTiming Message as defined in SAE J2735.

7.3.3.3.3.3 Flashing Yellow Arrow Permissive Movement

A flashing yellow arrow for a permissive movement is represented by a value of permissive-Movement-Allowed (5) for the eventState (DE_MovementPhaseState), found under data frame DF_MovementEvent in MSG_SignalPhaseAndTiming Message as defined in SAE J2735.

7.3.3.3.3.4 Protected and Permissive Clearance

A clearance state immediately following a protected-Movement-Allowed is represented by a value of protected-clearance (8) for the eventState (DE_MovementPhaseState), found under data frame DF_MovementEvent in MSG_SignalPhaseAndTiming Message as defined in SAE J2735.

A clearance state immediately following a permissive-Movement-Allowed is represented by a value of permissive-clearance (7) for the eventState (DE_MovementPhaseState), found under data frame DF_MovementEvent in MSG_SignalPhaseAndTiming Message as defined in SAE J2735.

7.3.3.3.3.5 Resolve Protected Versus Permissive Movement

An allowed movement that must yield to other movements at the intersection is represented by a value of permissive-Movement-Allowed (5) for the eventState (DE_MovementPhaseState), as defined in SAE J2735, and represented by a value of protected-Movement-Allowed (6) when the same allowed movement is not in conflict with another movement.

Also, while the TSCBM can indicate if the current movement state is green, yellow, or red, it does not indicate if the movement allowed or the clearance state is a protected movement/clearance or a permissive movement/clearance. The RSU receiving the TSCBM has to be configured to determine when a phase or overlap movement is protected or permissive. There is currently no standardized interface to configure this information.

7.3.3.3.3.6 Yield Causes Permissive

An allowed movement that must yield to other vehicle, pedestrian, or bicycle movements is represented by a value of permissive-Movement-Allowed (5) for the eventState (DE_MovementPhaseState), found under data frame DF_MovementEvent in MSG_SignalPhaseAndTiming Message as defined in SAE J2735.

7.3.3.3.3.7 Right-of-Way Causes Protected

An allowed movement that has the right-of-way is represented by a value of protected-Movement-Allowed (6) for the eventState (DE_MovementPhaseState), found under data frame DF_MovementEvent in MSG_SignalPhaseAndTiming Message as defined in SAE J2735.

7.3.3.3.3.8 WALK State Enumeration

A pedestrian WALK interval is represented by a value of protected-Movement-Allowed (6) for the eventState (DE_MovementPhaseState), found under data frame DF_MovementEvent in MSG_SignalPhaseAndTiming Message as defined in SAE J2735.

7.3.3.3.3.9 Flashing DON'T WALK State Enumeration

A pedestrian flashing DON'T WALK interval is represented by a value of protected-clearance (8) for the eventState (DE_MovementPhaseState), found under data frame DF_MovementEvent in MSG_SignalPhaseAndTiming Message as defined in SAE J2735.

7.3.3.3.3.10 Steady DON'T WALK State Enumeration

A pedestrian Steady DON'T WALK interval is represented by a value of stop-And-Remain (3) for the eventState (DE_MovementPhaseState), found under data frame DF_MovementEvent in MSG_SignalPhaseAndTiming Message as defined in SAE J2735.

7.3.3.3.3.11 Movement State for Signal Groups Identified

No design details provided at this time.

7.3.3.3.12 Dark Pedestrian Indications

When pedestrian indications at a connected intersection are currently dark, such as during off-peak flashing operation, the movement state for the pedestrian movement is the same value as the movement state for the corresponding vehicle indication the pedestrian is facing.

For example, during off-peak flashing operation, if the vehicle indication in the direction the pedestrian is facing is permissive-Movement-Allowed, then the movement state for that pedestrian movement is also permissive-Movement-Allowed, as defined by DE_MovementPhaseState in SAE J2735. If the pedestrian is facing a flashing red, then the movement state is stop-Then-Proceed, as defined by DE_MovementPhaseState in SAE J2735.

7.3.3.3.13 Prohibited Movements

A prohibited movement is represented by a value of stop-And-Remain (3) for the eventState (DE_MovementPhaseState), found under data frame DF_MovementEvent in MSG_SignalPhaseAndTiming Message as defined in SAE J2735.

Examples of prohibited movements include a steady double circular red for a through movement at a pedestrian hybrid beacon or a right turn into a railroad crossing when the gates are down.

7.3.3.3.14 Movements Allowed After a Stop

A movement allowed after a stop is represented by a value of stop-Then-Proceed (2) for the eventState (DE_MovementPhaseState), found under data frame DF_MovementEvent in MSG_SignalPhaseAndTiming Message as defined in SAE J2735.

This type of movement is commonly found at intersections where a right turn on red is allowed.

7.3.3.3.4 Next Movement State Design Details

The design details to fulfill the requirements for the next movement state of a signal group follow. These requirements are defined in 6.3.3.3.4.

Annex C contains a table that summarizes the values for the next movement state based on the mode of operation of the TSC.

7.3.3.3.4.1 Next Movement State

MSG_SignalPhaseAndTiming Message provides a data frame, DF_MovementEventList, that contains 1 to 16 entries for the same movement at an intersection. Each entry (represented by DF_MovementEvent) represents a movement state for that movement over a period of time.

- The first entry describes the current movement state (i.e., DE_MovementPhaseState) and the time change details for the current movement (startTime, minEndTime, maxEndTime, and nextTime).
- The second entry describes the movement state immediately after the current movement state terminates and the start, minimum end, and maximum end times (i.e., startTime, minEndTime, maxEndTime, and nextTime) for the next movement state.

If the TSC infrastructure knows the next movement state, the TSC infrastructure shall provide the next movement state in the second entry of DF_MovementEventList, as eventState (DE_MovementPhaseState), found under data frame DF_MovementEvent in MSG_SignalPhaseAndTiming Message as defined in SAE J2735.

For example, in Figure 10, lane #1 is tied to signal group #2 and currently a permitted left turn (FY (Flashing Yellow) in Figure 10). The minimum end time for signal group #2 is currently 34675 deciseconds and the maximum end time is 35244 deciseconds from the top of the hour. At this point in time, the TSC infrastructure has not determined if the next movement state is a clearance interval or a protected left turn. So, the SPaT message for this movement would be the following:

```
{ "signalGroup":2, "state-time-speed":{ "eventState": "permissive-Movement-Allowed", "timing":{ "startTime":36111, "minEndTime":34675, "maxEndTime":35244, "nextTime":36111 } }, { "eventState": "unavailable", "timing":{ "startTime":34675, "minEndTime":34675, "maxEndTime":36111, "nextTime":36111 } } }
```

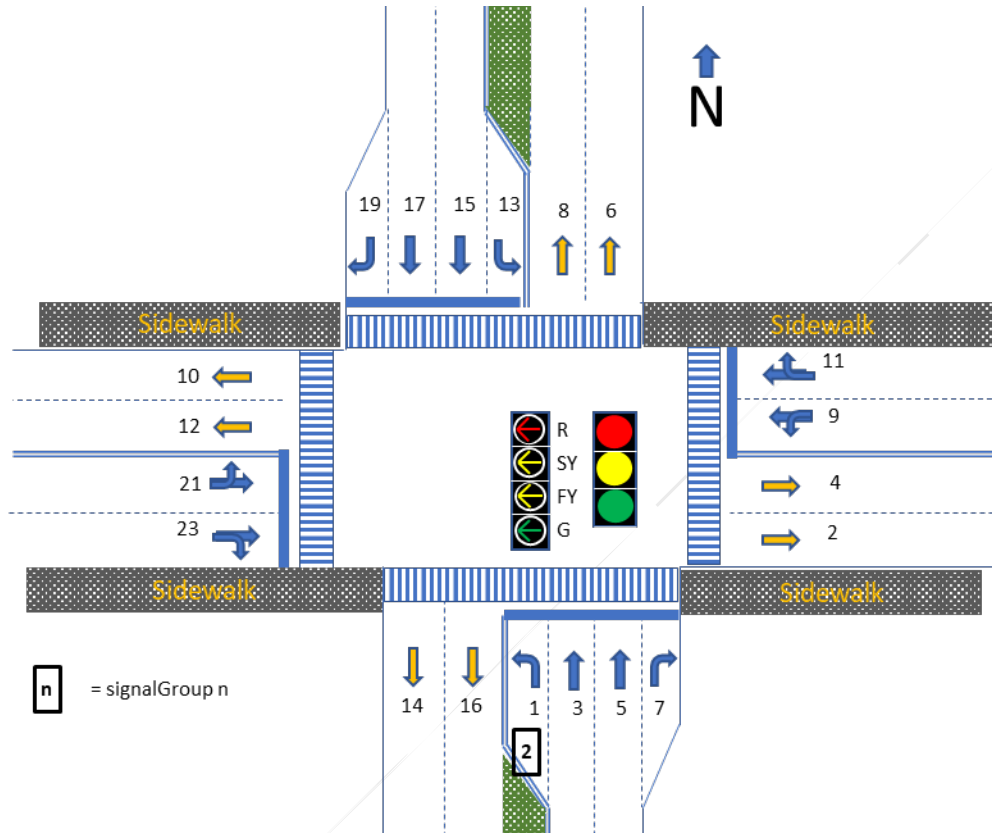


Figure 10 - Example next movement state

Several seconds later, two different scenarios may occur. In the first scenario, the TSC infrastructure does not detect any more demand for the left turn, so the TSC infrastructure decides to terminate the permissive left at 34675 deciseconds after the top of the hour and the next movement interval will be a clearance interval of 4 seconds (SY (Steady Yellow) in Figure 10). So, the SPaT message for this movement is now:

```
{ "signalGroup":2, "state-time-speed":{ "eventState": "permissive-Movement-Allowed", "timing":{ "startTime":36111, "minEndTime":34675, "maxEndTime":34675, "nextTime":34975 } }, { "eventState": "permissive-clearance", "timing":{ "startTime":34675, "minEndTime":34715, "maxEndTime":34715, "nextTime":34975 } } }
```

However, in the second scenario, if the TSC infrastructure detects additional demand for the left turn, the TSC infrastructure may decide the next movement interval is a minimum 6-second protected left turn (G (Green) in Figure 10) with a maximum 24-second duration, in which case the SPaT message for this movement is:

```
{ "signalGroup":2, "state-time-speed":{ "eventState": "permissive-Movement-Allowed", "timing":{ "startTime":36111, "minEndTime":34675, "maxEndTime":34675, "nextTime":34975 } }, { "eventState": "protected-Movement-Allowed", "timing":{ "startTime":34675, "minEndTime":34735, "maxEndTime":34915, "nextTime":34975 } } }
```

7.3.3.3.4.2 Unknown Next Movement State

MSG_SignalPhaseAndTiming Message provides a data frame, DF_MovementEventList, that contains 1 to 16 entries for the same movement at an intersection. Each entry (represented by DF_MovementEvent) represents a movement state for that movement over a period of time.

- The first entry describes the current movement state (i.e., DE_MovementPhaseState) and the time change details for the current movement (startTime, minEndTime, maxEndTime, and nextTime).
- The second entry describes the movement state immediately after the current movement state terminates and the start, minimum end, maximum end, and next times for the next movement state.

If the next movement state, as represented by DE_MovementPhaseState, is unknown, a second entry for the movement (DF_MovementEvent) shall be sent in DF_MovementEventList as unknown.

For example, in Figure 10, lane #1 is tied to signal group #2 and currently a permissive left turn. The minimum end time for signal group 2 is currently 34675 deciseconds and the maximum end time is 35244 deciseconds from the top of the hour. At this point in time, the TSC infrastructure has not determined if the next movement state is a clearance interval or a protected left turn. So, the SPaT message for this movement would be the following:

```
{
  "signalGroup": 2,
  "state-time-speed": [
    {
      "eventState": "permissive-Movement-Allowed",
      "timing": {
        "startTime": 36111,
        "minEndTime": 34675,
        "maxEndTime": 35244,
        "nextTime": 34975
      }
    },
    {
      "eventState": "unavailable",
      "timing": {
        "startTime": 34675,
        "minEndTime": 36111,
        "maxEndTime": 36111,
        "nextTime": 34975
      }
    }
  ]
}
```

7.3.3.3.4.3 No Past State

No design details provided at this time.

7.3.3.3.5 Time Change Details Design Details

The design details to fulfill the requirements for when the current signal interval state for a signal group may change follow. These requirements are defined in 6.3.3.3.5, Time Change Details Requirements.

Annex C contains a table that summarizes the values for when the current signal interval state for a signal group may change based on the mode of operation of the TSC.

7.3.3.3.5.1 Time Change Details

The details on when the current movement state of a movement through an intersection will change is represented as timing (DF_TimeChangeDetails) and found under data frame DF_MovementEvent in MSG_SignalPhaseAndTiming Message in SAE J2735.

Each movement is tied to an identifier called the signalGroup (DE_SignalGroupID), which represents a collection of movements of a common type through the intersection.

Note the signalGroup identifier is not necessarily equal to the phase number. For example, overlap movements also are assigned a signalGroup identifier.

7.3.3.3.5.2 Unknown Time Change Detail

If a time change detail is required for every movement to be transmitted in the SPaT message, but the value is unknown, then that time change detail is represented by a value of 36111 for DE_TimeMark, found under data frame DF_TimeChangeDetails in MSG_SignalPhaseAndTiming Message as defined in SAE J2735.

CTI 4501 requires that the following time change details for each allowed movement be included in all SPaT messages transmitted:

- Start Time. The earliest time the next movement state is expected to start. Uses a value of Unknown for the current movement state.
- Minimum End Time. The earliest time when the current movement state is expected to end.
- Maximum End Time. The latest time when the current movement state is expected to end.
- Next Time. The estimated time when this movement will again be allowed, i.e., green.

For any times that are not known by the TSC infrastructure, a value of unknown is used.

NOTE: The value of DE_TimeMark indicating unknown changed from a value of 36001 in SAE J2735_201603 to a value of 36111 starting with the July 2020 version to properly address leap seconds.

7.3.3.3.5.3 Minimum End Time

The minEndTime is the earliest time that the current and any future interval could end. It is expressed as a time mark (DE_TimeMark) in the data frame DF_TimeChangeDetails in MSG_SignalPhaseAndTiming Message in SAE J2735.

The minEndTime is based on the current timing plan for each signal group at an intersection and should not consider that the interval could abruptly change due to unpredictable events such as signal preemptions or failures such as a watchdog failure or a conflict monitor trigger.

For green intervals, the minEndTime shall be based on the maximum time remaining in each of the following controller timers: the minimum green time setting, the sum of the pedestrian WALK and flashing DON'T WALK intervals, the coordination splits (minus the yellow change and red clearance intervals), the vehicle extension, or the AGP. If an agency is using a trailing overlap, the green portion of the overlap phase is considered as part of the minEndTime.

For yellow change intervals, the minEndTime is based on the duration of the yellow change interval for the movement.

For red intervals, the minEndTime can be estimated as the current time plus sum of the red clearance intervals of the current signal (if used by the IOO) and the expected duration of all the movements that have active demand prior to service of the phase or overlap.

Figure 11 is an example of minimum end times for an actuated intersection that includes Rest in Green. In this scenario, the signal is operating in a time dependent mode. When the signal first turns green (t=0 seconds), the initial minEndTime setting is controlled by the either the minimum green or the WALK plus the pedestrian clearance interval (whichever is greater). In this example, the minEndTime would be set to 00220, the duration of the WALK and the Pedestrian Clearance intervals. Before the pedestrian clearance interval expires, a TSC detects a vehicle passing through its detection zone (at t=20 seconds) and extends the green interval an additional 5 seconds. This actuation causes the minEndTime time mark to increase from 00220 to 00250. Three seconds later (at t=3 seconds), a second vehicle triggers the AGP, causing the signal to extend another 5 seconds, making the green interval minEndTime to become 00280. At t=28 seconds, all extension timers expire, and the traffic signal rests in green as a call for service does not exist on a conflicting phase. At this time, the minEndTime will increase in 0.1-second increments until a call for service occurs on a conflicting interval or the current phase receives another extension. Finally, at t=38 seconds, a call occurs on a conflicting phase, causing the TSC to begin terminating the phase by activating the yellow change interval. When the TSC activates the yellow change interval, the minEndTime is set to the duration of the yellow change interval (5 seconds). The minEndTime of the yellow change interval becomes 00430.

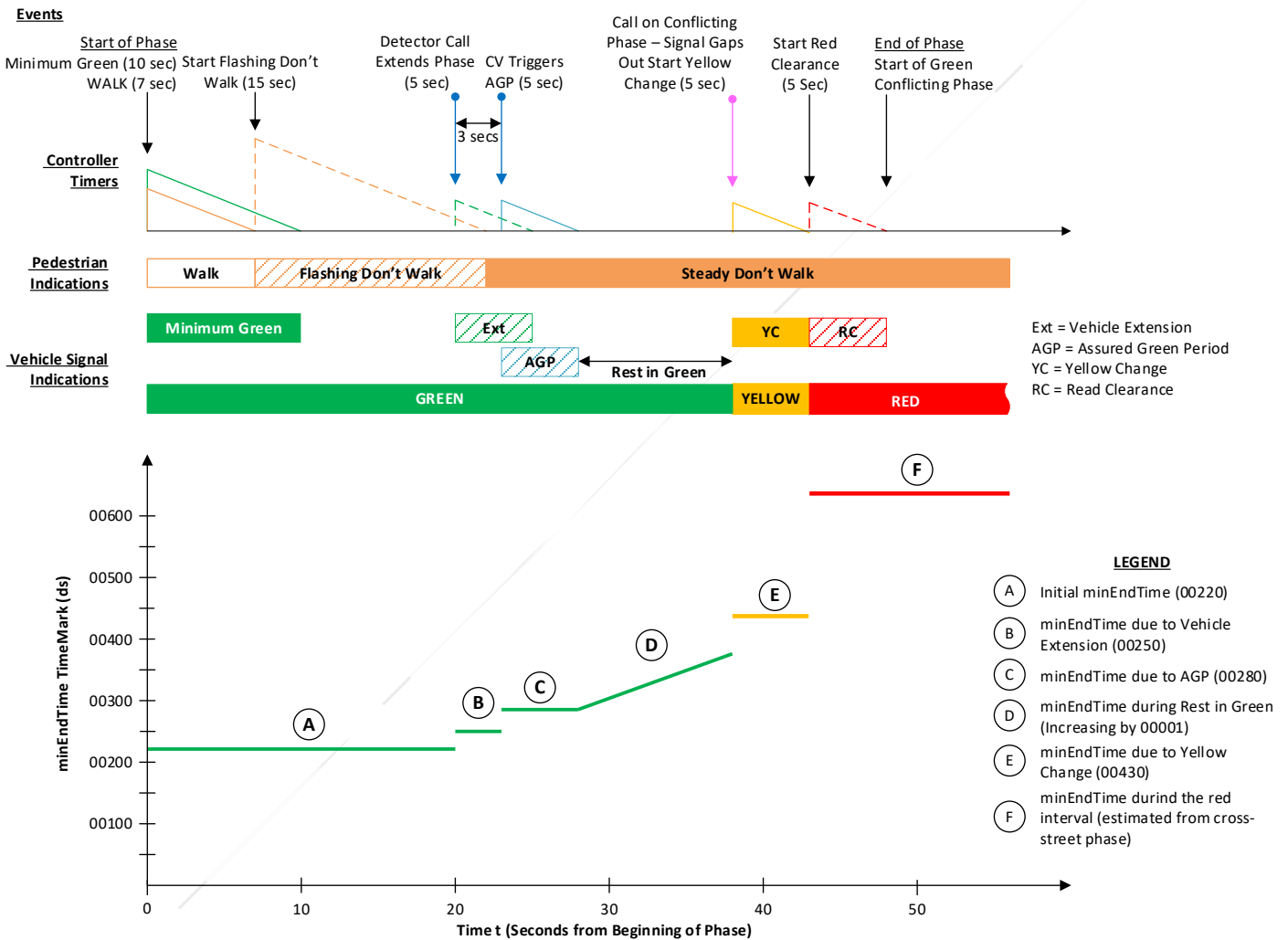


Figure 11 - Example minimum end time, rest in green

7.3.3.3.5.4 Maximum End Time

The latest time that the current and any future interval could end is represented by maxEndTime (DE_TimeMark), found under the data frame DF_TimeChangeDetails in MSG_SignalPhaseAndTiming Message in SAE J2735.

The latest time that an interval could end may be constrained by the maximum green time settings or coordination force-offs. When the interval duration is fixed, such as when the TSC infrastructure is operating in fixed time or the yellow interval duration, the minimum end time will equal the maximum end time.

7.3.3.3.5.5 Unknown Maximum End Time

See 7.3.3.3.5.2, Unknown Time Change Detail.

