Cooperative Automation Research: CARMA Proof-of-Concept TSMO Use Case Testing: Transit Management (Transit Signal Priority) Concept of Operations

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FOREWORD

The Federal Highway Administration's (FHWA) Cooperative Driving Automation (CDA) Program, formerly known as the CARMA℠ Program, is an initiative to enable collaboration for research and development of CDA technologies. The CDA Program develops and maintains an ecosystem of open-source software tools, which together are known as the CARMA Ecosystem, to enable CDA research. The CARMA Ecosystem is a research environment that enables communication between vehicles and roadside infrastructure devices to support coordinated movement to improve safety, traffic throughput, and energy efficiency of the transportation network.

In 2015, the FHWA's Office of Operations Research and Development developed a cooperative adaptive cruise control proof-of-concept prototype that was installed in five research vehicles. From there, the CARMA Ecosystem further evolved through testing and integration. At the time of this writing, the CDA Program is advancing into automated driving systems that leverage infrastructure to support cooperative automation strategies. This project expands CARMA functionality to include transportation systems management and operations (TSMO) strategies on surface arterials with intersections.

This concept of operations (ConOps), which is the sixth in a series of nine ConOps focused on TSMO use cases and capabilities, is focused on transit management. The intended audience for this report is CDA stakeholders, such as system developers, analysts, researchers, application developers, and infrastructure owners and operators.

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15. Supplementary Notes The Federal Government Task Managers were Govindarajan Vadakpat (HRSO-50; ORCID: 0000-0001-9060-3216) and Taylor Lochrane (HRSO-40; ORCID: 0000-0002-1933-6554).
16. Abstract Cooperative driving automation (CDA) aims to improve the safety, traffic throughput, and energy efficiency of the transportation network by enabling vehicles and infrastructure to work together to coordinate movement. The objective of this project is to advance the CARMA℠ ecosystem to enable further capabilities for CDA participants to interact with the road infrastructure, to enhance infrastructure performance, to improve network efficiency, and ultimately, to reduce traffic congestion through transportation systems management and operations (TSMO) strategies on arterials. The concept of operations focuses on TSMO transit management (TM) transit signal priority (TSP), which investigates active traffic management applied to traffic signal corridors. TSP is a TM tool that helps a transit vehicle maintain schedule or headway adherence and reduce travel time delay attributable to traffic signals. The proposed approach for TSMO TM TSP has three components: local traffic signal optimization to reduce delay to one or more transit vehicles using CARMA Streets, corridor-coordinated TSP to optimize signal timing between transit stops using CARMA Cloud℠, and a transit dwell hold strategy to schedule the transit vehicle into a "transit green band" between transit stops using CARMA Platform℠. The proposed control framework is expected to improve schedule or headway adherence.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1,000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2,000 lb)	0.907	megagrams (or “metric ton”)	Mg (or “t”)
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or “t”)	megagrams (or “metric ton”)	1.103	short tons (2,000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	2.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003)

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS

ADS	automated driving system
BLIP	bus (transit) lane intermittent priority
BRT	bus rapid transit
CACC	cooperative adaptive cruise control
C-ADS	cooperative automated driving system
CDA	cooperative driving automation
ConOps	concept of operations
C–V2X	cellular vehicle-to-everything
DSRC	dedicated short-range communication
ETA	estimated time of arrival
FHWA	Federal Highway Administration
GHG	greenhouse gas
GPS	global positioning system
HRSO	Office of Safety Operations Research and Development
HD	high definition
Hz	hertz
I2V	infrastructure-to-vehicle
ID	identifier
IOOs	infrastructure owners and operators
MMITSS	Multimodal Intelligent Traffic Signal System
NTCIP	National Transportation Communications for Intelligent Transportation Systems Protocol
OBU	onboard unit
PRS	priority request server
R&D	research and development
RSE	roadside equipment
RSU	roadside unit
SPaT	signal phase and timing
SRM	signal request message
SSM	signal status message
STOL	Saxton Transportation Operations Laboratory
TM	transit management
TSMO	transportation systems management and operations
TSP	transit signal priority
UC	use case
V2I	vehicle-to-infrastructure
V2V	vehicle-to-vehicle
V2X	vehicle-to-everything

CHAPTER 1. SCOPE AND SUMMARY

IDENTIFICATION

This document is a concept of operations (ConOps) for a transportation systems management and operations (TSMO) use case (UC) on arterials. This ConOps focuses on transit management (TM), specifically transit signal priority (TSP) or TSP for transit vehicles.

DOCUMENT OVERVIEW

Background

The Federal Highway Administration (FHWA) Office of Safety and Operations Research and Development (HRSO) performs transportation operations research and development (R&D). Onsite R&D is conducted at the Saxton Transportation Operations Laboratory (STOL), which is located at the Turner-Fairbank Highway Research Center. HRSO conducts operations R&D based on a national perspective of the transportation needs of the United States.

In 2015, HRSO designed, built, and installed a cooperative adaptive cruise control (CACC) proof-of-concept prototype system in a fleet of five vehicles. The CACC system was built on a CARMA Platform℠ as an advancement of standard adaptive cruise control (ACC) systems by utilizing vehicle-to-vehicle (V2V) dedicated short-range communications (DSRC) to automatically synchronize the longitudinal movements of many vehicles within a string. This proof-of-concept system was the first in the United States to demonstrate the capabilities of this technology with a five-vehicle CACC string.

Under a subsequent task order, HRSO developed CARMA2, a new reference platform to enable research capabilities to be easily shared and integrated into industry research vehicles. The project advanced CACC functionality and developed a proof-of-concept platooning application that enabled leader–follower behavior and allowed vehicles to begin to negotiate with one another. The project also developed the Integrated Highway Prototype I, which integrated speed harmonization, lane change/merge, and platooning into one trip.

Under a current task order, HRSO is producing the third iteration of CARMA℠. CARMA3 takes the platform into the world of automated driving systems (ADS) with SAE International® Level 3 and above automation.(1) The approach takes advantage of an open-source ADS platform to enable ADS functionality to be used for cooperative automation strategies.

CARMA Cloud℠ , CARMA Messenger, and CARMA Streets are also being developed along with CARMA Platform. CARMA Cloud represents the infrastructure piece of cooperative driving automation (CDA), whereby vehicles and other entities may communicate with the infrastructure to increase the safety and efficiency of the transportation network. CARMA Messenger represents the capability of moving, but not automated, entities (e.g., first-responder vehicles, pedestrians, and buses) to communicate with CARMA-equipped vehicles and the infrastructure to improve the transportation network performance. CARMA Streets enables vehicles to communicate with the infrastructure at intersections and provides an interface to the traffic signal controller to optimize travel through an intersection. CARMA Cloud, CARMA

Messenger, CARMA Streets, and CARMA Platform are open source and built with the goal of benefitting CDA research. Table 1 lists the various projects associated with this development.

Table 1. Projects associated with this development effort.

Task Order	Product	Title
STOL I T-13005	CARMA	Development of a Platform Technology for Automated Vehicle Research
STOL II 0013	CARMA2	Development of Connected and Automated Vehicle Capabilities: Integrated Prototype I
STOL II 693JJ318F000225	CARMA3	Development of Cooperative Automation Capabilities: Integrated Prototype II
STOL II 693JJ319F000369	CARMA IHP2	Cooperative Automation Research: CARMA IHP2

IHP2 = Integrated Highway Prototype II.

Objectives

This project extends the research from Integrated Highway Prototype II (IHP2) by utilizing CARMA Streets, CARMA Platform, and CARMA Cloud to provide CDA participants with the capabilities to interact with road infrastructure, including traffic signal controllers. All TSMO UCs in this project consider CDA operations on at-grade intersections. The UC in this ConOps focuses on active traffic management that incorporates signal optimization, signal coordination, and transit vehicle management. This project addresses three objectives: reduce traffic congestion, improve energy efficiency, and increase transit mobility, which includes improving on-time performance (e.g., not late, or not behind on a design headway by more than a defined threshold). This project investigates the extent to which these objectives can be achieved for different CDA cooperation classes, as given by the SAE J3216 standard.(2) This project will be supported by a team of CARMA participants for development and testing. This document aims to address one of TSMO arterial UCs: TM—traffic signal priority.

Audience

The intended audience for this ConOps includes the following entities:

- U.S. Department of Transportation and cooperative automation program stakeholders, including the Federal Transit Administration.
- System developers who will create and support CDA algorithms based on the system concepts described in this document.
- Analysts, researchers, and CDA application developers.

Document Structure

The structure of this document is generally consistent with the System Operational Concept described in “Annex A” of *ISO/IEC/IEEE Standard 29148:2011*.(3) A document conforming to this structure is called a ConOps in U.S. transportation systems engineering practice, and that title is retained for this document. Some sections of this ConOps have been enhanced to accommodate more detail than is described in Standard 29148:2011; titles of some sections may have been edited to capture those details more specifically.

- Chapter 1 defines the scope of the ConOps.
- Chapter 2 describes the current situation and identifies the need for changes with respect to processes and systems that will be affected by the ConOps.
- Chapter 3 describes the concept for the new TSMO TM system capabilities and its operations, and it presents detailed descriptions of operational concepts.
- Chapter 4 describes operational scenarios of TSMO TM at signalized intersections.
- Chapter 5 provides an analysis of the expected improvements, operational and research impacts, validation plans, disadvantages, and limitations.

CHAPTER 2. CURRENT SITUATION AND OPPORTUNITIES FOR CHANGES

This chapter discusses existing approaches to TM on signalized arterials using TSP. Transit is capable of reducing congestion by moving more people per vehicle.(4) Reducing transit delay and making transit more schedule/headway reliable makes TSP a more attractive solution.(5,6) This chapter highlights the advantages and disadvantages of the existing solutions because transit agencies are now motivating the development of new CDA solutions to congestion and energy problems at signalized intersections.

BACKGROUND AND CURRENT SITUATION

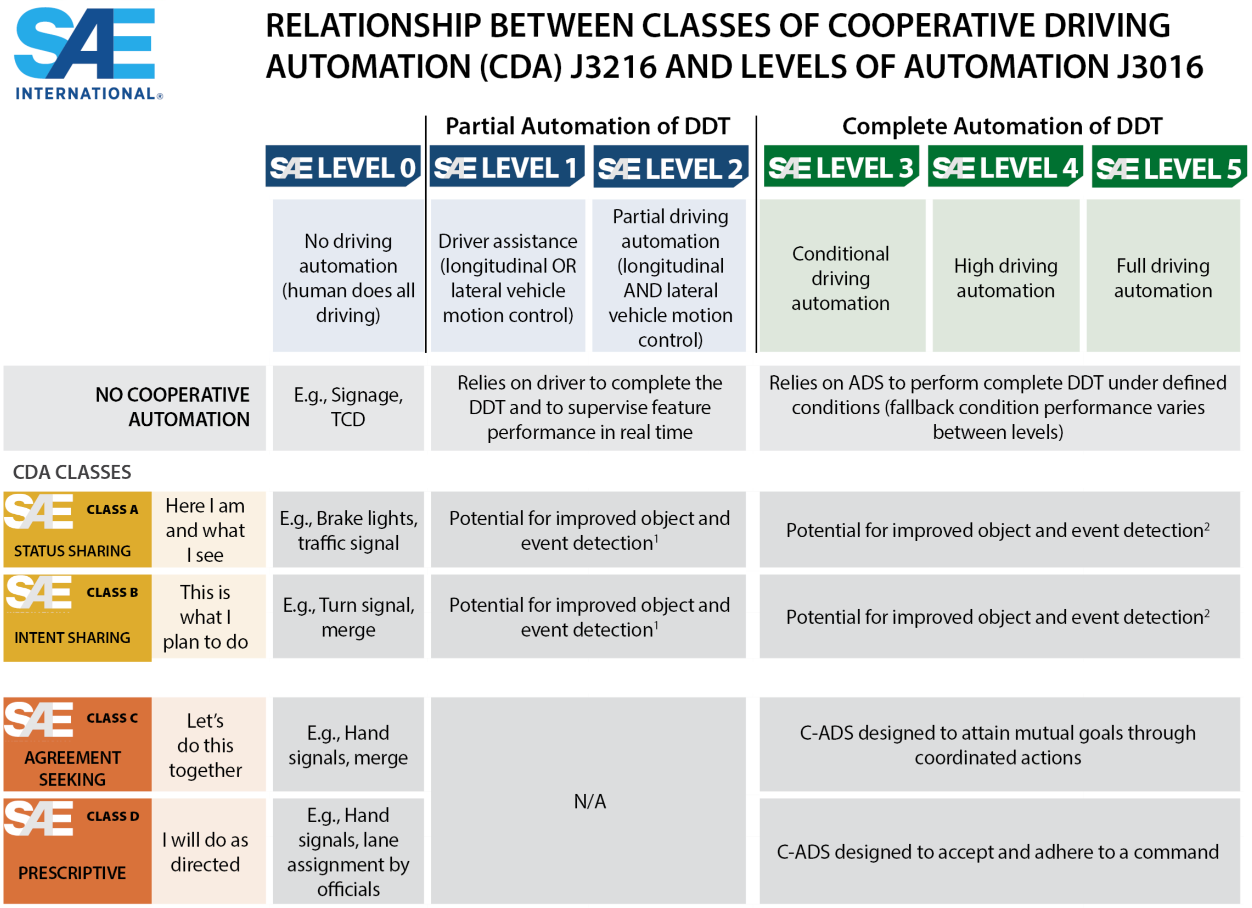
Various roadway facilities intersecting through a roadway network to provide access to commuters can cause conflicts among vehicles from various movement traffic streams. Inappropriate operations of a conflict area (e.g., signalized/unsignalized intersections, merging roadways) result in unstable traffic flow (i.e., stop-and-go traffic), which may exacerbate travel delay, energy consumption, emissions, driving discomfort, and safety risks. However, operations of conflict movements at a common conflict area may change in the advent of CDA technology. Cooperative automated driving system (C-ADS)-equipped vehicles use communication and automation technologies to allow them to coordinate with each other and with the infrastructure to maximize safety and network efficiency. C-ADS-equipped infrastructure components, such as CARMA Streets, enable the infrastructure to be an active participant in the coordination of vehicle needs—especially special classes of vehicles, including transit. C-ADS-equipped vehicles and intersections are part of a connected ecosystem—which relies on V2V, vehicle-to-infrastructure (V2I), and infrastructure-to-vehicle (I2V) communications—in which each component plays a role to help improve the network. For example, facilities at a common conflict area can be equipped with traffic sensors, edge processors, and communication networks (e.g., DSRC systems) to help support C-ADS-equipped vehicle coordination.

