Cooperative Automation Research: High-Level Framework of CARMA℠ Proof-of-Concept TSMO Use Case Testing for CARMA Streets℠

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FOREWORD

This report provides a high-level framework for CARMA Streets℠, a CDA application developed as an initial step to define a set of testable use cases that demonstrate the potential impact of CARMA Streets on transportation systems management and operations (TSMO). CARMA Streets is part of CARMA℠, an initiative led by the Federal Highway Administration (FHWA) to enable collaboration in cooperative driving automation (CDA) research and development. The end goal in developing CDA, which enables communication among vehicles and roadside infrastructure devices to support coordinated movement, is to improve transportation network safety, traffic throughput, and energy efficiency.

In 2015, the Office of Operations Research and Development at the FHWA, as part of the CARMA initiative, developed a proof-of-concept prototype for cooperative adaptive cruise control that was installed in five research vehicles. Since then, the CARMA initiative has evolved and expanded to encompass an ecosystem that includes CARMA Streets, CARMA Cloud℠, CARMA Messenger℠, and CARMA Platform℠. The CARMA ecosystem is composed of open-source software and support services that aim to help infrastructure move traffic more efficiently by advancing TSMO strategies. At the time of this report's publication, the CARMA ecosystem is advancing into automated driving systems (ADSs) to support ADS-equipped vehicles' participation in cooperative automation strategies. This effort expands CARMA functionality to include TSMO strategies on surface arterials with intersections.

The intended audience for this report is CDA stakeholders, including system developers, analysts, researchers, and application developers.

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16. Abstract
The United States Department of Transportation Federal Highway Administration has initiated the CARMA℠ program to advance research and development of cooperative driving automation (CDA) to accelerate market readiness and deployment. CDA aims to improve the safety, traffic throughput, and energy efficiency of the transportation network by allowing road users and infrastructure to communicate and cooperate. CARMA Streets℠ is a component of the CARMA ecosystem that enables coordination among different transportation users. This component provides an interface for CDA participants to interact with the road infrastructure. CARMA Streets is also an edge-computing unit that improves the efficiency and performance of transportation systems management and operations strategies. This document presents a concept of operations for the CARMA Streets system to support its development and implementation.

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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)

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LIST OF ABBREVIATIONS

ABS	anti-lock braking system
ACC	adaptive cruise control
ADS	automated driving system
C-ADS	cooperative ADS
C-V2X	cellular vehicle-to-everything
CACC	cooperative adaptive cruise control
CAV	connected and automated vehicle
CDA	cooperative driving automation
ConOps	concept of operations
CTSE	critical time step estimation
DOT	department of transportation
DSRC	dedicated short-range communications
FHWA	Federal Highway Administration
ICM	integrated corridor management
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IHP	Integrated Highway Prototype
IICS	isolated intersection traffic control
IOO	infrastructure owner and operator
ISO	International Organization for Standardization
ITS	intelligent transportation system
LiDAR	light detection and ranging
LTE	long-term evolution
MMITSS	multimodal intelligent traffic signal system
NHTSA	National Highway Traffic Safety Administration
NTCIP	National Transportation Communications for ITS Protocol
OBU	onboard unit
PSM	personal safety message
R&D	research and development
RSE	roadside equipment
RWIS	road weather information systems
SO	signal optimization
SPaT	signal phase and timing
STOL	Saxton Transportation Operations Laboratory
TMC	traffic management center
TIM	traffic incident management
TSP	transit signal priority
TS	trajectory smoothing
TSMO	transportation systems management and operations

UC1	use case 1
UC2	use case 2
UC3	use case 3
USDOT	United States DOT
V2I	vehicle-to-infrastructure
V2P	vehicle-to-pedestrian
V2V	vehicle-to-vehicle
V2X	vehicle-to-everything

CHAPTER 1. INTRODUCTION

IDENTIFICATION

This document serves as a concept of operations (ConOps) for CARMA Streets℠, which is sponsored by the Office of Operations Research and Development of the Federal Highway Administration (FHWA). Development of this ConOps is an initial step in the current CARMA Streets effort to define a set of testable use cases that demonstrate how CARMA Streets can improve traffic efficiency and safety at intersections.

DOCUMENT OVERVIEW

Background

The Office of Operations Research and Development performs transportation operations research and development (R&D) for the FHWA. On-site R&D is conducted at the Saxton Transportation Operations Laboratory (STOL) established at Turner-Fairbank Highway Research Center. The Office of Operations R&D conducts operations R&D based on perceived national transportation needs of the United States.

In 2015, the Office of Operations R&D designed, built, and installed a cooperative adaptive cruise control (CACC), proof-of-concept prototype system in a fleet of five research vehicles. The CACC system was built on 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.

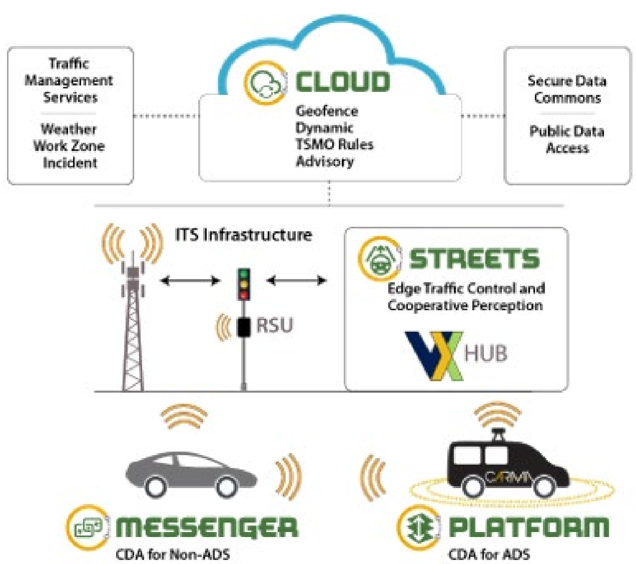
A subsequent task order (Task Order 13 DTFH6116D00030-0013), Development of Connected and Automated Vehicle (CAV) Capabilities: Integrated Highway Prototype I (IHPI), was tasked with developing a new reference platform. The new platform, CARMA2, used the Robot Operating System™ to enable research capabilities 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 IHPI, which combined speed harmonization, lane change/merge, and platooning into one trip. This research focused on understanding negotiations between entities and how such negotiations can be done efficiently to help improve traffic flow based on cooperative tactical maneuvers.

A current task order (Task Order 693JJ318F000225), Development of Cooperative Automation Capabilities: Integrated Prototype 2, is producing the third iteration of CARMA. CARMA3 takes the platform into the world of Automated Driving Systems (ADSs) with SAE Level 3 and up automation. The approach takes advantage of an open-source ADS platform, Autoware, to enable the use of ADS functionality for cooperative automation strategies.

Another current task order (Task Order 693JJ319F000360), Cooperative Automation Research: CARMA Proof-of-Concept Transportation Systems Management and Operations (TSMO) Use Case Testing, extends the research from Prototype II (693JJ318F000225). It enhances the CARMA ecosystem to enable further capabilities of cooperative driving automation (CDA), allowing participants to interact with the road infrastructure and navigate priority TSMO use cases. The ultimate goal of this task order is to apply CDA to enhance TSMO and improve transportation system safety and efficiency.

Along with that, CARMA Cloud℠, CARMA Messenger℠, and CARMA Streets are also being developed. CARMA Cloud represents the infrastructure piece of CDA where vehicles and other entities may communicate with 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, buses) to communicate with CARMA Platform-equipped vehicles and infrastructure to improve the performance of the network. CARMA Streets enables vehicles to communicate with the infrastructure at conflict areas (e.g., intersections) and provides an interface to roadside units; it supports edge computing to optimize travel through conflict areas and reduce the computing burden of CDA vehicles. All CARMA components (i.e., Platform, Cloud, Messenger, and Streets) are open source and are being built with the goal of benefitting the CDA research of universities and other research groups.

The development of TSMO and CDA use cases is part of the CARMA effort. The platform is being developed using an Agile software development process to facilitate collaboration with the stakeholder community. An illustration of CARMA products is shown in Figure 1.



Source: FHWA.
ITS = Intelligent Transportation System.

Figure 1. Illustration of CARMA products.

Table 1 lists the various projects associated with the CARMA Streets development effort for reference.

Table 1. Other projects associated with the CARMA Streets 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 Integrated Highway Prototype II"
OPS IV 693JJ318F000327	V2X Hub	"Integrated Data Exchange Hub for Modular Operational Data Environment (MODE)"
STOL II 693JJ319F000360	CARMA TSMO	"Cooperative Automation Research: CARMA Proof-of-Concept TSMO Use Case Testing"

Objective

The CARMA Streets system is being developed as part of the "FHWA Cooperative Automation Research: CARMA Proof-of-Concept TSMO Use Case Testing" project. This document focuses on the CARMA Streets high-level system framework, its requirements, and its potential impacts on transportation systems. The ConOps focuses on 10 operational use cases and describes whether and—if applicable—how CARMA Streets will impact these use cases. This project's development and testing will be supported by a team of CARMA participants.

Audience

The intended audience for this document includes the following entities.

- United States Department of Transportation (USDOT) and CDA, arterial, and freeway transportation stakeholders, including—but not limited to—program managers, assistant managers, research engineers, and transportation technology specialists.
- Academia stakeholders, including faculty members, researchers, and students.
- Private sector stakeholders, including consultant companies and Original Equipment Manufacturers (OEMs).
- 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 outline of a System Operational Concept document described in Annex A of *ISO [International Organization for Standardization]/IEC [International Electrotechnical Commission]/IEEE [Institute of Electrical and Electronics Engineers]Standard 29148:2011*.[1] A document conforming to this content structure is called a ConOps in U.S. transportation systems engineering practice, and that title is retained for this document. Some sections have been enhanced to accommodate more detailed content than what is described in the standard, and titles of some sections may have been edited to capture those enhancements more specifically. Following is a summary of the document's content.

- Chapter 1 defines the scope of the ConOps.
- Chapter 2 describes the current situation and identifies necessary changes in relation to processes and systems affected by the ConOps.
- Chapter 3 describes the concept for CARMA Streets system capabilities, infrastructure configuration and needs, and performance metrics.
- Chapter 4 provides examples of operational scenarios that may be impacted by CARMA Streets. This chapter also presents descriptions of operational needs and functional requirements.
- References provides a list of reference documents.

CHAPTER 2. THE CURRENT SITUATION, OPPORTUNITIES FOR CHANGE

This chapter discusses existing arterial management approaches. It examines current traffic management practices at corridors and analyzes advantages and disadvantages of existing solutions. This analysis demonstrates a need to develop a new system to mitigate problems in corridor management. The next chapters will then discuss the theoretical details of such a new system.

Various roadway facilities intersect through the roadway network to provide access for commuters, causing conflicts among vehicles from various movements of 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 and emissions, driving discomfort, and safety risks. Traffic Engineers try to mitigate these issues by placing traffic control devices (e.g., stop signs, traffic signals) with relatively appropriate settings based on various factors such as intersection geometry, traffic demand at different approaches, and so on.

Even in traditional environments that include traffic control devices with appropriate settings, vehicles are not fully aware of traffic at other approaches or intersection conditions in the near future. Thus, they may still need to go through repeated stop-and-go traffic cycles until they pass the conflict area; this increases shock wave propagations, thus increasing energy consumption, harmful emissions, and crashes.