7.3.3.3.5.6 Current Movement State Start Time

No design details provided at this time.

7.3.3.3.5.7 Next Movement State Start Time

MSG_SignalPhaseAndTiming Message provides a data frame, DF_MovementEventList, that contains 1 to 16 entries for the same movement at an intersection. Each entry (represented by DF_MovementEvent) represents a movement state for that movement over a period of time.

- The first entry describes the current movement state (i.e., DE_MovementPhaseState) and the time change details for the current movement (startTime, minEndTime, maxEndTime, and nextTime).
- The second entry describes the movement state immediately after the current movement state terminates and the start, minimum end, maximum end, and next times for the next movement state.

The start time for the current interval is indicated as unknown. The start time for the next movement state, represented by startTime (DE_TimeMark) and found under the data frame DF_TimeChangeDetails in MSG_SignalPhaseAndTiming Message in SAE J2735, is the second entry and is equal to the minEndTime of the current movement state. Note that the minEndTime and maxEndTime are also included in the second entry, even if the value is unknown.

If the next movement state, as represented by DE_MovementPhaseState, is unknown, a second entry for the movement (DF_MovementEvent) is sent in DF_MovementEventList as unknown.

NOTE: The value of DE_TimeMark indicating unknown changed from a value of 36001 in SAE J2735_201603 to a value of 36111 starting with the July 2020 version to properly address leap seconds.

See the example in 7.3.3.3.4.1, Next Movement State.

7.3.3.3.5.8 Next State Time Start Equals Current State Minimum End Time

The start time of the next movement state, represented by startTime (DE_TimeMark) in the second entry of data frame DF_MovementEventList, is the same time point as the minimum end time of the current movement state, as represented by minEndTime (DE_TimeMark) in the first entry of data frame, DF_MovementEventList.

7.3.3.3.6 Next Green Design Details

The design details to fulfill the requirements for when a movement at an intersection is next allowed to proceed (e.g., permissive or protected movement allowed) follow. These requirements are defined in 6.3.3.3.6, Next Allowed Movement Requirements.

7.3.3.3.6.1 Time of Next Allowed Movement

The next time that the current movement is allowed to move is represented by nextTime (DE_TimeMark), found under the data frame DF_TimeChangeDetails in MSG_SignalPhaseAndTiming Message in SAE J2735. A movement is "allowed to move" when the signal indication for that movement is green or a flashing yellow arrow for a vehicle movement; or a "WALK" signal for a pedestrian movement; or, more precisely, the movement state, as represented by DE_MovementPhaseState, is permissive-Movement-Allowed or protected-Movement-Allowed.

Next time may be used by ECO (environmental) applications on an OBU/MU to determine when the vehicle or pedestrian is estimated to be allowed to move again. This may affect if a driver is advised to travel faster or slower to improve overall fuel consumption.

For fixed time and coordinated signals (and possibly others), next time can be estimated by the TSC infrastructure, subject to unpredictable events such as signal preemptions or failures such as a watchdog failure or a conflict monitor trigger. If next time cannot be estimated with a high level of confidence, a value of unknown is used, represented by a value of 36111 for DE_TimeMark.

The same value of nextTime is provided in both the first and second entry (DF_MovementEvent) of DF_MovementEventList, which represents the current and next movement states.

NOTE: The value of DE_TimeMark indicating undefined or unknown changed from a value of 36001 in SAE J2735_201603 to a value of 36111 starting with the July 2020 version to properly address leap seconds.

For example, Figure 12 is a mid-block pedestrian crossing with a pedestrian push button for the cross walk. The signal indication for the vehicle movement (signal group 1) is currently green with a minimum end time of 34675 deciseconds, and the maximum end time is 35244 deciseconds from the top of the hour. At this point in time, the TSC infrastructure does not know when the movement will end, so it does not know the next time the movement will be allowed again. So, the SPaT message for this movement would be the following:

```
{ "signalGroup":1, "state-time-speed":{ "eventState":"protected-Movement-Allowed", "timing":{"startTime":36111, "minEndTime":34675, "maxEndTime":35244, "nextTime":36111}}, {"eventState":"unavailable", "timing":{"startTime":36111, "minEndTime":36111, "maxEndTime":36111, "nextTime":36111}}}
```

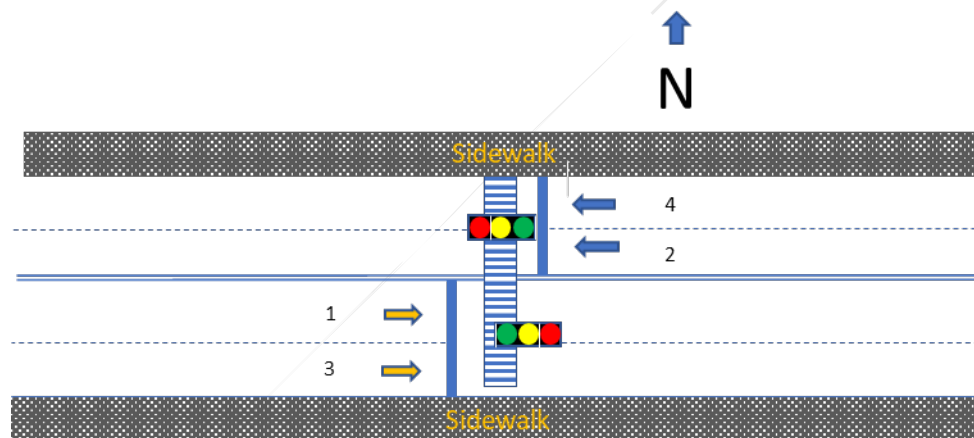


Figure 12 - Example next time

Several seconds later, a pedestrian depresses the push button and the TSC infrastructure decides to terminate the green at 34675 deciseconds after the top of the hour, with a clearance interval of 4 seconds. The pedestrian WALK plus flashing DON'T WALK time is 26 seconds. The next time is now known to be 34975 deciseconds after the top of the hour. So, the SPaT message for this movement is now the following:

```
{ "signalGroup":1, "state-time-speed":{ "eventState":"protected-Movement-Allowed", "timing":{"startTime":36111, "minEndTime":34675, "maxEndTime":34675, "nextTime":34975}}, {"eventState":"protected-clearance", "timing":{"startTime":34675, "minEndTime":34715, "maxEndTime":34715, "nextTime":34975}}}
```

7.3.3.3.7 Enabled Lanes Indication

Active ('enabled') revocable lanes for an intersection are represented by the lane identifier (DE_LaneId) in enabledLanes (DF_EnabledLaneList), found under data frame DF_IntersectionState in MSG_SignalPhaseAndTiming Message as defined in SAE J2735.

This requirement is mandatory to be supported but is conditional to be included in the SPaT message. If no revocable lane is defined in the MAP message for the intersection (see 7.3.3.4.6, Revocable Lanes) OR no revocable lane is currently active ('enabled'), then the data frame DF_EnabledLaneList is not transmitted in the SPaT message.

However, if the MAP message for the intersection defines a revocable lane for the intersection AND a revocable lane is currently active ('enabled'), then the data frame DF_EnabledList shall be transmitted as part of the SPaT message for the intersection.

This is an example:

```
{"messageId":19,"value":{"intersections":[{"id":{"id":173},"revision":89,"status":"0000","moy":19230,"timeStamp":45484,"states":[{"signalGroup":2,"state-time-speed":{"eventState":"protected-Movement-Allowed","timing":{"startTime":36111,"minEndTime":34654,"maxEndTime":35244,"nextTime":36111}}}],{"signalGroup":4,"state-time-speed":{"eventState":"stop-And-Remain","timing":{"startTime":34711,"minEndTime":34711,"maxEndTime":35301,"nextTime":36111}}}]}}}
```

```
{"messageId":19,"value":{"intersections":[{"id":{"id":173},"revision":89,"status":"0000","moy":19230,"timeStamp":45484,"enabledLanes":5,"states":[{"signalGroup":2,"state-time-speed":{"eventState":"protected-Movement-Allowed","timing":{"startTime":36111,"minEndTime":34654,"maxEndTime":35244,"nextTime":36111}}}],{"signalGroup":4,"state-time-speed":{"eventState":"stop-And-Remain","timing":{"startTime":34711,"minEndTime":34711,"maxEndTime":35301,"nextTime":36111}}}]}}}
```

An implementation should provide a check that a SPaT message does not assert mutually exclusive enabled lanes simultaneously.

NOTE: NTCIP 1202 defines a table, spatEnabledLanesConcurrencyTable, that indicates which lanes may be active concurrently and serves as a check that mutually exclusive enabled lanes are not enabled simultaneously.

7.3.3.3.8 SPaT Message Accuracy

No design details provided at this time.

7.3.3.4 Roadway Geometry Data Design Details

Not applicable.

7.3.3.4.1 Intersection Geometry Design Details

Not applicable.

7.3.3.4.2 Lane Attributes

Not applicable.

7.3.3.4.3 Lane Maneuvers

Not applicable.

7.3.3.4.4 Connections Between Lanes

Not applicable.

7.3.3.4.5 Speed Limit Information Design Details

Not applicable.

7.3.3.4.6 Revocable Lanes

Not applicable.

7.3.3.4.7 Signal Timing and Roadway Geometry Synchronization Design Details

The design details to fulfill the requirements to ensure that the roadway geometry information being broadcast reflect the current operating state used to generate the signal timing data follow. These requirements are defined in 6.3.3.4.7, Signal Timing and Roadway Geometry Information Synchronization.

7.3.3.4.7.1 Matching SPaT and MAP Version Design Details

The purpose of this requirement is that the contents of the SPaT message is consistent with the MAP message being broadcasted. An example of consistency includes that the SPaT message provides state and timing information for a left turn into a lane that is defined and allowed in the MAP message.

The intent of requirement 6.3.3.4.7.1, Matching SPaT and MAP Version is NOT that a connected intersection be able to "automatically" identify that the SPaT and MAP messages are consistent with each other. Rather, the intent of this requirement is that the IOO managing the connected intersection define policies and guidelines to prevent situations where SPaT and MAP messages may conflict with each other. Policies and guidelines should address temporary situations, such as a temporary work zone, and permanent situations, such as permanent changes to the intersection configuration.

For example, the traffic signal timing plan currently being implemented by a TSC infrastructure is designed for a specific geometric configuration. However, what happens during the following scenarios:

- There are changes to the lane striping. Should the connected intersection stop broadcasting the SPaT message and/or the MAP message while the striping work is underway?
- What if the egress lane for a left-turn lane movement is temporarily closed for a construction? Should the MAP allowing that left turn still be broadcasted?
- After a re-striping project, should the SPaT and MAP message be checked and verified before the messages are broadcasted again? This is particularly important if the SPaT and MAP messages are generated from different sources (e.g., a traffic engineering department for the SPaT message and a street construction department for the MAP message).

Be aware that some OBUs may have the capability to store MAP information, so OBU applications may reference its stored copy of the MAP data even if the MAP message is not broadcasted by the connected intersection.

This requirement is verified (tested) by inspection and/or demonstration. The method of verification can be decided by the IOO.

7.3.3.4.7.2 Matching Intersection Reference Identifier Design Details

This requirement is verified (tested) by inspection and/or demonstration.

NOTE: Starting with CTI 4501 v02, the guidance is to use OpOrgID (Operator Organization Identifier) in the IEEE 1609.2 certificate. Refer to CTI 4501, Annex A.1, Road Authority Identifier for a detailed explanation and guidance on the intersection reference identifiers.

7.3.3.4.7.3 Complete List of Signal Group Identifiers Design Details

No design details provided at this time.

7.3.3.4.7.4 Matching Signal Group Identifier Movements Design Details

No design details provided at this time.

7.3.3.5 Positioning Messages

Not applicable.

7.3.3.6 Vehicle Messages Design Details

The design details to fulfill the requirements for receiving vehicle data broadcasted by CVs follow.

7.3.3.6.1 Vehicle Position

See MSG_BasicSafetyMessage (BSM) in SAE J2735. The data elements to provide vehicle position are contained in DF_BSMcoreData, which is mandatory for MSG_BasicSafetyMessage.

7.3.3.6.2 Vehicle Kinematics

See MSG_BasicSafetyMessage (BSM) in SAE J2735. The data elements to provide vehicle kinematics are contained in DF_BSMcoreData, which is mandatory for MSG_BasicSafetyMessage.

7.3.4 Security Design Details

The design details to fulfill the security requirements for a connected intersection follow. These requirements are defined in 6.3.4.

7.3.4.1 Connected Intersection Data Trustworthiness Design Details

See the RTM in CTI 4501/3 for the design guidance to fulfill the Data Trustworthiness: Sources and Processing Requirements.

7.3.4.2 Connected Intersection Data Communications Security Design Details

See the RTM in CTI 4501/3 for the design guidance to fulfill the Data Communications Security Requirements.

7.3.4.3 Trustworthiness of TSC-Originating Information: Design Details

See the RTM in CTI 4501/3 for the design guidance to fulfill the Trustworthiness of TSC-originating Information Requirements.

7.3.4.4 Approaching Vehicle Information Trustworthiness: RSU: Design Details

See the RTM in CTI 4501/3 for the design guidance to fulfill the Approaching Vehicle Information Trustworthiness: RSU Requirements.

7.3.4.5 Approaching Vehicle Information Trustworthiness: TSC: Design Details

See the RTM in CTI 4501/3 for the design guidance to fulfill the Approaching Vehicle Information Trustworthiness and AGP: TSC Requirements.

7.3.4.6 Time Source Trustworthiness: Design Details

See the RTM in CTI 4501/3 for the design guidance to fulfill the Time Source Trustworthiness Requirements.

7.3.4.7 SPaT Message Trustworthiness and Reliability: Design Details

See the RTM in CTI 4501/3 for the design guidance to fulfill the SPaT Message Trustworthiness and Reliability Requirements.

7.3.4.8 MAP Message Trustworthiness and Reliability: Design Details

Not applicable.

7.3.4.9 RTCM Message Trustworthiness and Reliability: Design Details

Not applicable.

7.3.4.10 Consistency between MAP and SPaT Messages: Design Details

See the RTM in CTI 4501/3 for the design guidance to fulfill the Consistency Between MAP and SPaT Messages Requirements.

7.3.4.11 Unavailability Indications: Design Details

See the RTM in CTI 4501/3 for the design guidance to fulfill the Unavailability Indications Requirements.

7.3.4.12 Intersection Identifier Trustworthiness: Design Details

See the RTM in CTI 4501/3 for the design guidance to fulfill the Intersection Identifier Trustworthiness Requirements.

7.3.4.13 System Management and Recovery: Design Details

Not applicable.

7.3.4.14 Support Systems and Functions: Design Details

Not applicable.

7.3.4.15 Updates and Update Planning: Design Details

Not applicable.

7.3.4.16 System Operational Modes, Accesses, and Status: Design Details

Not applicable.

7.3.4.17 V2X Message Transmission: Design Details

Not applicable.

7.3.4.18 Verification of Connected Intersection System Security Design Details

See the RTM in CTI 4501/3 for the design guidance to fulfill the CI Security Verification Requirements.

7.3.5 Operations and Maintenance Design Details

No additional design details.

8. CONNECTED INTERSECTION TESTING

This section presents a testing framework to verify that the SPaT messages broadcasted by an implementation and the implementation receives BSMs that conform to CTI 4501. This testing framework provides guidance on how to create a verification plan that tests SPaT messages for a conformant CTI 4501 implementation. The purpose of a verification plan is to confirm that the implementation fulfills all the requirements defined for a connected intersection(s).

This section presents EXAMPLES of:

- Conformance Testing for SPaT Message Verification

The reader is encouraged to read CTI 4501/4 before reading the remainder of this section.

8.1 Conformance Testing Areas

CTI 4501 conformance testing for SPaT Message Verification and BSM Verification can be characterized as:

- SPaT Message Verification. Describes the scope, testing activities, and test documentation to verify a connected intersection fulfills the CTI 4501 requirements for a SPaT message. Refer to SAE J3238/1, Testing and Validation of SPaT information broadcast from Connected Intersections to support in-vehicle Red Light Violation Warning, which describes a testing and verification methodology to verify the accuracy and utility of SPaT to support red light violation warning. See 8.2.1, SPaT Message Verification.
- BSM Verification. Describes the scope, testing activities, and test documentation to verify a connected intersection fulfills the CTI 4501 requirements for a BSM message. See 8.2.2, BSM Verification.

8.2 Requirements to Test Case Traceability Matrix (RTCTM)

An example requirements-to-test-case traceability matrix (RTCTM) is provided in Table 7 - RTCTM - SPaT Message Verification and Table 8 - RTCTM – BSM Verification. The RTCTM is used to:

- Define the relationships between CTI 4501 requirements and specific (verification) test cases.
- Indicate what requirements might need to be tested to verify that an implementation conforms to CTI 4501 for that category.
- Ensure that all the requirements identified for CTI 4501 conformance testing are verified by the verification activities.

CTI 4501/4, 8.4, Test Documentation provides an overview of the different types of documentation, their relationships among each other, and the importance of test document. Each requirement to be verified is traced to a verification (test) case, which then can be traced to the appropriate stage(s) in the verification (test) procedures. A verification case is a logical grouping of communications interface and performance requirements that are to be verified together.

Each RTCTM provided identifies an initial list of example test cases to be performed for CTI 4501 conformance testing for each testing area. To confirm that an implementation fulfills a requirement, the implementation under test shall successfully pass all test cases that trace to that requirement. Collectively, the RTCTMs identify the requirements that must be fulfilled to conform with CTI 4501 and test cases that must be successfully performed to claim conformance with CTI 4501.

Each RTCTM contains the following information:

- Requirement No. The identifier of the requirement that is being verified by the test case.
- Requirement. A short description of the requirement.
- Test Case Identifier. A unique identifier for the test case(s).
- Test Case Name. A name for the test case(s).

- **Verification Method.** Identifies the method of verification to be used for the verification case. Valid values are Analysis, Demonstration, Inspection, and Test. The definitions for each method are:
 - **Analysis.** Verification of system using models, calculations, and testing equipment. This test method is used for a requirement that is fulfilled indirectly through a logical conclusion or mathematical analysis of a result. For example, algorithms for congestion: the designer may need to show that the requirement is met through the analysis of count and occupancy calculations in software or firmware.
 - **Demonstration.** Manipulation of the system to verify that the results are as planned or expected. This test method is used for a requirement that the system can demonstrate without external test equipment.
 - **Inspection.** Examination of the system using one of your five senses (auditory, olfactory, tactile, taste, visual). This test method is used for verification through a sensory comparison that the requirement has been satisfied. For example, the Vendor shall provide training on the troubleshooting of the system, including local intersection and central portions.
 - **Test.** Verification of system using a controlled and predefined series of inputs to ensure specific and predefined outputs are produced. This test method is used for a requirement that requires some external piece of test equipment (such as a logic analyzer or voltmeter).
- **Mandatory.** Identifies if the requirement is mandatory to conform with CTI 4501. A 'Y' indicates that the requirement is mandatory and an implementation must successfully pass the test case(s) to claim conformance with CTI 4501. An 'N' indicates the requirement is optional, but if the test case is performed, the test case must still pass to be conformant to CTI 4501.

The requirements in the following tables (see Table 7) should be fulfilled to claim conformance to CTI 4501. The test cases referenced in Table 7 are examples of test cases. The test case details and activities may vary for each agency based on the agency's policies, test methodologies and preferred test tools.