A connected ecosystem combined with the current level of vehicle automation provides an opportunity for traffic flow improvements at a common conflict area that may produce mobility, safety, and environmental benefits. With these emerging technologies, the passing sequence of C-ADS-equipped vehicles at an intersection can be improved with proper coordination (e.g., allowing movements without conflict to take place simultaneously at an intersection rather than only allowing one vehicle to proceed at the intersection at a time) to increase traffic throughput.

Furthermore, vehicles can be aware of downstream traffic and the conflict area’s conditions so they can determine the approximate time they can enter the conflict area. Special classes of vehicles, including transit vehicles (e.g., bus rapid transit (BRT), light rail, express, local, and streetcars), may receive preferential treatment by clearing queues to allow them to reach a nearside stop or cross the stop bar earlier than they would without preferential treatment. Among various CDA applications related to conflict areas, control strategies near signalized intersections have received increasing attention because they are capable of communicating with traffic signal controllers and receiving real-time signal phase and timing (SPaT) information. These control strategies usually have two aspects. First, the traffic signal timing plan can be optimized to efficiently serve different traffic approaches according to their demands. Second, C-ADS-equipped vehicles can be controlled to simultaneously smooth their trajectories (i.e., paths vehicles follow in space as a function of time) to minimize fuel consumption, driving discomfort, and travel delay. A number of studies have been conducted on these two aspects. On the traffic signal side, several studies aim to optimize the signal timing plan to improve the traffic efficiency (see references 4, 5, 6, 7, 8, and 9).

OPPORTUNITIES FOR CHANGES

The emergence of CDA leverages V2V and V2I communications to create opportunities for vehicles to share information and cooperate. This feature of CDA creates improvements in TSMO and provides opportunities to improve TM on arterial roadways. Similar to the levels of automation defined in SAE J3016,(1) the new standard, SAE J3216,(2) defines classes of cooperation. The classes address different capabilities of a C-ADS-equipped vehicle that would affect its ability to cooperate with other CDA participants (e.g., vehicles and infrastructure). Figure 1 summarizes the cooperation classes. Table 2 shows examples of CDA features relating to cooperative traffic signals at intersections and considering different cooperation classes. A number of these examples are taken from the SAE J3216 standard. However, the effects of different cooperation classes defined in SAE J3216 have not been investigated.



RELATIONSHIP BETWEEN CLASSES OF COOPERATIVE DRIVING AUTOMATION (CDA) J3216 AND LEVELS OF AUTOMATION J3016

			Partial Automation of DDT		Complete Automation of DDT		
		SAE LEVEL 0	SAE LEVEL 1	SAE LEVEL 2	SAE LEVEL 3	SAE LEVEL 4	SAE LEVEL 5
		No driving automation (human does all driving)	Driver assistance (longitudinal OR lateral vehicle motion control)	Partial driving automation (longitudinal AND lateral vehicle motion control)	Conditional driving automation	High driving automation	Full driving automation
NO COOPERATIVE AUTOMATION		E.g., Signage, TCD	Relies on driver to complete the DDT and to supervise feature performance in real time		Relies on ADS to perform complete DDT under defined conditions (fallback condition performance varies between levels)		
CDA CLASSES							
SAE CLASS A STATUS SHARING	Here I am and what I see	E.g., Brake lights, traffic signal	Potential for improved object and event detection[1]		Potential for improved object and event detection[2]		
SAE CLASS B INTENT SHARING	This is what I plan to do	E.g., Turn signal, merge	Potential for improved object and event detection[1]		Potential for improved object and event detection[2]		
SAE CLASS C AGREEMENT SEEKING	Let's do this together	E.g., Hand signals, merge	N/A		C-ADS designed to attain mutual goals through coordinated actions		
SAE CLASS D PRESCRIPTIVE	I will do as directed	E.g., Hand signals, lane assignment by officials			C-ADS designed to accept and adhere to a command		

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[1] Improved object and event detection prediction through CDA class A and B status and intent sharing may not always be realized, given that Level 1 and 2 driving automation features may be overridden by the driver at any time and otherwise have limited sensing capabilities compared with Level 3, 4, and 5 ADS-operated vehicles.

[2] Class A and B communications are two of many inputs to an ADS' object and event detection and prediction capability, which may not be improved by the CDA message.

DAS = driving automation system; DDT = dynamic driving task; N/A = not applicable; TCD = traffic control device.

Figure 1. Chart. Overview of SAE International cooperation classes and automation levels.(2)

Table 2. Examples of cooperative signalized intersection features.

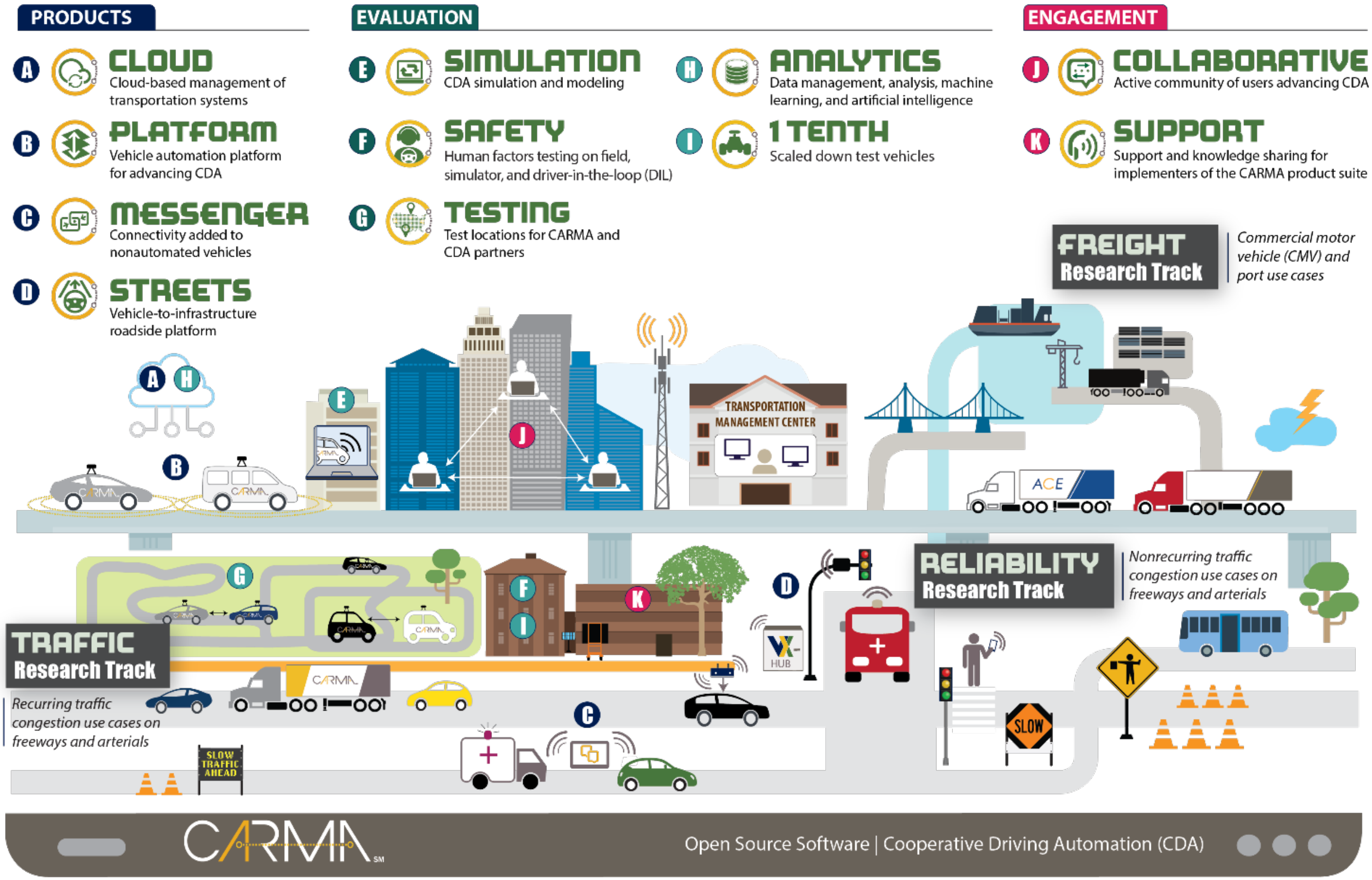
Feature	Class of CDA	CDA Device Transmission Mode and Directionality	Information Exchanged	Level of Functionality
Signal priority	A) Status sharing	One-way: C-ADS-equipped vehicles → RSE	Vehicle location, speed, and priority status (e.g., transit vehicle that is behind schedule)	Enabling signal timing changes based on the approaching vehicle
Eco-approach and departure	A) Status sharing B) Intent sharing	One-way: RSE→ C-ADS-equipped vehicles	SPaT messages	Enabling C-ADS-equipped vehicles to plan their motions based on the future signal phase that would otherwise be unavailable
Tandem approach and departure	C) Agreement seeking	Two way: C-ADS-equipped vehicles → RSE RSE → C-ADS-equipped vehicles C-ADS-equipped vehicles → C-ADS-equipped vehicles	SPaT messages Velocity profile Negotiations results	Enabling SPaT changes based on the approaching vehicle Enabling C-ADS-equipped vehicles to plan their motions and optimize their velocity based on the future (and possibly optimized) signal phases and the status of the other vehicle Supporting more efficient motion plans with increased reliability and look-ahead distance to reduce energy consumption and emissions

RSE = roadside equipment.

Note: In practice, one-way transmission will typically send the message to multiple CDA devices in the vicinity.

To fill the existing research gaps, this ConOps proposes an edge computing-based cooperative control framework for C-ADS-equipped vehicles, including passenger vehicles as well as transit vehicles, at a signalized intersection in the TSMO context. This ConOps serves as part of the CARMA framework and distinguishes between the levels of vehicle automation and classes of vehicle cooperation.

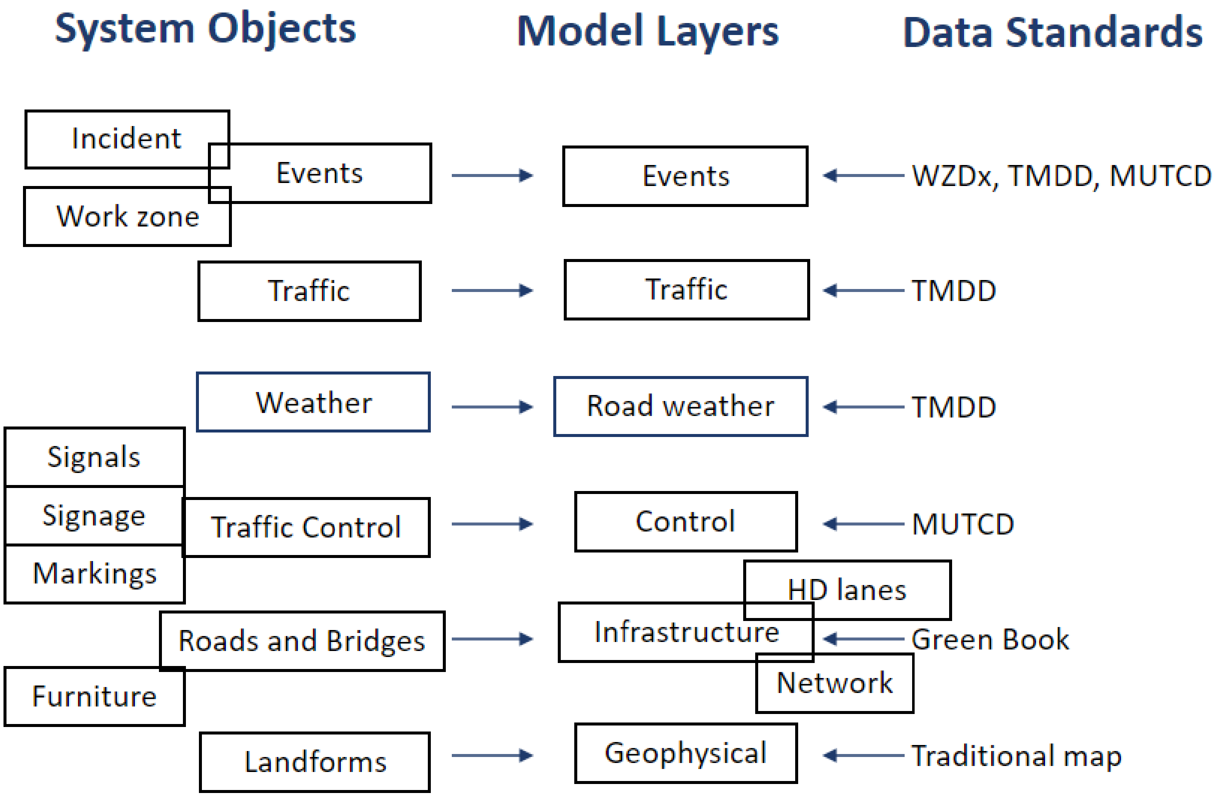
The CARMA framework is a platform for R&D of emerging automated driving and vehicle-to-everything (V2X) communications. Figure 2 illustrates the CARMA ecosystem, which is composed of open-source software products, evaluation and testing support tools, and an engagement and support community.



Source: FHWA.

Figure 2. Illustration. CARMA ecosystem.[(10)]

The CARMA products provide a framework for CDA application development. CARMA Cloud provides an overall system-level capability to integrate TSMO strategies utilizing information from a variety of different systems. Figure 3 illustrates the system objects and layers that represent different TSMO systems, including work zones, traffic, weather, traffic control, roads and bridges, and landforms. Each TSMO system contains a collection of system objects that represent the key entities and capabilities to create model layers of information. Many of the system objects are created based on standards that have been developed to support interoperability and uniformity across the different systems. Utilizing a cloud-based platform for this information integration provides a powerful capability for the development of CDA applications for other transportation needs such as TM.



Source: FHWA.

Institute of Transportation Engineers. 2020. *Traffic Management Data Dictionary (TMDD) Standard v3.1 for the Center-to-Center Communications*. Washington, DC: ITE. https://www.ite.org/technical-resources/standards/tmdd/3-1/, last accessed February 10, 2022.

FHWA. 2012. *Manual on Uniform Traffic Control Devices for Streets and Highways 2009 Edition*. Washington, DC: FHWA. https://mutcd.fhwa.dot.gov/pdfs/2009r1r2/pdf_index.htm, last accessed February 10, 2022.