Movement operations at a common conflict area may change with the advent of CDA technology. Vehicles equipped with cooperative automated driving systems (C-ADSs) have communication and automation technologies that allow them to coordinate with each other and with infrastructure to maximize safety and network efficiency. They are part of a connected ecosystem in which each component of communication the vehicles are equipped with—V2V, vehicle-to-infrastructure (V2I), and vehicle-to-pedestrian (V2P)—has a role in helping to improve the network. Facilities at a common conflict area can be provided with equipment to help support C-ADS-equipped vehicle coordination.

Multiple studies propose a decentralized control scheme in which each vehicle is treated as an autonomous agent that maximizes its own performance by determining its own operations based on information sensed or received from other vehicles and roadside equipment (RSE). While this approach offers some advantages that suit real-time applications (e.g., a short communication range and distributing computational burden among different entities), the self-selective nature of this decentralized control scheme prevents the system from achieving the maximum benefits of CDA operations. Therefore, to achieve maximum traffic efficiency while maintaining safety, an edge-computing infrastructure unit should be employed. This unit can determine the optimal departure sequence of vehicles passing the conflict area, maximizing system performance.

Minimizing total travel time delay and maximizing the throughput of traffic flow at a conflict area are among the most common systematic objectives. Regarding these objectives, numerous studies have been conducted on CDA operations, seeking a proper departure sequence of C-ADS-equipped vehicles (see references 2, 3, 4, 5, 6, 7, 8, and 9). Further, several other studies aim to optimize signal-timing planning to improve traffic efficiency (see references 10, 11, 12, 13, 14, and 15). From a real-world testing perspective, only a few studies have conducted field experiments with a centralized unit to determine optimal departure sequence or signal-timing plans. Field trials were conducted in the city of Carson, CA, along two corridors with six connected, signalized intersections capable of communicating their signal phase and timing (SPaT) information. Additionally, the "Integrated Prototype I" project created the Glidepath Prototype System[(16)], which developed, demonstrated, and evaluated a partially automated vehicle system with an eco-approach and departure feature. Omidvar et al.[(17)] deployed an intelligent, real-time IICS system in mixed traffic at a Florida DOT closed-course facility. The mixed traffic scenario consisted of one SAE Level 4 autonomous vehicle, three V2I-connected vehicles equipped with DSRC, and two non-connected human-driven vehicles.

Although these studies and experiments provide advantageous insights into CDA operations at traffic conflict areas, challenges still exist regarding system efficiency and scalability. An efficient system should not put all computational burden on one or few centralized unit(s), as doing such may substantially increase operational complexity and associated risks and liabilities in real-time applications. An edge-computing structure can mitigate these issues by distributing the computational burden among different entities and thus is most suitable for real-time applications.

Furthermore, an appropriate control scheme should consider various cooperative behaviors, as the cooperative capabilities of C-ADS-equipped vehicles might not always be the same. For example, not all vehicles accept and follow prescriptive plans calculated by centralized units and sent by RSE. Therefore, a centralized unit should be able to receive real-time vehicle status and update the plan accordingly. The SAE has already standardized how cooperation between vehicles is regarded. Much as levels of automation were defined in the SAE J3016™ automated-driving graphic, the new standard—the SAE J3216 automated driving graphic[(18)]—defines cooperation classes. The classes address various capabilities of a C-ADS-equipped vehicle that affect its ability to cooperate with other CDA participants (e.g., vehicles and infrastructure). Table 2 summarizes cooperation classes and table 3 illustrates opportunities provided by CDA technology by depicting examples of CDA features relating to cooperative traffic signaling at intersections with consideration of different cooperation classes. A number of these examples are taken from the SAE J3216 standard.

Table 2. Overview of SAE cooperation classes and automation levels.

No Automation		Partial Automation of DDT			Complete Automation of DDT		
		Level 0: No Driving Automation (human does all driving)	**Level 1: Driver Assistance (longitudinal or lateral vehicle motion control)**	**Level 2: Partial Driving Automation (longitudinal and lateral vehicle motion control)**	**Level 3: Conditional Driving Automation**	**Level 4: High Driving Automation**	**Level 5: Full Driving Automation**
No Cooperative Automation		E.g., signage, TCD	Relies on driver to complete DDT and supervise feature performance in real time		Relies on ADS to complete DDT under defined conditions (fallback condition performance varies between levels)		
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[*]		Potential for improved object and event detection[**]		
SAE class B: Intent Sharing	**This is what I plan to do**	E.g., turn signal, merge	Potential for improved object and event prediction[*]		Potential for improved object and event prediction[**]		
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	N/A		C-ADS designed to accept and adhere to a command		

[*] = 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 to Level 3, 4, and 5 ADS-operated vehicles.

[**] = class A and B communications are one of many inputs to an ADS's object and even detection and prediction capability, which may not be improved by the CDA message.

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

Table 3. 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	Two-way: C-ADS-equipped vehicles → RSE; RSE→C-ADS-equipped vehicles	Vehicle location, speed, and priority status (e.g., emergency vehicles)	Enabling signal-timing changes based on an approaching vehicle.
Signal Preemption	A) Status Sharing	One-way: C-ADS-equipped vehicles → RSE	Vehicle location, speed, and priority status (i.e., emergency vehicles)	Enabling signal-timing changes based on an 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 a 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 Negotiation results	Enabling SPaT changes based on an approaching vehicle. Enabling C-ADS-equipped vehicles to plan their motions and optimize their velocity based on future (and possibly optimized) signal phases and the status of other vehicles. Supporting more efficient motion plans with increased reliability and look-ahead distance to reduce energy consumption and emissions.

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

In a project initiated by FHWA, a vehicle-to-everything (V2X) software platform called V2X Hub was built to act as a network intermediary that allows for messages to be sent and received among vehicles, infrastructure, and personal communication devices in a connected system. V2X Hub encodes and decodes DSRC Message Set Dictionary SAE J2735[19] standard messages and exchanges them in a format that is understood by both connected vehicles and infrastructure. V2X Hub software architecture can be broken down into two main layers: V2X Hub Core and plugins. The Core performs all message routing between plugins and displays the current configuration status via a web browser. Plugins are the interface for two-way communication between the V2X Hub Core and external subsystem components. Despite this breakthrough, V2X Hub does not provide sufficient functionality, interoperability, and computational power to support various TSMO use cases to improve traffic management practices using emerging CDA technologies.

As such, to fill existing gaps, this ConOps proposes the framework and requirements for an edge-computing infrastructure unit called CARMA Streets that serves as part of the CARMA ecosystem.

STAKEHOLDERS IN TRANSPORTATION SYSTEM MANAGEMENT AND OPERATIONS

Stakeholders are entities whose actions influence travel in the transportation environment; these may include transportation users engaged in travel on publicly accessible roadways, emergency responders, and infrastructure owners and operators (IOOs). This section identifies two types of TSMO stakeholders—transportation users and IOOs—and their corresponding needs. Following this, it discusses a high-level description of CARMA Streets presented to 100 stakeholders attending a webinar, the stakeholder demographics considered for CARMA Streets, and the webinar attendees' responses to a survey.

Transportation Users

A transportation user is a traffic participant on or adjacent to an active roadway for the purpose of traveling from one location to another. Motorized vehicles—human-driven or automated—and vulnerable road users (e.g., pedestrians and bicyclists) are the main users of traffic systems. The general needs of transportation users include the following:

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

Additionally, CARMA Streets seeks to support and enhance the following benefits for transportation users.

- Smoother, faster, more efficient travel: CARMA Streets can enhance cooperative coordination of vehicles at intersections and controlling trajectories, thus increasing intersection throughput and reducing friction and energy consumption in traffic flow by improving vehicle-following stability.
- Greater operational efficiency and travel-time reliability: Cooperative vehicle coordination can substantially reduce travel delay and uncertainty in travel times by

better scheduling vehicles at intersections, smoothing traffic, and enabling real-time prediction of travel times.

- Improved traffic safety: Reducing crashes is one of the most significant potential benefits of CDA technology. The National Highway Traffic Safety Administration (NHTSA) estimates that the combined use of V2V and V2I communications has the potential to significantly reduce unimpaired driver crashes.[20]
- More productive travel experience: The overall travel experience can be improved by CARMA Streets and various CDA features such as vehicle cooperative coordination and trajectory smoothing (TS). Improvements include, but are not limited to, the elimination of stop-and-go movements, reduction in travel delay and energy consumption, and improvement of travel time reliability.

Table 4 identifies four categories of transportation users and defines the characteristics and needs of each category.

Table 4. Transportation user characteristics and needs.

Driving Mode	Transportation User Categories	User Characteristics and Needs
Human Driving	Non-connected human driver	Non-connected human drivers have neither connectivity nor automation capability, and have uncertain driver behavior. Needs align with general user 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	Non-connected ADS-equipped vehicle	Non-connected, ADS-equipped vehicles operate independently, relying 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 vehicle, C–ADS-equipped vehicles partner with other CDA participants in the traffic stream to improve overall traffic performance. Needs include availability of other vehicles to perform cooperative actions, thus 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, and private-sector entities that operate in accordance with applicable laws at Federal, State, and local levels.

IOOs aim to manage traffic safely and efficiently. This includes monitoring and managing traffic and the factors affecting traffic flow, such as incidents, weather, and intersections; disseminating route information; and other actions that increase traffic flow efficiency. Aims of IOOs may include the following:

- 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 car-sharing options. (Travelers can consider potentially driverless CAVs to be a separate mode of transportation from unconnected driving.)[(21)]

From the perspective of IOOs, CARMA Streets may support and enhance the following benefits:

- Realize efficiency goals more rapidly: Adoption of CARMA Streets at intersections may enable greater congestion management—increasing throughput, enhancing safety, and improving driver experience. These benefits may increase as the percentage of C-ADS-equipped vehicles using the intersection increases.

- Maximize resource utilization for more efficient solutions: Traditional approaches to managing congestion, such as capacity expansion, are increasingly facing funding constraints and the inherent limitations of alleviating transportation problems. CARMA Streets can enhance operational strategies that offer the potential for innovative solutions to congestion and travel time variability at intersections that plague facilities.

- Accommodate the future of mobility technology with organizational evolution: Organizations that respond to rapid technological change may be more likely to thrive in this era of rapid technological enhancement in the transportation field.

CARMA Streets Stakeholder Feedback

To identify the needs and expectations of the stakeholders and what factors and use case scenarios matter to them, their feedback was collected through a survey following a webinar hosted by FHWA on November 10, 2020. At the webinar, more than 100 stakeholder attendees were presented with a high-level description of the expected CARMA Cloud℠ and CARMA Streets systems. Following is a summary of the webinar attendees' demographics:

- Federal Government: 14 percent.
- State DOTs: 13 percent.

- Public agencies: 5 percent.
- Private agencies: 21 percent.
- Academia: 35 percent.
- Other or unknown affiliations: 11 percent.

The CARMA Streets system was described in the webinar with a presentation that included high-level system architectural diagrams prepared by a research team and approved by FHWA task managers. Several use case applications that could be impacted by the CARMA Streets system were also presented. After the presentation, some of the attendees responded to a survey. Following is a summary of the questions asked of the stakeholders:

- How does CARMA Streets apply to stakeholder research?

- What stakeholder needs are pertinent to CARMA Streets?

- What additional features could be added to CARMA Streets?

- How could CARMA Streets be improved?