8.2.1 SPaT Message Verification

SPaT message verification for CTI 4501 consists of verifying that the SPaT messages broadcasted from the RSU fulfill all the requirements identified in the RTCTM for SPaT message verification (see Table 7). The test cases referenced in the table are examples and may vary by implementation

Table 7 - RTCTM - SPaT message verification

FR ID	Functional Requirement	Test Case Identifier	Test Case Name	Verification Method	Mandatory
6.3	Requirements				
6.3.1	Architectural Requirements				
6.3.1.1	LTE-V2X Communication				
6.3.1.1.1	Traffic Class Requirements				
6.3.1.1.1.1	ProSe Per Packet Priority - SPaT Message	TC-SPaT Data-Capture-1	SPaT Data Capture 1 - Message Structure and Content. See Table 11.	Analysis	Y
6.3.3	Message Requirements				
6.3.3.1	Message Performance Requirements				
6.3.3.1.1	Uniform Message Requirements				
6.3.3.1.1.1	SPaT Message - SAE J2735	TC-SPaT Data-Capture-1	SPaT Data Capture 1 - Message Structure and Content. See Table 11.	Analysis	Y
6.3.3.1.1.2	SPaT Message - Mandatory Data Elements	TC-SPaT Data-Capture-1	SPaT Data Capture 1 - Message Structure and Content. See Table 11.	Analysis	Y
6.3.3.1.1.3	SPaT Message - Required Data Elements	TC-SPaT Data-Capture-1	SPaT Data Capture 1 - Message Structure and Content. See Table 11.	Analysis	Y
6.3.3.1.1.4	SPaT Message PSID	TC-SPaT Data-Capture-1	SPaT Data Capture 1 - Message Structure and Content. See Table 11.	Analysis	Y
6.3.3.1.3	Concise Messages Requirements				
6.3.3.1.3.1	Transport Message Size - WAVE	TC-SPaT Data-Capture-1	SPaT Data Capture 1 - Message Structure and Content. See Table 11.	Analysis	Y
6.3.3.1.4	Advanced Notification Requirements				
6.3.3.1.4.1	Data Coverage - Every Ingress Lane	TC-SPaT Data-Capture-1	SPaT Data Capture 1 - Message Structure and Content. See Table 11.	Analysis	Y
6.3.3.1.4.2	Advanced Notification - Time	TC-SPaT Data-Capture-1	SPaT Data Capture 1 - Message Structure and Content. See Table 11.	Analysis	Y
6.3.3.1.5	Timeliness Requirements				
6.3.3.1.5.1	SPaT Message - Broadcast Latency and Accuracy	TC-SPaT Data-Capture-1	SPaT Data Capture 1 - Message Structure and Content. See Table 11.	Analysis	Y
6.3.3.1.6	Quality Assurance Requirements				
6.3.3.1.6.1	Completeness - SPaT Message	TC-SPaT Data-Capture-1	SPaT Data Capture 1 - Message Structure and Content. See Table 11.	Analysis	Y
6.3.3.1.6.3	SPaT Message - Time Mark Accuracy	TC-SPaT Data-Capture-1	SPaT Data Capture 1 - Message Structure and Content. See Table 11.	Analysis	Y
6.3.3.2	Generic Message Requirements				
6.3.3.2.1	Time Accuracy	TC-SPaT Data-Capture-1	SPaT Data Capture 1 - Message Structure and Content. See Table 11.	Analysis	Y
6.3.3.2.2	Message Revision Requirements				

FR ID	Functional Requirement	Test Case Identifier	Test Case Name	Verification Method	Mandatory
6.3.3.2.2.1	SPaT Message - Revision Counter Increment	TC-SPaT Data-Capture-1	SPaT Data Capture 1 - Message Structure and Content. See Table 11.	Analysis	Y
6.3.3.2.2.2	SPaT Message - Revision Counter Not Increment	TC-SPaT Data-Capture-1	SPaT Data Capture 1 - Message Structure and Content. See Table 11.	Analysis	Y
6.3.3.2.3	Time Stamp Requirements				
6.3.3.2.3.1	SPaT Message - Message Time Stamp	TC-SPaT Data-Capture-1	SPaT Data Capture 1 - Message Structure and Content. See Table 11.	Analysis	Y
6.3.3.2.3.2	SPaT Message - Intersection Time Stamp	TC-SPaT Data-Capture-1	SPaT Data Capture 1 - Message Structure and Content. See Table 11.	Analysis	Y
6.3.3.3	Signal Timing Data Requirements				
6.3.3.3.1	Intersection Identification Requirements				
6.3.3.3.1.1	Intersection Signal Timing Information	TC-SPaT Data-Capture-1	SPaT Data Capture 1 - Message Structure and Content. See Table 11.	Analysis	Y
6.3.3.3.1.2	Intersection Identifier	TC-SPaT Data-Capture-1	SPaT Data Capture 1 - Message Structure and Content. See Table 11.	Analysis	Y
6.3.3.3.1.3	Road Authority Identifier	TC-SPaT Data-Capture-1	SPaT Data Capture 1 - Message Structure and Content. See Table 11.	Analysis	Y
6.3.3.3.2	Intersection Status Requirements				
6.3.3.3.2.1	Manual Control	TC-SPaT Data-Capture-1	SPaT Data Capture 1 - Message Structure and Content. See Table 11.	Analysis	Y
6.3.3.3.2.2	Stop Time	TC-SPaT Data-Capture-1	SPaT Data Capture 1 - Message Structure and Content. See Table 11.	Analysis	Y
6.3.3.3.2.3	Failure Flash	TC-SPaT Data-Capture-1	SPaT Data Capture 1 - Message Structure and Content. See Table 11.	Analysis	Y
6.3.3.3.2.4	Preemption	TC-SPaT Data-Capture-1	SPaT Data Capture 1 - Message Structure and Content. See Table 11.	Analysis	Y
6.3.3.3.2.5	Priority	TC-SPaT Data-Capture-1	SPaT Data Capture 1 - Message Structure and Content. See Table 11.	Analysis	Y
6.3.3.3.2.6	Fixed Time	TC-SPaT Data-Capture-1	SPaT Data Capture 1 - Message Structure and Content. See Table 11.	Analysis	Y
6.3.3.3.2.7	Traffic Dependent Mode	TC-SPaT Data-Capture-1	SPaT Data Capture 1 - Message Structure and Content. See Table 11.	Analysis	Y
6.3.3.3.2.8	Standby Mode	TC-SPaT Data-Capture-1	SPaT Data Capture 1 - Message Structure and Content. See Table 11.	Analysis	Y
6.3.3.3.2.9	Failure Mode	TC-SPaT Data-Capture-1	SPaT Data Capture 1 - Message Structure and Content. See Table 11.	Analysis	Y
6.3.3.3.2.10	Controller Off	TC-SPaT Data-Capture-1	SPaT Data Capture 1 - Message Structure and Content. See Table 11.	Analysis	Y
6.3.3.3.2.11	Recent MAP Update	TC-SPaT Data-Capture-1	SPaT Data Capture 1 - Message Structure and Content. See Table 11.	Analysis	Y

FR ID	Functional Requirement	Test Case Identifier	Test Case Name	Verification Method	Mandatory
6.3.3.3.2.12	New Lane IDs	TC-SPaT Data-Capture-1	SPaT Data Capture 1 - Message Structure and Content. See Table 11.	Analysis	Y
6.3.3.3.2.13	No MAP Available	TC-SPaT Data-Capture-1	SPaT Data Capture 1 - Message Structure and Content. See Table 11.	Analysis	Y
6.3.3.3.2.14	No SPaT Available	TC-SPaT Data-Capture-1	SPaT Data Capture 1 - Message Structure and Content. See Table 11.	Analysis	Y
6.3.3.3.3	Current Movement State Requirements				
6.3.3.3.3.1	Current Movement State for a Signal Group	TC-SPaT Data-Capture-1	SPaT Data Capture 1 - Message Structure and Content. See Table 11.	Analysis	Y
6.3.3.3.3.2	Unknown Current Movement State for a Signal Group	TC-SPaT Data-Capture-1	SPaT Data Capture 1 - Message Structure and Content. See Table 11.	Analysis	Y
6.3.3.3.3.3	Flashing Yellow Arrow Permissive Movement	TC-SPaT Data-Capture-1	SPaT Data Capture 1 - Message Structure and Content. See Table 11.	Analysis	Y
6.3.3.3.3.4	Protected and Permissive Clearance	TC-SPaT Data-Capture-1	SPaT Data Capture 1 - Message Structure and Content. See Table 11.	Analysis	Y
6.3.3.3.3.5	Resolve Protected Versus Permissive Movement	TC-SPaT Data-Capture-1	SPaT Data Capture 1 - Message Structure and Content. See Table 11.	Analysis	Y
6.3.3.3.3.6	Yield Causes Permissive	TC-SPaT Data-Capture-1	SPaT Data Capture 1 - Message Structure and Content. See Table 11.	Analysis	Y
6.3.3.3.3.7	Right-of-Way Causes Protected	TC-SPaT Data-Capture-1	SPaT Data Capture 1 - Message Structure and Content. See Table 11.	Analysis	Y
6.3.3.3.3.8	WALK State Enumeration	TC-SPaT Data-Capture-1	SPaT Data Capture 1 - Message Structure and Content. See Table 11.	Analysis	Y
6.3.3.3.3.9	Flashing DON'T WALK State Enumeration	TC-SPaT Data-Capture-1	SPaT Data Capture 1 - Message Structure and Content. See Table 11.	Analysis	Y
6.3.3.3.3.10	Steady DON'T WALK State Enumeration	TC-SPaT Data-Capture-1	SPaT Data Capture 1 - Message Structure and Content. See Table 11.	Analysis	Y
6.3.3.3.3.11	Movement State for Signal Groups Identified	TC-SPaT Data-Capture-1	SPaT Data Capture 1 - Message Structure and Content. See Table 11.	Analysis	Y
6.3.3.3.3.12	Dark Pedestrian Indications	TC-SPaT Data-Capture-1	SPaT Data Capture 1 - Message Structure and Content. See Table 11.	Analysis	Y
6.3.3.3.3.13	Prohibited Movements	TC-SPaT Data-Capture-1	SPaT Data Capture 1 - Message Structure and Content. See Table 11.	Analysis	Y
6.3.3.3.3.14	Movements Allowed After a Stop	TC-SPaT Data-Capture-1	SPaT Data Capture 1 - Message Structure and Content. See Table 11.	Analysis	Y
6.3.3.3.4	Next Movement State Requirements				
6.3.3.3.4.1	Next Movement State	TC-SPaT Data-Capture-1	SPaT Data Capture 1 - Message Structure and Content. See Table 11.	Analysis	Y
6.3.3.3.4.2	Unknown Next Movement State	TC-SPaT Data-Capture-1	SPaT Data Capture 1 - Message Structure and Content. See Table 11.	Analysis	Y

FR ID	Functional Requirement	Test Case Identifier	Test Case Name	Verification Method	Mandatory
6.3.3.3.4.3	No Past State	TC-SPaT Data-Capture-1	SPaT Data Capture 1 - Message Structure and Content. See Table 11.	Analysis	Y
6.3.3.3.5	Time Change Details Requirements				
6.3.3.3.5.1	Time Change Details	TC-SPaT Data-Capture-1	SPaT Data Capture 1 - Message Structure and Content. See Table 11.	Analysis	Y
6.3.3.3.5.2	Unknown Time Change Detail	TC-SPaT Data-Capture-1	SPaT Data Capture 1 - Message Structure and Content. See Table 11.	Analysis	Y
6.3.3.3.5.3	Minimum End Time	TC-SPaT Data-Capture-1	SPaT Data Capture 1 - Message Structure and Content. See Table 11.	Analysis	Y
6.3.3.3.5.4	Maximum End Time	TC-SPaT Data-Capture-1	SPaT Data Capture 1 - Message Structure and Content. See Table 11.	Analysis	Y
6.3.3.3.5.5	Unknown Maximum End Time	TC-SPaT Data-Capture-1	SPaT Data Capture 1 - Message Structure and Content. See Table 11.	Analysis	Y
6.3.3.3.5.6	Current Movement State Start Time Unknown	TC-SPaT Data-Capture-1	SPaT Data Capture 1 - Message Structure and Content. See Table 11.	Analysis	Y
6.3.3.3.6	Next Allowed Movement Requirements				
6.3.3.3.6.1	Time of Next Allowed Movement	TC-SPaT Data-Capture-1	SPaT Data Capture 1 - Message Structure and Content. See Table 11.	Analysis	Y
6.3.3.3.7	Enabled Lanes Indication	TC-SPaT Data-Capture-1	SPaT Data Capture 1 - Message Structure and Content. See Table 11.	Analysis	Y
6.3.3.3.8	SPaT Message - Accuracy	TC-SPaT Data-Capture-1	SPaT Data Capture 1 - Message Structure and Content. See Table 11.	Analysis	Y
6.3.3.4.7	Signal Timing and Roadway Geometry Information Synchronization				
6.3.3.4.7.1	Matching SPaT and MAP Version	TC-SPaT Data-Capture-1	SPaT Data Capture 1 - Message Structure and Content. See Table 11.	Analysis	Y
6.3.3.4.7.2	Matching Intersection Reference Identifiers	TC-SPaT Data-Capture-1	SPaT Data Capture 1 - Message Structure and Content. See Table 11.	Analysis	Y
6.3.3.4.7.3	Complete List of Signal Group Identifiers	TC-SPaT Data-Capture-1	SPaT Data Capture 1 - Message Structure and Content. See Table 11.	Analysis	Y
6.3.3.4.7.4	Matching Signal Group Identifier Movements	TC-SPaT Data-Capture-1	SPaT Data Capture 1 - Message Structure and Content. See Table 11.	Analysis	Y

(1) Added in CTI 4501 v02.

8.2.2 BSM Verification

BSM handling verification for CTI 4501 consists of verifying that the BSMs received fulfill all the requirements identified in the RTCTM for BSM Verification (see Table 8). The test cases referenced in the table are examples and may vary by implementation.

Table 8 - RTCTM - BSM verification

FR ID	Functional Requirement	Test Case Identifier	Test Case Name	Verification Method	Mandatory
6.3.3	Message Requirements				
6.3.3.6	Vehicle Messages Requirements				
6.3.3.6.1	Vehicle Position		Refer to SAE J3161/1A		
6.3.3.6.2	Vehicle Kinematics		Refer to SAE J3161/1A		

8.3 Planned Activities

A verification plan must describe the activities to verify that a system fulfills the requirement. In this context, the verification plan describes the activities to test if a connected intersection conforms to CTI 4501. This section presents some example test methodology concepts, example approaches to testing and conformance, and example test environments.

Refer to 8.3 in CTI 4501/4 for information on verification plans.

8.3.1 CTI 4501 Conformance Testing by Stage - SPaT Messages

Table 9 represents an example of when a subset of CTI 4501 conformance testing for SPaT messages may be performed or repeated during the different stages of a connected intersection's life cycle.

Table 9 - Verification by stage - SPaT message

Stage	Test Scope
Component Testing	Not applicable for CTI 4501 conformance testing. Applicable per device-level certification.
Integration Testing	Perform all test cases for all mandatory and selected requirements.
Integration Testing - Field	Minimally perform the test cases for a subset of mandatory and selected requirements.
System Testing	Perform the test cases for a subset of mandatory and selected requirements.
Burn-in Testing	Perform the test cases for a subset of mandatory and selected requirements.
Operations and Maintenance	Perform a subset of SAE J3238/1 after changes to firmware or hardware.

8.3.2 CTI 4501 Conformance Testing by Stage - BSM Messages

Table 10 represents an example of when a subset of CTI 4501 conformance testing for BSM messages may be performed or repeated during the different stages of a connected intersection's life cycle.

Table 10 - Verification by stage - BSM message

Stage	Test Scope
Component Testing	Not applicable.
Integration Testing	Perform all test cases for all mandatory and selected requirements.
Integration Testing - Field	Minimally perform the test cases for a subset of mandatory and selected requirements.
System Testing	Perform the test cases for a subset of mandatory and selected requirements.
Burn-in Testing	Perform the test cases for a subset of mandatory and selected requirements.
Operations and Maintenance	To be determined.

8.3.3 Example Test Methodology - SPaT Messages

SAE J3238/1, Testing and Validation of SPaT information broadcast from Connected Intersections to support in-vehicle Red Light Violation Warning, also describes testing and validation methodologies to verify the accuracy and utility of SPaT to support red light violation warnings.

8.3.3.1 SPaT Test Case

The test case described in Table 11 was used to validate the SPaT messages during a validation phase of CTI 4501 v01, which took place between April and September 2021. The findings from performing this test case are found in CTI 4502. The test case has been updated to reference the current version of CTI 4501 and SAE J2735 as of the publication date.

Figure 13 is an illustration depicting the relevant data flows used during the conduct of this test case.

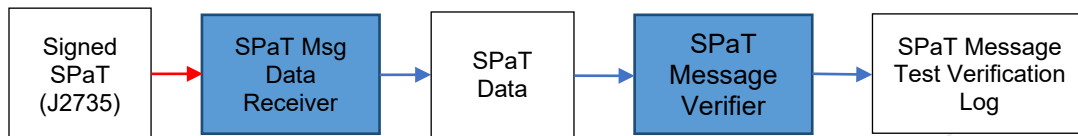


Figure 13 - CI SPaT message data structure and content test case diagram

The Signal Timing Information sent to the RSU will be verified as an output of the RSU, as captured by the SPaT Msg Data Receiver. The input Signal Timing Information sent to the RSU will not be tested. Whether the RSU has valid certificates will not be tested in this test case.

Table 11 - Example test case - SPaT data capture 1 - message structure and content

Test Case	
ID: TC-SPaT Data-Capture-1	SPaT Data Capture 1 - Message Structure and Content
Purpose:	Verify format, message content values, and structure of SPaT data stream output from the RSU are correct per SAE J2735_202309 ⁽¹⁾ and CTI 4501.
Objective:	Verify system interface between an RSU and RSU Message Receiver. The test case verifies that the SPaT message broadcast from the RSU contains all the mandatory objects and that the objects conform with the valid value ranges as specified in SAE J2735_202309 ⁽¹⁾ and CTI 4501.
Inputs:	Table 4 contains a complete SPaT data specification.
Expected Outcome(s):	All SPaT data and message structure are verified as correct, including structure of data and valid value of data content.
Feature Pass/Fail Criteria:	All mandatory SPaT data elements within the message are verified as correct. Message structure of SPaT is correct. Fail: Any other outcome.
Preconditions:	Either the RSU has IEEE Std 1609.2 certificates and can sign (preferred) or the RSU is in diagnostic mode per CTI 4001 and is creating non-secured data in the format specified in that standard. Every device (RSU) is certified prior to testing against the CI testing defined herein.

⁽¹⁾ Updated from SAE J2735_202007 to SAE J2735_202309.

8.3.3.2 CI SPaT-MAP Data Consistency Test Case

The test case described here was used to verify that the intersection identifier in the SPaT and MAP messages for the same intersection are the same. This test case was used during a validation phase of CTI 4501 v01, which took place between April and September 2021. The findings from performing this test case are found in CTI 4502. The test case has been updated to reference the current version of CTI 4501 and SAE J2735 as of the publication date. Figure 14 is an illustration identifying the relevant data flows used in the CI SPaT-MAP Data Consistency Message Level Test Cases.

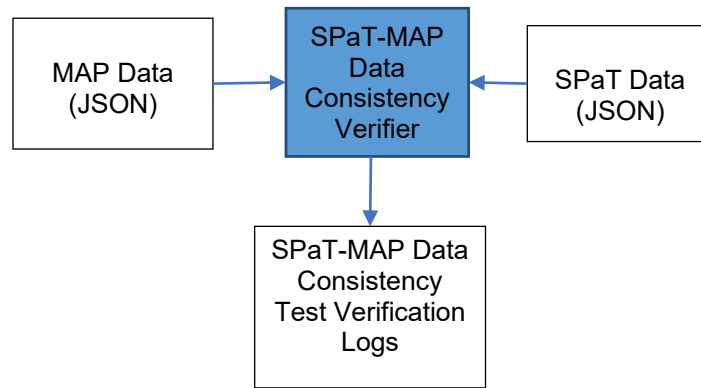


Figure 14 - CI SPaT-MAP data consistency test case diagram

Table 12 - Example test case - SPaT-MAP data consistency

Test Case	
ID: SPaT-MAP-Data-Consistency-1	SPaT-MAP Data Consistency
Purpose:	Verify data consistency between SPaT and MAP for the following data elements from SAE J2735_202309 ⁽¹⁾ : DF_RoadAuthorityID ⁽²⁾ DE_IntersectionID
Objective:	Verify system interface between an RSU and RSU Message Receiver. The test case verifies the RSU broadcasts valid SPaT and MAP messages that are consistent.
Inputs:	Table 4 contains a complete SPaT Data specification. CTI 4501/2, Table 2 contains a complete MAP Data specification.
Expected Outcome(s):	Data consistency between MAP and SPaT data are verified as correct for the specific data elements defined in the Purpose section of this test case.
Feature Pass/Fail Criteria:	Referential integrity between MAP and SPaT is verified for the specific data elements defined in the Purpose section of this test case. Fail: Any other outcome.
Preconditions:	Dependencies: Must have executed and passed: Test Case SPaT Data Capture 1 - Message Structure and Content Test Case MAP Data Capture 1 - Message Structure and Content

⁽¹⁾ Updated from SAE J2735_202007 to SAE J2735_202309.

⁽²⁾ Updated from DF_RoadRegulatorID to DF_RoadAuthorityID.

8.3.4 Test Methodology - BSM Messages

SAE J3161/1A provides verification methodologies and data verification procedures that may be used to verify that an instrument under test (IUT) satisfies the vehicle-level requirements specified in SAE J3161/1. This includes the contents of a BSM message.

SAE J3161/1A to be completed at component testing (device-level) through certification process.