HD = high definition; WZDx = work zone data exchange; TMDD = *Traffic Management Data Dictionary*; MUTCD = *Manual on Uniform Traffic Control Devices*, Green Book = *A Policy on Geometric Design of Highways and Streets.*

Figure 3. Diagram. CARMA Cloud components.(11,12,13)

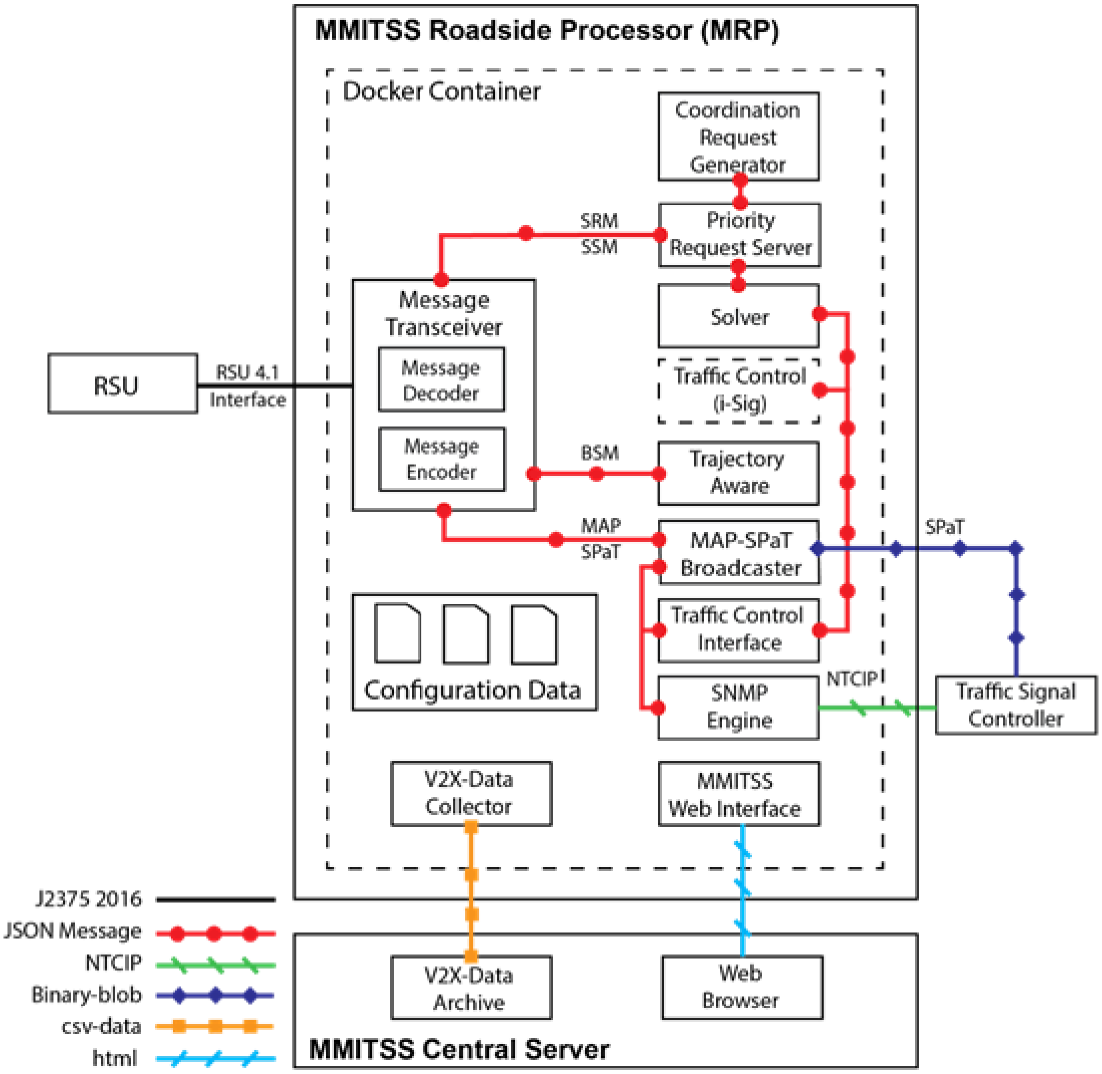
CARMA Streets is a relatively new addition to the CARMA ecosystem. CARMA Streets provides roadside edge computing that integrates communication between the infrastructure and CDA-equipped vehicles as well as other connected vehicles. CARMA Streets provides the capability for real-time applications as part of CDA applications.

CARMA Platform provides a research and testing platform for vehicle automation. It has been applied to demonstrate advanced CDA capabilities, such as CACC, eco-driving, and other automated capabilities. CARMA Messenger is a vehicle platform for communicating with nonautomated connected vehicles.

In addition to the emergence of CDA and the development of the CARMA ecosystem, the Connected Vehicle Pooled Fund has led the development of the Multimodal Intelligent Traffic Signal System (MMITSS), which provides intelligent priority-based traffic signal control using data from connected vehicles.(14,15) Figure 4 and figure 5 show the software architecture of MMITSS. MMITSS has components that are deployed on the roadside (called the MMITSS roadside processor (MRP) as shown in Figure 4), including a central server that supports data archiving and a web-based user interface and components that are deployed on the vehicle (called the vehicle-side processor (VSP) (figure 5)).

Both the VSP and MRP have message transceivers that encode the protocol for talking to roadside unit (RSU) and onboard unit (OBU) devices as well as a message library that can pack and unpack the SAE J2735 messages.(16) The VSP hosts the priority request generator that is responsible for locating the vehicle on the map—based on the local global positioning system (GPS) position and the SAE J2735 MAP (broadcast of data describing physical intersection geometry) message received by the OBU—and broadcasting a signal request message (SRM). The VSP has a special lights and siren manager component that can sense the lights and siren circuit on an emergency vehicle (e.g., firetruck, ambulance, police car). In addition, a data capture component called "V2X data client" archives data from the other VSP components. Because the VSP does not have a persistent Internet connection, the V2X data compressor manages the captured data by compressing and deleting the oldest data to ensure the device's storage is adequate.

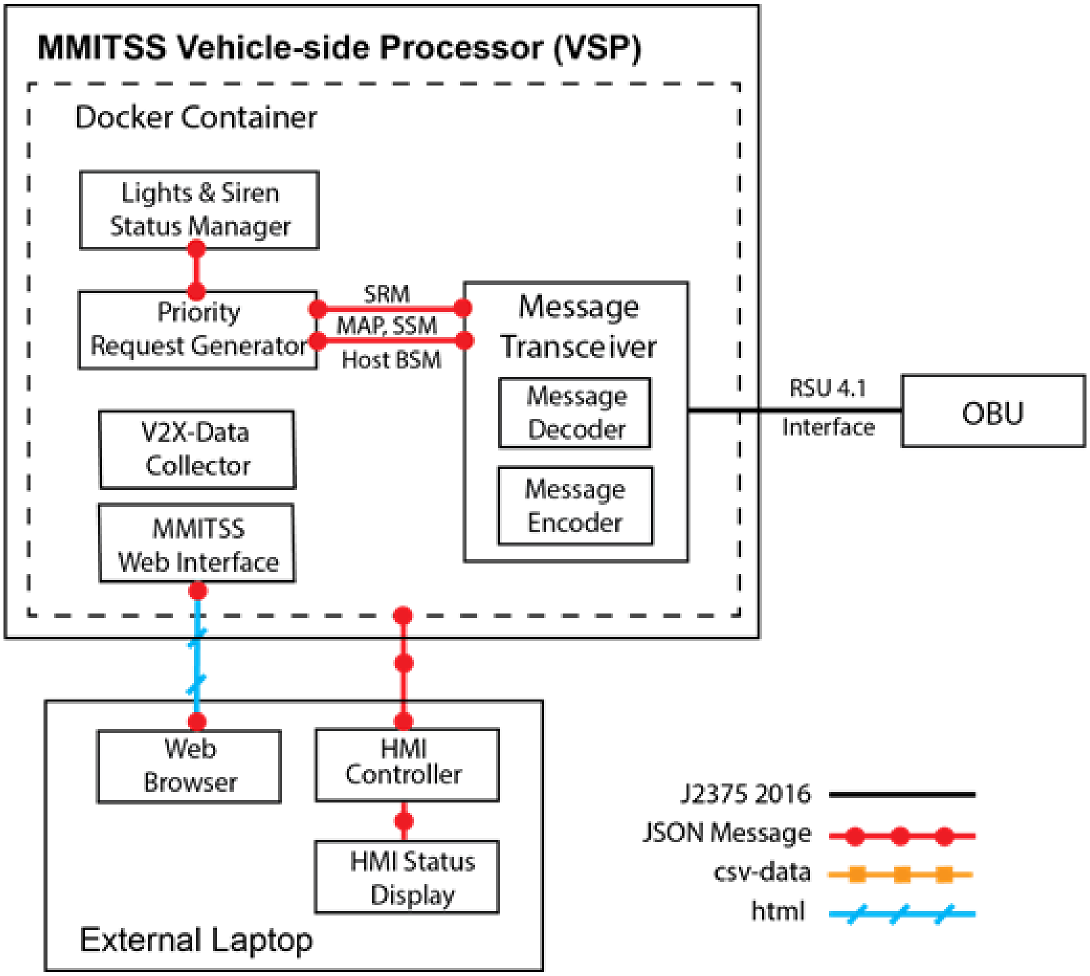
The MRP hosts the algorithms that realize the MMITSS intelligent priority control by using the connected vehicle data. When a vehicle broadcasts an SRM, the MRP message transceiver will forward it to the priority request server (PRS). The PRS is responsible for collecting and managing requests from multiple vehicles and from the coordination request generator. The reason for this design is because MMITSS implements a coordinated traffic signal control as a form of priority. Given a set of active priority requests, the priority request solver will solve an optimal scheduling problem to determine the desired traffic control schedule that is sent to the traffic control interface for implementation on the traffic signal controller though National Transportation Communications for Intelligent Transportation Systems Protocol (NTCIP) objects (call, hold, force-off, and omit).(17) The traffic signal controller provides SPaT data that are modified by the MAP-SPaT broadcaster to include the MMITSS control schedule. Currently, the trajectory-aware and intelligent traffic signal control (i-Sig) applications are not utilized in MMITSS.(7) They require 20–30 percent minimum market penetration of connected vehicles to be effective. The emergence of CDA, the CARMA ecosystem, and MMITSS provides a strong case for creating a new effective TM system for signalized arterials.



Source: FHWA. Adapted from Connected Vehicle Pooled Fund Study, MMITSS phase 3 development, DOT Dynamic Mobility Application Program.

SSM = signal status message; BSM = basic safety message; HMI = Human-Machine Interface; HTML = HyperText Markup Language; JSON = JavaScript Object Notation; CSV = comma-separated values; SNMP = Simple Network Management Protocol.

Figure 4. Diagram. Software architecture of the MRP.(14,18)



Source: FHWA. Adapted from Connected Vehicle Pooled Fund Study, MMITSS phase 3 development, DOT Dynamic Mobility Application Program.

Figure 5. Diagram. Software architecture of MMITSS VSP.(14,18)

TSMO STAKEHOLDERS

Stakeholders are people and entities influencing travel in the transportation environment. Stakeholders may include transportation users engaged in travel on publicly accessible roadways, emergency responders, transit vehicles, transit riders, pedestrians, and infrastructure owners and operators (IOOs). This section discusses transportation users and IOOs and their corresponding needs.

Transportation Users

A transportation user is a traffic participant on or adjacent to an active roadway used to travel from one location to another. For TSMO, motorized vehicles, including transit vehicles, whether human-driven or automated, are the main users of the traffic systems at intersections. Transportation users' needs are as follows:

- Smooth, low-stress, and fast travel.
- Reliable travel times.
- Energy-efficient and safe trips.
- Accurate information to make optimal decisions about driving tasks (decision support systems).

Integrating CDA technology into TSMO, from the transportation user's perspective, may support and enhance the following improvements:

- Smoother, faster, and lower-stress travel: Providing traffic signal priority for transit vehicles can reduce traffic signal delay.(4,5,6) This reduction improves the quality of transit service and makes it a more attractive mode alternative for travelers. C-ADS transit vehicles may reduce fuel consumption when they are provided with SPaT data that will enable them to adjust their trajectories when approaching a signalized intersection, where they might be delayed.

- Greater operational efficiency and travel time reliability: Delivering intelligent traffic signal priority can improve travel time reliability by reducing traffic signal delay and allowing vehicles that are behind schedule or have longer headways than desired to return to the designed schedule/headway.(7,8,9)

- Improved traffic safety: Utilizing CDA technology can reduce the number of vehicle crashes. The National Highway Traffic Safety Administration estimates the combined use of V2V and V2I communications has the potential to significantly reduce unimpaired driver crashes.(19)

Table 3 identifies four categories of transportation users and the characteristics and needs of each category.

Table 3. Transportation user characteristics and needs.

Driver	Transportation User Category	User Characteristics and Needs
Human driving	Regular human driver	• Regular human drivers have neither connectivity nor automation capability. • Regular human drivers have uncertain driver behaviors. • Needs align with general user needs.
Human driving	Transit vehicle human driver	• Transit vehicle human drivers have training as highly skilled commercial vehicle operators and generally follow agency operating policies. • Needs align with fleet operator needs.
Human driving	Connected human driver	• Connected human drivers receive additional traveler information and can make better informed travel decisions. • Needs align with general user needs.
Automated driving	Nonconnected ADS-equipped vehicle	• Nonconnected ADS-equipped vehicles operate independently, rely on local sensor information and automated control software, and usually have conservative behavior to provide increased comfort and safety margins. • Needs include accurately sensing local traffic conditions and actuating control of vehicles to ensure safety and travel efficiency.
Automated driving	C-ADS-equipped vehicle	• Compared with ADS-equipped vehicles, C-ADS-equipped vehicles operate by partnering with other CDA participants in the traffic stream, including the infrastructure, to improve overall traffic performance. • Needs include relying on the availability of other vehicles to perform cooperative actions and improving overall system safety and efficiency while guaranteeing individual vehicle travel experiences.

Infrastructure Owners and Operators

IOOs are traffic participants who provide, operate, and maintain roadways and supporting infrastructure for the mobility needs of transportation users. IOOs include public, public–private, or private sector entities that operate in accordance with applicable laws at the Federal, State, or local levels. Transit providers can be either public, public–private, or private sector agencies that provide a variety of transit services (e.g., BRT, express, local, commuter rail, light rail, streetcar, and demand responsive services), so that travelers can meet their travel needs by choosing alternatives to personal vehicles.(4,6,7)

The primary goal of IOOs is safe and efficient traffic management. This management practice includes monitoring and managing traffic and the factors affecting traffic flow, such as incidents, weather, intersections, dissemination of routing information, and other actions that increase traffic flow efficiency. IOOs may have the following goals:

- Reducing recurring congestion.
- Improving reliability and safety.
- Reducing travel times, fuel consumption, and emissions.
- Maintaining and increasing use of alternative and emerging transportation modes, such as transit or car-sharing options. Connected and automated vehicles are considered a separate mode by travelers.