- What should be the top priority for use case scenarios for future testing and deployment of the CARMA Streets system among the following choices? *(Twenty-five stakeholder attendees responded to this question.)*

    - Cooperative scheduling at stop-controlled intersections *(16 percent chose this option).*

    - Traffic signal control using CDA technologies at isolated intersections *(32 percent chose this option).*

    - Transit signal priority (TSP) with the main objective of mobility *(28 percent chose this option).*

    - Freight signal priority with the main objectives of safety and fuel efficiency; note that freight vehicles may be in platoons and, as such, need to receive messages sooner *(4 percent chose this option).*

    - Emergency vehicle signal preemption *(20 percent chose this option).*

- What should be the top priority for use case scenarios for future testing and deployment of the CARMA Streets system among the following choices? *(Thirty-seven stakeholder attendees responded to this question.)*

    - Interaction with pedestrians and bicyclists *(41 percent chose this option).*

    - Cooperative scheduling at roundabouts *(5 percent chose this option).*

    - Work zones *(35 percent chose this option).*

- Weather events *(14 percent chose this option)*.
- Ramp metering *(5 percent chose this option)*.

The feedback received from the stakeholder attendees of the webinar helped to provide a basis from which to proceed with CARMA Streets development. Additionally, to seek further feedback from stakeholder partners, a survey was developed and sent to the CARMA collaborative stakeholder group, which includes members from Federal and State Governments, academia, and public and private agencies. Twenty-seven collaborative stakeholder group members responded to this second survey; of these, thirteen were university faculty members and researchers, eight were State DOT employees, and six were private consultants. Questions and responses for the second survey are summarized as follows:

- What is your level of exposure to CARMA and/or Cooperative Driving Automation? *(Twenty-seven stakeholder partners responded to this question.)*
    - Not familiar *(4 percent chose this option)*.
    - Somewhat familiar *(48 percent chose this option)*.
    - Very familiar *(48 percent chose this option)*.
- How would you rate the nine possible use case scenarios below on a scale of one to five, where one is 'not important' and five is 'very important'?
    - Unsignalized intersections (e.g., stop-controlled, roundabouts) *(averaged 3.88 out 5)*.
    - Vehicle trajectory and signal optimizations (SOs) at signalized intersections *(averaged 4.37 out of 5)*.
    - Signal priority for transit and freight *(averaged 4.00 out of 5)*.
    - Signal preemption for traffic incident management (TIM) (e.g., emergency vehicles) *(averaged 4.41 out of 5)*.
    - Interactions with pedestrians and bicyclists *(averaged 4.59 out of 5)*.
    - Work zones *(averaged 4.67 out of 5)*.
    - Weather events *(averaged 4.04 out of 5)*.
    - Corridor management (e.g., signal coordination) *(averaged 4.00 out of 5)*.
    - Shared perception *(averaged 4.07 out of 5)*.
- Is there anything you would list for each use case scenario above (e.g., specific needs and requirements) that you believe it is important to consider?

The feedback received from this second survey helped to guide the development of CARMA Streets operational needs and functional requirements presented in Chapter 4 of this document.

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 with automated vehicle sensors). As more advanced sensing and computing capabilities are integrated with ADS, a key consideration is what changes must take place to enable deployment of CARMA Streets or any other similar system and what additional capabilities and possibilities can be expected. This section discusses the nature of those changes.

Organizational/Institutional Changes

The following organizational/institutional changes should be implemented to enable the deployment of a system like CARMA Streets.

- Adopt a traffic engineering process approach: A traffic engineering process is important for developing operational scenarios to accommodate CARMA Streets applications on intersections. ConOps can be developed at the regional level and for a corridor of focus.

- Adopt a systems engineering process approach: A systems engineering process can help in identifying additional system requirements to accommodate target operation scenarios. System requirements can be developed for the system.

- Develop a performance management system: Identifying agency performance standards and holistic data requirements can help transportation agencies leverage data sources across the organization. A performance management system collects and processes relevant data to determine whether system goals and performance targets for all operational alternatives are being achieved.

- Develop a data collection and management system: An appropriate data collection and management system can maintain all relevant data, in real time, from various vehicles, onboard sensors, wireless devices, RSE, roadway traffic sensors, weather systems, message boards, and other related systems. The data can be placed in, or be accessible from, a common data environment.

- Include rich, accurate data from a variety of sources such as the following:
    - Real-time traffic data: These data include vehicle speed and location data collected and disseminated by vehicles as part of a connected system and traditional detection data sources (e.g., inductive loop detectors, overhead radar, and closed-circuit television cameras) that provide traffic data to the system.
    - Traffic signal plan data: These data include planned SPaT data at signalized intersections collected from the signals.

  - Weather condition data: Infrastructure-based road weather information systems (RWIS) and third-party weather data feeds can supplement vehicle-acquired weather data.
  - Pavement condition data: Real-time pavement surface conditions (e.g., dry, wet, snowy, icy, salted) can be provided by in-pavement sensors.
  - Crowdsourced data: Data collected from platforms that have large installed user bases can supplement data from other sources.
  - Historical data: Historical data can help improve the accuracy of traffic analysis and the prediction of traffic conditions.

Technical/Technological Changes

The following technical/technological changes should be implemented to enable the deployment of a system like CARMA Streets.

- Procure new hardware to support the technology.
  - Enhance the infrastructures at intersections by installing broadcast-based and/or network-based communication channels (e.g., DSRC, cellular V2X [C-V2X], long-term evolution [LTE], 5G, and other hardware to support algorithms that enable CDA applications.)
  - Equip vehicles that use CDA systems with onboard units (OBUs), vehicle awareness devices, cameras, light detection and ranging (LiDAR) technology, radar sensors, and other computational resources to implement the new control software.
- Develop/acquire new software. The application(s) should do the following:
  - 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 real time.
  - Contain microscopic and macroscopic traffic simulations to evaluate and adapt traffic use cases and applications that will use CARMA Streets or a similar system.
  - Incorporate real-time data.
  - Utilize traffic optimization models.
  - Encourage the constant evaluation, adjustment, and improvement of traffic optimization models (this requires an increase in computational capability and long-term storage of historical data).

- Evolve and improve algorithms and methods based on performance measurements.
- Include broadcast-based and/or network-based communication channels (e.g., DSRC, C-V2X, LTE, 5G) and software elements that enable the developed CDA system to act on received information.

Operational Policy Changes

The operational policies of transportation infrastructure are generally designed to accommodate traffic operations that meet the goals of operators. Key questions to determine proper operational policies of intersections include:

- 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 experience 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 facility type, configuration, operations, and existing equipment, the following categories of facility infrastructure changes may be needed.

- V2I infrastructure (e.g., RSE) to transmit central information to all vehicles within the communication area; if nonequipped vehicles are allowed, traditional dynamic message signs should be used to convey public traveler information.
- Roadside sensors (e.g., video cameras, radars, and loop detectors) to detect or estimate real-time vehicle trajectories of nonequipped vehicles at the upstream of intersections.
- Signal controllers to adjust signal-timing plans. The signal controllers need to support appropriate protocols (e.g., National Transportation Communications for Intelligent Transportation System Protocol [NTCIP]).
- Temporary signage to convey relevant dynamic information to all drivers (both equipped and nonequipped).

CHAPTER 3. OPERATIONAL CONCEPT OF THE PROPOSED SYSTEM

This chapter details the operational concept of CARMA Streets and provides a high-level overview of the CARMA Streets system design. The chapter also discusses the CARMA Streets role in supporting and enabling automated driving technology to help manage the transportation system to address congestion and improve safety and energy efficiency during routine travel at arterials.

SYSTEM DESIGN OVERVIEW

CARMA Streets is a roadside interface and an edge-computing device that enables communication between infrastructure and various transportation modes and users. CARMA Streets aims to enhance TSMO strategies to improve transportation efficiency and safety. This section of the document provides a high-level description of the CARMA Streets system design, components, and features.

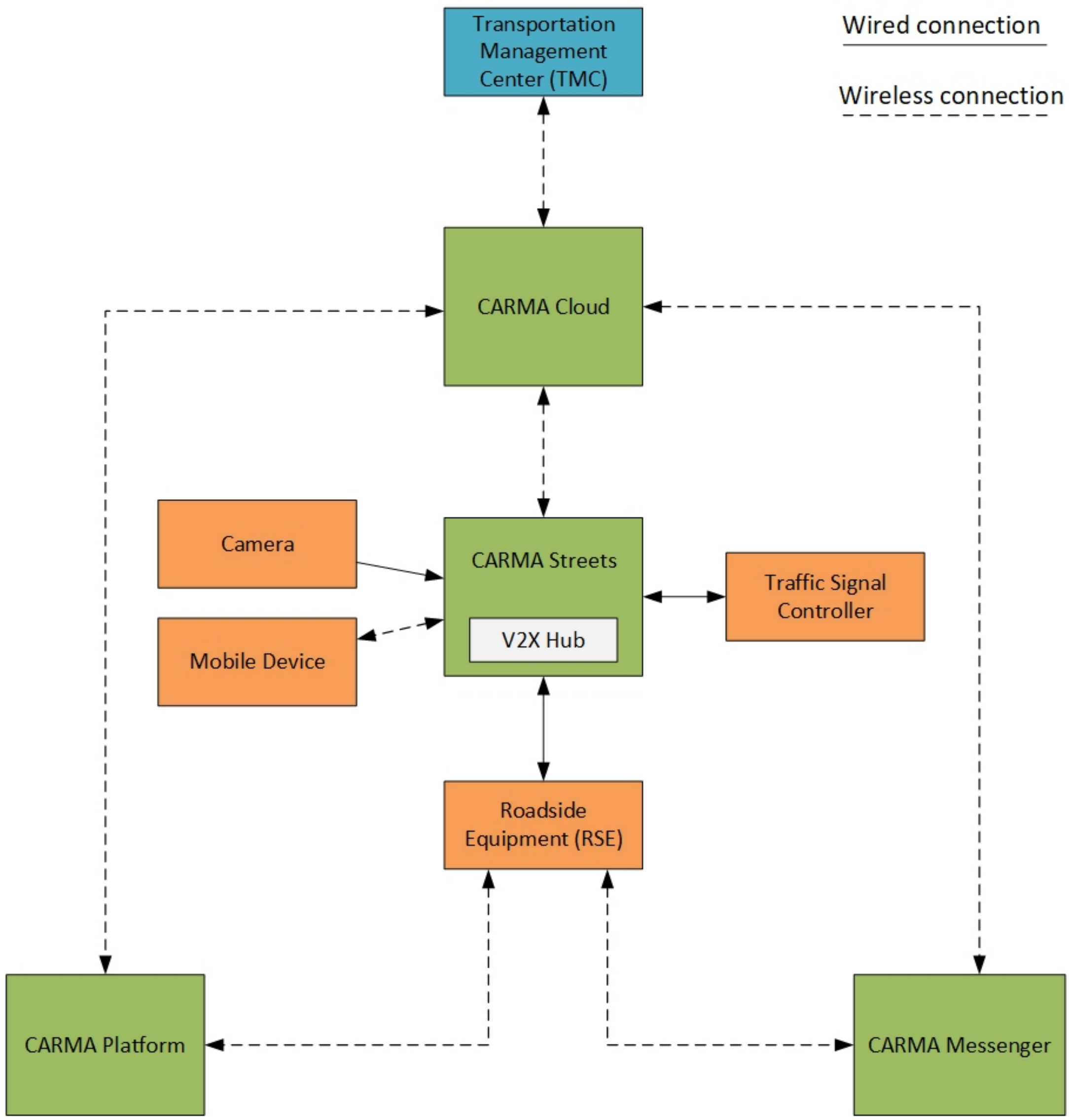
On the following page, figure 2 illustrates the connection between different CARMA ecosystem and V2X Hub components. As shown in this figure, CARMA Streets serves as an edge computing traffic device that may be connected to different traffic control devices, sensors, and mobile devices (e.g., RSE, signal controllers, cameras, and cellphones) to send and receive necessary information in real time. CARMA Streets can send all or part of this information to other components of the CARMA ecosystem, i.e., CARMA Cloud, CARMA Platform, and CARMA Messenger. CARMA Streets can also receive other information from these components and then store, process, and send the processed information to the connected devices in real time. The network components and information type and frequency may differ from one use case to another.