Refer to SAE J3161/1A for example verification methodologies and procedures.

8.3.5 Test Environment

A verification plan needs to describe the test environment to provide a basis for comprehensive and consistent testing. Refer to CTI 4501/4, 8.3.5 for an example on how to describe the test environment.

8.4 Test Documentation

See CTI 4501/4 Section 8.4, Test Documentation for a description of the different types of test documentation that should be developed for testing and validation.

9. NOTES

9.1 Revision Indicator

A change bar (|) located in the left margin is for the convenience of the user in locating areas where technical revisions, not editorial changes, have been made to the previous issue of this document. An (R) symbol to the left of the document title indicates a complete revision of the document, including technical revisions. Change bars and (R) are not used in original publications, nor in documents that contain editorial changes only.

PREPARED BY SAE CONNECTED TRANSPORTATION INTEROPERABILITY COMMITTEE

ANNEX A - CONNECTED INTERSECTION TRAFFIC CONTROLLER ISSUES AND RECOMMENDATIONS [INFORMATIVE]

This annex provides informative information related to generating and broadcasting SPaT messages.

A.1 TSCBM AND SPAT DATA

This section provides additional guidance if the Traffic Signal Controller Broadcast Message (TSCBM) is exchanged between the TSC infrastructure and the RSU to generate a SPaT message.

NTCIP 1202 v02 did not address the interface between the ASC and the RSU. Therefore, the TSCBM, defined in Section 3 in the V2I Hub ICD, was developed to complement NTCIP 1202 v02 for early connected vehicle pilots. The information in the TSCBM from the ASC was used by RSUs in addition to NTCIP 1202 v02 data to generate SPaT messages.

Table 5 describes the sources for each of the data frames and data elements that comprise the SPaT message broadcasted by the RSU based on how the connected intersection is configured and what SPaT information message is used between the TSC infrastructure and the RSU. Three potential SPaT information messages are identified in CTI 4501, the SAE J2735 SPaT Message, NTCIP 1202, and the TSCBM. However, since the CI Committee does not recommend deploying TSCBM at new locations, Table 13 did not include the source of the data frames and data elements for the SPaT message when using the TSCBM.

However, since most existing implementations use the TSCBM to provide information from the TSC infrastructure to the RSU, this section and Table 5 are provided for additional guidance based on the design content in CTI 4501. Similar to Table 5, Table 13 contains links to the specific sections in CTI 4501 with the design details for generating that data element value, based on the UPER-encoded SPaT Message and the TSCBM.

- SAE J2735 Data Element, Bit column describes the data element (and bit) of interest.
- SAE J2735 SPaT Message column is a link to a section describing that data element in more detail.
- TSCBM column describes the byte(s) and bits within the TSCBM containing the data source for the data element (and bit) of interest.
- Notes column contains additional information about using the TSCBM byte(s) and bits.

Table 13 - Mapping of SAE J2735 elements to TSCBM

SAE J2735 Data Element, Bit	CTI 4501 Reference	TSCBM	Notes
timeStamp (DE_MinuteOfTheYear)	See 7.3.3.2.3	Bytes 236-240: spatTimeStamp (5 bytes, hours-minute-second-millisecond) Clock source may not be UTC.	Generated by the RSU, spatTimestamp describes the time within the day when the TSCBM is generated. The RSU needs to convert this time to the Minute of the Year. The time source used to generate spatTimestamp may vary. Thus, the RSU may need to convert this time to UTC (universal time coordinate) time.
id=DF_IntersectionReferenceID	See 7.3.3.3.1		
region=DE_RoadRegulatorID	See 7.3.3.3.1.3	Unsupported.	Defined in the RSU.
id=DE_IntersectionID	See 7.3.3.3.1.2	Unsupported.	Defined in the RSU.
revision=DE_MsgCount	See 7.3.3.2.2.1	Byte 234: spatDiscontinuousChangeFlag Bits 3-7	spatDiscontinuousChangeFlag is static and fixed at 0x11. Thus, the binary will look like: 0b00010XXX, where XXX is variable.
status=DE_IntersectionStatusObject (manualControllsEnabled(0))	See 7.3.3.3.2.1	Byte 232: spatIntersectionStatus Bit 0: Manual Control Enable Active	Bit 0 is the MSB. 0x80 would be manual control.
status=DE_IntersectionStatusObject, stopTimeIsActivated(1)	See 7.3.3.3.2.2	Byte 232: spatIntersectionStatus Bit 1: Stop Time (all rings) Active	
status=DE_IntersectionStatusObject, failureFlash(2)	See 7.3.3.3.2.3	Byte 232: spatIntersectionStatus Bit 2: Fault Flash Active	
status=DE_IntersectionStatusObject, preemptIsActive(3)	See 7.3.3.3.2.4	Byte 232: spatIntersectionStatus Bit 3: Preempt Active	
status=DE_IntersectionStatusObject, signalPriorityIsActive(4)	See 7.3.3.3.2.5	Byte 232: spatIntersectionStatus Bit 4: TSP Active	
status=DE_IntersectionStatusObject, fixedTimeOperation(5)	See 7.3.3.3.2.6	Unsupported.	
status=DE_IntersectionStatusObject, trafficDependentOperation(6)	See 7.3.3.3.2.7	Unsupported.	
status=DE_IntersectionStatusObject, standbyOperation(7)	See 7.3.3.3.2.8	Byte 232: spatIntersectionStatus Bit 7: Programmed Flash Active	
status=DE_IntersectionStatusObject, failureMode(8)	See 7.3.3.3.2.9	Unsupported.	
status=DE_IntersectionStatusObject, off(9)	See 7.3.3.3.2.10	Unsupported.	Value cannot come from the controller if it is off.
status=DE_IntersectionStatusObject, recentMAPmessageUpdate(10)	See 7.3.3.3.2.11	Unsupported.	Generated by the RSU or is blank.

SAE J2735 Data Element, Bit	CTI 4501 Reference	TSCBM	Notes
status=DE_IntersectionStatusObject, recentChangeinMAPAssignedLanesUsed(11)	See 7.3.3.3.2.12	Unsupported.	Generated by the RSU or is blank.
status=DE_IntersectionStatusObject, noValidMAPisAvailableAtThisTime(12)	See 7.3.3.3.2.13	Unsupported.	Generated by the RSU or is blank.
status=DE_IntersectionStatusObject, noValidSPATisAvailableAtThisTime(13)	See 7.3.3.3.2.14	Unsupported.	Generated by the RSU or is blank.
timeStamp=DE_Dsecond	See 7.3.3.2.3.2	Bytes 236-240: spatTimeStamp Clock source may not be UTC.	Generated by the RSU, spatTimestamp (5 bytes, hours-minute-second-millisecond) describes the time within the day when the TSCBM is generated. The RSU needs to convert this time to milliseconds in the current UTC minute. The time source used to generate spatTimestamp may vary. Thus, the RSU may need to convert this time to UTC (universal time coordinate) time.
enabledLanes=DF_EnabledLaneList	See 7.3.3.3.7	Unsupported.	Generated by the RSU.
states=DF_MovementList	See 7.3.3.3.3		
signalGroup=DE_SignalGroupID	See 7.3.3.3.3.1	Unsupported.	The RSU must provide a means to relate Vehicle, Pedestrian, and Overlap phases in the TSCBM to signal groups in the SAE J2735 SPaT message.
state-time-speed=DF_MovementEventList			
eventState=DE_MovementPhaseState (Current Movement)	See 7.3.3.3.3	Vehicle Phases Bytes 210-211: phaseStatusGroupReds Bytes 212-213: phaseStatusGroupYellows Bytes 214-215: phaseStatusGroupGreens Vehicle Overlaps Bytes 222-223: overlapStatusGroupReds Bytes 224-225: overlapStatusGroupYellows Bytes 226-227: overlapStatusGroupGreens Pedestrians Bytes 216-217: phaseStatusGroupDontWalks	The RSU must provide a means to configure the protected or permissive state of the signal group related to the TSCBM Vehicle, Pedestrian, or Overlap phases, including configuring a protected permissive signal group. For example, the TSCBM does not indicate if a left turn is a permitted left turn or a protected turn. The distinction is made in a (proprietary) table within the RSU and used when the RSU generates the SAE J2735 SPaT message for broadcast.

SAE J2735 Data Element, Bit	CTI 4501 Reference	TSCBM	Notes
		Bytes 218-219: phaseStatusGroupPedClears Bytes 220-221: phaseStatusGroupWalks	
eventState=DE_MovementPhaseState (Next Movement)	See 7.3.3.3.4	Unsupported. Defined by vendor.	TSCBM does not support providing the next state of the movement as required by CTI 4501.
timing=DF_TimeChangeDetails	See 7.3.3.3.5		
startTime=DE_TimeMark	See 7.3.3.3.5.7, 7.3.3.3.5.8	Unsupported. Defined by vendor.	TSCBM does not support providing the start time of the next movement as required by CTI 4501.
minEndTime=DE_TimeMark	See 7.3.3.3.5.3	Vehicle Phases Byte 2: phase number Bytes 3-4: spatVehMinTimeToChange Up to 16 phases are supported in bytes in 2-209. Vehicle Overlaps Byte 2: phase number Bytes 11-12: spatOvpMinTimeToChange Up to 16 overlaps are supported in bytes in 2-209. Pedestrians Byte 2: phase number Bytes 7-8: spatPedMinTimeToChange Up to 16 phases are supported in bytes in 2-209.	Generated by the RSU. The TSCBM was developed based on the 2009 version of SAE J2735 (SAE J2735_200911), where DE_TimeMark indicates how much time remains before an event occurs. The 2015 version (SAE J2735_201509) updated DE_TimeMark to indicate the time within the hour at which a signal phase is expected to change. Thus, the RSU must convert the time to change in the TSCBM to time of change in the SAE J2735 SPaT message.
maxEndTime=DE_TimeMark	See 7.3.3.3.5.4	Vehicle Phases Byte 2: phase number Bytes 5-6: spatVehMaxTimeToChange Up to 16 phases are supported in bytes in 2-209. Vehicle Overlaps Byte 2: phase number Bytes 12-13: spatOvpMaxTimeToChange Up to 16 overlaps are supported in bytes in 2-209. Pedestrians Byte 2: phase number	Generated by the RSU. The TSCBM was developed based the 2009 version of SAE J2735 (SAE J2735_200911), where DE_TimeMark indicates how much time remains before an event occurs. The 2015 version (SAE J2735_201509) updated DE_TimeMark to indicate the time within the hour at which a signal phase is expected to change. Thus, the RSU must convert the time to change in the TSCBM to time of change in the SAE J2735 SPaT message.

SAE J2735 Data Element, Bit	CTI 4501 Reference	TSCBM	Notes
		Bytes 9-10: spatPedMaxTimeToChange Up to 16 phases are supported in bytes in 2-209.	
nextTime=DE_TimeMark	See 7.3.3.3.6.1	Unsupported. Defined by vendor.	TSCBM does not support providing the time of the next allowed movement as required by CTI 4501.

A.2 LATENCY AND TIMING ERROR ANALYSIS FOR CONNECTED INTERSECTIONS

A.2.1 Latency

The Red Light Violation Warning (RLVW) application described in 5.6.1, Red Light Violation Warning (RLVW) Application of CTI 4501 has been a catalyst for discovering new needs and requirements for connected intersections. In a non-connected environment, human drivers and highly automated vehicles depend on the displayed signal indications as the method of communication from the signal system. In a CI environment, however, information flow takes two different pathways to convey signal phase information to the driver. As shown in Figure 15, a Traffic Signal Controller (TSC) generates new signal state information every tenth of second (10 Hz Processing Loop). Pathway #1 illustrates TSC issuing commands over the traffic cabinet system's communications bus to activate the appropriate signal indications. Pathway #2 illustrates TSC transmitting the corresponding SPaT information through an Ethernet connection for processing and transmission (usually performed in a RSU over-the-air to CVs).

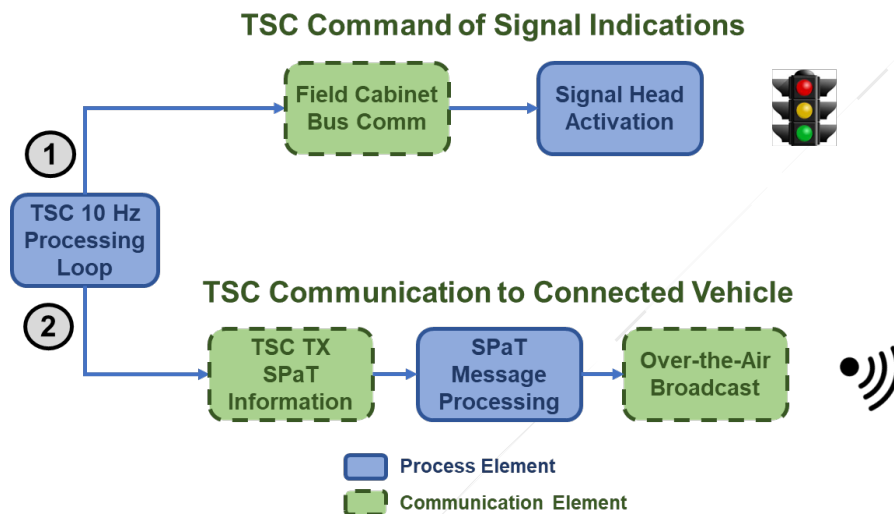


Figure 15 - Flow of roadway information in a connected intersection

The RLVW application in a CV generates advisories, warnings, or alerts based on the received SPaT information and the vehicle dynamics to allow a driver to take appropriate action. To be safe and effective, it is important that the visual indication provided in Pathway #1 and the SPaT information provided in Pathway #2 are congruent in the information generation time interval, the phase activation time, and the duration of the signal state in order to avoid confusion or ambiguity to the driver. Delay in either pathway for providing the information could result in an unsafe driving condition. For instance, a vehicle traveling at 45 mph (72.5 kph) travels 66 feet (20 m) in 1 second.

Latency includes delays due to information processing, including security signing and verification, V2X, and Ethernet interface latency (medium access plus propagation delay) and Cabinet Data Bus Latency:

Pathway #1 Latency = Information Processing Time + Cabinet Data Bus Communications Latency

Pathway #2 Latency = Information Processing Time + V2X and Ethernet Interface Latency

Where:

- Information Processing Time is the delay associated with generating SPaT. For example, the amount of processing time to generate the UPER-encoded SPaT message. This delay also includes security signing and verification. The information processing by the TSC is not included in the estimates because it occurs inside the TSC 10 Hz Processing Loop before the start of the two pathways.

- V2X and Ethernet Interface Latency is the delay associated with communicating the intended information over the communication link using the specified protocol. This delay includes the amount of time waiting for a scheduled transmit opportunity over the Ethernet interface between the TSC and RSU, as well as the over-the-air (OTA) interface between RSU and vehicle.
- Cabinet Data Bus Communications Latency is the delay associated with communicating the intended information over the traffic cabinet system's serial data bus.

These latencies can be calculated for both pathways shown in Figure 15. Tables 14 and 15 list estimated maximum latencies for Pathway #1 from the TSC to signal activation. They are provided for discussion, testing, and agreement with stakeholders. In the case of the Field Cabinet Bus Communications, there is a range of 100 to 220 ms. For purposes of this discussion, 220 ms will be used.

Table 14 - Example maximum latency for Pathway #1 from the TSC to signal activation using the minimum field cabinet communications delay

Description	Time (milliseconds)
Field Cabinet Bus Communications	
<ul style="list-style-type: none"> • High-Level Data Link Control (HDLC) using Serial Interface Units (SIUs) - or - • Synchronous Data Link Control (SDLC) using Bus Interface Units (BIUs) 	100
Signal Head Activation	
<ul style="list-style-type: none"> • Time to turn on the signal light (includes time taken by switch packs) 	30
Total	130

Table 15 - Example maximum latency for Pathway #1 from the TSC to signal activation using the maximum field cabinet communications delay

Description	Time (milliseconds)
Field Cabinet Bus Communications	
<ul style="list-style-type: none"> • High-Level Data Link Control (HDLC) using Serial Interface Units (SIUs) - or - • Synchronous Data Link Control (SDLC) using Bus Interface Units (BIUs) 	220
Signal Head Activation	
<ul style="list-style-type: none"> • Time to turn on the signal light (includes time taken by switch packs) 	30
Total	250

Tables 16 and 17 list estimated maximum latencies for Pathway #2 from the TSC to the OTA broadcast of the SPaT message. Per SAE J3161 and SAE J3161/1, the LTE-V2X packet delay budget (PDB) setting for SPaT is 100 ms, which results in a maximum channel access delay of 90 ms. However, the actual maximum channel access delay is dependent on the channel busy ratio (CBR) during operation. When the channel is less than 10% loaded ($CBR < .1$), maximum channel access delay is reduced to 20 ms, and when the channel is between 10 and 75% loaded ($.1 < CBR < .75$), it is reduced to 50 ms. Only when the channel is more than 75% loaded ($CBR > .75$) will the maximum channel access delay be 90 ms. They are provided for discussion, testing, and agreement with stakeholders.

Table 16 - Example maximum latency for Pathway #2 from the TSC to the OTA broadcast of the SPaT message using the minimum RSU over-the-air message broadcast delay

Description	Time (milliseconds)
TSC Transmission of SPaT Information to RSU	
<ul style="list-style-type: none"> Maximum delay to send the SPaT information corresponding to setting the signal states 	25
<ul style="list-style-type: none"> Ethernet communication of NTCIP/TSCBM SPaT information 	10
SPaT Message Processing	
<ul style="list-style-type: none"> Generate UPER encoded SPaT message per SAE J2735 	50
RSU Over-the-Air Message Broadcast	
<ul style="list-style-type: none"> Maximum channel access delay 	20
Total	105

Table 17 - Example maximum latency for Pathway #2 from the TSC to the OTA broadcast of the SPaT message using the maximum RSU over-the-air message broadcast delay

Description	Time (milliseconds)
TSC Transmission of SPaT Information to RSU	
<ul style="list-style-type: none"> Maximum delay to send the SPaT information corresponding to setting the signal states 	25
<ul style="list-style-type: none"> Ethernet communication of NTCIP/TSCBM SPaT information 	10
SPaT Message Processing	
<ul style="list-style-type: none"> Generate UPER encoded SPaT message per SAE J2735 	50
RSU Over-the-Air Message Broadcast	
<ul style="list-style-type: none"> Maximum channel access delay 	90
Total	175

Since it is the desire for the latency of the two pathways to be the same, then an allowable latency difference (ALD) between the two pathways needs to be established. It is likely that each application on the CV that uses CI information may have a different ALD for which it can be effective. For the RLVW application, it has been proposed that the ALD is 200 ms. The ALD is not a norm, and it is assumed that the systems are able to maintain the 100 ms SPaT message interval. Computing the maximum latency estimates from Tables 14, 15, 16, and 17, the expected latency difference will be the absolute value of the difference in latencies of Pathway #1 and Pathway #2 as shown in Table 18.

Table 18 - Expected latency difference for each combination of communication delay

Expected Latency Differences
130 ms - 105 ms = 25 ms
250 ms - 105 ms = 145 ms
130 ms - 175 ms = 45 ms
250 ms - 175 ms = 75 ms

In all cases, the expected latency difference is below the 200 ms ALD.

The values in Tables 14 through 17 are estimates and should be validated through testing, then adjusted accordingly. In this analysis, it is assumed that the TSC begins both pathways nearly simultaneously inside the TSC. If testing identifies a significant time difference in starting the two pathways, then an additional latency could be added to the calculations.

Recommendations are as follows:

- a. The latencies in Tables 14 through 17 should be tested to validate the estimates.
- b. It is essential that all of the subsystems maintain UTC time. It is recommended that the real-time clock of the TSC be maintained by using Network Time Protocol (NTP) and with the RSU as the NTP server. The Advanced Transportation Controller (ATC) Standard already requires NTP on ATC units and CTI 4001 is being updated to require that RSUs be able to act as NTP servers.
- c. ITS standards for traffic cabinet systems need to be updated to tighten tolerances and reduce latency variability for both Pathway #1 and Pathway #2.
- d. The ATC Application Programming Interface (API) Standard and the open-source software API Reference Implementation (APIRI) should be updated to perform the transmission of the SPaT information to the RSU. API software runs on ATC units and already handles communications on the traffic cabinet communication bus. Using this "middleware to also perform the SPaT message transmission would provide more control between the two paths, and the software could potentially compensate for larger variances in latencies occurring between the two pathways. This recommendation came from the TSC manufacturers to reduce latency and have more consistent operation across manufacturers.
- e. Since the first ATC standard was approved in 2006, a minimum ATC standard should be identified in order to help identify traffic signal controllers that may need full replacement or possibly an ATC Engine Board replaced.