From the perspective of IOOs, TSMO may support and enhance the following advances:

- Faster realization of efficiency goals: Adopting CDA early at existing intersections may enable improved transit operations and give IOOs greater congestion management abilities to increase throughput, enhance safety, and improve driver experience. These benefits may increase as the number of C-ADS-equipped vehicles using the intersection increases compared with the total number of users. However, these benefits may also reduce the number of transit vehicles required to serve a transit route.

- Maximized resource utilization for more efficient solutions: Enhancing reliability and improving transit operations by reducing travel time can encourage travelers to switch modes and utilize transit to meet their travel needs.(6,9) Traditional approaches to managing congestion, such as capacity expansion, are increasingly facing funding constraints and inherent limitations in alleviating transportation problems. CDA technologies are operational strategies that offer the potential for innovative solutions to congestion and travel time variability at intersections.

- First-mover advantage acquisition: Managing their vehicle fleets and having close partnerships with traffic operations departments/agencies gives transit agencies first-mover advantage. If operators currently primed to accommodate C-ADS-equipped vehicles on their facilities do not voluntarily test and advance this technology, third parties outside the operators' organizations are likely to fill that role and dictate the direction of CDA technology development. This direction may or may not be in line with a specific agency's goals or organizational capacity.

- Organizational evolution to accommodate the future of mobility technology: By responding to rapid technological change, organizations may be more likely to thrive in this era of rapid technological enhancement in the transportation field.

JUSTIFICATION FOR, AND NATURE OF, CHANGES

The transportation industry is moving toward improving safety with ADS by enhancing various vehicle technologies (i.e., levels of automation and ubiquitous sensing using automated vehicle sensors). As more advanced sensing and computing capabilities are integrated with ADS, two key questions need to be considered: What changes must take place to enable CDA system deployment? What additional capabilities and possibilities can be expected, including deployment of CDA technology-compatible infrastructure systems? This section discusses the nature of those changes.

Organizational/Institutional Changes

The following organizational/institutional changes can be implemented to enable deployment of CDA systems:

- Adopt a systems engineering process approach: Develop a ConOps for the system (regional level) and for the corridor in question. A systems engineering process is important for developing operational scenarios to accommodate CDA applications on intersection facilities.

- Develop a performance management system: Design a performance management system that collects and processes relevant data to determine whether system goals and performance targets for all CDA applications and operational alternatives are being achieved. C-ADS-equipped vehicles aligned with agency performance standards and holistic data requirements can help transportation agencies leverage data sources across the organization.

- Develop a data collection and management system: Create a system in which data can be placed in, or be accessible from, a common data environment. Obtain all relevant data in realtime from the various vehicles, onboard sensors, wireless devices, RSUs, roadway traffic sensors, weather systems, message boards, and TM systems.

- Include accurate data from a variety of sources:

    - Real-time traffic data: These data include vehicle speed and location information collected and disseminated by vehicles as part of a connected system. They also include traditional detection sources (e.g., inductive loop detectors, overhead radar, closed-circuit television cameras) that provide traffic data for the system.

    - Traffic signal plan data: These data include information on planned SPaT at signalized intersections from traffic signal controllers.

  - Traffic signal timing data: These data include the actual SPaT data at signalized intersections from traffic signal controllers. The actual data may differ from the planned data if the control methods include actuated, adaptive, and priority traffic signal controls.

  - Transit system data: These data include information on the current status of transit vehicles, including the vehicle occupancy, schedule adherence, lateness, or headway delay.

  - Weather condition data: These data include information on infrastructure-based road weather information systems and third-party weather data feeds, which can supplement vehicle-acquired weather data.

  - Pavement condition data: These data include information on real-time pavement surface conditions (e.g., dry, wet, snowy, iced, salted) that can be provided by in-pavement sensors.

  - Crowdsourced data: These data, which can be collected from platforms that have large installed user bases, can supplement data from other sources. Examples of crowdsourced data include smartphone applications that track a user's movements.

  - Historical data: These data can help improve the accuracy of traffic analysis and the prediction of traffic conditions.

Technical/Technological Changes

The following technical/technological changes can enable deployment of CDA systems:

- Procure new hardware to support technology:
  - Enable connectivity of infrastructures through a popular CDA communication protocol (e.g., DSRC or cellular vehicle-to-everything (C-V2X)).
  - Improve computing power of infrastructures by installing other hardware for deploying CDA applications.
  - Equip vehicles that use the CDA system with communication radios (OBUs, vehicle awareness devices), cameras, light detection and ranging technology, radar sensors, and other computational resources to implement the new control software.
- Develop/acquire new software:
  - Make use of the frequently collected and rapidly disseminated multisource data drawn from connected travelers, vehicles, and infrastructure.

  - Include a vehicle awareness application (e.g., an OBU installed either by the vehicle manufacturer or as an aftermarket integrated device); a personal wireless application (e.g., a smartphone or other handheld device); or another application that can collect, receive, and disseminate needed CDA data.
  - Enable systems and algorithms that can generate traffic condition predictions, alternative scenarios, and solution evaluations in realtime.
  - Contain microscopic and macroscopic traffic simulations.
  - Incorporate real-time and historical data.
  - Utilize traffic optimization models.
  - Encourage the constant evaluation, adjustment, and improvement of traffic optimization models (which requires an increase in computational capability and long-term storage of historical data).
  - Evolve and improve the software's algorithms and methods based on performance measurements.
  - Include emerging communication technology (e.g., DSRC or C-V2X) and software elements that enable the developed CDA system to act on the received information.

Operational Policy Changes

The operational policies of intersections are generally designed to accommodate traffic operations that meet the goals of IOOs. The following key questions can be used to determine proper operational policies of intersections:

- Who are the stakeholders and users of the system?
- What are the elements and capabilities of the system?
- Where are the affected systems?
- When and where will activities be performed?
- Why are the strategies being used?
- How will the system be operated and maintained?
- How will the performance of the system be measured?

All stakeholders should have clear expectations and incentives to participate. Improved throughput and smoother travel experiences are shared goals between IOOs and CDA applications. Users can also create agreements or compacts to set expectations, encourage investments, and measure performance.

Facility Infrastructure Changes

Depending on the facility type, configuration, operations, and existing equipment, the following categories of facility infrastructure changes might be needed:

- I2V infrastructure (e.g., RSE) to transmit central information to all vehicles within the communication area. If nonequipped vehicles are allowed, traditional dynamic message signs are used to convey public traveler information.
- Roadside sensors (e.g., video cameras, radars, or loop detectors) to detect or estimate real-time vehicle trajectories of nonequipped vehicles upstream of intersections.
- Striping and pavement markings.
- Appropriate signage to convey relevant information to all drivers (both equipped and nonequipped).

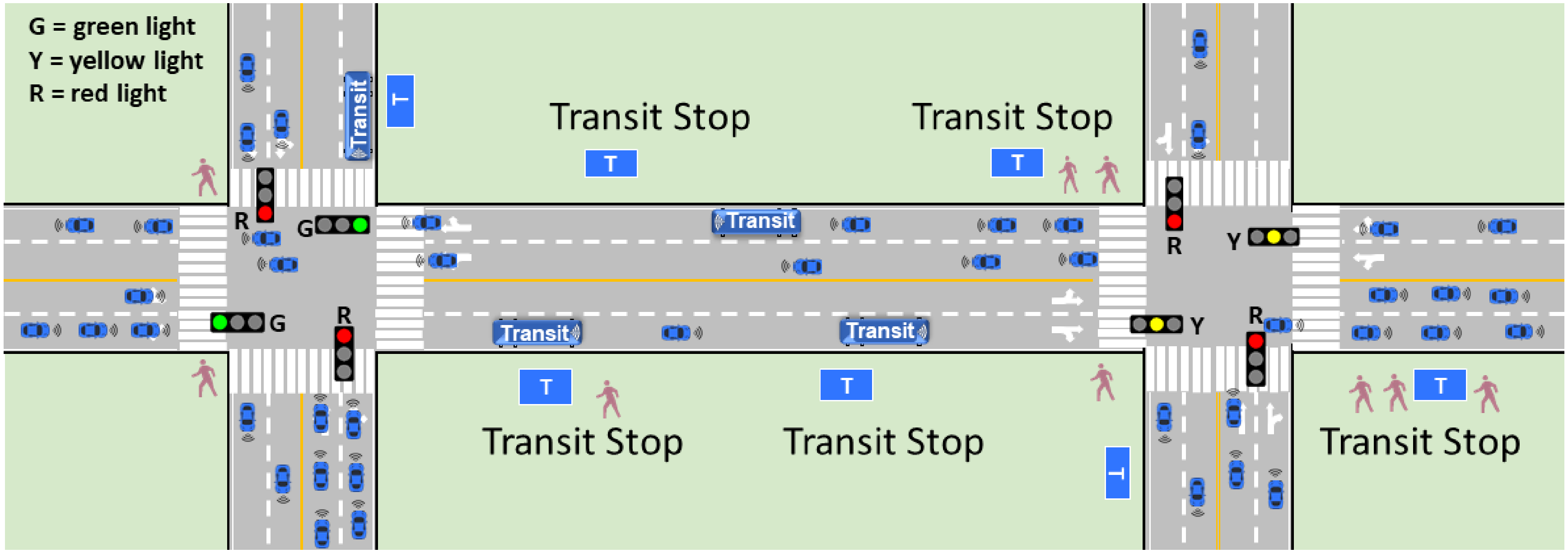
For early CDA deployment, infrastructure equipped with existing communication devices offers the opportunity to begin integrating CDA systems into traffic. Due to the enabled cooperation capabilities, even a small number of C-ADS-equipped vehicles might impact traffic operations at intersections and, therefore, improve system performance and an individual traveler's experience. Transit fleets are attractive early adopters for CDA technologies.

CHAPTER 3. OPERATIONAL CONCEPT OF THE PROPOSED SYSTEM

This chapter details the operational concept of the TSMO TM TSP UC. The chapter describes how automated driving technology can be used in a cooperative manner from when C-ADS-equipped transit vehicles enter the communication area of signalized intersections to provide traffic signal priority to reduce delays and improve the quality of service. The CARMA ecosystem and the MMITSS are key technological advances that enable a CDA approach to TSMO TM using TSP.

TECHNOLOGICAL FRAMEWORK FOR TSMO BASIC ARTERIAL TRAFFIC UC

This section describes the algorithm framework for an active traffic management feature to be used for the TSMO TM UC. Many TSMO strategies can be used for TM. This framework focuses on an arterial with several signalized intersections and transit stops, as illustrated in figure 6. At any time, several transit vehicles might be traveling on the arterial or on the cross streets. Each transit vehicle is serving a run on a route that has a defined schedule or headway operating plan. All transit vehicles are assumed to be equipped with CDA technologies, and each intersection is similarly equipped with an RSU, edge processor, and a traffic signal controller that provides SPaT data and is capable of providing priority for transit vehicles when requested. CDA-capable transit vehicles have high-definition (HD) maps that will be used to determine the vehicle approach, desired time of service, or estimated time of arrival (ETA) at the intersection stop bar. This decision can depend on several factors, including the presence of a nearside transit stop, schedule or headway lateness, and vehicle occupancy. If the transit vehicle does send a request for traffic signal priority, the RSU will forward the message to the edge processor, where it will be considered along with requests from other priority-eligible vehicles. At any single intersection, several transit vehicles may have requested priority.

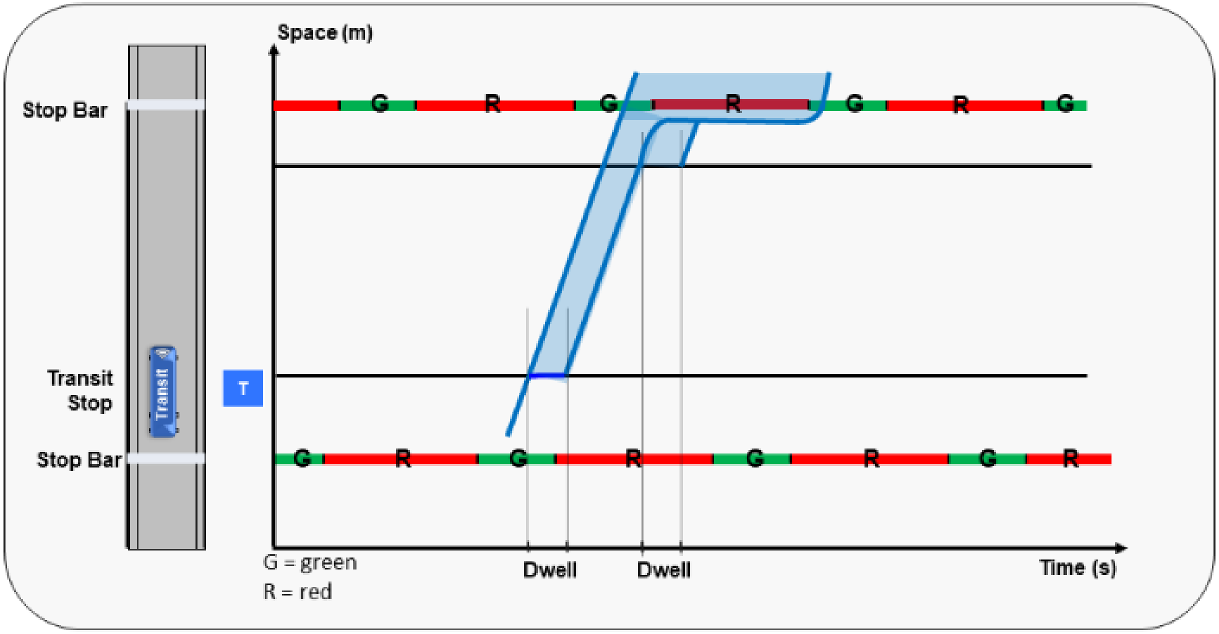


Source: FHWA.

Figure 6. Illustration. An arterial traffic signal corridor with transit operations.

The traffic signals in an arterial network are generally operated in a coordinated mode that provides progression for vehicles traveling along the primary direction of movement. Generally, coordination signal timing (cycle length, offset, and phase splits) design is based on general passenger vehicle flow along the route.

Transit vehicles may stop and dwell at the transit stops to allow passengers to board and alight. If transit vehicles stop and dwell, they might not progress along with the passenger vehicles and could fall behind the traffic signal progression provided by the coordination. Figure 7 illustrates this uncertainty in travel along an arterial. The transit vehicle travels along a trajectory until it reaches the transit stop. It will either pass the transit stop, if no passengers want to board or alight, or it will stop and dwell. The dwell time will depend on the number of boarding and alighting passengers and the vehicle type, and possibly, on the schedule/headway compliance. Once the vehicle departs the transit stop, it will travel to the next stop and the dwell process will repeat. If the total dwell time is too long, the vehicle will have to stop at the signal and wait for the next green traffic signal. The shaded area along the transit vehicle's trajectory illustrates the uncertainty in the trajectory.