As an example, in a signalized corridor, each intersection can be equipped with a CARMA Streets computer that is connected to RSE and a signal controller at each intersection. Each CARMA Street component can communicate with surrounding C-ADS vehicles (e.g., CARMA Platform-equipped vehicles) to receive their status and intent information. This communication can be facilitated by RSE equipped with broadcast-based and/or network-based communication technology. The information received by CARMA Streets can be temporarily stored and processed. Depending on the predetermined policy and use cases, CARMA Streets may calculate “optimal“ signal-timing plans and transmit those decisions to the connected RSEs and signal controllers. CARMA Streets may also send this information to CARMA Cloud and to surrounding CARMA Platform-equipped vehicles as well as to the vehicles equipped with CARMA Messenger so that they can plan their trajectories to pass through the corridor. Several operational examples are provided in Chapter 4.

As illustrated in figure 2, CARMA Streets may use multiple existing V2X Hub plugins to convert messages to appropriate standards (e.g., NTCIP 1202 to SAE J2735 standards) to send to the other participating components. CARMA Streets is connected to other traffic control and mobile devices such as RSEs, signal controllers, cameras, and cellphones to receive real-time traffic information and send relevant decision variables determined by CARMA Streets. RSE plays a connecting role to transform information between CARMA Streets and CARMA

Platform and Messenger through broadcast-based and/or network-based communication technology methods. CARMA Streets also communicates with CARMA Cloud via cellular network to transmit relevant information to the cloud source and possibly traffic management centers (TMCs), which may be used for more global transportation management applications.

The detailed CARMA Streets system architecture will be described in the CARMA Streets Architecture document. High-level details are provided here for readability.



Source: FHWA.

Figure 2. Illustration of the CARMA Streets connection with the Vehicle-to-Everything Hub (another CARMA ecosystem) and other components.

INFRASTRUCTURE CONFIGURATION AND NEEDS

This section describes the high-level needs of technological and institutional infrastructure and explains the role of IOOs in developing and deploying a system like CARMA Streets.

One key feature of CDA operations is the dynamic vehicle-infrastructure interactions, particularly the exchange of real-time vehicular and roadway information that an ADS-equipped vehicle can understand and share. In the CARMA ecosystem, CARMA Streets serves as an edge-computing component and an interface to execute various use case-specific functions. In this ecosystem, one or more units of RSE will relay real-time information from CARMA Platform (for C-ADS-equipped vehicles) and CARMA Messenger (for connected human-driven vehicles) to CARMA Streets. Based on this information, CARMA Streets can calculate and send different use case-specific decision variables to the vehicles via the RSE unit(s). This communication can happen using broadcast-based and/or network-based communication technology with appropriate protocols.

In addition, CARMA Streets may share part of this information to CARMA Cloud via cellular network. CARMA Cloud may relay information about transportation system behavior to TMCs for the purpose of determining and providing appropriate traffic guidance and furnishing traffic guidance and traveler information messages to vehicles to maintain safety and efficiency across the system.

These information exchanges constitute the foundation of CARMA CDA applications, which include both cooperative perception and cooperative vehicle control/traffic management. CDA participants, vehicles, and infrastructure may use this information to improve situational awareness and expand operational design domain.

With this background and perspective, there is then a limited set of user needs relevant to interactions between TMCs (operators) and vehicles (travelers). While travelers are the primary beneficiaries, they can also be the information providers. Traffic operators, working on behalf of the infrastructure, are the primary service and information providers. They receive information from C-ADS-equipped and connected human-driven vehicles, process and analyze it with all other available information and send resulting pertinent information back to the vehicles. Table 5 lists needs of both road users and IOOs; in this table, road users are vehicles with connectivity capability (i.e., C-ADS-equipped and connected human-driven vehicles), such that one-way or two-way information exchange can occur between road users and IOOs. From a communication perspective, traffic management services or TMC cloud services can rely on broadcast-based and/or network-based communication channels (e.g., DSRC, C-V2X, LTE, 5G) subject to low latency and high frequency. As long as information is communicated between vehicles and the TMC cloud within a reasonable amount of time (on the order of subseconds), they maintain the value for guiding vehicles and informing TMCs.

Table 5. Road user needs and responsibilities and infrastructure owner and operator responsibilities.

Road User Needs and Responsibilities	IOO Responsibilities
Get maps for navigating to destinations, including turns.	Monitor traffic conditions, including the presence of incidents.
Get information on traffic conditions ahead.	Monitor environmental conditions.
Get information on incidents.	Receive traffic condition information from travelers.
Get information on weather conditions.	Synthesize collected data and translate them into actionable operational strategies.
Get information on accessible lanes.	Characterize incidents (location; vehicles, people, and objects involved; lanes blocked; etc.).
Get information on current local speed limits.	Inform emergency services of incidents.
Get information on work zones.	Control access to lanes.
Get information on any special rules that are currently being enforced.	Control access to roadways.
Get information on parking availability.	Control speed limits.
Get alerts about the presence of vulnerable users.	Control use case-specific policies (e.g., first-in-first-out policy on unsignalized intersections).
Inform IOOs of observed traffic conditions.	Inform travelers of traffic conditions.
Inform IOOs of observed incidents.	Inform travelers of incidents.
Inform IOOs of observed weather conditions.	Inform travelers of weather conditions.
Inform IOOs of planned trajectories.	Inform travelers of accessible lanes.
Inform IOOs of statuses, intents, and any other observations.	Inform travelers of current local speed limits.
N/A	Inform travelers of work zones.
N/A	Inform travelers of any special rules that are currently being enforced.

Additionally, as shown in table 6, CARMA Streets will send a set of planning rules to and will receive some perception and vehicle operational information from C-ADS-equipped and connected human-driven vehicles via RSE unit(s).

Table 6. Exchanges between CARMA Streets and vehicles.

CARMA Streets to Vehicle	Vehicle to CARMA Streets
Planning Rules	**Cooperative Perception**
• Speed rules. • Mapping rules. • SPaT data. • Infrastructure sensor data. • Use case-specific policies and decisions. • Other vehicles' information. • Cooperative perception data (e.g., pedestrian locations and headings).	• Vehicles' current status, intent, and so on. • Local world information sensed by each connected vehicle.

FUNCTIONAL PERFORMANCE METRICS

The effectiveness of CARMA Streets on the transportation system needs to be evaluated for its capability to positively impact performance metrics from three perspectives: traffic performance, vehicle behaviors (vehicle operations during execution of different use case scenarios), and communication. Each perspective may involve various subcategories, as discussed in the following section.

Performance Metrics for Traffic Performance

This subsection identifies the performance measures on traffic performance to be used to evaluate the impact of CARMA Streets on traffic flow. Six main categories of impacts[(22)] are identified as follows.

- Safety.
- Throughput.
- Delay.
- Flow stability.
- Flow breakdown and reliability.
- Sustainability.

Safety

Safety is a key factor in evaluating the impacts of any new technologies on transportation systems. As a majority of crashes are due to human error[(23)], connected vehicles have the potential to significantly decrease the number of crashes, specifically at high market penetration levels. One way to quantify safety improvements is by calculating safety surrogate measures (e.g., time to collisions).

Throughput

CDA and connected vehicle technologies are expected to increase the flow throughput of transportation facilities by increasing flow densities. However, such impacts are dependent on the market penetration and the cooperation level of those technologies. Throughput can be quantified by measuring the number of vehicles passing through the intersection per hour and the variability of speeds within a facility segment.

Delay

Delay is a popular and important performance measure. CARMA Streets could estimate delays for individual intersections, corridors, and networks. This information is critical for transportation agencies to improve mobility.

Flow Stability

There are several stability indices developed by the industry that can be used. For example, flow stability refers to the traffic stream's ability to recover its steady-state properties (density-speed) after incurring a perturbation.

Flow Breakdown and Reliability

Flow breakdown is a traffic phenomenon in which throughput/capacity drops due to a perturbation (e.g., accident or sudden braking). CDA and connected vehicle technologies are expected to improve traffic-flow reliabilities by providing smoother, safer, and more responsive vehicle operations. The use case can use multiple measures to quantify impacts on flow breakdown and reliability such as occurrence of shock waves and the severity of shock waves formed.

Sustainability

The environmental impacts of CDA and connected vehicles are uncertain. On one hand, the smoother operations associated with CDA and connected vehicles can lead to lower greenhouse gas emissions and energy consumption. On the other hand, the CDA impacts on travel demand are uncertain and could result in higher overall travel volume, which would increase emissions and energy consumption. The trade-offs between the higher efficiency of flows and higher demand requires further research.

Calculating emissions and energy consumption is usually an offline process that uses data previously obtained by simulation or observed data[(24)]. Several methods are available in the literature for that purpose at different data aggregation levels. As an example, emissions and fuel consumption can be calculated using the speed profiles of vehicles (trajectories) at high temporal resolution obtained by the simulation platform. The proposed performance measures include carbon dioxide, nitrogen oxide, and particulate matter emissions and the amount of energy (volume) consumed.

Performance Metrics for Vehicle Behavior

Key performance metrics for monitoring and evaluating vehicle operations during execution of different use case scenarios involving CARMA Streets may include the following:

- Separation distance: Separation distances are the longitudinal distances between the vehicles in the test. This performance metric is used to determine the frequency of minimum safe distance violations.
- Travel speeds driven: Travel speeds driven are the speeds driven by each vehicle during the tests, which will be used for evaluating the driving smoothness within the control area.
- Acceleration profile: The acceleration profile is the acceleration of each vehicle at different time steps during the tests, which will be used for approximating fuel/energy consumption.
- Speed control error: Speed control error refers to the differences between the advised speed and the actual speed driven by each vehicle during the tests. This performance metric is used to investigate how accurately each vehicle follows its planned trajectory.

Performance Metrics for Communication

The performance metric for data exchanges during communication/negotiation captures all data exchanges from V2V and V2I to determine whether communication and/or maneuver negotiations took place as designed. The data exchanges are to include the following data types:

- Total duration of the negotiation process.
- Total number of negotiation successes and/or failures.
- Percentage of messages rejected by cooperative vehicles: Measure of the accuracy and appropriateness of the message content produced by CARMA Streets at the application level. If Class C cooperative vehicles reject more messages than they accept, then vehicle behavior and traffic performance measures will also be negatively affected.
- Percentage of messages rejected by infrastructure: Measure of percentage of requests (e.g., traffic signal priority) rejected by infrastructure. This performance measure is helpful for transportation agencies to improve operational strategy of arteria.

CHAPTER 4. OPERATIONAL SCENARIOS

This chapter identifies nine representative operational scenarios that could benefit from the deployment of a system like CARMA Streets. These operational scenarios were identified through brainstorming sessions and by collecting feedback from industry webinars and stakeholder feedback surveys. The operational scenarios discussed in this chapter focus on roadways with different traffic control approaches (e.g., stop-controlled and signalized intersections). In these scenarios, a portion of vehicles is assumed to be equipped with CDA technologies and a portion is assumed to be composed of non-ADS connected vehicles—equipped with CARMA Platform and CARMA Messenger, respectively.