A.2.2 Timing Error

In addition to latency, the accuracy of the TSC's or the RSU's UTC estimate used to time stamp the SPaT data may introduce additional performance challenges that relate to latency. One source of time stamp error is the difference between UTC and the TSC's estimate of UTC. The error in this estimate may be exacerbated by TSC processing delays, so the overall communication range and the length of the assured green period may need to be further optimized to compensate for timing error. Future revisions of this document may provide more guidance on how to compensate for errors in UTC estimates.

ANNEX B - SECURITY PROFILES [NORMATIVE]

This annex shows the IEEE Std 1609.2 security profiles and related material for a SPaT message and BSM message.

An implementation, such as an RSU, may have a separate security certificate for each security profile, i.e., have separate security certificate for each message, or may have a security certificate that contains a security profile for more than one V2X message or V2X application.

B.1 SECURITY PROFILE FOR SPAT MESSAGES

This section addresses the following topics:

- Identification of application message constraints and usage of application-sensitive SAE J2735 SPaT message fields
- IEEE Std 1609.2 certificate Service Specific Permissions (SSP) required to permit sensitive application activities
- IEEE Std 1609.2 security profile for message sending, receiving and security management

B.1.1 Summary

A security summary of the application is provided in Table 19.

Table 19 - SPaT application security summary

V2I Application / Message	SPaT
PSID	0x82
Certificate Type	IEEE Std 1609.2 Certificate
Message Signer	RSU
Message Sender	RSU
Message Receiver	OBU
Entity Activities Requiring Authorization	Entity activities requiring SSP-based authorization within this application message are: <ul style="list-style-type: none"> – Communicate speed advisories (if they are regulatory-authorized) – State conformance with RLVW performance requirements

B.1.2 SPaT PDU Field Use and Convention

This section imposes additional rules, definitions, and constraints on the SPaT message PDU defined in SAE J2735.

Communication of Advisory Speeds in the PDU

The SPaT message allows for communication of intersection state information, with an option for advisory speeds in the field *SPaT.intersections.states.state-time-speeds.speeds*.

If advisory speed information is included via inclusion of the field *SPaT.intersections.states.state-time-speeds.speeds*, then there is an assumption that the RSU is able to provide static or dynamic advisory speeds based on intersection sensor inputs and/or configuration.

Inclusion of a speed advisory implies the IOO is allowed and able to provide speed advisories and that intersection sensors, RSU, and traffic signal controller have been carefully installed, configured, and tested prior to being used to convey the intersection state information. Advice for speeds too high can negatively impact safety; too low can impede efficient mobility. Additionally, a compromised or stolen RSU can cause greater impact if it is allowed to convey speed advisories than if it is not.

Indication that the SPaT Sender is Verified as Able to be in Conformance with the Requirements for RLVW

An intersection that sends SPaTs may be in one of three states:

- Operated by an operator who is capable of validating that the intersection meets the requirements to send messages suitable for RLVW and currently meeting those requirements.
- Operated by an operator who is capable of validating that the intersection meets the requirements to send messages suitable for RLVW and not currently meeting those requirements.
- Operated by an operator who does not intend (or does not have the capability) to send messages suitable for RLVW and so not meeting those requirements.

If an intersection that is not qualified for RLVW use sends SPaTs that could be read as indicating that an RLVW is about to occur, it could cause receiving vehicles to take incorrect actions such as raising an incorrect alert to the driver, annoying the driver, and possibly causing them to disregard future messages. Therefore, it is important to distinguish between intersections that are capable of meeting the RLVW requirements and intersections that are not.

B.1.3 Security Specific Permissions [Normative]

This section defines the Service Specific Permissions (SSP) for the SPaT application.

SSP Format

This section provides the Service Specific Permissions (SSP) format for the SPaT application.

SSP type: IEEE Std 1609.2-2022 BitmapSsp

SSP length: 2-Octets

Bit Order: Most Significant Bit (MSB) is transmitted first

Encoding: Canonical Octet Encoding Rules (COER)

Table 20 indicates the SPaT SSP octet scheme.

Table 20 - SPaT SSP octet scheme

Octet(s)	Definition
0	SSP Version Current value: Binary 0 (0000 0001): This version - Version 1
1	See Table 19.
6-30	Reserved for future use. Absent in current use.

Table 21 indicates the SSP authorizations for the SPaT application message:

Table 21 - SPaT service-specific permissions

Octet	Bit	Application Activity Authorizations	Value
1	0	<i>SPaT.intersections.states.speeds</i> has one or more entries for speed advisories from a regulatory source.	0: Certificate may not sign 1: Certificate may sign
1	1	Intersection operator is authorized to set the Conformance With 2025 RLVW Requirements ⁽¹⁾ bit	0: Certificate may not sign 1: Certificate may sign
1	2-7	Reserved	0

⁽¹⁾ Proposed. The Conformance with 2025 RLVW bit assumes that this bit is added to DE_IntersectionStatusObject.

SSP Usage

This section provides conventions for utilizing the SPaT application message.

Sending SPaT messages

The SPaT message sender shall sign the PDU with an IEEE Std 1609.2 certificate indicating the signer is authorized to send a SPaT PDU, i.e., certificate contains the SPaT PSID.

The SPaT PSID shall be accompanied by an SSP. Octet 0 shall be (in binary) 0000 0001 (version 1, the version of this SSP).

If the SPaT PDU also includes any advisory speed information for the intersection state, the signer shall sign the SPaT with a certificate whose SSP Octet 1, Bit 0 is set to 1 for the SSP associated with the SPaT PSID.

If the SPaT PDU includes the Conformant With 2025 RLVW Requirements (see Table 21) bit, the signer shall sign the SPaT with a certificate whose SSP Octet 1, Bit 1 is set to 1 for the SSP associated with the SPaT PSID.

Validating SPaT messages

Upon receiving the SPaT message, the message receiver [OBU] carries out IEEE Std 1609.2 validation. This includes checking that the signing certificate contains a SPaT PSID.

If the SSP associated with the SPaT PSID is present, the message is invalid unless the SSP version is 1 (Octet 0 of the SSP is, in binary, 0000 0001).

If advisory speed is included, the message is invalid unless the SSP Octet 1, Bit 0 is set to '1.'

If the Conformant With 2025 RLVW Requirements (see Table 21) bit is set in the SPaT, the message is invalid unless the SSP Octet 1, Bit 0 is set to '1.'

B.1.4 IEEE Std 1609.2 Security Profile Identification [Normative]

Table 22 provides the identification features for the SPaT application security profile.

Table 22 - SPaT application security profile identification

Name	Recommended Values	Description
<i>Security Profile Version</i>	IEEE Std 1609.2-2025	
<i>Name</i>	"SPaT Security Profile_SAE_V1"	
<i>PSIDs</i>	0x82 (uncompressed)	
<i>Information Flows</i>	The application contains only one V2X information flow, and this security profile addresses that flow.	
<i>SDEE Role</i>	Only one role: SPaT sender	
<i>Other considerations</i>	None	

B.1.5 Sending

Table 23 provides the security profile for message sending within the SPaT PSID.

Table 23 - SPaT application security profile for sending messages

Name	Recommended Values	Notes
<i>Sign Data</i>	TRUE	The information flow requires integrity and authorization.
<i>Signed Data Payload Types</i>	“Encapsulated Data”	Including the signed data in the payload makes processing easier and does not add overhead.
<i>HeaderInfo: Include Generation Time</i>	FALSE	dDateTime is used in the payload and provides a time stamp that is rollover-resistant, so there is no need to include the generation time in the security headers.
<i>HeaderInfo: Include Generation Location</i>	FALSE	Generation location is indicated in the payload.
<i>Geographic Information Type</i>	Area or point	SPaT may describe one intersection, identified by its reference point, or multiple intersections.
<i>Geographic Information Source</i>	See notes	Location comes from the associated MAP.
<i>HeaderInfo: Include Expiry</i>	FALSE	No need to set an expiry time in the security headers.
<i>HeaderInfo:Lifetime for Expiry</i>	N/A	
<i>Signer Identifier Types</i>	“Certificate / digest”	SPDUs are to be signed with a certificate, not with a raw public key.
<i>Signer Identifier: Inter CertTime</i>	0.475 second	This value is a reasonable setting for a certificate reattachment interval as it accommodates both rapidly and slowly changing PDU content.
<i>Signer Identifier: Additional</i>	See Notes	The certificate is to be attached to the first message signed after every certificate change, even if this is closer in time to the last certificate attachment than 0.5 second. (Certificate change is infrequent but happens when a fresh certificate replaces an expiring certificate.)
<i>Sign With Fast Verification</i>	Compressed	This is the convention for SAE applications.
<i>EC Point Format</i>	Compressed	This is the convention for SAE applications.
<i>Encrypt Data</i>	No	
<i>PDU Functional Types</i>	Application PDU	
<i>Carrying SDEE for Asserted Data</i>	FALSE	No asserted data in message.
<i>Repeat Signed SPDUs</i>	FALSE	Each message sent is freshly generated and signed.
<i>Time Between Signing</i>	N/A	
<i>Send Operating Organization ID</i>	In certificate only	Intersection identifier is a combination of Operating Organization ID in certificate plus <DE_RelativeRoadAuthorityID> (optionally) plus <DE_IntersectionID> (required) from the payload.
<i>Signer Identifier: Certificates to Attach</i>	1	Attach one certificate only, that of the signer
<i>p2pcd_flavor</i>	Out of band	Convention for SAE applications - refer to SAE J2945/1 and SAE J3161/1
<i>p2pcd_maxResponseBackoff</i>	.25 second	Convention for SAE applications - refer to SAE J2945/1 and SAE J3161/1
<i>p2pcd_responseActiveTimeout</i>	.25 second	Convention for SAE applications - refer to SAE J2945/1 and SAE J3161/1
<i>p2pcd_requestActiveTimeout</i>	.25 second	Convention for SAE applications - refer to SAE J2945/1 and SAE J3161/1
<i>p2pcd_observedRequestTimeout</i>	.25 second	Convention for SAE applications - refer to SAE J2945/1 and SAE J3161/1
<i>p2pcd_currentlyUsed-TriggerCertificateTime</i>	1 minute	Convention for SAE applications - refer to SAE J2945/1 and SAE J3161/1
<i>p2pcd_responseCountThreshold</i>	3	Convention for SAE applications - refer to SAE J2945/1 and SAE J3161/1

B.1.6 Receiving

Table 24 provides the message reception security features for the SPaT application security profile.

Table 14 - SPaT application security profile for receiving messages

Name	Recommended Values	Notes
<i>Use Preprocessing</i>	TRUE	Needed for any information flow that receives signed SPDUs.
<i>Verify Data</i>	TRUE	The information flow requires integrity and authorization.
<i>Source of PSID from Context</i>	WSMP headers	WSMP header PSID must be consistent with PSID in the 1609.2 HeaderInfo.
<i>Generation Time Source</i>	Payload	dDateTime is used in the payload, so there is no need to obtain the generation time from the security headers.
<i>Expiry Time Source</i>	N/A	
<i>Relevance: Replay</i>	FALSE	The receiver is assumed to be able to handle freshness checks and repeat messages.
<i>Relevance: Generation Time in Past</i>	FALSE	The receiver is assumed to be able to handle freshness checks.
<i>Relevance: Generation Time in Past: Tolerance</i>	N/A	
<i>Relevance: Generation Time in Future</i>	FALSE	
<i>Relevance: Generation Time in Future: Tolerance</i>	N/A	
<i>Relevance: Expiry Time</i>	FALSE	No need to set expiry time in the security headers.
<i>Relevance: Location</i>	FALSE	
<i>Relevance: Location: Tolerance</i>	N/A	
<i>Identified Region Representation Accuracy</i>	10 m	Convention for SAE applications
<i>Dubious Certificate Handling</i>	Overdue CRL Tolerance	Convention
<i>Overdue CRL Tolerance</i>	30 days	Recommended default value
<i>Relevance: Certificate Expiry</i>	TRUE	The IEEE Std 1609.2 security services will check if the signing certificate has expired as a condition of the validity of the message.
<i>Consistency between Future Payload Data and Certificate</i>	No check	Assume the content is not with respect to a future time period for which certificate validity needs to be checked.
<i>Accept Encrypted Data</i>	NO	Information flow is in plaintext.
<i>Additional Geographic Consistency Conditions</i>	None	
<i>Consistency: Operating Organization ID</i>	FALSE	SPaT payload does not contain an OperatingOrganizationId and so there is no consistency check.

B.1.7 Security Management

Table 25 provides the security management features for the SPaT application security profile.

Table 25 - SPaT application security management security profile

Name	Recommended Values	Notes
<i>Signing Key Algorithm</i>	ecdsaNistP256withSha256	Convention for SAE applications.
<i>Encryption Algorithm</i>	N/A	Information flow is in plaintext.
<i>Implicit or Explicit Certificates</i>	IMPLICIT	Convention for SAE applications.
<i>EC Point Format: Certificates</i>	COMPRESSED	Compressed elliptic curve point formatting reduces total message size.
<i>Non-global Geographic Validity in Certificate</i>	Optional	Certificates may contain specific geographic validity region but are not required to.
<i>Supported Geographic Region Types</i>	"All"	Convention for SAE applications.
<i>Maximum Full Certificate Chain - Length</i>	4	
<i>CertificateID Type</i>	"Name" or "Binary ID"	
<i>Use Individual Linkage ID</i>	No	Certificates are individually revoked.
<i>Use Group Linkage ID</i>	No	
<i>Additional CertificateID Constraints</i>	None	
<i>Signature Algorithms In Chain or CRL</i>	ecdsaNistP256withSha256	Convention for SAE applications.

ANNEX C - SPaT GUIDANCE

The following table is a summary of the expected contents in a SPaT message based on the Mode of Operation for a TSC.

Mode of Operations	Description	Intersection Status Object	Time Change Details						
			Current Movement State			Next Movement State			
			Movement Phase State	minEndTime	maxEndTime	Movement Phase State	minEndTime	maxEndTime	
Manual Control	When the controller receives an MCE or Manual Advance input, the SPaT generation shall be updated accordingly to be consistent with the current set of possible dwell/advance options. The TimeChangeDetails shall be adjusted accordingly. While in this mode, the TSC is controlled by an external source and does not know the duration of green intervals. The duration of all clearance intervals is known.	Bit 0 Enabled (see 7.3.3.3.2.1)	Defined by phase sequence	Undefined	Undefined	Undefined	Defined by next interval in phase	Undefined	Undefined

Mode of Operations	Description	Intersection Status Object	Time Change Details					
			Current Movement State			Next Movement State		
			Movement Phase State	minEndTime	maxEndTime	Movement Phase State	minEndTime	maxEndTime
Stop Time Control	When the controller receives a stop time input, the active controller state on the affected (stopped/frozen) ring shall remain as the basis for SPaT generation. Since stop time duration is unknown, the confidence factor will be adjusted; however, the SPaT output will remain consistent to the time remaining for each current phase timers at the stop time command was issues. Once the stop time command is removed from the controller, the timers will resume and continue to count down the time remaining for each signal indication. If this form of stop time input allows continuation of countdown timers for clearance intervals or other timers, SPaT shall be adjusted accordingly.	Bit 1 Enabled (see 7.3.3.3.2.2)	Defined by current phase movement state	Initial endtime values based on time remaining in interval at the time when the stop time command was issued to the controller. Endtime values increase by 0.1 second each time step when the stop time command to the controller is active. Endtime values become constant values based on time remaining in each phase after stop time is removed.		Defined by next interval in phase	Initial endtime values based on time remaining in interval at the time when the stop time command was issued to the controller. Endtime values increase increments by 0.1 second each time step when stop time command to controller is active. Endtime values become constant values based on the time remaining in each phase after the stop time is removed.	
Cabinet (Exception) Flash	Any type of flash that is initiated and terminated by sources external to the controller. This includes "Monitor (mmu) Flash" and "Local Flash."	Bit 2 Enabled (see 7.3.3.3.2.3)	Based on programmed flash pattern used by IOO	Undefined	Undefined	Undefined	Undefined	Undefined

Mode of Operations	Description	Intersection Status Object	Time Change Details					
			Current Movement State			Next Movement State		
			Movement Phase State	minEndTime	maxEndTime	Movement Phase State	minEndTime	maxEndTime
(Section 4.3.3.3.2.3 calls this ""Failure Flash"")	<i>Fault Monitoring</i> - Fault Monitor Flash occurs when the controller detects an anomaly in the TSC Infrastructure, such as a mismatch between its copy of the permissive channels and the monitor's copy of the permissive channels. The way the controller causes Fault Monitor Flash differs by cabinet architecture. Fault Monitor Flash is different than Fault Flash, which is initiated by the monitor. When a Fault Flash occurs, the intersection will remain in flash until the intersection has been reset by a technician. To exit Fault Monitor Flash, the controller can automatically return to service when the anomaly is no longer present.	Bit 2 Enabled (see 7.3.3.3.2.3)	Based on programmed flash pattern used by IOO	Undefined	Undefined	Undefined	Undefined	Undefined
Preemption	Preemption is a special timing mode under which normal control is transferred to a special signal operating mode to serve railroad crossings or to allow passage of emergency, mass transit, or other special vehicles. Preemption requires terminating normal traffic control to provide the service needed for the special task. During preemption, AGP is not available.	Bit 3 Enabled (see 7.3.3.3.2.4)	Varies depending on stage of preemption.					

Mode of Operations	Description	Intersection Status Object	Time Change Details					
			Current Movement State			Next Movement State		
			Movement Phase State	minEndTime	maxEndTime	Movement Phase State	minEndTime	maxEndTime
	<i>Entry Transition</i> - This stage consists of the operation that the traffic signal performs to terminate the existing movements in a safe manner in preparation to service the preempt request. During this process, the signal controller safely terminates all current phases (including pedestrians) necessary to transfer right-of-way to the desired phase(s). AGP is not applied during preemption. This stage may be skipped if all minimums have been satisfied.	Bit 3 Enabled (see 7.3.3.3.2.4)	Defined by controller	Defined by Controller (all phases)	Defined by Controller (all phases)	Defined by preempt routine	Undefined (conflicting phases) Defined (non-conflicting phases)	Undefined (conflicting phases) Defined (non-conflicting phases)
	<i>Track Clearance Interval</i> - This stage includes the operation that traffic signal performs to clear the traffic in preparation to service the preempt request. During this process, the signal controller services all phases (including pedestrians) necessary to transfer right-of-way to the desired phase(s). AGP is not applied during preemption.	Bit 3 Enabled (see 7.3.3.3.2.4)	Defined by controller	Defined by Controller (all phases)	Defined by Controller (all phases)	Defined by preempt routine	Undefined (conflicting phases) Defined (non-conflicting phases)	Undefined (conflicting phases) Defined (non-conflicting phases)

Mode of Operations	Description	Intersection Status Object	Time Change Details					
			Current Movement State			Next Movement State		
			Movement Phase State	minEndTime	maxEndTime	Movement Phase State	minEndTime	maxEndTime
	<i>Dwell</i> - This stage includes the operation that the traffic signal performs after transferring the right-to-way to the desired movement. The controller will remain in this stage until the preemption request is lifted (or has timed out). Generally, conflicting movements are restricted from moving during this portion of operations; however, some controllers can provide limited service to non-conflicting phases.	Bit 3 Enabled (see 7.3.3.3.2.4)	Stop and Remain (conflicting phases) Defined by Controller (non-conflicting phases)	Undefined (conflicting phases) Defined by Controller (non-conflicting phases)	Undefined (conflicting phases) Defined by Controller (non-conflicting phases)	Undefined (conflicting phases) Defined by Controller (non-conflicting phases)	Undefined (conflicting phases) Defined by Controller (non-conflicting phases)	Undefined (conflicting phases) Defined by Controller (non-conflicting phases)
	<i>Recovery (or Exit)</i> - This stage includes that portion of operations after the preempt command has been lifted and the traffic signal controller returns to normal operation. A number of strategies are available to support recovery, depending on the controller manufacturer. In most cases, the controller manages phase durations to transition the intersection into normal operations.	Bit 3 Enabled (see 7.3.3.3.2.4)	Defined by Controller	Defined by Controller (all phases)	Defined by Controller (all phases)	Defined by Controller	Defined by Controller (all phases)	Defined by Controller (all phases)