Source: FHWA.

Figure 7. Illustration. Time space diagram showing the trajectory of a transit vehicle that stops at a transit stop to board and alight passengers.

TSP is a tool that can be used to provide several potential benefits. The TSMO TSP UCs include the following benefits:

- TSMO UC TSP-1: Adapting the traffic signal timing (e.g., green extension or early green) to the traffic signal to accommodate active priority requests. A green extension will hold a green signal green longer than it might have been green due to the TSP. An early green will provide a green indication earlier than it would have become green without TSP.

- TSMO UC TSP-2: Providing queue clearance to allow a transit vehicle to approach a nearside stop.
- TSMO UC TSP-3: Considering downstream congestion when making the decision to grant or deny an upstream TSP request.
- TSMO UC TSP-4: Providing a queue jump to allow a transit vehicle to depart a traffic signal before other lanes of traffic to allow them to change lanes if the route makes a left turn at the downstream intersection.
- TSMO UC TSP-5: Providing a hierarchical control system to address different types of transit service (e.g., BRT, express, local, and demand responsive service) in a system.

In addition to TSP, there are two other TM UCs of interest:

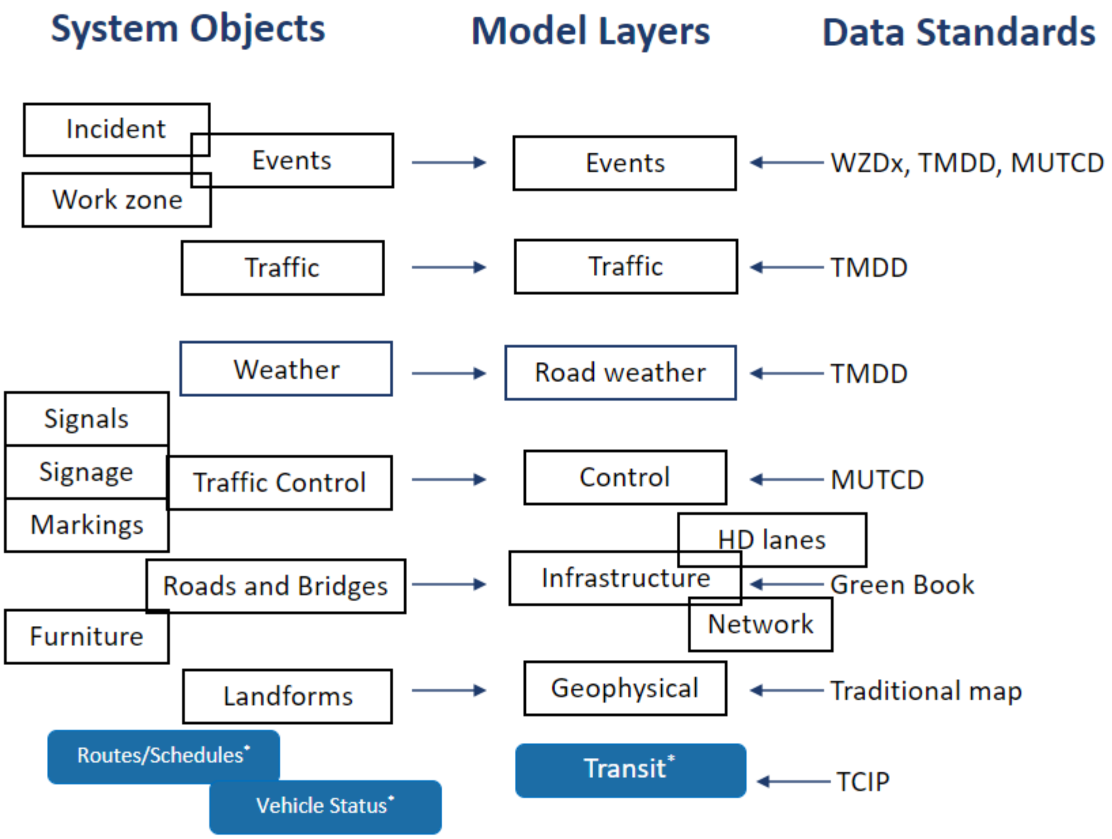
- TSMO TM UC-1: Bus (transit) lane intermittent priority (BLIP), which allows a lane that is reserved for transit vehicles to be shared with passenger vehicles when no transit vehicles are present.
- TSMO TM UC-2: Eco-transit driving that changes the transit vehicle's speed based on the SPaT data that indicate when the traffic signal will change to green.

TSMO UC TSP-1: Adaptation of the Traffic Signal Timing to the Traffic Signal to Accommodate Active Priority Requests

Adaptation of the traffic signal timing is one TSP tool that can provide benefits for transit. The transit vehicle, using its known location (e.g., GPS), can pinpoint itself on the HD map and send an SRM to the RSU that is then forwarded to the CARMA Streets-enabled edge processor. The MMITSS PRS, which will be running on the CARMA Streets processor, will receive the request and add it to the active request table, which is used to form the signal status message (SSM) that is forwarded to the RSU to broadcast as an acknowledgment to the requesting vehicle. The MMITSS priority request solver uses the traffic controller configuration and parameters (e.g., phases in use, minimum green time, yellow change time, red clearance time, maximum green, walk, and pedestrian clear) and current state (active phases and time spent in the current phases) to formulate an optimal scheduling problem that it solves to determine the best signal timing to minimize the delay to the transit vehicle within the signal controller constraints.

If there are multiple transit vehicles requesting priority on the main street and/or cross streets, the MMITSS PRS will consider the total (weighted) delay that the signal timing, or schedule, has on the collection of requests. Similarly, if the arterial is operated as a coordinated system, MMITSS will treat coordination as a form of traffic signal priority and schedule coordination requests based on the cycle length, offset, and phase splits. Transit priority requests and coordination requests are all considered in the development of the signal timing schedule. The use of the weights allows the operating agency to define a preferential policy for different modes and operating strategies.

The decision to request priority or to grant the request could depend on several factors, including schedule lateness, headway gap, and/or vehicle occupancy. The CDA-capable vehicle may know its status in terms of schedule/headway and occupancy. If the vehicle is on schedule/headway or if its vehicle occupancy is below a desired threshold, it might not request priority. If the CDA-capable vehicle does not have access to its status or the capacity to determine the request criterion, the PRS may be able to obtain the transit vehicle status through the TM system. This capability would be supported through the addition of a CARMA Cloud layer and data objects that can acquire transit data from a TM system. The CARMA Streets-hosted PRS would validate any requests through the CARMA Cloud transit layer. Figure 8 illustrates the idea of adding a transit layer and transit objects to CARMA Cloud.



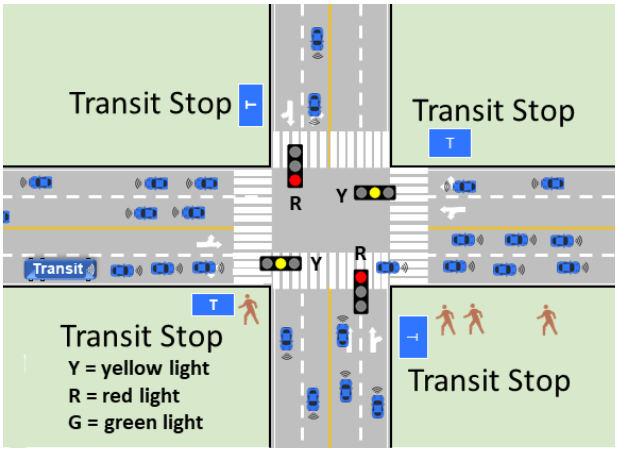
Source: FHWA.
*Potential new system objects for TM.
TCIP = transit communications interface protocol.

Figure 8. Illustration. CARMA Cloud with a new transit layer and transit objects.(11,12,13)

TSMO UC TSP1 is the most common TSP application and represents a CDA class A automation.(2) The transit vehicles send their statuses as SRMs to notify the infrastructure of their desire for preferential treatment at the traffic signal.

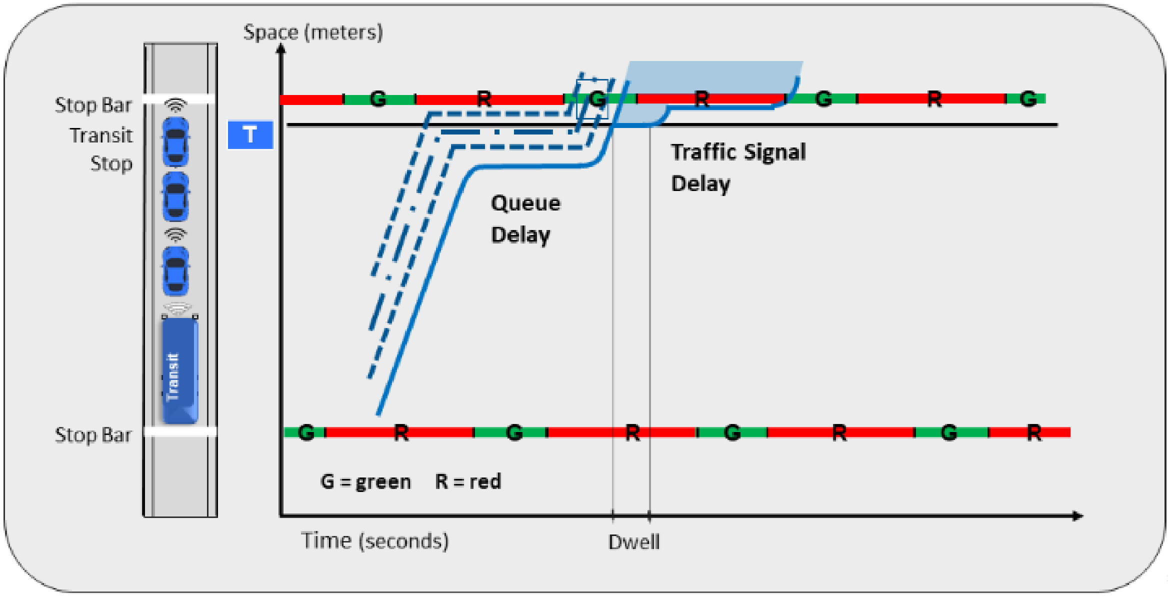
TSMO UC TSP-2: Queue Clearance to Allow a Transit Vehicle to Approach a Nearside Stop

Nearside transit stops are attractive to passengers who are boarding and alighting, especially when they are connecting to routes on crossing arterials. Figure 9-A and 9-B illustrate the nearside transit stop's situation and the need to clear the queue of vehicles between the transit vehicle and the transit stop.



Source: FHWA.

A. Bird's-eye view.



Source: FHWA.

B. Space-time trajectory plot.

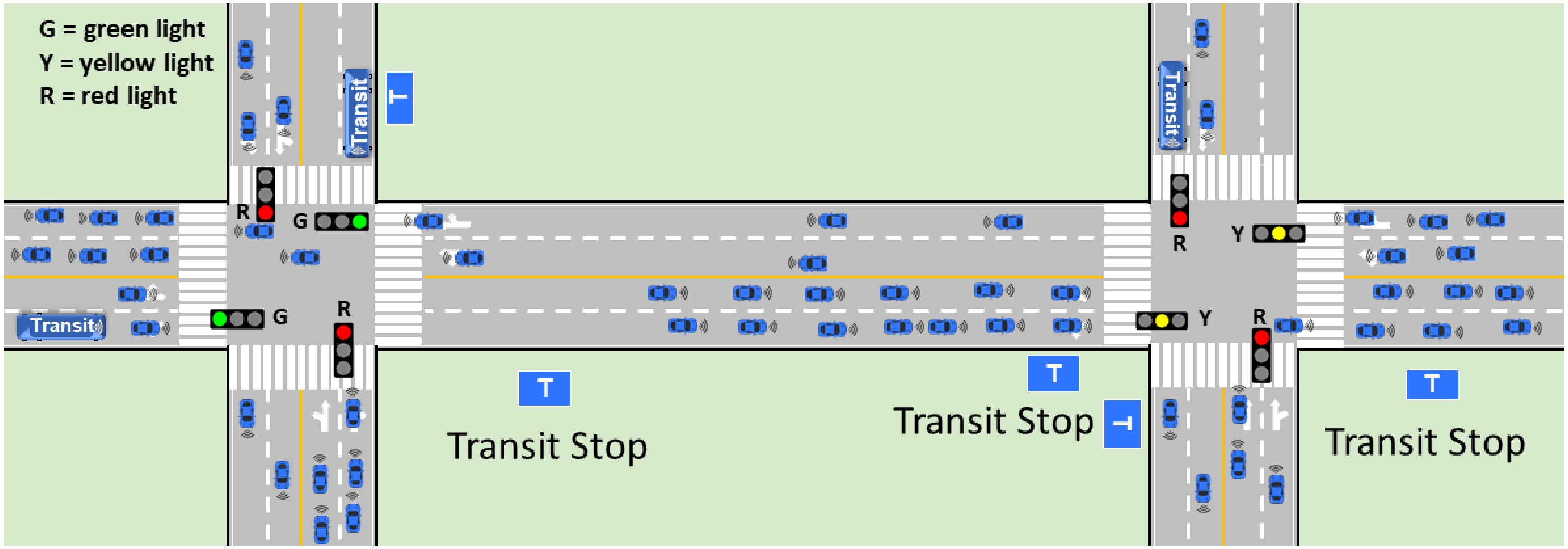
Figure 9. Illustration. Nearside transit stop with standing traffic queue.

An adaptation of the traffic signal timing can be made to clear the queue to allow passengers to board and alight during the red interval. In the situation shown on figure 9-A, three vehicles are queued as the signal transitions from green to yellow. A short extension of approximately 6 s would allow these vehicles to clear and the transit vehicle to reach the stop. Depending on the time required for the passengers to board and alight, an early green could reduce the traffic signal delay.

To determine the time required to advance the transit vehicle to the transit stop, it is necessary to estimate the queue length. If the queued vehicles are CDA vehicles, then this estimation is straightforward. If some of the vehicles in the queue are not CDA, then queue estimation requires additional functionality. If none of the vehicles are CDA vehicles, then only the transit vehicle position and velocity will be available to estimate the queue length and the time required to clear the queue and advance the transit vehicle to the transit stop. Additional information that can provide useful queue information may be available from a stop bar detector in the queueing lane. Infrastructure-based cooperative perception can provide the exact queue lengths. The queue clearance for nearside stop is a CDA class A application.(2) The transit vehicle sends an SRM to the infrastructure, and the infrastructure must know about the nearside stop. This information could be available from the CARMA Cloud transit layer or could be locally configured in the CARMA Streets edge processor and the MMITSS PRS.