BACKGROUND

For each of the following scenarios, the operational needs and functional requirements of the CARMA Streets system are described to summarize the discussion on key CARMA Streets features and guide the future development of requirements of the system. The communication area is defined as the area around the conflict point (e.g., intersection) in which infrastructure can communicate with vehicles. If needed, the communication area can be expanded by adding more RSE or using CARMA Cloud to relay communications. This way, all vehicles inside the communication area of the conflict area can broadcast real-time information regarding their operational status (e.g., location, speed, acceleration, movement group, vehicle type) and intents (e.g., entering time and speed at the intersection box) to RSE unit(s) and surrounding vehicles. In addition, CARMA Streets can assist in communications by optimizing and transmitting the necessary information (e.g., SPaT data) to vehicles.

Additionally, emerging CDA technologies can create a cooperative environment where transportation users will be able to share their perception information with each other, thus improving transportation safety and efficiency. This information-sharing capability enables an advanced feature in a cooperative environment called "cooperative perception," or alternately, "shared perception." The research team is developing a separate ConOps[1] that will address the cooperative perception feature's descriptions, requirements, and potential impacts on transportation systems.

Cooperative perception can be applied simultaneously with other transportation operations, including the use cases proposed in this chapter. It increases the perception range of connected vehicles by exchanging and fusing information from onboard vehicle sensors (e.g., camera, radar, and LiDAR) and infrastructure sensors (e.g., RSE, camera, and loop detector). This will allow connected vehicles to improve their detection range, which will help them in situations where their own sensors are not able to adequately detect the surrounding environment. For example, in situations where a vehicle sensor's field of vision is blocked by external objects such as other vehicles or buildings, surrounding objects detected by other vehicles or infrastructure units can be shared with the vehicle with limited perception. Similarly, in adverse weather conditions where visibility is limited and a vehicle sensor's field of vision camera may not be

1 FHWA. Research report with title to be determined (TBD) on cooperative automation involving CARMA cooperative perception using CARMA proof-of-concept TSMO use case testing. Washington, DC: forthcoming.

able to detect objects at a distance, this feature could be extremely useful in increasing perceived visibility.

CARMA Streets will provide an interface and an edge-computing framework that will significantly contribute to the sensor data fusion exchange needed to foster a cooperative environment. In the CARMA ecosystem, CARMA Platform (for ADS vehicles) and CARMA Messenger (for non-ADS, connected vehicles) can send CARMA Streets the onboard vehicle sensor information either in raw or processed formats. CARMA Streets can also communicate with other infrastructure such as RSE and camera unit(s) to get their real-time information. With the help of relevant algorithms, CARMA Streets can process the received data, fuse the information from different sources, and detect all surrounding external objects in the area. Then, CARMA Streets will share the location and type of these objects to all surrounding vehicles (through CARMA Platform and CARMA Messenger). If needed, each vehicle can then combine the received information with the detected objects from their own sensors to improve their detection accuracy and thus enhance travel safety and efficiency.

In the following sections, nine representative operational use case scenarios are identified. For each of these use case scenarios, CARMA Streets impacts on the use case scenario are discussed. Furthermore, to guide the future development of the CARMA Streets system, operational needs and requirements for each of these use case scenarios are identified.

SCENARIO 1: UNSIGNALIZED CONFLICT AREAS

This scenario focuses on unsignalized intersections such as stop-controlled intersections and roundabouts. The former is based on the operational concept of TSMO Use Case 1 (UC1).(25) This group of scenarios includes the following operational subscenarios:

- Passenger vehicles and trucks approaching a stop-controlled intersection where stop signs are present. The vehicles must stop completely and then yield to vehicles that arrived at the intersection sooner or find an acceptable gap in conflicting traffic before entering the intersection.
- Passenger vehicles and trucks approaching a roundabout. The vehicles must slow down to a safe speed and then find an acceptable gap in conflicting traffic before entering the intersection.
- Passenger vehicles and trucks driving along an arterial where they need to merge to another roadway segment while yielding to traffic coming from different approaches.

In traditional traffic control systems at unsignalized conflict areas, lack of communications between vehicles on the same or different approaches of a conflict area may cause substantially inefficient traffic operations, including stop-and-go traffic patterns, backward shockwave propagations, and reduced roadway capacity. Fortunately, the advent of CDA technologies can completely change the operations of conflict movements at unsignalized conflict areas.

The TSMO UC1 ConOps overviews an edge-computing-based cooperative control framework for C-ADS-equipped vehicles at stop-controlled intersections, which could be generalized to the above-mentioned scenario group. CARMA Streets can improve this scenario group by calculating an optimal schedule for vehicles to pass through an unsignalized conflict area. For instance, one of the components that is proposed in the TSMO UC1 ConOps is critical time step estimation (CTSE).

The CTSE is called at CARMA Streets in a centralized manner and aims to estimate a set of critical time steps for each C-ADS-equipped vehicle (e.g., time of stop at stop bar, time of entry into conflict area). CARMA Streets may impose any scheduling rule determined by the local traffic agency. For example, for stop-controlled intersections, a first-come-first-serve rule may be applied based on the sequence of vehicles stopping at the stop bar. This indicates that as soon as a vehicle stops at the stop bar, it will reserve the next position in the departure sequence through CARMA Streets and thus cannot enter the intersection box earlier than the previously stopped vehicles. As such, each C-ADS-equipped vehicle can adjust its trajectory based on information received from other vehicles or RSE (processed and relayed by CARMA Streets) to mitigate backward shockwave propagations and stop-and-go traffic patterns at conflict areas. A similar ConOps applies to the other operational subscenarios.

This use case scenario is not considered for CARMA Streets development and testing in the "CARMA Proof-of-Concept TSMO Use Case Testing" project. However, to guide further development of the CARMA Streets system, table 7 provides a list of operational needs that are pertinent to this use case scenario.

Table 7. CARMA Streets operational needs for scenario 1.

ID#	Relevant Component	Need Statement
N01	CARMA Streets	Needs to store static infrastructure data (e.g., map, speed limits, and lane restrictions).
N02	RSE	Needs to communicate with one or more RSE unit(s).
N02.01	RSE	Needs to relay all or part of the current and processed information.
N03	CARMA Platform	Needs to communicate with CARMA Platform installed in all surrounding C-ADS-equipped vehicles.
N03.01	CARMA Platform	Needs to receive CARMA Platform data including vehicle status and intent information.
N03.02	CARMA Platform	Needs to send use case-specific variables (e.g., optimal vehicle entering times and vehicles sequence).
N03.03	CARMA Platform	Needs to send vulnerable user information (e.g., type, location, heading, and speed) determined by fusing data received from different sources (i.e., vehicles and infrastructure units).
N04	CARMA Messenger	Needs to communicate with CARMA Messenger installed on all surrounding non-ADS connected vehicles.
N04.01	CARMA Platform	Needs to receive CARMA Messenger data including vehicle status information.

ID#	Relevant Component	Need Statement
N04.02	CARMA Messenger	Needs to send the use case-specific variables (e.g., optimal vehicle entering times and vehicles sequence).
N04.03	CARMA Messenger	Needs to send vulnerable user information (e.g., type, location, heading, and speed) determined by fusing data received from different sources (i.e., vehicles and infrastructure units).
N07	Camera	Needs to receive and temporarily store camera data in real time.
N07.01	Camera	Needs to process camera videos to detect presence of vulnerable users (e.g., pedestrians and bicyclists).
N08	Mobile Device	Needs to communicate with pedestrian cell-phone devices that have required communication hardware and software requirements.
N08.01	Mobile Device	Needs to receive and process pedestrian crossing requests for mid-block crossing points.
N09	CARMA Streets	Needs to temporarily store and process the data received from all components in real time.
N09.01	CARMA Streets	Needs to estimate near future vehicle trajectories.
N09.02	CARMA Streets	Needs to compute the optimal vehicles schedule sequence according to specific use case or a policy.
N09.03	CARMA Streets	Needs to fuse data from different sources (i.e., vehicles and infrastructure units) to determine vulnerable users' information (e.g., type, location, heading, and speed).
N09.04	CARMA Streets	Needs to aggregate traffic information received from individual vehicles and sensors.
N11	CARMA Streets, CARMA Platform, CARMA Messenger, CARMA Cloud	Need to have proper cybersecurity platforms and strategies to protect and recover from cyber threats.

SCENARIO 2: VEHICLE TRAJECTORIES AND SIGNAL SHARING/OPTIMIZATIONS AT SIGNALIZED INTERSECTIONS

This scenario focuses on signalized intersections at arterials and is based on the operational concept of TSMO Use Case 2 (UC2)[2] and Use Case 3 (UC3)[3]. This group of scenarios includes the following operational subscenarios:

1. Passenger vehicles and trucks approaching a signalized intersection with a fixed-time setting from different approaches.

2. Passenger vehicles and trucks approaching a signalized intersection with the actuated setting from different approaches. The actuation may be triggered depending on the traffic on the minor approach(es).

3. Passenger vehicles and trucks approaching a signalized intersection with the adaptive setting from different approaches. The signal-timing plan may be adapted based on the real-time traffic on different approaches.

Conventional signalized traffic operations may result in excessive travel delay, energy consumption and emissions, driving discomfort, and safety risks due to lack of proper communications between vehicles and infrastructure. The V2I communications provided in a connected ecosystem can significantly improve traffic efficiency and safety. In such an ecosystem, vehicles can be aware of the downstream intersection traffic and so adjust their speeds to reduce their travel delay, which will reduce or eliminate the stop-and-go traffic patterns. Further, in adaptive signal settings, signal-timing plans can be optimized according to the observed real-time traffic data to increase traffic throughput at the intersection.

The TSMO UC2 ConOps focuses on advancing the first two subscenarios mentioned above with CDA technologies. According to this Concept-of-Operation, each C-ADS-equipped vehicle smooths its own trajectory based on the received SPaT information from the RSE. In TSMO UC2, no decision regarding the SPaT plan is required, and the SPaT plan at the investigated intersection is assumed to be given and shared to the surrounding vehicles. The proposed cooperative framework has two main components: CTSE and TS. First, the CTSE component estimates an entering time to the intersection box for each C-ADS-equipped vehicle. This component is called either at each C-ADS-equipped vehicle in a decentralized manner (in cooperation classes A, B, and C), or at CARMA Streets (in cooperation classes C and D) in a centralized manner. Second, the TS component is called at each C-ADS-equipped vehicle in a decentralized manner to smooth C-ADS-equipped vehicle trajectory with the received information from other vehicles or CARMA Streets, to mitigate the backward shockwave propagations and the stop-and-go traffic patterns at signalized intersections.

The TSMO UC3 ConOps focuses on the third subscenario. In this subscenario, the SPaT plan at signalized intersections is optimized in real time based on the received real-time operational

[2] FHWA. Research report with title TBD on cooperative automation involving CARMA proof-of-concept TSMO UC3—fixed-time and actuated traffic signals. Washington, DC: forthcoming.

[3] FHWA. Research report with title TBD on cooperative automation involving CARMA proof-of-concept TSMO UC3—traffic signal optimization with CDA at signalized intersections. Washington, DC: forthcoming.

information from C-ADS-equipped vehicles, and then each C-ADS-equipped vehicle smooths its trajectory with the available and optimized SPaT plan. The TSMO UC3 ConOps adds another component prior to the CTSE and TS components defined in TSMO UC2, which is SO. The SO component is designed to run at CARMA Streets to determine a proper departure sequence of vehicles and convert it to a SPaT plan. Then, the CTSE component will estimate entering times of vehicles to the intersection box based on the converted SPaT plan or the determined departure sequence from the SO component. Finally, the TS component is called at each C-ADS-equipped vehicle in a decentralized manner to smooth C-ADS-equipped vehicle trajectory with the received information from other vehicles or CARMA Streets.