Mode of Operations	Description	Intersection Status Object	Time Change Details					
			Current Movement State			Next Movement State		
			Movement Phase State	minEndTime	maxEndTime	Movement Phase State	minEndTime	maxEndTime
	<i>Preempt Flash</i> - Some agencies may elect to flash their traffic signals at signalized intersection, particularly those at highway rail grade crossings. Typically, the conflicting movements would be flashed red while no non-conflicting movements might receive a yellow flash. As the duration of the preempt operation is unknown, the duration of the flashing operation is also unknown. There will be a period of recovery in which the traffic signal will transition from flash back to normal operations. Phase durations may not be known during this transition phase.	Bit 3 Enabled (see 7.3.3.3.2.4)	Based on programmed flash pattern used by IOO	NTCIP 1202: preemptDwellGreen	NTCIP 1202: preemptMaximumPresence	Defined by preempt recovery	Defined by Demand (all phases)	Defined by Demand (all phases)
Priority	A mode of signal operations for providing preferential treatment to specific vehicle class (such as transit vehicles, emergency service vehicles, or commercial fleet vehicles) over another vehicle class at a signalized intersection without causing the traffic signal controller to drop from coordinated operations.	Bit 4 Enabled (see 7.3.3.3.2.5)	Defined by Controller	Defined by Controller (all phases)	Defined by Controller (all phases)	Defined by Controller	Defined by Controller (all phases)	Defined by Controller (all phases)
Fixed Time	<i>General</i> - This is an operation where all the phases are active in the same sequence and duration each cycle, regardless of demand. The TSC does not use the detection system to determine call for service at the intersection	Bit 5 Enabled (see 7.3.3.3.2.6)	Defined by Controller based of phase sequence	Set to maximum phase duration	Defined by Controller (all phases)	Defined by Controller	Defined by Controller (all phases)	Defined by Controller (all phases)

Mode of Operations	Description	Intersection Status Object	Time Change Details					
			Current Movement State			Next Movement State		
			Movement Phase State	minEndTime	maxEndTime	Movement Phase State	minEndTime	maxEndTime
	<i>Rest in Walk</i> - A scenario when a TSC that is operating in Fixed Time is programmed to extend the phase's "Walk" interval beyond its default walk time by a known amount of time so that the phase's pedestrian clearance interval will end at the time the phase is terminated. This operation occurs when the Walk Time Modifier is enabled for a non-actuated phase. (See NEMA TS2)	Bit 5 Enabled (see 7.3.3.3.2.6)	Defined by Controller based of phase sequence	Corresponding non-actuated vehicle phase: determined by programmed max times. Pedestrian movements: Vehicle max time - pedestrian clearance interval	Corresponding non-actuated vehicle phase: determined by programmed max times. Pedestrian movements: Vehicle max time - pedestrian clearance interval	Defined by Controller	Defined by Controller (all phases)	Defined by Controller (all phases)
	<i>Automatic Flash</i> - This flashing operation is commanded by NTCIP Pattern 255. Some IOOs use this operation during off-peak or late-night conditions. This pattern may be implemented manually or on a schedule. If implemented manually, end times are undefined. If implemented by scheduler, endtimes are defined.	Bit 5 Enabled (see 7.3.3.3.2.6)	Based on programmed flash pattern used by IOO	Undefined (manual entry) Defined by Scheduler (TOD entry) - If status changes in hour, indicate number of seconds to change; otherwise, use "undefined"	Undefined (manual entry) Defined by Scheduler (TOD entry) - If status changes in hour, indicated number of seconds to change; otherwise, use "undefined"	Defined by start-up sequence in controller	Defined by Demand (all phases)	Defined by Demand (all phases)
Traffic Dependent	<i>General</i> - This is an operation where the sequence and duration of one or more phases at an intersection are based on demand. Demand for service is determined through calls by the detection system.	Bit 6 Enabled (see 7.3.3.3.2.7)	Defined by Controller	Defined by Controller (all phases)	Defined by Controller (all phases)	Defined by Controller	Defined by Controller (all phases)	Defined by Controller (all phases)
	<i>Rest in Green</i> - A scenario when the main street is resting in green until a call is received on a conflicting movement or the maximum green is reached.	Bit 6 Enabled (see 7.3.3.3.2.7)	Defined by Controller	Defined by the Controller but not less than 0.1 second unless a call is received or the maxEndTime is reached.	Defined by Controller (all phases)	Defined by Controller	Defined by Controller (all phases)	Defined by Controller (all phases)

Mode of Operations	Description	Intersection Status Object	Time Change Details					
			Current Movement State			Next Movement State		
			Movement Phase State	minEndTime	maxEndTime	Movement Phase State	minEndTime	maxEndTime
	<i>Rest in Walk</i> - A scenario when the main street is resting with concurrent pedestrian indications after completing the initial "Walk" phase. Upon receiving a call for a conflicting movement, the TSC will initiate a pedestrian clearance interval before terminating the phase. During the resting portion of the operation, the minEndTime and maxEndTime for all phases are unknown; however, once a call is received, the TSC minEndTime and maxEndTimes are set based on the pedestrian clearance intervals.	Bit 6 Enabled (see 7.3.3.3.2.7)	Defined by Controller	Defined by the Controller but not less than 0.1 second unless a call is received or the maxEndTime is reached.	Defined by Controller (all phases)	Defined by Controller	Defined by Controller (all phases)	Defined by Controller (all phases)
	<i>Rest in Red</i> - A scenario when all phases are resting in red until a call is received on a conflicting movement or the maximum green is reached.	Bit 6 Enabled (see 7.3.3.3.2.7)	Defined by Controller	Defined by the Controller but not less than 0.1 second unless a call is received or the maxEndTime is reached.	Defined by Controller (all phases)	Defined by Controller	Defined by Controller (all phases)	Defined by Controller (all phases)
	<i>Semi-actuated/Actuated Coordinated</i> - A scenario in which cross-street or turning movement phases are actuated, and any unused green time is added to the main-street phases.	Bit 6 Enabled (see 7.3.3.3.2.7)	Defined by Controller	Defined by the Controller but not less than 0.1 second unless a call is received or the maxEndTime is reached.	Defined by Controller (all phases) but maxEndTime is unknown when the main street is green until a call is received.	Defined by Controller	Defined by Controller (all phases)	Defined by Controller (all phases)
Standby Mode	<i>Startup Flash</i> - A transitory interval timed immediately after the monitor transfers control to the controller. The duration is controlled by NTCIP Object unitStartupFlash.	Bit 7 Enabled (see 7.3.3.3.2.8)	Based on programmed flash pattern used by IOO	NTCIP 1202: unitStartupFlash	NTCIP 1202: unitStartupFlash	Based on programmed flash pattern used by IOO	Defined by Demand (all phases)	Defined by Demand (all phases)

ANNEX D - LOGICAL PROCESSES IN A CONNECTED INTERSECTION

This annex describes the proposed communications interfaces between a TSC and an RSU in a V2X environment to support a RLVW application. This annex only focuses on the flows/communications interface to support the RLVW application. This annex does not consider other processes that may exist for the RSU to broadcast MAP messages or any other messages, except to consider if a broadcasted SPaT message is consistent with the MAP message (e.g., the signal group identifiers are properly assigned in both messages).

The motivation for this annex is to provide guidance on how to design and implement an interoperable V2X environment, as described in USDOT National V2X Deployment Plan. At the time this annex was produced, updates of the relevant standards and recommended practices were in development. If consensus can be reached among the stakeholders on the guidance, the proposed contents and recommendations will be reflected and supported in a consistent manner within those appropriate documents.

This annex is organized as follows.

- a. Background.
- b. Logical Architecture. Describes a logical architecture for the exchange of information among the RSU, TSC, and an external device to support the RLVW applications.
- c. RLVW Applications - Generating SPaT Messages. Contains requirements to provide SPaT information from the TSC to the RSU to support RLVW applications.
- d. RLVW Applications - Basic Safety Messages for AGP. Contains requirements to provide information in BSMs from the RSU to the TSC to support RLVW applications.

D.1 BACKGROUND

One of the key V2X applications that is expected to result in significant safety benefits is the RLVW application at signalized intersections. As depicted in this document, the information exchanged between the TSC infrastructure and the RSU consists of SPaT information from the TSC to the RSU and potentially information from Basic Safety Messages (BSMs) received by the RSU and forwarded to the TSC to support Assured Green Period (AGP). There may be an external device between the TSC and RSU. See Figure 16.

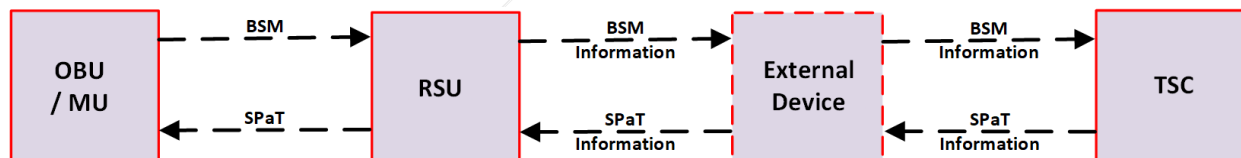


Figure 16 - Physical architecture - RLVW application

This annex provides guidance on what requirements, design, and/or standards should be used across the interface between the TSC and RSU, with a potential physical device in between.

Subsection 6.3.2, TSC Infrastructure to RSU Requirements describes the communications interface between the TSC and RSU so a RSU can broadcast a SPaT message.

Subsection 6.3.3, Message Requirements describes the communications interface between the RSU and TSC so a TSC can use the information in a BSM (or Personal Safety Message [PSM]) message.

D.2 LOGICAL ARCHITECTURE

This section describes a logical architecture for the exchange of information among the RSU, TSC, and an external device to support the RLVW applications. Other V2X applications may also be supported by the logical architecture. This logical architecture defines the functions to be performed to support these applications, and the data flows between the various components in the physical architecture depicted in Figure 16.

D.2.1 Components

As noted earlier, this annex addresses the communications interfaces among a TSC, an RSU, and possibly an external device between the TSC and RSU to support RLVW applications. The logical architecture presented provides an understanding of the functions to be performed and the data exchanges that must exist to support this V2X application.

The high-level functions (or processes) of the logical architecture are presented in Figure 17.

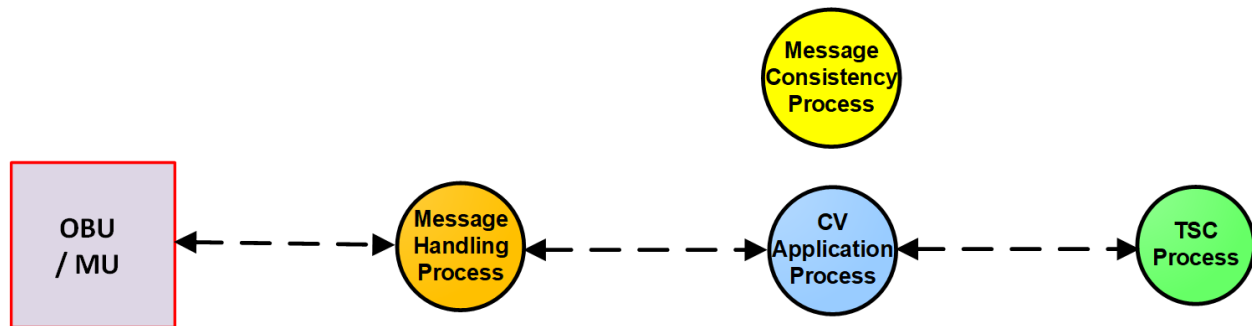


Figure 17 - Logical architecture

The functions for each process are defined below.

D.2.1.1 Message Handling Process

The primary functions of the Message Handling Process are:

1. Signs messages to be broadcasted via a wireless radio to connected vehicles and travelers (OBU/MU).
2. Broadcasts signed messages via the wireless radio to connected vehicles and travelers (OBU/MU).
3. Receives messages and authenticates messages received from connected vehicles and travelers (OBU/MU) via the wireless radio. The Process authenticates each received message by inspecting the IEEE Std 1609.2 certificates that are included with each message. If the Process verifies that the IEEE Std 1609.2 certificate is authenticated (properly formatted and not on a revocation list), it may process or forward the message. If the Process cannot authenticate the IEEE Std 1609.2 certificate, it will discard the message.
4. Forwards authenticated messages received via the wireless radio.
5. Allows a system to monitor and manage the wireless radio.

The functions of the Message Handling Process are normally physically located in (and performed by) an RSU. The Message Handling Process consists of sub-processes to manage broadcasting and receiving over-the-air (wireless) messages in a V2X environment.

The Message Handling Process may also perform other functions, such as send and manage security certificates, signing messages that are broadcasted, and authenticate received messages. These functions are addressed in NTCIP 1218.

NOTE: The Network Interface and Wireless Interface in NTCIP 1218 is part of the Message Handling Process.

D.2.1.2 TSC Process

The primary functions of the Traffic Signal Controller (TSC) Process are:

1. Controls traffic operations at a signalized intersection to allow different conflicting movements to travel across a roadway in a safe, orderly manner.
2. Provides signal phase and timing information and signal operations status.
3. Uses inputs from other sources to measure demand for specific movements, including inputs from specialized travelers, such as responding public safety vehicles.
4. Allows a system to monitor and manage the TSC.

The functions of the TSC Process are normally physically located in (and performed by) a TSC. The TSC Process consists of the functions that provide control of a signalized intersection, possibly using inputs that indicate the traffic demand around the intersection. The source of those inputs may be detection subsystems located within or connected to the same traffic cabinet as the TSC or the CV Application Process. The TSC Process allows a management station, such as a traffic management system, to monitor and manage the traffic signal controller and generates signal phase and timing information that is shared with the CV Application Process.

D.2.1.3 CV Application Process

The primary functions of the Connected Vehicle (CV) Applications Process are:

1. Generates messages for broadcasting to support one or more V2X applications
2. Processes received messages to support one or more V2X applications

The CV Application Process consists of sub-processes that support the V2X environment. The sub-processes may include receiving and processing signal phase and timing information from the TSC Process to generate the SPaT messages to be broadcasted by the message handling process or processing BSMs and PSMs received from the message handling process. A management station (traffic management system) may also configure a CV Application Process to use BSMs and PSMs as inputs to the TSC Process.

A SPaT message generation process is an example of a CV Application sub-process.

D.2.1.4 Message Consistency Process

The primary function of the Message Consistency Process is to check for consistency between the SPaT and MAP messages to be broadcasted for a signalized intersection. The Message Consistency Process must have access to the contents of both the SPaT and the MAP message for the same intersection. The Message Consistency Process is an optional process. This process may also be integral (i.e., part of) the CV Application Process.

Subsection 6.3.3.4.7, Signal Timing and Roadway Geometry Information Synchronization describes the requirements for SPaT-MAP consistency.

D.2.2 Potential Physical Architectures

This subsection presents several possible physical infrastructure architectures to support the RLVW application.

The data exchanges among the RSU, TSC, and external device, if one exists, are dependent on the relationships among them and what functions (processes) are allocated to what devices. The Message Handling Process is normally allocated to the RSU and the TSC Process is normally allocated to the TSC - the physical device where the CV Application Process is allocated to is the main factor that defines how the RLVW application is supported. The location of the optional Message Consistency Process is discussed later.

There are three physical architectures where the CV Application Process is likely to reside.

D.2.2.1 Physical Architecture 1

In Physical Architecture 1, the CV Application Process resides in the TSC, i.e., the functions of the CV Application Process are performed by the TSC (see Figure 18). For Physical Architecture 1, it is assumed that the TSC has sufficient processing power to perform the CV Application Process.

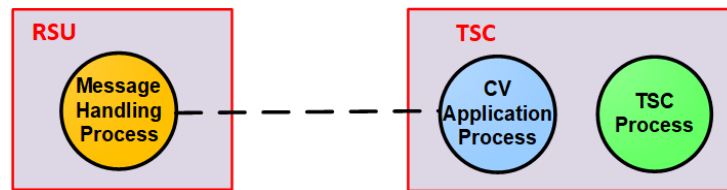


Figure 18 - Physical Architecture 1

Some potential advantages of the CV Application Process residing in the TSC include:

- The TSC can process the raw BSMs and PSMs for only information it needs and not have to rely on another device to process the information.
- Lowers the risk of misinterpretation or incorrect translation of information by other devices - i.e., the TSC generates the actual data for the SPaT message or uses the raw data in the received messages (e.g., BSM, PSM).
- An agency can easily acquire TSCs (e.g., a city council may not approve the purchase of RSUs, but it will less likely deny the purchase of TSCs).

D.2.2.2 Physical Architecture 2

In Physical Architecture 2, the CV Application Process resides in the RSU - i.e., the functions of the CV Application Process are performed by the RSU (see Figure 19). For Physical Architecture 2, it is assumed that the RSU has sufficient processing power to perform the CV Application Process.

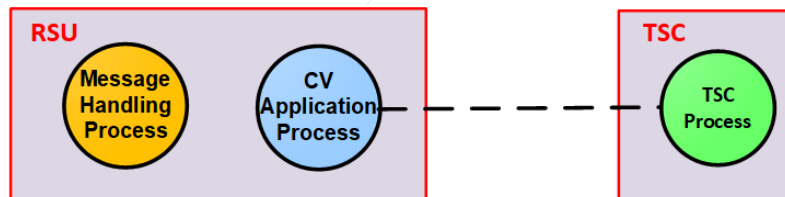


Figure 19 - Physical Architecture 2

The advantages of the CV Application Process residing in the RSU include:

- The RSU may have to set some bits in the DE_IntersectionStatusObject, such as a bit to indicate the controller is off, and sign the message before generating a SPaT message.
- The RSU can confirm the consistency between the SPaT and MAP messages before signing and broadcasting the SPaT and MAP messages.
- The RSU can combine SPaT information from multiple TSCs into a single SPaT message.

D.2.2.3 Physical Architecture 3

With Physical Architecture 3, the CV Application Process resides in an external device that is between the RSU and the ASC (see Figure 20). In this physical architecture, the functions of the CV Application Process are performed in the External Device. It is assumed that the External Device has sufficient processing power to perform the CV Application Process. The External Device could be a separate processor in the same traffic cabinet with the TSC. Examples of an External Device in this context includes the V2X Hub and the MMITSS processor.

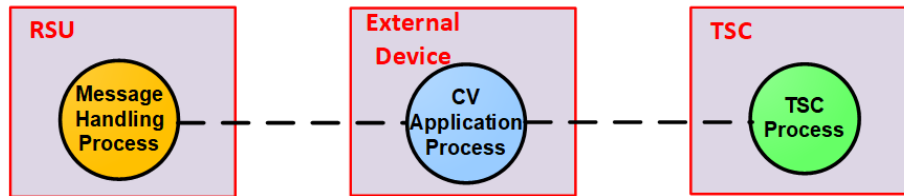


Figure 20 - Physical Architecture 3

The advantages of the CV Application Process residing in the External Device include:

- The External Device has the processing power to store and perform the desired function, so a less powerful RSU and/or TSC (and theoretically less expensive) are needed.
- Allows the agency more control over the application (e.g., the application may be owned and updated by the agency).

D.2.2.4 Alternate Physical Architectures

There are other physical architectures that may be deployed, where the functions of the CV Application Process are shared among an RSU, a TSC, and an External Device. Figure 21 depicts those potential physical architectures.

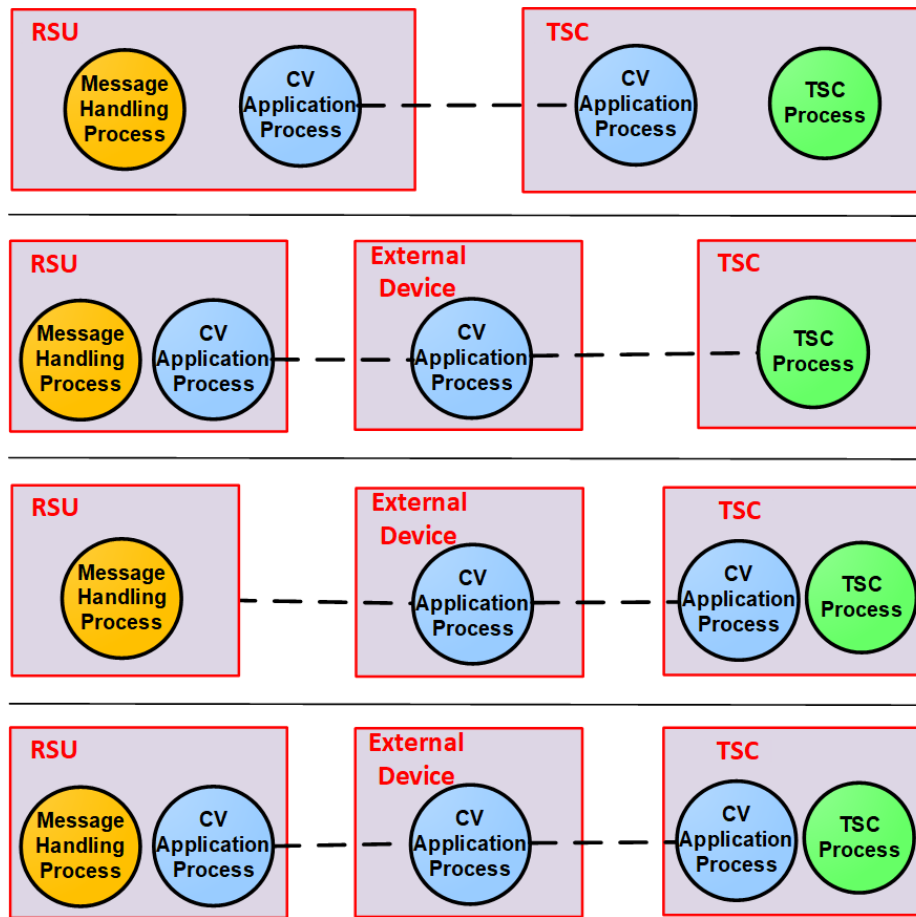


Figure 21 - Alternate physical architecture

The physical architectures depicted in Figure 21 are all valid, but it is the responsibility of the implementer to clearly define which physical device performs which functions of the CV Application Process.