TSMO UC TSP-3: Consideration of Downstream Congestion When Making the Decision to Grant or Deny an Upstream TSP Request

Providing priority for a transit vehicle at one intersection may not benefit the vehicle if there is congestion on the downstream arterial that will cause further delay. Figure 10 illustrates this UC. Congestion is defined as the failure of a traffic signal to fully discharge a queue during one cycle. Downstream congestion will significantly impact transit quality of service. If downstream congestion is present, a request for priority at an upstream signal will not improve the overall transit route performance and might add additional vehicles to the downstream congestion. Knowledge of downstream congestion can be derived from CDA vehicles as well as from more traditional performance measures that require infrastructure detection. This information can be available to the PRS to determine the value of providing priority through the CARMA Cloud traffic layer and the transit layer (to determine the route path and location of the congestion).

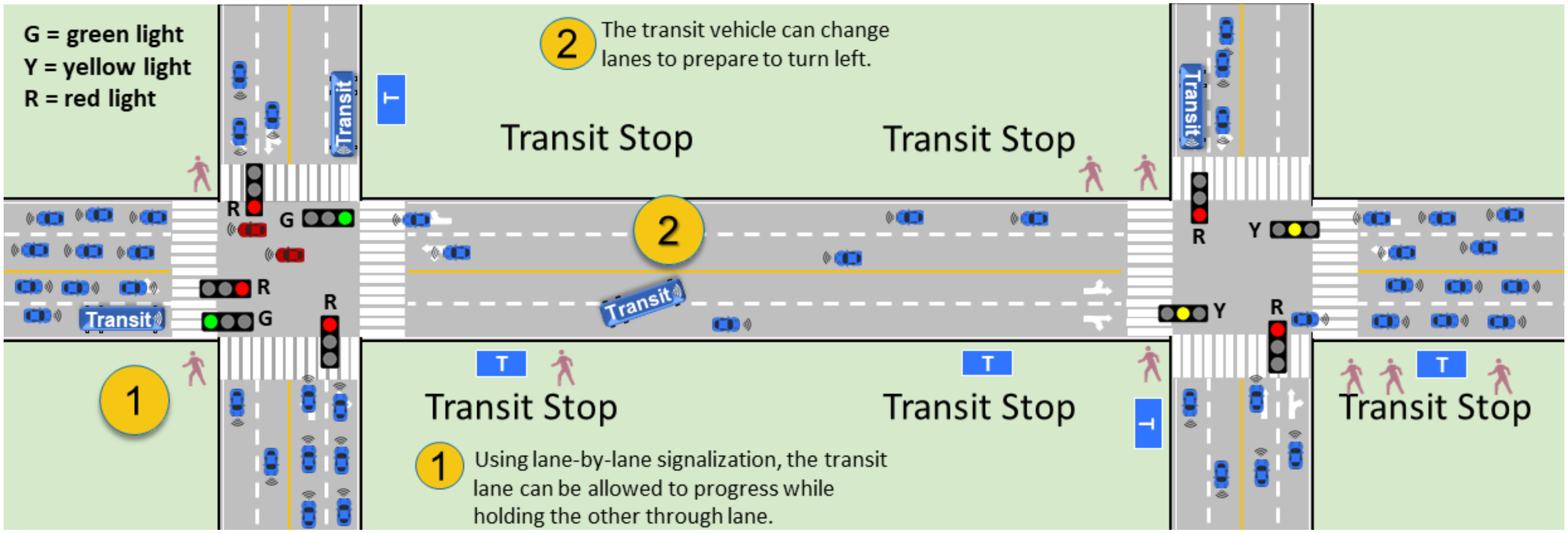


Source: FHWA.

Figure 10. Illustration. Downstream congestion along a transit route.

TSMO UC TSP-4: Providing a Queue Jump to Allow a Transit Vehicle to Depart a Traffic Signal before Other Lanes of Traffic to Allow Transits to Change Lanes if the Route Makes a Left Turn at the Downstream Intersection

A queue jump uses lane-by-lane signaling and allows a transit vehicle to move in front of other vehicles in other lanes. Figure 11 illustrates the queue jump UC. This treatment allows the transit vehicle to change lanes to make a turn (e.g., left turn) at a downstream intersection or to prevent a vehicle from making a turn in front of the transit vehicle. The latter case is useful for light-rail systems when the transit vehicle operates in the middle of the street and there is a left turn to the right of the light-rail tracks.



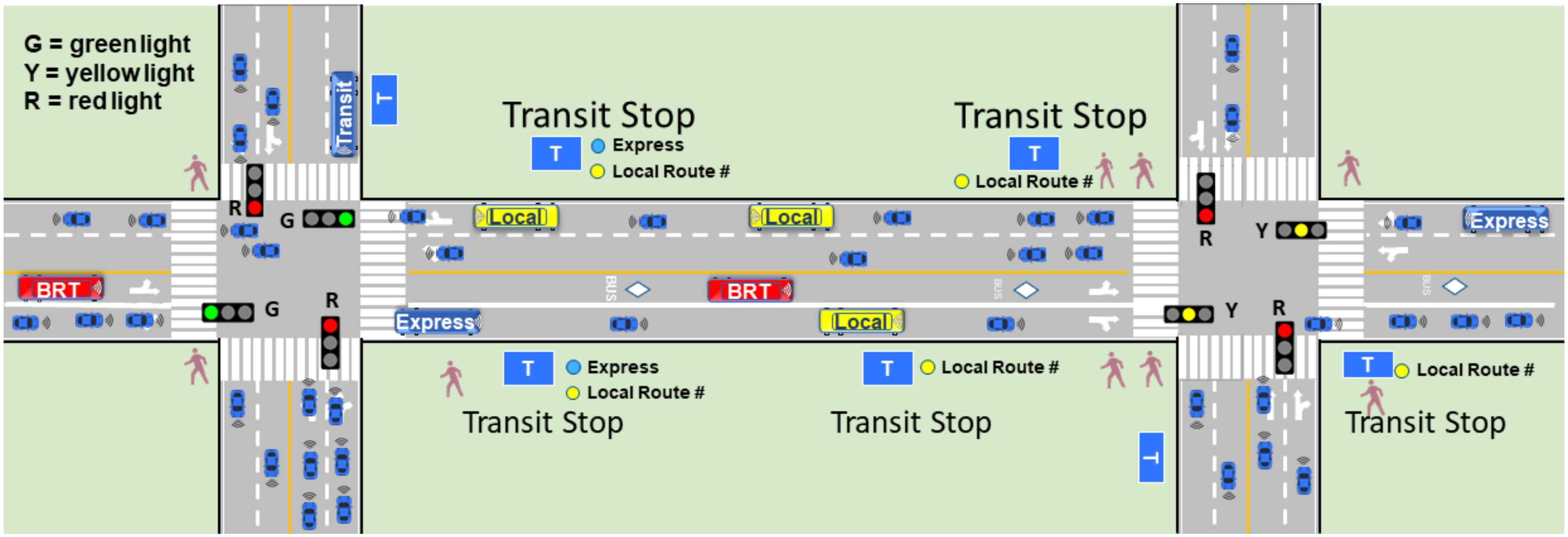
Source: FHWA.

Figure 11. Illustration. Queue jump UC.

The queue jump requires lane-by-lane signalization. This process is often used when there are exclusive transit-only lanes, but it can also be used in more general situations such as arterial streets. If there is a queue in front of the transit vehicle, the vehicles in the queue will be allowed to proceed when the lane receives a green signal. Because the vehicles in the queue depart ahead of the transit vehicle, they will not prevent the transit vehicle from making a lane change.

TSMO UC TSP-5: Providing a Hierarchical Control System to Address Different Types of Transit Service in a System

Many transit systems operate multiple routes and types of service along a corridor, as shown in figure 11. In this system, a BRT service utilizes the center lane and only has BRT stops at a few locations. The BRT stops are not shown in figure 11; the BRT service is shown to use the center lane, and the express and local transit stops are shown on the lane farthest to the right of the roadway. An express service includes possible multiple express routes that only include a few of the transit stops, whereas several local service routes have frequent stops throughout the system. Similar to TSMO UC TSP-1, the arterial traffic signal system may be operated as a coordinated system of traffic signals. Transit and traffic operating agencies may agree to an operating policy that provides a higher degree of priority for some types of service, such as BRT and express. The ability to establish a hierarchical policy provides the transit and traffic management agencies with a useful tool for ensuring traveler mobility through the corridor.



Source: FHWA.

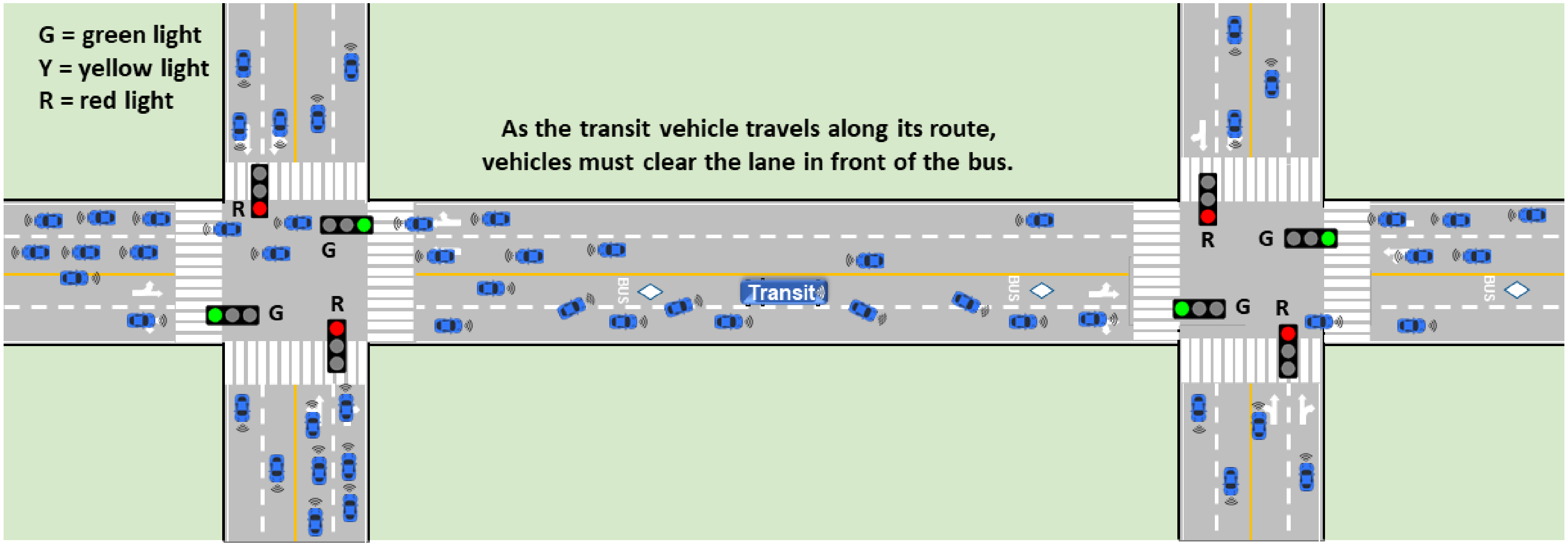
Figure 12. Illustration. An arterial with multiple transit routes and types of service.

All the transit vehicles are assumed to be CDA capable and can communicate with the RSUs at each intersection. Each vehicle will send an SRM, which either can be based on the type of service (e.g., BRT and express may always request), or may be sent if the transit vehicle is behind schedule/headway. Similar to TSMO UC TSP-1, the eligibility decision could be made at the roadside with information from the TM system through the transit layer in CARMA Cloud. The transit and traffic operating agencies may determine that some vehicles or routes should not receive traffic signal priority or may only receive priority during certain periods. The ability to set a hierarchical policy; define the types of service, routes, and schedule/headway lateness threshold; and integrate with coordinated traffic signal operations provide a powerful TM capability.

The hierarchical control system is a CDA class A application because the vehicles are only sharing their status (desire priority, late or behind headway).(2)

TSMO UC TM-1: Bus Lane Intermittent Priority That Allows a Lane Reserved for Transit Vehicles to Be Shared with Passenger Vehicles When No Transit Vehicles Are Present

Figure 12 shows a lane that is reserved for BRT service utilizing the right lane. Use of an exclusive lane provides a high level of priority but is a significant reallocation of roadway capacity for services that may be less frequent (e.g., 15- to 30-min headways) or services that only operate during defined times of the day. The BLIP concept, illustrated in figure 13, utilizes CDA class A/C capabilities to allow nontransit CDA-capable vehicles to share the lane.(12) Vehicles in the lane ahead of a transit vehicle are notified of the presence of a transit vehicle in the lane and are expected to change out of the lane. The notification can be shared between CDA vehicles or sent from the infrastructure to the vehicles on the downstream links. Vehicles are allowed to reenter the lane behind the transit vehicle.



Source: FHWA.

Figure 13. Illustration. BLIP.

One challenge for the BLIP operation occurs when traffic congestion limits the ability for CDA vehicles to change out of the lane designated for transit use. This challenge can be addressed using class C cooperative lane changing on capable vehicles. This capability makes the potential for BLIP deployment more attractive and feasible. BLIP is a class C CDA application because the transit vehicle is informing the other vehicles that it is approaching in a transit-designated lane and asking for their cooperation to change out of the lane.(2) The CDA vehicles can cooperate to create lane-change opportunities.

TSMO UC TM-2: Eco-Transit Driving That Changes the Transit Vehicle's Speed Based on the SPaT Data That Indicate When the Traffic Signal Will Change to Green

Operating expenses is a key factor in the operation of transit systems. Eco-transit driving is a CDA application adapted from the CDA eco-driving application that considers the traffic signal state through SPaT data, but it also considers the location of transit stops in making intersection approach trajectory decisions. If a transit vehicle is approaching a signalized intersection and the SPaT data indicate there will be some delay, the trajectory can be optimized for transit vehicle fuel or energy conservation. If there is a transit stop between the transit vehicle's location and the traffic signal, then the vehicle can plan its trajectory to include stopping at the transit stop before proceeding to the traffic signal. If the transit vehicle is requesting traffic signal priority, the SPaT data will change, based on the adapted signal timing, and the vehicle trajectory will need to be revised accordingly.

INFRASTRUCTURE CONFIGURATION AND NEEDS

This section describes technological and institutional infrastructure and explains the role of IOOs in developing CDA TM operating policies and procedures.