The TS component proposed in the TSMO UC2 and UC3 ConOps documents focuses on decentralized trajectory optimization of individual vehicles, where each vehicle optimizes its trajectory without cooperating with other vehicles. In this framework, there is a chance that vehicles scatter through the roadways rather than forming into platoons. In a cooperative trajectory framework, the trajectory of vehicle platoons can be optimized instead of trajectory optimization of individual vehicles. Depending on the platooning framework, CARMA Streets can send platooning rules, speed advisories, and/or scheduling information to the platoon leader so that all vehicles in the platoon can adjust their trajectories accordingly.

Overall, CARMA Streets will enable such a cooperative control framework to distribute the computational burden among different entities in an edge-computing structure and thus make it much more suitable for real-time applications.

This use case scenario is not considered for CARMA Streets development and testing in the "CARMA Proof-of-Concept TSMO Use Case Testing" project. However, to guide the further development of the CARMA Streets system, table 8 provides a list of operational needs that are pertinent to this use case scenario.

Table 8. CARMA Streets operational needs for scenario 2.

ID#	Relevant Component	Need Statement
N01	CARMA Streets	Needs to store static infrastructure data (e.g., map, speed limits, and lane restrictions).
N02	RSE	Needs to communicate with one or more RSE unit(s).
N02.01	RSE	Needs to relay all or part of the current and processed information.
N03	CARMA Platform	Needs to communicate with CARMA Platform installed in all surrounding C-ADS-equipped vehicles.
N03.01	CARMA Platform	Needs to receive CARMA Platform data including vehicle status and intent information.
N03.02	CARMA Platform	Needs to send the use case-specific variables (e.g., optimal vehicle entering times, vehicles sequence, and signal-timing plan information).
N03.03	CARMA Platform	Needs to send vulnerable user information (e.g., type, location, heading, and speed) determined by fusing data received from different sources (i.e., vehicles and infrastructure units).

ID#	Relevant Component	Need Statement
N04	CARMA Messenger	Needs to communicate with CARMA Messenger installed on all surrounding non-ADS connected vehicles.
N04.01	CARMA Platform	Needs to receive CARMA Messenger data including vehicle status information.
N04.02	CARMA Messenger	Needs to send the use case-specific variables (e.g., optimal vehicle entering times, vehicles sequence, and signal-timing plan information).
N04.03	CARMA Messenger	Needs to send vulnerable user information (e.g., type, location, heading, and speed) determined by fusing data received from different sources (i.e., vehicles and infrastructure units).
N06	Signal controller	Needs to communicate with a signal controller.
N06.01	Signal controller	Needs to send SPaT data.
N06.02	Signal controller	Needs to adapt the signal-timing plan (e.g., placing green extension calls).
N06.03	Signal controller	Needs to receive and process the requests from pedestrian mobile devices and send a pedestrian call to the signal controller.
N07	Camera	Needs to receive and temporarily store camera data in real time.
N07.01	Camera	Needs to process camera videos to detect presence of vulnerable users (e.g., pedestrians and bicyclists).
N08	Mobile device	Needs to communicate with pedestrian cell-phone devices that have required communication hardware and software requirements.
N08.01	Mobile device	Needs to receive and process pedestrian crossing requests for both intersections and mid-block crossing points.
N09	CARMA Streets	Needs to temporarily store and process the data received from all components in real time.
N09.01	CARMA Streets	Needs to estimate near future vehicle trajectories.
N09.02	CARMA Streets	Needs to compute the optimal vehicles schedule sequence according to specific use case or a policy.
N09.03	CARMA Streets	Needs to fuse data from different sources (i.e., vehicles and infrastructure units) to determine vulnerable users' information (e.g., type, location, heading, and speed).
N09.04	CARMA Streets	Needs to aggregate traffic information received from individual vehicles and sensors.
N09.05	CARMA Streets	Needs to compute the optimal signal-timing plan according to specific use case or a policy.
N11	CARMA Streets, CARMA Platform, CARMA Messenger, CARMA Cloud	Need to have proper cybersecurity platforms and strategies to protect and recover from cyber threats.

SCENARIO 3: SIGNAL PRIORITY FOR TRANSIT AND FREIGHT

This scenario prioritizes the arterial street mobility of transit and/or freight vehicles over other vehicles (e.g., passenger cars, pedestrians, and emergency vehicles traveling without sirens). TSP will be discussed in the operational concept of TSMO TSP use case testing.[4] Scenario 3 may include the following operational subscenarios:

- Transit vehicle(s) approaching a signalized intersection.
- Freight vehicle(s) approaching a signalized intersection.
- Transit vehicle(s) and freight vehicle(s) simultaneously approaching a signalized intersection.

For signal priority, the signal controller may give an early green signal or extend a green signal that is already displaying to reduce the travel delay of the transit vehicles. The main objective of TSP strategies is to increase the person throughput of the intersection. Active TSP strategy detects the presence of a bus and then predicts its arrival time at the intersection. In conventional active strategies, buses are usually detected by the signal controller installed on the dedicated lanes. In a connected environment, a bus can communicate to the signal controller using an onboard communication device (e.g., cellular network) to announce its existence.

Freight signal priority strategies are applied to extend a green time to allow a heavy-duty vehicle to make it through the intersection without stopping. The main objective is to increase safety by avoiding the freight vehicle running a traffic red indication. Delay and fuel consumption reductions are usually considered as secondary objectives.

The challenge for both transit and freight signal priority applications are twofold: how to properly detect and distinguish priority vehicles and how to accurately predict their arrival time at the intersection. Connected vehicle technologies can significantly help with both these challenges. The vehicle status information (e.g., vehicle type, current location, and speed) includes the most important variables required for all signal priority strategies. As an example, the multimodal intelligent traffic signal system (MMITSS) previously accomplished signal priority signal-timing adjustments based on surrounding connected vehicle data.[(26)]

Emerging CDA technologies provide promising opportunities for transit and freight signal priority practices by enabling cooperative maneuvers and negotiations. This is mainly due to transit and freight vehicles being able to share status and intent information with each other and with infrastructure to obtain required priority to reduce delays and/or reduce safety concerns. Further, transit and freight vehicles may be able to negotiate with other vehicles and with infrastructure. With CDA technologies, various algorithms can be developed to improve signal priority strategies in which CARMA Streets can facilitate the coordination among different CDA participants. For example, CARMA Streets can get necessary information (e.g., scheduling information, vehicle type) from the transit and freight vehicles or from CARMA Cloud to identify the vehicles that need priority. CARMA Streets can also send advisory messages to the vehicles to change their lanes in favor of the transit or freight vehicles that need priority. Finally,

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4 FHWA. Research report with title TBD on cooperative automation involving CARMA proof-of-concept TSMO testing—transit management (transit signal priority). Washington, DC: forthcoming.

CARMA Streets may grant priority to certain transit and freight vehicles and exchange necessary information to the signal controller and to the transit and freight vehicles. Each transit and freight vehicle may receive the updated signal-timing information from CARMA Streets and thus adjust its trajectory accordingly to pass through the intersection smoothly and safely. For freight vehicles that are formed in platoons, these trajectory adjustments may be conducted by the platoon leader.

Signal priority for transit is considered for CARMA Streets development and testing in the "CARMA Proof-of-Concept TSMO Use Case Testing" project. More detailed information about this use case scenario will be provided in a separate low-level ConOps document. To guide the development of this document, table 9 provides a list of operational needs that are pertinent to this use case scenario.

Table 9. CARMA Streets operational needs for Scenario 3.

ID#	Relevant Component	Need Statement
N01	CARMA Streets	Needs to store static infrastructure data (e.g., map, speed limits, and lane restrictions).
N02	RSE	Needs to communicate with one or more RSE unit(s).
N02.01	RSE	Needs to relay all or part of the current and processed information.
N03	CARMA Platform	Needs to communicate with CARMA Platform installed in all surrounding C-ADS-equipped vehicles.
N03.01	CARMA Platform	Needs to receive CARMA Platform data including vehicle status and intent information.
N03.02	CARMA Platform	Needs to send the use case-specific variables (e.g., scheduling and signal-timing plan information).
N03.03	CARMA Platform	Needs to send vulnerable user information (e.g., type, location, heading, and speed) determined by fusing data received from different sources (i.e., vehicles and infrastructure units).
N03.04	CARMA Platform	Needs to receive freight vehicles status information (e.g., weight and platooning status).
N04	CARMA Messenger	Needs to communicate with CARMA Messenger installed on all surrounding non-ADS connected vehicles.
N04.01	CARMA Platform	Needs to receive CARMA Messenger data including vehicle status information.
N04.02	CARMA Messenger	Needs to send the use case-specific variables (e.g., scheduling and signal-timing plan information).
N04.03	CARMA Messenger	Needs to send vulnerable user information (e.g., type, location, heading, and speed) determined by fusing data received from different sources (i.e., vehicles and infrastructure units).

ID#	Relevant Component	Need Statement
N04.04	CARMA Messenger	For transit bus, need to receive scheduling information (i.e., whether it is delayed, on-time, or ahead of the schedule).
N04.05	CARMA Messenger	For transit bus, need to receive number of riders on the bus (exact or an estimate).
N05	CARMA Cloud	Needs to communicate with CARMA Cloud.
N05.01	CARMA Cloud	Needs to relay all or part of the current and processed information.
N05.02	CARMA Cloud	Needs to receive signal-timing information from neighboring intersections.
N05.03	CARMA Cloud	Needs to send the current local aggregated traffic status information.
N05.04	CARMA Cloud	Needs to receive the current traffic status information from different areas of the corridor.
N06	Signal controller	Needs to communicate with a signal controller.
N06.01	Signal controller	Needs to send SPaT data.
N06.02	Signal controller	Needs to adapt the signal-timing plan (e.g., placing green extension calls).
N06.03	Signal controller	Needs to receive and process the requests from pedestrian mobile devices and send a pedestrian call to the signal controller.
N07	Camera	Needs to receive and temporarily store camera data in real time.
N07.01	Camera	Needs to process camera videos to detect presence of vulnerable users (e.g., pedestrians and bicyclists).
N08	Mobile Device	Needs to communicate with pedestrian cell-phone devices that have required communication hardware and software requirements.
N08.01	Mobile Device	Needs to receive and process pedestrian crossing requests for both intersections and mid-block crossing points.
N09	CARMA Streets	Needs to temporarily store and process the data received from all components in real time.
N09.01	CARMA Streets	Needs to estimate near future vehicle trajectories.
N09.03	CARMA Streets	Needs to fuse data from different sources (i.e., vehicles and infrastructure units) to determine vulnerable users' information (e.g., type, location, heading, and speed).
N09.04	CARMA Streets	Needs to aggregate traffic information received from individual vehicles and sensors.
N11	CARMA Streets, CARMA Platform, CARMA Messenger, CARMA Cloud	Need to have proper cybersecurity platforms and strategies to protect and recover from cyber threats.

SCENARIO 4: SIGNAL PREEMPTION FOR TRAFFIC INCIDENT MANAGEMENT

This scenario allows the disruption of a normal signal cycle so that emergency responders (police, fire, and emergency medical services) can pass through an intersection in a quicker and safer manner. It will be discussed in the operational concept of TSMO TIM use case testing.[5] In this scenario, a green interval can be extended or replace whole-cycle phasing and timing to serve an emergency vehicle. This group of scenarios includes the following operational subscenarios:

- An incident occurs downstream of a signalized intersection. An emergency vehicle needs a green time extension to pass through the intersection without stopping.
- An incident occurs in the middle or downstream of a signalized intersection. An emergency vehicle needs to pass through the intersection without stopping. The signal indication on all approaches needs to be set to red except for the one at which the emergency vehicle is approaching.