D.3 RLVW APPLICATIONS - GENERATING SPAT MESSAGES

This section defines the requirements to provide SPaT information from the TSC to the RSU to support RLVW applications and defines two acceptable profiles on how signal phase and timing information is sent from the TSC to the RSU in an interoperable manner. This allows the generation of SAE J2735 SPaT messages to be broadcasted by the RSUs to OBUs and mobile devices on travelers to manage traveler movements through intersections.

D.3.1 Summary

Table 26 summarizes the configurations for the different profiles and physical architectures that are described in Annex D.3 to support a RLVW application. The first four columns define where each of the four logical processes are physically located. The SPaT Information Format describes what format the SPaT information is provided to the RSU - either in NTCIP 1202 format or as an SAE J2735 SPaT message (unsigned). Note that when the configuration includes an external device, the external device receives the SPaT information in NTCIP 1202 format, then sends SAE J2735 SPaT messages to the RSU. The Reference column indicates what section describes the configuration.

Table 26 - Potential logical architecture configurations

	Message Handling Process	Message Consistency Process	CV Application Process	TSC Process	SPaT Information Format	Reference
Profile 1 - Implementation 1	In RSU	N/A	In RSU	In TSC	NTCIP 1202	See 4.1.4.1
Profile 1 - Implementation 2	In RSU	In RSU	In RSU	In TSC	NTCIP 1202	See 4.1.4.1
Profile 2 - Implementation 1	In RSU	N/A	In RSU & TSC	In TSC	SAE J2735 SPaT	See 4.1.4.2
Profile 2 - Implementation 2	In RSU	In RSU	In TSC	In TSC	SAE J2735 SPaT	See 4.1.4.2
External Device - Implementation 1	In RSU	N/A	In External Device	In TSC	NTCIP 1202 & SAE J2735 SPaT	See 4.1.4.3
External Device - Implementation 2	In RSU	In External Device	In External Device	In TSC	NTCIP 1202 & SAE J2735 SPaT	See 4.1.4.3
External Device - Implementation 3	In RSU	In RSU	In External Device & RSU	In TSC	NTCIP 1202 & SAE J2735 SPaT	See 4.1.4.3

D.3.2 Profile 1: SPaT Information between the TSC Process and the CV Application Process

This subsection defines the communications requirements and design between the TSC Process to the CV Application Process for Profile 1. For this data exchange, the TSC Process provides SPaT information using SNMP object definitions to the CV Application Process (see Figure 22). Profile 1 is generally used when the CV Application Process is located outside the TSC.

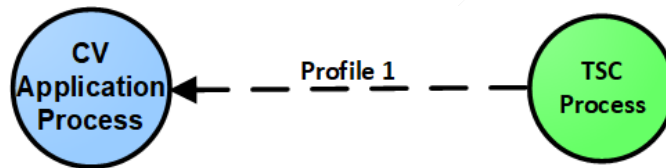


Figure 22 - Profile 1

Profile 1 is defined as follows:

- The interface between the ASC Process and CV Application Process is secured via DTLS 1.3.
- For NTCIP 1202 v03B implementations:
 - The SPaT information is contained in an NTCIP 1202 block object called rsuSignalStatusBlock. Refer to FR ID 3.5.4.3.1.1.9, SET rsuSignalStatusBlock in NTCIP 1202 v03B for the definition of the block object.
 - The SPaT information is transmitted (SET) at least once per 100 ms ± 2 ms, per FR ID 3.6.3.6 in NTCIP 1202 v03B.
- For NTCIP 1202 v04 implementations:
 - The SPaT information is contained in a block object called rsuSignalStatusBlock. Refer to NTCIP 1218 v01A, FR ID 3.5.1.4.3.3, Receive SPaT Movement Status - NTCIP 1202 v03B, where the TSC will SET rsuSignalStatusBlock, as defined in NTCIP 1218 v01A (5.22.13.3).
 - The SPaT information is transmitted (SET) at least once per 100 ms ± 2 ms, per FR ID 3.6.3.3 in NTCIP 1202 v04.

Subsection 6.3.2 in CTI 4501 defines the requirements for the TSC infrastructure (equivalent to the TSC Process) to provide signal timing information to an RSU. Subsection 6.3.2.1.1.1 represents Profile 1.

This annex distinguishes between two different implementations of Profile 1 based on whether the agency requires a Message Consistency Process (see 4.1.2.4) in its specification. Implementation 1 assumes that the IOO has policies and guidelines in place to address situations where SPaT and MAP messages may conflict with each other, while Implementation 2 requires executing a Message Consistency Process.

D.3.2.1 Profile 1 - Implementation 1

Figure 23 represents Implementation 1, when a Message Consistency Process is not implemented.

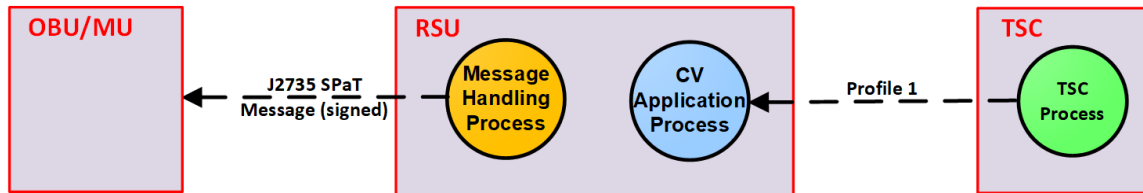


Figure 23 - Profile 1 - Implementation 1

With Implementation 1, if the CV Application Process has not received rsuSignalStatusBlock from the TSC (or external device) for more than 300 ms, the process sends a UPER-encoded SPaT message to the Message Handling Process with bits 9 (off) and 13 (noValidSPaTisAvailableAtThisTime) set to enabled (1).

In this scenario, since the CV Application Process and Message Handling Process are all internal to the RSU, the interfaces between these processes are not specified (i.e., it can be proprietary).

D.3.2.2 Profile 1 - Implementation 2

If an implementation only uses Profile 1 and a Message Consistency Process exists, the Message Consistency Process is likely located within the RSU and compares the contents of rsuSignalStatusBlock and the MAP message for consistency (see Figure 24). The Message Consistency Process must have access to the contents of the SPaT and the MAP message for the same intersection. The contents of the SPaT message are in the NTCIP 1202 rsuSignalStatusBlock object.

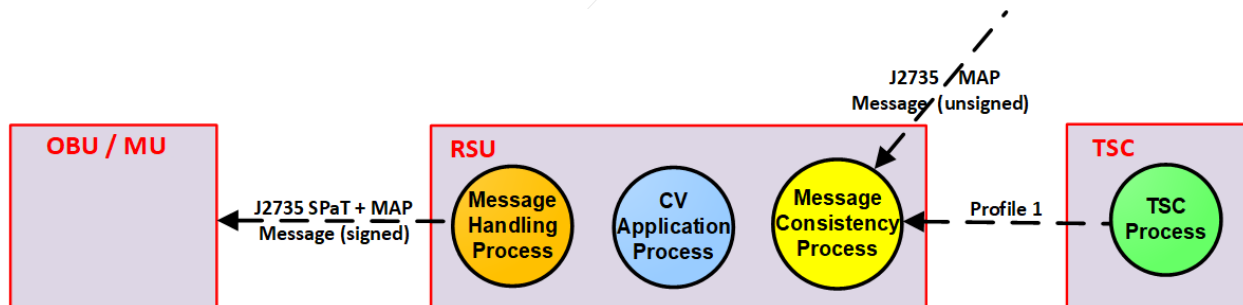


Figure 24 - Profile 1 - Implementation 2

Since the CV Application Process, Message Consistency Process, and Message Handling Process are all internal to the RSU, the interfaces among these processes are not specified.

The Message Consistency Process should check for SPaT-MAP Consistency. If the contents of rsuSignalStatusBlock and the MAP message are consistent for an intersection, then the CV Application Process generates the UPER-encoded SPaT message and forwards the SPaT message to the Message Handling Process for broadcast. Note that the TSC Process may already set noValidSPaTisAvailableAtThisTime (13) in the DE_IntersectionStatusObject to be enabled (1), but the CV Application Process will NOT change the bit value.

If the contents of `rsuSignalStatusBlock` and the MAP message are inconsistent, then the CV Application Process generates the UPER-encoded SPaT message with `noValidSPaTisAvailableAtThisTime` (13) in the `DE_IntersectionStatusObject` to be enabled (1) (to indicate the SPaT message is invalid) and forwards the SPaT message to the Message Handling Process for broadcast.

Similarly, if the Message Consistency Process determines that the MAP message is not valid, or determines that the SPaT message is not valid, then the CV Application Process generates the UPER-encoded SPaT message and sets `noValidMapisAvailableAtThisTime` (12) or `noValidSPaTisAvailableAtThisTime` (13), respectively, to be enabled (1) before forwarding the SPaT message to the Message Handling Process for broadcast.

D.3.2.3 Profile 1 Specifications

To support Profile 1, the agency should specify that the TSC and the RSU must support Profile 1 in its specification.

The agency also should specify if the RSU is required to implement the Message Consistency Process in its specification.

D.3.3 Profile 2: SPaT Information between the CV Application Process to the Message Handling Process

This section defines the communications requirements between the CV Application Process to the Message Handling Process for Profile 2. For this data exchange, the CV Application Process provides SPaT information in an UPER-encoded payload to the Message Handling Process's Immediate Forward Message table (see Figure 25). Profile 2 is generally used when the CV Application Process is primarily located outside the RSU.

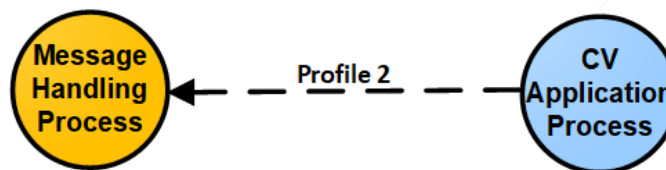


Figure 25 - Profile 2

Profile 2 is defined as follows:

- The interface between the CV Application Process and Message Handling Process is secured via DTLS 1.3.
- The CV Application Process transmits (SET) an UPER-encoded payload to the RSU Process's Immediate Forward Message Table.
- It is expected that CV Application Process will SET the UPER-encoded payload to the RSU Process's IFM Table at least once per $100\text{ ms} \pm 2\text{ ms}$.

Subsection 6.3.2 in CTI 4501 v02 defines the requirements for the TSC infrastructure (equivalent to the TSC Process) to provide signal timing information to an RSU. Subsection 6.3.2.1.1.3 represents Profile 2.

This paper distinguishes between two different implementations of Profile 1 based on whether the agency requires a Message Consistency Process (see D.2.1.4, Message Consistency Process) in its specification. Implementation 1 assumes that the IOO has policies and guidelines in place to address situations where SPaT and MAP messages may conflict with each other, while Implementation 2 requires executing a Message Consistency Process.

D.3.3.1 Profile 2 - Implementation 1

Figure 26 represents Implementation 1 when a Message Consistency Process is not implemented.

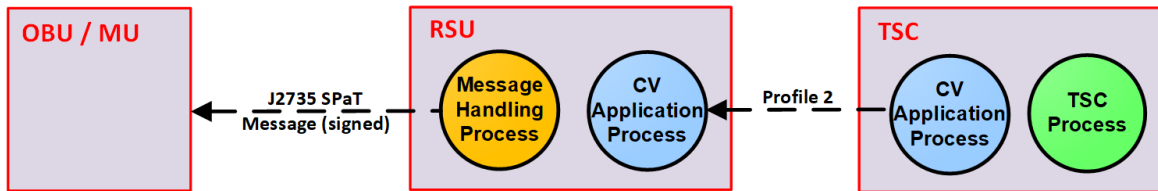


Figure 26 - Profile 2 - Implementation 1

With implementation 1, if the CV Application Process in the RSU has not received an UPER-encoded SPaT Message from the CV Application Process in the TSC for more than 300 ms, it sends a SPaT message to the Message Handling Process with bits 9 (off) and 13 (noValidSPaTisAvailableAtThisTime) set to enabled (1).

In this implementation, since the TSC Process and CV Application Process are both internal to the TSC, the interfaces between these processes are not specified (i.e., it can be proprietary). Similarly, since the CV Application Process and Message Handling Process are both internal to the RSU, the interfaces between these processes are not specified (i.e., it can be proprietary).

D.3.3.2 Profile 2 - Implementation 2

If an implementation only uses Profile 2 and a Message Consistency Process is required, the Message Consistency Process is likely located within the RSU and compares the contents of UPER-encoded SPaT Message and the MAP message for consistency (see Figure 27). The Message Consistency Process must have access to the contents of both the SPaT and the MAP message for the same intersection. The contents of the SPaT message are contained in an UPER-encoded SPaT message.

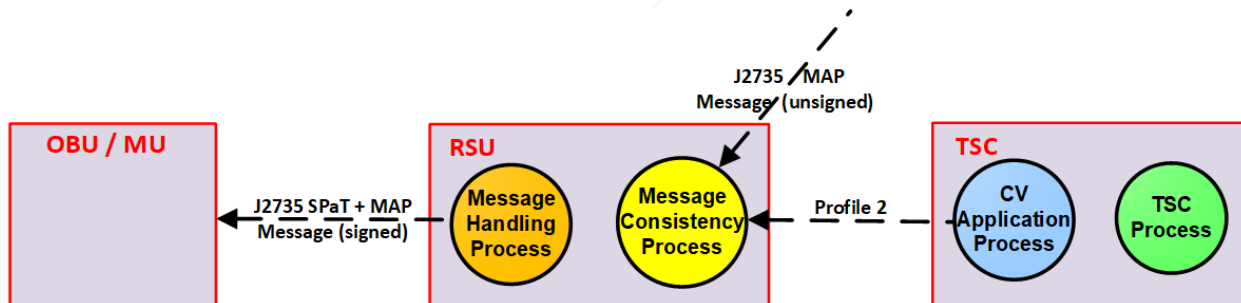


Figure 27 - Profile 2 - Implementation 2

Since the Message Consistency Process and Message Handling Process are both internal to the RSU, the interfaces between these processes are not specified (i.e., may be proprietary). Similarly, since both the TSC Process and the CV Application Process are internal to the TSC, the interface between TSC Process and the CV Application Process are not specified.

The Message Consistency Process checks for SPaT-MAP Consistency. If the contents of the SPaT message and the MAP message for an intersection are consistent, then the Message Consistency Process forwards the SPaT and MAP message to the Message Handling Process for broadcast. Note that the CV Application Process may already set noValidSPaTisAvailableAtThisTime (13) in the DE_IntersectionStatusObject to be enabled (1), but the Message Consistency Process will NOT change the bit value.

If the contents of SPaT and the MAP messages are inconsistent, then the Message Consistency Process forwards the SPaT message with noValidSPaTisAvailableAtThisTime (13) in the DE_IntersectionStatusObject to be enabled (1) (to indicate the SPaT message is invalid) and the MAP message to the Message Handling Process for broadcast.

Similarly, if the Message Consistency Process determines that the MAP message is not valid (e.g., does not have a valid IEEE 1609.2 certificate), or determines that the SPaT message is not valid, then the Message Consistency Process updates the SPaT message with noValidMapisAvailableAtThisTime (12) or noValidSPaTisAvailableAtThisTime (13), respectively, to be enabled (1) before forwarding the SPaT message and the MAP message to the Message Handling Process for broadcast.

D.3.3.3 Profile 2 Specifications

To support Profile 2, the agency should specify that the TSC and the RSU must support Profile 2 in its specification.

The agency should specify if the RSU is required to implement the Message Consistency Process in its specification.

D.3.4 SPaT Information Exchanges with an External Device

This subsection defines the communications requirements among the TSC Process, CV Application Process, Message Consistency Process, and the Message Handling Process when the physical architecture includes an external device between the RSU and the TSC. The CV Application Process is generally an external physical device (e.g., a Linux processor) between the TSC and the RSU.

The guidance is that the interface between the TSC Process and the CV Application Process uses Profile 1, while the interface between the CV Application Process and the Message Handling Process uses Profile 2 (see Figure 28).



Figure 28 - Profiles 1 and 2 example

This section distinguishes between three different implementations based on whether the agency requires a Message Consistency Process (see D.2.1.4, Message Consistency Process) in its specification and where the Message Consistency Process is located. Implementation 1 assumes that the IOO has policies and guidelines in place to address situations where SPaT and MAP messages may conflict with each other, while Implementations 2 and 3 require a Message Consistency Process.

D.3.4.1 External Device - Implementation 1

Figure 29 represents Implementation 1 when a Message Consistency Process is not implemented.

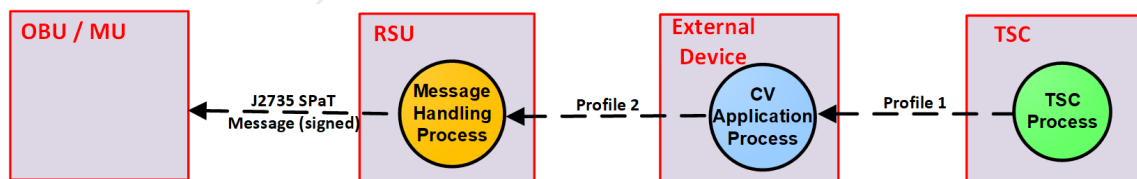


Figure 29 - External device - Implementation 1

With Implementation 1, if the CV Application Process has not received rsuSignalStatusBlock from the TSC (or external device) for more than 300 ms, it sends a SPaT message to the Message Handling Process with bits 9 (off) and 13 (noValidSPaTisAvailableAtThisTime) set to enabled (1).

D.3.4.2 External Device - Implementation 2

Figure 30 represents an implementation where the Message Consistency Process is located within an external device. The Message Consistency Process must have access to the contents of both the SPaT and the MAP message for the same intersection. The contents of the SPaT message are in the rsuSignalStatusBlock object.

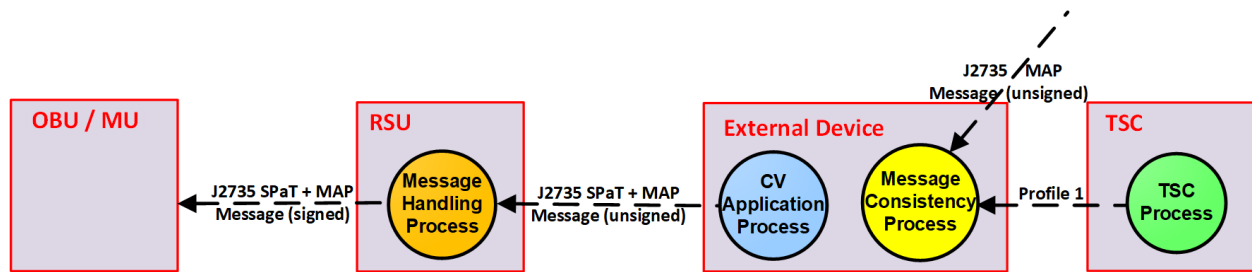


Figure 30 - External device - Implementation 2

If the Message Consistency Process is in the external device, it compares the contents of rsuSignalStatusBlock and the MAP message for consistency. If the contents of rsuSignalStatusBlock and the MAP message are consistent, then the CV Application Process generates the UPER-encoded SPaT message and forwards the SPaT message to the Message Handling Process for broadcast. Note that the TSC Process may already set noValidSPaTisAvailableAtThisTime (13) in the DE_IntersectionStatusObject to be enabled (1), but the CV Application Process will NOT change the bit value.

If the contents of rsuSignalStatusBlock and the MAP message are inconsistent, then the CV Application Process generates the UPER-encoded SPaT message with noValidSPaTisAvailableAtThisTime (13) in the DE_IntersectionStatusObject to be enabled (1) (to indicate the SPaT message is invalid) and forwards the SPaT message to the Message Handling Process for broadcast.