A key feature of CDA operations is the dynamic V2I interaction, in particular, the exchange of real-time vehicular and roadway information that an ADS-equipped transit vehicle can understand and share. This project considers RSE that includes an edge processor and a traffic signal controller that can be used to adapt traffic signal timing. The RSE can communicate to C-ADS-equipped vehicles, irrespective of the particular communication technologies, by using the appropriate protocols. C-ADS-equipped vehicles can also share their statuses and what they sense about the surrounding dynamic traffic environment for better static and dynamic world models. The two-way information exchange, which includes both cooperative perception and cooperative vehicle control, constitutes the foundation of CDA. For TM, intelligent infrastructure is also a key part of the automation. CDA participants, vehicles, and infrastructure may use this information to improve situational awareness and expand their operational design domains. The algorithm for several of these UCs leverages CARMA Cloud-based information to support sharing information between the TM system and the traffic signal control system. However, many of the UCs can be effective without the Cloud-based information.

A limited set of user needs relevant to operator–traveler interactions is available. Travelers are the primary beneficiaries but can also be information providers. Traffic operators, who work on behalf of the infrastructure, are the primary service and information providers. They receive information from C-ADS-equipped transit vehicles, process and analyze the information with all other available information, make appropriate changes to the traffic signal timing, and send the resulting pertinent information back to C-ADS-equipped vehicles. Table 4 shows a list of needs for road users and IOOs. In this table, road users are C-ADS-equipped transit and passenger vehicles, such that a one-way or two-way information exchange can occur between them and IOOs.

Table 4. Infrastructure needs for road users and responsibilities of road users and IOOs.

Road Users (C-ADS-Equipped Vehicles)	IOOs
Get maps that contain transit route and stop locations	Monitor traffic conditions
Get information on transit vehicle status, including schedule/headway lateness and vehicle occupancy	Estimate queues
Get information on traffic conditions downstream	Receive traffic condition information from travelers
Get information on weather conditions	Control traffic signal timing
Get information on accessible/assigned lanes	Control lane use
Get information on passengers requiring extra assistance boarding and alighting	Optimize signal timing considering different transit vehicle types and status
Get SPaT information	Inform travelers of the planned SPaT
Inform IOOs of observed traffic conditions	Inform travelers of the accessible lanes/assigned lanes
Inform IOOs of observed weather conditions	Inform travelers of traffic condition
Inform IOOs of their status, intents, transit vehicle occupancy levels	Inform travelers of weather conditions
	Inform travelers of accessible lanes

Based on the proposed control algorithm, the edge processor and intersection controller will exchange information for requesting and granting traffic signal priority for transit vehicles, as shown in table 5.

Table 5. Exchanges between RSE and vehicles.

RSE-to-Vehicle Priority Status and Signal Timing	Vehicle-to-RSE Cooperative Perception
• SSM (e.g., SRM acknowledgment). • SPaT plan. • Other vehicles' information. • Infrastructure-based cooperative perception such as queue lengths.	• SRM (e.g., request for signal priority). • Transit vehicle current status, intent, etc.

SUMMARY OF TSMO NEEDS AND REQUIREMENTS

This section describes the operational needs and functional requirements for C-ADS-equipped vehicles and the infrastructure. These needs and requirements are specified for different CDA cooperation classes and different components of the proposed control algorithm as follows:

- Static infrastructure data may include HD maps, speed limits, lane restrictions, and transit stop locations (by route).
- A C-ADS-equipped vehicle's status and intent data may include an identifier (ID) of the vehicle (e.g., license plate or temporary anonymous ID), vehicle type, location, speed, braking status, heading, priority position, desired time of service, ETA, intersection approach, lane, and vehicle role (e.g., transit, BRT, express, local, demand responsive). This dataset may vary across different cooperation classes.
- RSE advisory data may include acknowledgment information from a vehicle request for priority for each C-ADS-equipped vehicle; RSE signal data include the SPaT data. An edge processor and RSEs in all cooperation classes are needed because C-ADS-equipped vehicles must receive the SPaT data. However, edge processors might not be used for transferring information from one C-ADS-equipped vehicle to another if the V2V communication range is sufficient in the control area.

Table 6 provides a list of operational needs. Table 7 provides functional requirements for the C-ADS-equipped vehicles, RSEs, and central computer. These requirements are also specified for different cooperation classes.

Table 6. Operational needs for vehicles and infrastructure in TSMO TM UCs.

Actor	ID	Operational Need
CARMA Cloud to CARMA Platform to CARMA Messenger	TSMO TM UC-N01	Need to communicate transit schedule delay status to transit.
CARMA Platform to CARMA Messenger	TSMO TM UC-N02	Need to store and broadcast vehicle status and intent information (e.g., location, speed, and route). For transit, also need to include schedule information.
CARMA Platform to CARMA Messenger	TSMO TM UC-N03	For transit, need to send SRM to RSE once it is within the range of the RSE.
CARMA Cloud to CARMA Streets	TSMO TM UC-N04	For CARMA Streets, need to receive static infrastructure data (e.g., HD maps, speed limits, lane restrictions) from CARMA Cloud.
CARMA Platform to CARMA Messenger	TSMO TM UC-N05	Need to receive static infrastructure, vehicle-specific advisory, and SPaT data. For transit, also need to include priority request status information and

Actor	ID	Operational Need
		infrastructure-based cooperative perception data.
RSE	TSMO TM UC-N06	Need to receive vehicle status and intent information from C-ADS-equipped vehicles.
RSE	TSMO TM UC-N07	Need to receive SRM from transit.
RSE to CARMA Streets	TSMO TM UC-N08	Need to relay the received data to CARMA Streets.
RSE to CARMA Streets	TSMO TM UC-N09	Need to receive static infrastructure data, vehicle-specific advisory data, and SPaT data from CARMA Streets and broadcast this information.
CARMA Streets to RSE	TSMO TM UC-N10	Need to send SSM to RSE for broadcast to transit vehicles to acknowledge receipt of SRM.
CARMA Streets	TSMO TM UC-N11	Need to receive and store SPaT data.
CARMA Streets	TSMO TM UC-N12	Need to store data from various sources (e.g., transit, C-ADS-equipped vehicles, and traffic sensors).
CARMA Streets	TSMO TM UC-N13	Need to process data and calculate TSP-related variables (e.g., priority status, signal adaptation, queue length and dissipation estimation, speed advisory).
CARMA Cloud to CARMA Streets	TSMO TM UC-N14	Need to relay work zone and incident data to CARMA Streets.
CARMA Streets to signal controller	TSMO TM UC-N15	Need to communicate with the signal controller to adapt the signal timing.
CARMA Streets	TSMO TM UC-N16	Need to aggregate traffic information received from individual vehicles and sensors.
CARMA Cloud to CARMA Streets	TSMO TM UC-N17	For CARMA Streets, need to send the aggregate traffic information to CARMA Cloud.
All	TSMO TM UC-N18	Need to have proper cybersecurity platforms and strategies to protect and recover from cyber threats.

Table 7. Functional requirements for vehicles and infrastructure in TSMO TM UC.

ID	Functional Requirement	Cooperation Class(1,2)
TSMO TM UC-R01	A C-ADS-equipped transit vehicle, with at least cooperation class A, has an onboard computer with storage and computing functions.	A and above.
TSMO TM UC-R02	A C-ADS-equipped transit vehicle, with at least cooperation class A, broadcasts its location, speed, and heading. The communication frequency is approximately 10 Hz or more.	A and above (status data only for class A).
TSMO TM UC-R03	A C-ADS-equipped transit vehicle, with at least cooperation class A, determines the distance and time to the intersection stop bar and sends an SRM when traffic signal priority is desired. The vehicle may determine that it is not late or behind the desired headway and no priority is needed.	A and above.
TSMO TM UC-R04	A C-ADS-equipped transit vehicle, with at least cooperation class A, knows where transit stops are located and does not send an SRM until it has passed the transit stop, or it does send an SRM if the stop is a nearside stop.	A and above.
TSMO TM UC-R05	An edge processor at each intersection runs TSP algorithms (MMITSS) and communicates NTCIP to a traffic signal controller.(14,17)	A and above.
TSMO TM UC-R06	The central computer provides transit information, such as vehicle lateness and occupancy, to the edge processor at a signalized traffic intersection.	A and above.
TSMO TM UC-R07	The central computer provides downstream traffic congestion information to the intersection edge processor.	A and above.
TSMO TM UC-R08	RSE receives status and intent data from C-ADS-equipped transit vehicles, with at least cooperation class A, within the communication range. The communication frequency is approximately 10 Hz or more.	A and above.
TSMO TM UC-R09	RSE broadcasts the traffic signal status and intent data among C-ADS-equipped vehicles through DSRC or C-V2X communications within the communication range. The communication frequency is approximately 10°Hz or more.	A and above (optional for when CDA communication range is not enough and needs relay with the RSEs).

ID	Functional Requirement	Cooperation Class$^{(1,2)}$
TSMO TM UC-R10	RSE sends vehicle-specific advisory data and the determined SPaT through DSRC or C-V2X communications within its communication range. The communication frequency is approximately 10 Hz or more.	A and above.

Hz = hertz.

PERFORMANCE METRICS AND TARGETS TRAFFIC FLOW

The effectiveness of TSMO UCs can be evaluated by measuring the capability of positively impacting performance. Performance metrics are presented for traveler behavior and traffic flow.

Performance Metrics for Traveler Behavior

Performance metrics for evaluating vehicle operations during execution of this situation include the following traveler behaviors:

- Transit trip travel time: The time a traveler takes to travel from a desired origin to destination using a transit service. In a corridor, this time would include the time from when a traveler enters the corridor to when the traveler exits the corridor (or the time from when a traveler enters the corridor to the end of the traveler’s trip).

- Passenger vehicle travel time: The equivalent time for a traveler to make the same trip using a passenger vehicle rather than transit service.

- Transit schedule/headway lateness: The ability of transit vehicles to achieve a desired schedule/headway plan.

- Transit traffic signal delay: The amount of time a transit vehicle is stopped at a traffic signal, including the time in a traffic queue (e.g., when there is a nearside stop).

- Passenger vehicle traffic signal delay: The amount of time a nontransit vehicle is stopped at a traffic signal, including time spent in a traffic queue.

- Data exchanges during communication/negotiation: All data exchanges from V2V, V2I, and I2V that determine whether communication and/or the maneuver negotiations took place as designed. Data exchanges include the following data types:

    - Number of vehicles that request traffic signal priority.
    - Number of SRMs per vehicle request.
    - Number of attempts before a plan is accepted by all affected neighbors.
    - Frequency of packet loss.

- Message latency: Time difference between message origination on vehicle A to reading of message by infrastructure and vice versa. Latency time includes the time it takes to compose the message, the time it takes to send it from vehicle A's computer to vehicle A's OBU, the queuing time on vehicle A's OBU, the radio transmission time from vehicle A to the infrastructure, the message constitution and queueing time on the infrastructure's RSE, the transformation time from the infrastructure's RSE to the infrastructure's computer, the time required for retransmission in the case of message loss, and the time for the infrastructure's decomposition and reading time.

Performance Metrics for Traffic Performance

As shown in table 8, performance metrics for traffic performance evaluate the following impacts of TSMO UCs on traffic flow in corridors: traveler throughput (transit and nontransit travelers), traffic congestion (level of service), and sustainability.

Table 8. Summary of performance measures for TSMO UCs evaluation.

Category	Impact	Performance Measure
Traveler throughput	Increase in the number of travelers who can be served (e.g., passengers per vehicle)	Number of travelers passing through the corridor per hour
Vehicle throughput	Increase in traffic flow volumes	Number of vehicles passing through the corridor per hour
Throughput	Smoothness of traffic flow	Variability of speeds within traffic stream—for transit vehicles and nontransit vehicles
	Potential increase in delay for nontransit vehicles when priority is given to transit vehicles	Average traffic signal delay for nontransit vehicles
Sustainability	Impact on greenhouse gas emissions	Level of carbon dioxide, nitrogen oxide, and particulate matter-equivalent emissions
	Reduction in energy consumption	Amount of energy consumed
Traffic congestion	Potential impact in quality of service by shifting priority to transit vehicles	Level of service (per *Highway Capacity Manual*)(20)

Traveler Throughput and Transit

CDA technologies are expected to increase the throughput of travelers for transportation facilities by increasing the passenger-per-vehicle densities. Throughput can be quantified by measuring the number of travelers passing through a corridor per hour and the variability of speeds within a facility segment by mode (transit vehicles and nontransit vehicles). Transit vehicles stop at transit stops, which increases their travel time variability, but reducing the number of stops at traffic signals will improve their travel time variability.

Traffic Congestion

CDA technologies are applied to improve transit performance. This performance could impact other traffic traveling in the corridor. Vehicles traveling along with the transit vehicles may experience benefits, whereas those vehicles traveling across the transit vehicle routes may be negatively impacted. Traffic congestion can be measured by the level of service as defined in the *Highway Capacity Manual*.(20)

Traveler Throughput and Nontransit

CDA technologies are expected to improve the throughput of transit vehicles but could have a negative impact on nontransit vehicles that travel in a corridor. Throughput can be quantified by measuring the number of vehicles passing through a corridor per hour and the variability of speeds within a facility segment by mode (transit vehicles and nontransit vehicles). Transit vehicles stop at transit stops, which increases their travel time variability, but reduced stops at traffic signals will improve their travel time variability.

Sustainability

If CDA technologies improve the transit quality of service, then more travelers are expected to choose transit as their mode of travel. The mode shift to transit is expected to reduce greenhouse gas (GHG) emissions. In addition, smoother operations associated with CDA and TSP could lead to lower GHG emissions and energy consumption. Improved travel operations may induce travel demand, which could result in higher overall travel volume and increased GHG emissions and energy consumption, depending on the greatest modal growth. GHG emissions and energy consumption calculation usually relies on data previously obtained by simulation or on observed data. For the proposed UC, emissions and fuel consumption can be calculated using the speed profiles of transit and nontransit vehicles (trajectories) at high temporal resolution obtained by the simulation platform. The proposed performance measures include carbon dioxide, nitrogen oxides, particulate matter emissions, and the amount of energy (volume) consumed.

CHAPTER 4. OPERATIONAL SCENARIOS

This chapter identifies important TSMO TM operational scenarios to enhance TSMO in arterial corridors, where there is transit service. The operational scenarios also help with understanding the impact of early deployment of CDA participants and the UCs discussed in chapter 3 to address the needs of transit operations. Five operational scenarios are described. Each scenario may include one or more of the UCs discussed in chapter 3. The first operational scenario considers the basic use of traffic signal priority at each individual intersection in the corridor. This scenario is a CDA version of the common existing approaches to TSP. The second scenario extends the basic scenario to consider a corridor with multiple types of transit service and multiple routes through the corridor. The third scenario explores the use of CDA for BLIP. The fourth scenario considers the use of TSP, when there is a work zone that can cause a nonscheduled delay to the transit service. The fifth scenario considers the application of CDA transit eco-driving to reduce energy consumption and emissions. These scenarios are designed to cover all key features of the proposed control framework and to illustrate their potential benefits.