This scenario is similar to active signal priority to some extent. The system will detect the presence of an emergency vehicle and predict its arrival time at the intersection.

CDA technologies can advance this strategy in different ways by enabling cooperative environments. First, connected vehicles and infrastructure can identify the incident events and notify IOOs by communicating with infrastructure (e.g., CARMA Streets and CARMA Cloud). Second, emergency vehicles can broadcast their status and intent information with other vehicles and with infrastructure. In such an environment, CARMA Streets will be able to coordinate with different components and CDA participants to let emergency vehicle(s) proceed through the intersection with maximum speed and safety. For example, CARMA Streets can get necessary information (e.g., location, speed, and route) from the emergency vehicle(s) to create a signal preemption plan.

To improve efficiency and speed, if one or more emergency vehicles approach an intersection while out of the communication range of the intersection RSE, CARMA Cloud can send the necessary information to the CARMA Streets unit located at the intersection. Then CARMA Streets can exchange necessary information to the signal controller for the preemption request. When signal preemption is granted, CARMA Streets can notify the emergency vehicle(s) about this change either through RSE or CARMA Cloud. CARMA Streets can also send the updated signal-timing adjustment and advisory messages to all surrounding vehicles so that they move over to other lanes. According to the updated signal timing, each connected vehicle may adjust its lateral and longitudinal trajectories to let the emergency vehicle(s) pass through the intersection. When they have passed, CARMA Streets will request the signal controller recover the normal signal pattern and notify the surrounding vehicles about this change. Accordingly, vehicles may adjust their trajectories to pass through the intersection smoothly and safely.

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5 FHWA. Research report with title TBD on cooperative automation involving CARMA proof-of-concept TSMO testing—Traffic incident management. Washington, DC: forthcoming.

This use case scenario is considered for CARMA Streets development and testing in the "CARMA Proof-of-Concept TSMO Use Case Testing" project. More detailed information about this use case scenario will be provided in a separate low-level ConOps document. To guide the development of this document, table 10 provides a list of operational needs that are pertinent to this use case scenario.

Table 10. CARMA Streets operational needs for scenario 4.

ID#	Relevant Component	Need Statement
N01	CARMA Streets	Needs to store static infrastructure data (e.g., map, speed limits, and lane restrictions).
N02	RSE	Needs to communicate with one or more RSE unit(s).
N02.01	RSE	Needs to relay all or part of the current and processed information.
N03	CARMA Platform	Needs to communicate with CARMA Platform installed in all surrounding C-ADS-equipped vehicles.
N03.01	CARMA Platform	Needs to receive CARMA Platform data including vehicle status and intent information.
N03.02	CARMA Platform	Needs to send the use case-specific variables (e.g., signal-timing plan information).
N03.03	CARMA Platform	Needs to send vulnerable user information (e.g., type, location, heading, and speed) determined by fusing data received from different sources (i.e., vehicles and infrastructure units).
N04	CARMA Messenger	Needs to communicate with CARMA Messenger installed on all surrounding non-ADS connected vehicles.
N04.01	CARMA Platform	Needs to receive CARMA Messenger data including vehicle status information.
N04.02	CARMA Messenger	Needs to send the use case-specific variables (e.g., signal-timing plan information).
N04.03	CARMA Messenger	Needs to send vulnerable user information (e.g., type, location, heading, and speed) determined by fusing data received from different sources (i.e., vehicles and infrastructure units).
N04.06	CARMA Messenger	For emergency vehicle, need to receive the siren light status (i.e., on, off).
N05	CARMA Cloud	Needs to communicate with CARMA Cloud.
N05.01	CARMA Cloud	Needs to relay all or part of the current and processed information.
N05.02	CARMA Cloud	Needs to receive signal-timing information from neighboring intersections.
N05.03	CARMA Cloud	Needs to send the current local aggregated traffic status information.
N05.04	CARMA Cloud	Needs to receive the current traffic status information from different areas of the corridor.

ID#	Relevant Component	Need Statement
N06	Signal controller	Needs to communicate with a signal controller.
N06.01	Signal controller	Needs to send SPaT data.
N06.02	Signal controller	Needs to adapt the signal-timing plan (e.g., placing preemption calls).
N06.03	Signal controller	Needs to receive and process the requests from pedestrian mobile devices and send a pedestrian call to the signal controller.
N07	Camera	Needs to receive and temporarily store camera data in real time.
N07.01	Camera	Needs to process camera videos to detect presence of vulnerable users (e.g., pedestrians and bicyclists).
N08	Mobile Device	Needs to communicate with pedestrian cell-phone devices that have required communication hardware and software requirements.
N08.01	Mobile Device	Needs to receive and process pedestrian crossing requests for both intersections and mid-block crossing points.
N09	CARMA Streets	Needs to temporarily store and process the data received from all components in real time.
N09.01	CARMA Streets	Needs to estimate near future vehicle trajectories.
N09.03	CARMA Streets	Needs to fuse data from different sources (i.e., vehicles and infrastructure units) to determine vulnerable user information (e.g., type, location, heading, and speed).
N09.04	CARMA Streets	Needs to aggregate traffic information received from individual vehicles and sensors.
N11	CARMA Streets, CARMA Platform, CARMA Messenger, CARMA Cloud	Need to have proper cybersecurity platforms and strategies to protect and recover from cyber threats.

SCENARIO 5: INTERACTING WITH VULNERABLE USERS

Safety enhancement for vulnerable users is one of the most important objectives to account for within the CARMA Streets development. This scenario focuses on the interactions CARMA Streets may have with pedestrians and bicyclists and aims to improve the safety, mobility, and comfort of users. This group of scenarios mainly includes the following operational subscenarios:

- Pedestrians walking on the side of a roadway: The surrounding vehicles should operate safely.

- Bicyclists riding on the side of a roadway: The surrounding vehicles should operate safely.

- Pedestrian needing to cross a signalized intersection: A pedestrian call should be placed. When vehicles on the corresponding direction(s) are approaching the intersection, these vehicles will receive alerts that a pedestrian is about to cross the interaction. These vehicles can adjust their trajectories to completely stop at the stop bar in an optimal manner (e.g., minimum fuel consumption). This will also improve safety at signalized intersections. Vehicles and pedestrians can receive warnings to inform their status (e.g., location and speed) that will be very critical to avoid uncertainties in blind spots.

- Pedestrian needing to cross a mid-block crossing with vehicular traffic: A pedestrian call should be placed; similar to the above situation.

- Bicyclist needing to cross a mid-block crossing with vehicular traffic: A pedestrian call should be placed. The vehicles on the corresponding direction(s) should stop completely before the pedestrian can start crossing the intersection.

- Bicyclist needing to cross a signalized intersection: A pedestrian call should be placed. The vehicles on the corresponding direction(s) should stop completely before the bicyclist can start crossing the intersection.

In most current infrastructure settings, when a pedestrian or a bicyclist on the sidewalk wants to cross an intersection or a roadway, he or she needs to press a button to trigger a pedestrian call. However, this might not always be the safest and most efficient solution. For example, not every pedestrian and bicyclist may press the pedestrian call or wait until the vehicles stop before passing the intersection or the roadway. Further, pedestrian buttons are not installed everywhere (e.g., out of the crosswalk).

The CARMA ecosystem can provide a more efficient and safer environment for these vulnerable users. Ideally, pedestrians and bicyclists could be detected in real time by processing the videos captured by cameras installed at infrastructure. In this case, CARMA Streets will be able to provide necessary communication and computing power to process captured videos in real time. This information will be encoded by CARMA Streets to personal safety messages (PSMs). CARMA Streets will send these PSMs to RSE for broadcasting. Vehicles approaching the intersections can receive PSMs to be informed of the existence of pedestrians and bicyclists.

These vehicles could optimize their trajectories according to SPaT and PSMs to improve operational efficiency (e.g., mobility, safety, fuel consumption, and emissions). Additionally, the information on the number of pedestrians and bicyclists at each approach of an intersection could be used by CARMA Streets to optimize traffic signal timing for pedestrians to reduce unnecessary waiting time of vehicles in conflicting phases.

Alternatively, the pedestrian or bicyclist can place a request to cross the intersection or the roadway through an application on their mobile device. Once requested, it will be transferred to CARMA Streets through RSE via cellular network. CARMA Streets could use this information to optimize the traffic signal timing of the approaching vehicles and serve the pedestrian phase.

This use case scenario is not considered for CARMA Streets development and testing in the "CARMA Proof-of-Concept TSMO Use Case Testing" project. However, to guide the further development of the CARMA Streets system, table 11 provides a list of operational needs that are pertinent to this use case scenario.

Table 11. CARMA Streets operational needs for Scenario 5.

ID#	Relevant Component	Need Statement
N01	CARMA Streets	Needs to store static infrastructure data (e.g., map, speed limits, and lane restrictions).
N02	RSE	Needs to communicate with one or more RSE unit(s).
N02.01	RSE	Needs to relay all or part of the current and processed information.
N03	CARMA Platform	Needs to communicate with CARMA Platform installed in all surrounding C-ADS-equipped vehicles.
N03.01	CARMA Platform	Needs to receive CARMA Platform data including vehicle status and intent information.
N03.02	CARMA Platform	Needs to send the use case-specific variables (e.g., location and heading).
N03.03	CARMA Platform	Needs to send vulnerable user information (e.g., type, location, heading, and speed) determined by fusing data received from different sources (i.e., vehicles and infrastructure units).
N04	CARMA Messenger	Needs to communicate with CARMA Messenger installed on all surrounding non-ADS connected vehicles.
N04.01	CARMA Platform	Needs to receive CARMA Messenger data including vehicle status information.
N04.02	CARMA Messenger	Needs to send the use case-specific variables (e.g., location and heading).
N04.03	CARMA Messenger	Needs to send vulnerable user information (e.g., type, location, heading, and speed) determined by fusing data received from different sources (i.e., vehicles and infrastructure units).
N06	Signal controller	Needs to communicate with a signal controller.
N06.03	Signal controller	Needs to receive and process the requests from pedestrian mobile devices and send a pedestrian call to the signal controller.
N07	Camera	Needs to receive and temporarily store camera data in real time.
N07.01	Camera	Needs to process camera videos to detect presence of vulnerable users (e.g., pedestrians and bicyclists).
N08	Mobile Device	Needs to communicate with pedestrian cell-phone devices that have required communication hardware and software requirements.
N08.01	Mobile Device	Needs to receive and process pedestrian crossing requests for both intersections and mid-block crossing points.
N09	CARMA Streets	Needs to temporarily store and process the data received from all components in real time.
N09.01	CARMA Streets	Needs to estimate near future vehicle trajectories.

ID#	Relevant Component	Need Statement
N09.03	CARMA Streets	Needs to fuse data from different sources (i.e., vehicles and infrastructure units) to determine vulnerable user information (e.g., type, location, heading, and speed).
N11	CARMA Streets, CARMA Platform, CARMA Messenger, CARMA Cloud	Need to have proper cybersecurity platforms and strategies to protect and recover from cyber threats.

SCENARIO 6: WORK ZONES

This scenario focuses on how CARMA Streets can improve work-zone management to increase efficiency and safety of work zones. This scenario includes the following operational subscenarios:

- Passenger vehicles and trucks approaching stationary or mobile work zones.
- Passenger vehicles and trucks driving on the side of stationary or mobile work zones.
- Passenger vehicles and trucks departing from stationary or mobile work zones.
- Pedestrians walking on the side of a work zone.
- Bicyclists riding on the side of a work zone.