Similarly, if the Message Consistency Process determines that the MAP message is not valid, or determines that the SPaT message is not valid, then the CV Application Process generates the UPER-encoded SPaT message and sets noValidMapisAvailableAtThisTime (12) or noValidSPaTisAvailableAtThisTime (13), respectively, to be enabled (1) before forwarding the SPaT message to the Message Handling Process for broadcast.

D.3.4.3 External Device - Implementation 3

Figure 31 represents an implementation where the physical architecture includes an external device with the CV Application Process and the Message Consistency Process is located within the RSU. The Message Consistency Process must have access to the contents of both the SPaT and the MAP message for the same intersection. The contents of the SPaT message are in the UPER-encoded SPaT message.

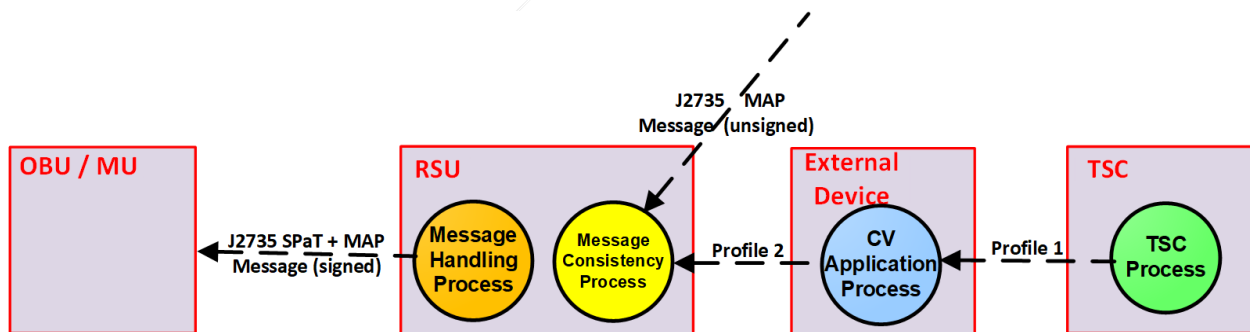


Figure 31 - External device - Implementation 3

Since the Message Consistency Process and Message Handling Process are both internal to the RSU, the interfaces between these processes are not specified (i.e., may be proprietary).

The Message Consistency Process checks for SPaT-MAP Consistency. If the contents of the SPaT message and the MAP message for an intersection are consistent, then the Message Consistency Process forwards the SPaT and MAP message to the Message Handling Process for broadcast. Note that the CV Application Process may already set noValidSPaTisAvailableAtThisTime (13) in the DE_IntersectionStatusObject to be enabled (1), but the Message Consistency Process will NOT change the bit value.

If the contents of SPaT and the MAP messages are inconsistent, then the Message Consistency Process forwards the SPaT message with `noValidSPATisAvailableAtThisTime` (13) in the `DE_IntersectionStatusObject` to be enabled (1) (to indicate the SPaT message is invalid) and the MAP message to the Message Handling Process for broadcast.

Similarly, if the Message Consistency Process determines that the MAP message is not valid (e.g., does not have a valid IEEE 1609.2 certificate); or determines that the SPaT message is not valid; then the Message Consistency Process updates the SPaT message with `noValidMapisAvailableAtThisTime` (12) or `noValidSPATisAvailableAtThisTime` (13), respectively, to be enabled (1) before forwarding the SPaT message and the MAP message to the Message Handling Process for broadcast.

D.3.4.4 External Device Specifications

In its specification, the agency should specify that the TSC must support Profile 1; the RSU must support Profile 2; and the External Device must support Profile 1 when interfacing with the TSC and support Profile 2 when interfacing the RSU.

In its specification, the agency should specify if the RSU or the External Device is required to implement the Message Consistency Process.

D.3.5 Alternate Physical Architectures - Generating SPaT Messages

There may be several alternate physical architectures where functions performed by the CV Application Process to generate SPaT messages are distributed to different physical components, such as an RSU, a TSC, and/or an external device.

With these alternate physical architectures, an agency specification must clearly distribute what functions assigned to the CV Application Process are performed in each physical device. The profiles defined in this annex may or may not be applicable. It is the responsibility of the agency to define which profile(s) are applicable across each of these interfaces - the profile may also be proprietary. Specifying a profile other than Profile 1 or Profile 2 as defined in this annex is not recommended.

D.3.6 Active Message File Format - CV Application Process to RSU Process

RSU Specification v4.1 defined a profile where a TSC or external device generates an Active Message file format, as defined in Appendix C Active Message, then transmits this Active Message file format to the RSU. The RSU then uses the data in the Active Message to generate and broadcast SAE J2735 messages. However, with this profile, the RSU cannot confirm the identity of trustworthiness of the source of the Active Message file, so this represents a potential security gap. Thus, this profile is no longer recommended.

D.4 RLVW APPLICATIONS - BASIC SAFETY MESSAGES FOR AGP

This section defines the requirements to provide information in BSMs from the RSU to the TSC to support RLVW applications. Information in BSMs may be used by a TSC to support an Assured Green Period (AGP), as defined in CTI 4501, but may be also used to support other V2X applications.

D.4.1 Summary

From the RSU to the TSC, this section describes how traveler information, such as the information received by the RSUs in the form of BSMs, are forwarded to the TSC. This information may be used by TSCs to determine traveler demand on the roadways and adjust the signal timings. The concepts described in this section may also apply to PSMs to support V2X applications.

The information in the BSMs might be used by the TSC to:

- Determine the type of (traveler) demand for service approaching a signalized intersection, and its movement through the intersection
- Determine if there are conflicting traffic (travelers) at the signalized intersection
- Support RLVW applications, such as to determine if an Assured Green Period (AGP) is needed

The Interface requirements for BSMs assume the following about the Message Handling Process:

- Optionally, the RSU Process may filter the BSMs. CTI 4001, Requirement 3.3.2.9.2.1, currently only filters (and forwards) BSMs when the vehicle first enters a defined zone, i.e., only the first BSM for a vehicle is forwarded to a defined destination.

NOTE: Further discussion on filtering is warranted. Topics include what to filter BSMs for and using different filters for different applications.

D.4.2 Profile A: Message Handling Process to CV Application Process

Except for the last paragraph, this subsection is reprinted from NTCIP 1202 v04, with some minor editorial edits (e.g., using TSC instead of ASC).

With Profile A, the Message Handling Process within the RSU first authenticates (validates the security certificate) the BSMs and PSMs received over-the-air by the V2X Radio. If the message is validated, CTI 4001 and NTCIP 1218 permit messages received (and validated) by the RSU to be forwarded to an IP address. Using this functionality, the Message Handling Process can forward BSMs and PSMs that have been validated (for proper IEEE Std 1609.2 certificates) to an TSC. The CV Application Process in the TSC can then extract details in the BSMs and/or the PSMs for inputs for its signal timing operations, such as determining traveler demand around the signalized intersection.

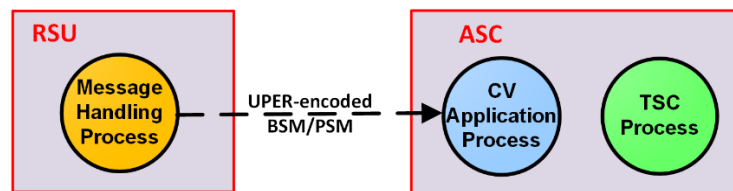


Figure 32 - Connected device detector - Profile A

The characteristics of Profile A are:

- The CV Application Process is within the TSC.
- The interface between the Message Handling Process and the CV Application Process is secured via DTLS 1.3.
- The Message Handling Process continuously forwards the UPER-encoded payload to the CV Application Process. CTI 4001 requirement 3.3.2.8.2, Forwarding of Messages Received by the RSU describes how messages received by the RSU can then be forwarded to a specific destination. CTI 4001, 4.3.2.13.5 describes how this requirement is fulfilled according to CTI 4001. The design to fulfill this requirement consists of a `rsuReceivedMsgTable`, where each entry describes which messages received by the RSU should be forwarded to specified destinations. Each entry includes the PSID of the message to be forwarded, the destination (IP address and Port), the protocol (currently on UDP), the minimum received signal strength (in dbm), the interval (e.g., every nth message), a start and stop date and time, and whether security headers should be included. The security headers are included - there is information in the IEEE Std 1609.2 security certificates that may be useful to the TSC, such as the `OpOrgID` and the `Service Specific Permissions (SSP)`, which define the permissions for an application that the certificate is valid for.
- CTI 4001 requirement 3.3.2.8.3.1 defines an allowable latency between reception on one interface to transmission on another interface of less than 50 ms, which includes the verification of the message.
- CTI 4001 requirement 3.3.2.9.2 defines how BSMs can be filtered by the RSU for the first BSM from each vehicle traveling into a specific zone. CTI 4001, 4.3.2.14.4 describes how this requirement is fulfilled according to CTI 4001. Additional details about the proposed object definitions are found in CTI 4001, C.3.6.

Note that the Message Handling Process may filter which BSMs or PSMs are forwarded to the TSC. As noted, the Message Handling Process may filter such that every nth message is forwarded or filter by a geofence. It is important to configure the RSU so the appropriate and necessary BSMs and PSMs are forwarded to the TSC for its use. How the RSU filters the BSMs and/or PSMs, and how the TSC uses the BSM/PSM data, are not defined in NTCIP 1202.

The CV Application Process remotely “actuates” a connected device detector when the data in the BSM or PSM satisfies all the criteria for that detector. The data used is not limited to BSMs or PSMs - the CV Application Process may use data in other messages, such as a Signal Request Message (SRM) for signal priority or preemption applications. The criteria (filter) that is used to determine if a remote actuation should be placed is not defined by this recommended practice and may include a geofence (the detection zone), traveler type (e.g., transit vehicle, bicyclist), traveler speed, traveler heading, etc.

This Profile could also be used in other use cases where the ‘Message Handling Process’ is another device, such as a video incident detection system (VIDS), that provides traveler trajectories to the TSC Process. Currently, the NTCIP standards do not support a user need to provide traveler path trajectories (such as a vehicle’s movement or a vulnerable road user’s [VRU’s] movements through an intersection). Movement information might include the traveler’s location, its current speed, whether it makes a left turn, its travel time through a defined area, etc. This use case would allow another device to send the traveler’s movement through a defined area via surrogate BSMs (for vehicles) or PSMs (for VRUs). This would have to be considered.

D.4.3 Profile B: CV Application Process to ASC Process

This section defines the communications requirements between the CV Application Process and ASC Process so the CV Application Process can provide the TSC with actuations when the presence of a connected device (e.g., an OBU or Mobile Unit) that satisfies the filters for a detection zone is detected.

Except for the last two paragraphs, the remainder of this section is reprinted from NTCIP 1202 v04, with some minor editorial edits (e.g., using TSC instead of ASC).

With Profile B, the CV Application Process is external to the physical TSC and is likely physically located within the RSU or an external device. The CV Application Process receives the BSMs and PSMs from the Message Handling Process, similar to the process described in Profile A, processes the messages, then determines if the data in the messages satisfies the criteria to “actuate” a connected device detector. The connected device detector is a “virtual” detector that when actuated indicates a traveler has been detected that satisfies all the criteria defined for that detector. The CV Application Process then exchanges the actuation with the TSC Process.

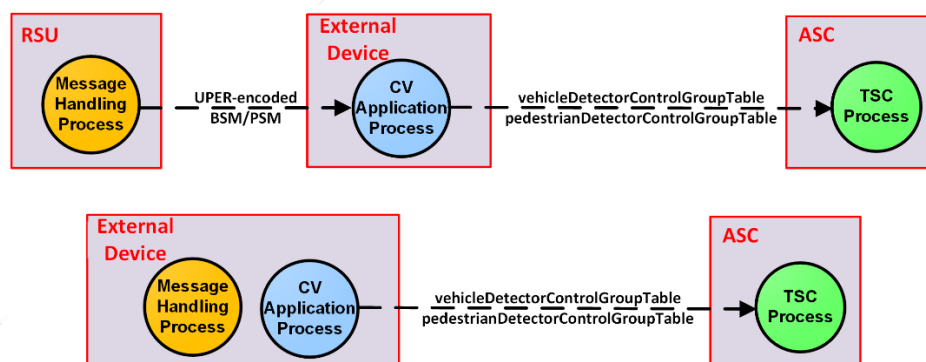


Figure 33 - Connected device detector - Profile B

The characteristics of Profile B are:

- The CV Application Process is external to the TSC. The CV Application Process may be within the RSU or an external device.
- The interface between the CV Application Process and the TSC Process is secured via DTLS 1.3.
- Section 3.5.4.3.1.7 in NTCIP 1202 defines how a TSC receives vehicle detector calls (SET-requests) from an CV Application Process. The vehicleDetectorControlGroupTable contains a bit for each of up to 255 vehicle detectors supported by the TSC. A bit = 1 indicates that a CV Application Process has placed a vehicle detector call as a vehicle satisfies the filters for the detection zone has been detected.

For example, if the CV Application Process detects a BSM within the detection zone of connected device detector 50 that is mapped to vehicle detector 50, and the BSM satisfies the filters for that detector, such as the vehicle heading is northbound, the CV Application Process will SET bit = 1 in the vehicleDetectorControlGroupTable for vehicle detector 50 (vehicleDetectorControlGroupActuation.7 = 2).

- Section 3.5.4.3.1.8 in NTCIP 1202 defines how a TSC receives pedestrian detector calls (SET-requests) from an CV Application Process. The pedestrianDetectorControlGroupTable contains a bit for each of up to 255 pedestrian detectors supported by the TSC. A bit = 1 indicates that a CV Application Process has placed a pedestrian detector call as a pedestrian satisfies the filters for the detection zone has been detected. The vehicleDetectorControlGroup is used for bicyclists.

For example, if the CV Application Process detects a PSM within the detection zone of connected device detector 60 that is mapped to vehicle detector 51, and the PSM identifies a bicyclist, the CV Application Process will SET bit = 1 in the vehicleDetectorControlGroupTable for vehicle detector 51 (vehicleDetectorControlGroupActuation.7 = 4).

- Section 3.5.4.3.1.9 in NTCIP 1202 defines how a TSC receives preemption calls (SET-requests) from an CV Application Process. The preemptControlTable contains a value bit all supported preempts supported by the TSC. A value = 1 indicates that a CV Application Process has placed a preempt call.

For example, if the CV Application Process detects a SRM for preempt 3, the CV Application Process will set value = 1 in preemptControlTable for preempt 3 (preemptControlState.3 = 1).

Object definitions to configure the detection zones or the filters for each detection zone are not defined in NTCIP 1202.

Commentary: This profile allows the ASC to retrieve actuation reports from the CV Application Process periodically, for example, every 100 ms. Each detection zone is defined in the CV Application Process, which could be in an external device or an RSU. An actuation indicates that a connected device (such as an OBU or a mobile device) has been detected that satisfies the filters for that detection zone. The detection zone can be a physical detector (e.g., loop detector) or a virtual detector (e.g., processed based on the location and kinematics in a BSM).

The filter can be simple or complex. The filter could be as simple as ANY traveler (e.g., a vehicle or a pedestrian) in the detection zone or could be complex (e.g., a truck traveling greater than the posted speed limit traveling northbound). The cvDetectionGroupTable allows up to 255 detectors. It is also possible to assign different detectors for the same detection zone but with different filters. For example, detectors 25 and 26 have the same detection zone. However, detector 25 is (virtually) actuated when a vehicle is detected within the detection zone, but the vehicle speed, as reported by the BSM, is at or below the posted speed limit; and detector 26 is (virtually) actuated when a vehicle is detected within the detection zone, but the vehicle speed, as reported by the BSM, is above the posted speed limit.

It is recommended that, to avoid confusion, a detector input number that is currently in use by the TSC (e.g., via the traffic cabinet or a detector rack) not be used in the cvDetectionGroupTable.

D.4.4 Profile C

The remainder of this subsection is reprinted from NTCIP 1202 v04.

There is potentially a third profile, expected to be called Profile C, which uses a Sensor Sharing Service (SSS), defined in SAE J3224, to describe objects detected by either the infrastructure or OBUs/MUs. The descriptions of these objects are expected to be processed by an CV Application Process and shared with the ASC. However, at the time of this publication, SAE J3224/1, which is proposed to define a specific profile of SAE J3224 hosted by RSUs, is in development, so the details of a Profile C are not available yet.

D.4.5 Alternate Physical Architectures - Basic Safety Messages for AGP

There may be several alternate physical architectures where functions performed by the CV Application Process to process BSMs to support AGP are distributed to different physical components, such as an RSU, a TSC, and/or an external device. Figure 21 depicts several potential alternate physical architectures.

With these alternate physical architectures, an agency specification must clearly distribute what functions assigned to the CV Application Process are performed in each physical device. The profiles defined in this annex may or may not be applicable. It is the responsibility of the agency to define which profile(s) are applicable across each of these interfaces - the profile may also be proprietary. Specifying a profile other than Profile A or Profile B as defined in this annex is not recommended.

ANNEX E - REVISIONS FROM CTI 4501 v01 [INFORMATIVE]

This annex identifies the changes that have been made to CTI 4501. The Technical Committee makes reasonable efforts to ensure that documents are as backward compatible as possible, but the primary purpose of these documents is to provide interoperability by developing recommended practices in a consensus environment. When changes are required to meet these objectives, the problematic elements, such as user needs, requirements, and design guidance, are refined (if the issue is primarily editorial) or deprecated and, in most cases, replaced with updated needs, requirements, and guidance.

This annex identifies why each of these changes has been made.

E.1 UPDATES TO REQUIREMENTS

The following identifies changes from CTI 4501 v01 to CTI 4501/1 for SPaT-related requirements.

NOTE: References to CTI 4501 v01 in this annex applies to both CTI 4501 v01.00 dated September 2021 or CTI 4501 v01.01 dated June 2022.

E.1.1 Deprecated TSC Infrastructure SPaT Information Message Transmission Rate

Deprecated requirement 3.3.2.1.2, TSC Infrastructure SPaT Information Message Transmission Rate in CTI 4501 v01. Replaced this requirement with 6.3.2.1.6, TSC Signal State Periodicity and 6.3.2.1.7, TSC Signal Indication Phase State and SPaT Information Consistency.

E.1.2 Deprecated TSC Infrastructure SPaT Information Message Transmission Failure Threshold

Deprecated requirement 3.3.2.1.3, TSC Infrastructure SPaT Information Message Transmission Failure Threshold in CTI 4501 v01. Replaced this requirement with 6.3.2.1.6, TSC Signal State Periodicity and 6.3.2.1.7, TSC Signal Indication Phase State and SPaT Information Consistency.

E.1.3 Deprecated TSC Infrastructure Average Message Update Latency

Deprecated requirement 3.3.2.1.4, TSC Infrastructure SPaT Information Average Message Update Latency in CTI 4501 v01. Replaced this requirement with 6.3.2.1.6, TSC Signal State Periodicity and 6.3.2.1.7, TSC Signal Indication Phase State and SPaT Information Consistency.

E.1.4 Deprecated TSC Infrastructure Processing Latency

Deprecated requirement 3.3.2.1.5, TSC Infrastructure Processing Latency in CTI 4501 v01. Replaced this requirement with 6.3.2.1.6, TSC Signal State Periodicity and 6.3.2.1.7, TSC Signal Indication Phase State and SPaT Information Consistency.

E.1.5 Deprecated Support Green Extension for AGP

Deprecated requirement 3.3.2.1.5, Support Green Extension for AGP in CTI 4501 v01. Replaced this requirement with 6.3.3.1.5.4, SPaT Message - Broadcast Latency and Accuracy.

E.1.6 Deprecated SPaT Message - Broadcast Periodicity

Deprecated requirement 3.3.3.1.5.1, SPaT Message - Broadcast Periodicity in CTI 4501 v01. Replaced this requirement with 6.3.3.1.5.4, SPaT Message - Broadcast Latency and Accuracy.

E.1.7 Deprecated SPaT Message - Broadcast Latency

Deprecated requirement 3.3.3.1.5.2, SPaT Message - Broadcast Latency in CTI 4501 v01. Replaced this requirement with 6.3.3.1.5.4, SPaT Message - Broadcast Latency and Accuracy.

E.1.8 Deprecated WALK State Enumeration (Potential Conflict)

Deprecated requirement 3.3.3.3.8, WALK State Enumeration (Potential Conflict) in CTI 4501 v01 because the definition of a protected movement is updated in CTI 4501 v02. All pedestrian movements with a WALK indication have the right of way. Using permissive-Movement-Allowed would tell the pedestrian they must yield to conflicting traffic even though they have the WALK indication, which is not the case.