SCENARIO 1: ARTERIAL SYSTEM WITH TRANSIT OPERATIONS

This scenario represents basic TSP operations on a corridor and includes the application of UCs TSMO UC TSP-1 (signal timing adaptation) and TSMO UC TSP-2 (queue clearance) for cases when there is a nearside stop. This scenario is illustrated in figure 6 and figure 9. The traffic signals in the corridor are assumed to be operated as a coordinated system and have coordination signal timing plans (e.g., cycle length, offset, and phase spits) that were selected based on the traffic volumes for the time-of-day period.

In this scenario, transit vehicles operate in both directions based on a fixed schedule (e.g., with a transit vehicle every 10 min) on a major arterial and on the cross streets with a fixed schedule (e.g., with a transit vehicle every 15 min). As each transit vehicle enters the range of an RSU, it will check to see whether it is within the extent of the HD map and on an approach to a signalized intersection. If it is, it will form an SRM based on its speed and distance to the intersection stop bar.

The RSU will forward any received SRMs to the CARMA Streets edge processor, where the MMITSS PRS resides. First, the PRS will determine whether there are any transit stops between the vehicle’s current location and the intersection stop bar by using transit route information obtained from CARMA Cloud. If there is no transit stop, the PRS will check to determine whether the vehicle is behind schedule by using information obtained from CARMA Cloud. If the transit vehicle is not more than a configurable parameter late (e.g., 3 min), the PRS will label the SRM “on schedule” and not add it to the collection of active requests. If the transit vehicle is more than a determined threshold late, the PRS will add the SRM request to the collection of active requests and solve the optimal scheduling problem to determine the best signal timing (including coordination) to serve the set of active requests. If there is a stop, the PRS will determine the transit vehicle is a nearside stop. If the transit vehicle is not a nearside stop, or if the estimated queue does not extend beyond the transit stop, the PRS will hold the SRM in a pending state until the transit vehicle passes the transit stop.

Once the transit vehicle passes the transit stop, assuming the schedule lateness test showed a late vehicle, the PRS will add the SRM to the collection of active requests, and the optimal scheduling problem will be solved (including coordination) to determine the best traffic signal timing. Once the transit vehicle crosses the intersection stop bar, the transit vehicle will send a cancel SRM so that the transit vehicle's request can be removed from the collection of requests being considered.

This basic transit priority scenario in an arterial system captures several key operating characteristics as follows:

- Multiple vehicles may be requesting priority at a single intersection at a time.
- The traffic signals are operated as a coordinated system.
- Only vehicles that are later than a configurable threshold will receive traffic signal priority.

This scenario will allow performance to be evaluated to better understand the following effects:

- Benefits of TSMO-TSP on transit operations, including transit travel time, travel time variability, and the impact on nontransit vehicles.
- Impact of schedule/headway (e.g., transit frequency) on system performance.
- Impact of conflicting transit route requests (e.g., main arterial and cross streets).
- Impact of providing priority in a coordinated system of traffic signals.
- Benefit of queue clearance to get transit vehicles to the transit stop locations.

This scenario highlights several needs. First, the route and run information are required to determine whether a transit vehicle is behind schedule. Either the transit vehicle needs to make this determination (whether it is behind schedule) and not send an SRM, unless the transit vehicle is late or the system needs to track the transit vehicles on the route and make an association with the route and run on the schedule, or the transit vehicle needs to send additional information to the SRM, with changes to the standard proposed to the SAE committee, to identify the route and run. Part of this information is available in the optional RequesterDescription field in the SAE J2735 SRM, which allows a string to contain information about the transit route but not the run.(16) If the transit vehicle has to make the decision about lateness or whether to include the route and run information, CARMA Platform will require an interface to the transit vehicle management system to obtain the vehicle status and/or information.

SCENARIO 2: ROUTE PRIORITY AND MULTIPLE SERVICE TYPES

This scenario extends the basic TSP system in scenario 1 to include a mixture of transit routes (TSMO UC TSP-4) and types of service (TSMO UC TSP-5) that will result in more frequent and less periodic transit services in the arterial system. It also provides the system with the ability to create a hierarchical priority policy to favor one type of service, or traffic signal coordination, over others. In addition, this scenario, illustrated in figure 10, considers the value of providing priority at an intersection if there is congestion downstream, where there will be significant delay regardless (TSMO UC TSP-3). Overall, this scenario represents a more systematic consideration of TSP as an integral part of an arterial traffic system.

The mixture of transit routes (and schedules/headway) creates a situation, illustrated in figure 12, where there will likely be more frequent and less periodic requests for priority and the need for different priority treatments, such as a queue jump to allow a transit vehicle to change lanes to make a left turn at a downstream intersection (figure 11). More frequent transit service may be accompanied by more requests for traffic signal priority and potentially more disruption to the basic coordinated service for the nontransit vehicles.

The consideration of transit service type and the creation of a hierarchical policy for different service types and/or routes provide a powerful TSP tool for transit and traffic management agencies to manage the higher frequency by assigning a higher priority value to certain modes. For example, to encourage travelers to use BRT, TSP can be used to help reduce traffic signal delays and help create a service that competes with, or exceeds, other modes of travel. Because BRT has dedicated lanes, it is feasible the travel time experienced by a BRT traveler could be less than that experienced by a traveler in a passenger vehicle or other transit modes impacted by congestion. Similarly, it may be desired to provide an express service with a higher degree of priority. An express service generally includes fewer stops than a standard local transit service. Providing TSP to help express transit vehicles should reduce traffic signal delay and improve travel time.

Although transit vehicles are a normal part of traffic operations, providing TSP shifts some of the intersection capacity away from nontransit vehicles to improve transit performance. In a system that is near or at operating capacity, this shift could induce the onset of congestion sooner than if no TSP had been provided. Hence, the value of TSP needs to be considered throughout an arterial corridor. If a vehicle is granted priority at an upstream traffic signal only to be delayed due to downstream congestion, the single intersection benefit may not translate into an overall trip benefit. TSMO UC TSP-3 considers this downstream impact on the decision to grant priority at upstream traffic signals.

The route priority and multiple types of transit scenarios in an arterial system capture several key operating characteristics as follows:

- Multiple vehicles may request priority at a single intersection at a time.
- Traffic signals are operated as a coordinated system.
- Only vehicles that are later than a configurable threshold will receive traffic signal priority.
- More frequent priority requests may be made because of multiple routes and service types.
- A hierarchical policy for considering priority requests can be used to address value and frequency of results, with more preference given to highly valued types of service.
- Consideration of downstream traffic congestion can be used to influence the decision to grant an upstream request to ensure reassignment of capacity is valued.

This scenario will allow performance to be evaluated to better understand the following effects:

- Benefits of TSMO-TSP on transit operations, such as transit travel time, travel time variability, and impact on nontransit vehicles, including different types of transit services.
- Impact of schedule/headway (e.g., transit frequency) on system performance.
- Impact of conflicting transit route requests (e.g., main arterial and cross streets).
- Impact of providing priority in a coordinated system of traffic signals.
- Benefit of queue clearance to get transit vehicles to the transit stop locations.
- Benefit of having an overall system performance from both transit and nontransit views.

This scenario highlights several needs. In addition to the schedule/headway lateness identified in scenario 1, route information for each vehicle is required to determine whether special service, such as a queue jump, is needed. This information can be provided in the SAE J2735 SRM.(16)

SCENARIO 3: BLIP

This scenario includes the basic TSP UC and utilizes the V2V and V2I CDA capability to provide a lane that is utilized for transit but allows other CDA vehicles to occupy the lane until a transit vehicle approaches. This operation can benefit both transit and nontransit vehicles by creating additional capacity.(21) Transit vehicles in the BLIP lane would likely be BRT service vehicles and would ask each traffic signal for priority treatment to help ensure a reduced trip travel time.

This scenario will allow performance to be evaluated to better understand the following factors:

- Ability of TSP to reduce transit vehicle delay at traffic signals.
- Potential corridor capacity improvements by allowing use of the BLIP lane when transit vehicles are not present.

SCENARIO 4: WORK ZONE IN TRANSIT CORRIDOR

Work zones generally have significant delays attributable to reduced speed and lane availability. In this scenario, TSP can be used to help a transit vehicle that has traversed a work zone to get back on schedule or headway downstream from the work zone. Also, if there is a work zone downstream from a transit vehicle, TSP can help a transit vehicle use the upstream intersections to meter the volume of traffic that enters the work zone ahead of a transit vehicle. This metering could reduce the queue entering the work zone. This scenario will allow work zone information to be available for TM in arterial corridors.

This scenario will allow performance to be evaluated to better understand the following factors:

- Use of TSP to meter flow of traffic into a work zone.
- Ability to help a transit vehicle delayed in a work zone to get back on schedule/headway.

SCENARIO 5: ECO-TRANSIT DRIVING

Reducing operating costs while maintaining a high level of service is important to transit agencies. Combining TSP and eco-transit driving to allow vehicles that will be delayed at intersections to reduce energy consumption can result in better travel times. If the TSP at a signal cannot provide sufficient priority to allow a vehicle to progress through the intersection without stopping, the vehicle can use the eco-transit driving capability (adapted from eco-driving) to reduce energy consumption.

This scenario will allow performance to be evaluated to better understand the following qualities:

- Benefit of TSP to reduce traffic signal delay to transit vehicles.
- Benefit of eco-transit driving to reduce energy consumption and emissions.
- Benefit of transferring eco-driving to eco-transit driving as a CDA capability.

CHAPTER 5. ANALYSIS OF THE PROPOSED SYSTEM

This chapter provides an analysis of the benefits, advantages, limitations, and disadvantages of TSMO TM UCs on signalized arterials. Scenario 1 from chapter 4 has been selected for analysis. The chapter also discuss a high-level system validation plan.

SUMMARY OF POTENTIAL BENEFITS AND OPPORTUNITIES

CDA technologies enable mobility applications that are not achievable by individual ADS-operated vehicles. CDA technologies do so by sharing information that can be used to increase the safety, efficiency, and reliability of the transportation system, and that may serve to accelerate the deployment of driving automation in on-road motor vehicles. CDA aims to improve the mobility of travelers in transportation systems. This improvement can be accomplished, for example, by sharing information about transit vehicle status (lateness, occupancy) and estimations of queues and traffic congestion and by providing preferential treatment on signalized arterials. Cooperation among multiple participants and perspectives in traffic, especially at conflict areas (e.g., intersections, merging roadways), can improve safety, mobility, situational awareness, and operations.

For TSMO TM UC, an integrated control framework is proposed to efficiently manage traffic on signalized arterials. Vehicle capabilities, such as determining status (lateness, occupancy) and forming SRMs, can be processed on CDA-capable vehicles with CARMA Platform. SRM can be shared with the infrastructure with CDA-enabled wireless communications, regardless of the particular technology. By using CARMA Streets, the infrastructure can provide adaptive signal timing that specifically accommodates transit vehicle requests and needs. By integrating with TM systems, CARMA Cloud could provide information about vehicle status, transit routes, and transit stop locations. For the purpose of this first investigation analysis, only CARMA Platform and CARMA Streets are considered.

SYSTEM VALIDATION PLAN

This section describes system validation methods to validate the developed algorithms and software systems for TSMO TM UC. The purpose of the validation testing is to ensure the developed TSMO TM UC system can meet the operational needs listed in table 6 for scenario 1.

Simulation Testing

Simulations can be designed to test the developed algorithm for TSMO TM UC by using the performance metrics identified in chapter 3 of transit vehicle and infrastructure behavior and traffic system performance. Different types of simulation can be used and combined for testing purposes.

Traffic simulators offer the possibility to scale the evaluation up to an intersection corridor/network level (compared with the limited number of vehicles and length of the roadway for ADS simulators) to study the CDA impact on transportation system performance (as measured by traffic performance metrics such as safety, efficacy, stability, and sustainability). Traffic simulators can evaluate different scenarios such as traffic demand, TSP, and intersection geometry, including nearside bus stops. Usually, the CDA control algorithms will be simplified for calibrated/validated CDA behavioral models/algorithms that are implementable for large-scale testing.

Field Testing

To ensure the developed algorithm can be reliably and easily implemented into CARMA Platform, a set of proof-of-concept tests will be conducted on a closed test track. This test can be demonstrated onsite at a signalized intersection. Multiple CARMA vehicles loaded with necessary features can be instructed to run loops on the test track to represent continuous driving, as shown in figure 13. The operational scenarios discussed in chapter 4 can be tested. The purpose of testing can be to verify the software, collect vehicle behavior performance measures, and validate whether the software meets the requirements. Data collected from the test track can be used not only to calculate vehicle behavior performance metrics, but also to calibrate traffic simulation CDA behavior models. Field testing will provide data to create a validated evaluation model of CDA's traffic impacts by using simulation.

SUMMARY OF IMPACTS

From a research perspective, the proposed control strategy for TSMO TM UC offers an approach for efficiently managing transportation systems at signalized intersections and reducing disutilities, such as excessive delays and emissions. The benefits of TSMO TM UC can be demonstrated by using CDA transit vehicles that send SRMs to the infrastructure when transit vehicles are behind schedule/headway. The infrastructure components accept the SRMs and adapt the traffic signal timing, within the structure of the traffic signal controller, to provide benefits to the transit vehicles. From an operations perspective, the proposed control strategy for TSMO TM UC presents changes to how TSMO is conducted at signalized intersections. Intelligent transportation systems infrastructure would need to be upgraded to accommodate the CDA system needs, such as RSE services and supporting information technologies. Agencies would need to evaluate and build capabilities for operating such emerging systems. The conventional processes of monitoring and reporting transportation system performance could be revolutionized with the prevalence of C-ADS-equipped vehicles and advanced sensors. Conventional strategies for TSMO, which agencies are already familiar with, may be enhanced by CDA technologies.

DISADVANTAGES AND LIMITATIONS

The proposed control strategy for TSMO TM UC provides insights into CDA operations at signalized intersections, but it may also present the following limitations:

- Traffic signal priority for transit vehicles can impact the performance of nontransit traffic. The shifting of traffic signal timing to benefit transit vehicles will likely have a negative impact on other traffic.

- Simulation of transit operations in terms of schedule adherence is challenging. Most simulation studies give every transit vehicle priority at every intersection. Prioritization may increase the negative impacts on nontransit vehicles and overestimate the benefits to transit vehicles. Ideally, late transit vehicles will benefit, but most transit vehicles should be on schedule/headway and not need TSP help.

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