Most typical work zones have a few warning devices such as signs, cones, barrels, and flaggers upstream, in the middle, and downstream of the work zone to advice the drivers on how to travel safely. Traditional work zone management practices may still cause safety and efficiency concerns.

Connected vehicle and cooperative automation technologies can improve the performance of work zones in several ways. First, vehicles, pedestrians, and bicyclists within a certain range of a planned or an active work zone can be notified via connected infrastructure units (e.g., CARMA Streets). This notification may include various information details such as start time, end time, location, number of closed lanes, and so on. This information will help travelers decide whether to find another route, and if they need to travel along the work zone, how to safely and efficiently proceed. Second, work zone-related and surrounding traffic information can help vehicles plan their trajectories to improve safety, fuel efficiency, and driving comfort and reduce travel delay. Third, surrounding vehicles can be alerted to the presence of workers and other vulnerable users (e.g., pedestrians and bicyclists) around the work zone area can be notified to improve safety.

In all these ways, CARMA Streets can contribute to the safety and efficiency of work zones by exchanging necessary work zone-related data between the surrounding users (vehicles, pedestrians, etc.); TMC (though CARMA Cloud); and roadside devices (warning signs, cameras, signal controllers, etc.). CARMA Streets can also receive planned work zone information from TMCs (through CARMA Cloud) and then compare it with real-time work zone status information received from road users (through CARMA Platform and CARMA Messenger). As such, CARMA Streets can notify the road users about any identified discrepancy.

This use case scenario is not considered for CARMA Streets development and testing in the "CARMA Proof-of-Concept TSMO Use Case Testing" project. However, to guide the further development of the CARMA Streets system, table 12 provides a list of operational needs that are pertinent to this use case scenario.

Table 12. CARMA Streets operational needs for Scenario 6.

ID#	Relevant Component	Need Statement
N01	CARMA Streets	Needs to store static infrastructure data (e.g., map, speed limits, and lane restrictions).
N02	RSE	Needs to communicate with one or more RSE unit(s).
N02.01	RSE	Needs to relay all or part of the current and processed information.
N03	CARMA Platform	Needs to communicate with CARMA Platform installed in all surrounding C-ADS-equipped vehicles.
N03.01	CARMA Platform	Needs to receive CARMA Platform data including vehicle status and intent information.
N03.03	CARMA Platform	Needs to send vulnerable user information (e.g., type, location, heading, and speed) determined by fusing data received from different sources (i.e., vehicles and infrastructure units).
N03.05	CARMA Platform	Needs to send work zone information (e.g., configuration, map, presence of workers).
N04	CARMA Messenger	Needs to communicate with CARMA Messenger installed on all surrounding non-ADS connected vehicles.
N04.01	CARMA Platform	Needs to receive CARMA Messenger data including vehicle status information.
N04.03	CARMA Messenger	Needs to send vulnerable user information (e.g., type, location, heading, and speed) determined by fusing data received from different sources (i.e., vehicles and infrastructure units).
N04.07	CARMA Messenger	Needs to send work zone information (e.g., configuration, map, presence of workers).
N05	CARMA Cloud	Needs to communicate with CARMA Cloud.
N05.01	CARMA Cloud	Needs to relay all or part of the current and processed information.
N05.02	CARMA Cloud	Needs to receive signal-timing information from neighboring intersections.
N05.03	CARMA Cloud	Needs to send the current local aggregated traffic status information.
N05.04	CARMA Cloud	Needs to receive the current traffic status information from different areas of the corridor.
N05.05	CARMA Cloud	Needs to receive work zone information (e.g., configuration, map, presence of workers).
N06	Signal controller	Needs to communicate with a signal controller.

ID#	Relevant Component	Need Statement
N06.01	Signal controller	Needs to send SPaT data.
N06.02	Signal controller	Needs to adapt the signal-timing plan (e.g., placing green extension calls).
N06.03	Signal controller	Needs to receive and process requests from pedestrian mobile devices and send pedestrian calls to signal controller.
N07	Camera	Needs to receive and temporarily store camera data in real time.
N07.01	Camera	Needs to process camera videos to detect presence of vulnerable users (e.g., pedestrians and bicyclists).
N08	Mobile Device	Needs to communicate with pedestrian cell-phone devices that have required communication hardware and software requirements.
N08.01	Mobile Device	Needs to receive and process pedestrian crossing requests for both intersections and mid-block crossing points.
N09	CARMA Streets	Needs to temporarily store and process the data received from all components in real time.
N09.03	CARMA Streets	Needs to fuse data from different sources (i.e., vehicles and infrastructure units) to determine vulnerable user information (e.g., type, location, heading, and speed).
N09.04	CARMA Streets	Needs to aggregate traffic information received from individual vehicles and sensors.
N11	CARMA Streets, CARMA Platform, CARMA Messenger, CARMA Cloud	Need to have proper cybersecurity platforms and strategies to protect and recover from cyber threats.

SCENARIO 7: WEATHER MANAGEMENT

This scenario focuses on maximizing arterial street mobility and safety during adverse weather events such as rainstorms, snowstorms, and thick fog. This group of scenarios includes the following operational subscenarios:

- The roadway surface is incapable of safely supporting normal travel speeds.
- The safe headways between vehicles are increased by limited visibility. This assumes some vehicles are human driven vehicles, and/or some CDA vehicles depend on human assistance.
- The roadway surface is incapable of safely supporting normal travel speeds, and the safe headways between vehicles are increased by limited visibility. (Both risks above exist.)

Depending on the weather emergency, TMCs currently use RWIS, the National Weather Service, third-party weather data providers, and so on to gather information on existing and forecasted weather conditions. The data support decisionmaking for responding to weather events such as winter storms, flooding, and hurricanes. With emerging connected vehicle technologies, the data can be collected and shared with other transportation system users at higher spatial and temporal resolutions.

In addition to typical weather-related data collected by TMCs, information collected and shared by connected vehicles can also significantly contribute to the awareness of transportation users and managers about weather events. Examples of such information broadcast by vehicles include road surface data, air temperature, air pressure, braking status, anti-lock braking system (ABS) engagement status, and traction control status.

In addition, CARMA Streets can help by collecting all this information from CARMA Platform, CARMA Messenger, and CARMA Cloud, processing and fusing the collected data from different sources and sharing advisory messages with the surrounding traffic and with the cloud. At intersection level, CARMA Streets could process the data received from cameras or other sensors to detect adverse weather conditions to warn approaching road users about situations including, but not limited to, flooding and poor visibility.

Additionally, during adverse weather conditions safe vehicle speeds are lower, and safe vehicle headways may be larger. Default signal timing at arterials may produce inefficient traffic flow at these lower speeds. CARMA Streets can influence arterial street mobility and safety through both signal-timing adjustments (e.g., trigger predefined signal-timing plans for adverse weather conditions or adjust signal timing in real time according to the data received) and vehicle trajectory adjustments.

Finally, the CARMA ecosystem can provide a safer environment for vulnerable users. If visibility is reduced due to adverse weather, the presence of these users could be detected and shared by connected vehicles and roadside cameras. CARMA Streets will be able to provide necessary communication and computing power to process videos captured by cameras in real time. This information will be encoded by CARMA Streets to PSMs. CARMA Streets will send these PSMs to RSE for broadcasting. As a result, the surrounding vehicles could receive PSMs to be informed about the existences of vulnerable users. In addition, in a cooperative environment, vehicles will be able to share their perception information to infrastructure (e.g., CARMA Streets) and other vehicles with limited perception, which can significantly improve safety in adverse weather conditions.

This use case scenario is not considered for CARMA Streets development and testing in the "CARMA Proof-of-Concept TSMO Use Case Testing" project. However, to guide the further development of the CARMA Streets system, Table 13 provides a list of operational needs that are pertinent to this use case scenario.

Table 13. CARMA Streets operational needs for Scenario 7.

ID#	Relevant Component	Need Statement
N01	CARMA Streets	Needs to store static infrastructure data (e.g., map, speed limits, and lane restrictions).
N02	RSE	Needs to communicate with one or more RSE unit(s).
N02.01	RSE	Needs to relay all or part of the current and processed information.
N03	CARMA Platform	Needs to communicate with CARMA Platform installed in all surrounding C-ADS-equipped vehicles.
N03.01	CARMA Platform	Needs to receive CARMA Platform data including vehicle status and intent information.
N03.03	CARMA Platform	Needs to send vulnerable user information (e.g., type, location, heading, and speed) determined by fusing data received from different sources (i.e., vehicles and infrastructure units).
N03.06	CARMA Platform	Needs to send weather-related information (e.g., road surface data, air temperature, air pressure).
N03.07	CARMA Platform	Needs to receive special vehicle status information caused by adverse weather (e.g., braking status, ABS engagement status, traction control status).
N04	CARMA Messenger	Needs to communicate with CARMA Messenger installed on all surrounding non-ADS connected vehicles.
N04.01	CARMA Platform	Needs to receive CARMA Messenger data including vehicle status information.
N04.03	CARMA Messenger	Needs to send vulnerable user information (e.g., type, location, heading, and speed) determined by fusing data received from different sources (i.e., vehicles and infrastructure units).
N04.08	CARMA Messenger	Needs to send weather-related information (e.g., road surface data, air temperature, air pressure).
N04.09	CARMA Messenger	Needs to receive special vehicle status information caused by adverse weather (e.g., braking status, ABS engagement status, traction control status).
N05	CARMA Cloud	Needs to communicate with CARMA Cloud.
N05.01	CARMA Cloud	Needs to relay all or part of the current and processed information.
N05.03	CARMA Cloud	Needs to send the current local aggregated traffic status information.
N05.04	CARMA Cloud	Needs to receive the current traffic status information from different areas of the corridor.
N05.06	CARMA Cloud	Needs to receive weather-related information (e.g., road surface data, air temperature, air pressure).

ID#	Relevant Component	Need Statement
N05.07	CARMA Cloud	Needs to send aggregated special vehicle status information caused by adverse weather (e.g., braking status, ABS engagement status, traction control status).
N06	Signal controller	Needs to communicate with a signal controller.
N06.01	Signal controller	Needs to send SPaT data.
N06.02	Signal controller	Needs to adapt the signal-timing plan (e.g., placing pedestrian calls).
N06.03	Signal controller	Needs to receive and process the requests from pedestrian mobile devices and send a pedestrian call to the signal controller.
N07	Camera	Needs to receive and temporarily store camera data in real time.
N07.01	Camera	Needs to process camera videos to detect presence of vulnerable users (e.g., pedestrians and bicyclists).
N08	Mobile Device	Needs to communicate with pedestrian cell-phone devices that have required communication hardware and software requirements.
N08.01	Mobile Device	Needs to receive and process pedestrian crossing requests for both intersections and mid-block crossing points.
N09	CARMA Streets	Needs to temporarily store and process the data received from all components in real time.
N09.03	CARMA Streets	Needs to fuse data from different sources (i.e., vehicles and infrastructure units) to determine vulnerable user information (e.g., type, location, heading, and speed).
N09.04	CARMA Streets	Needs to aggregate traffic information received from individual vehicles and sensors.
N09.05	CARMA Streets	Needs to process and fuse special vehicle status information caused by adverse weather (e.g., braking status, ABS engagement status, traction control status).
N11	CARMA Streets, CARMA Platform, CARMA Messenger, CARMA Cloud	Needs to have proper cybersecurity platforms and strategies to protect and recover from cyber threats.

SCENARIO 8: CORRIDOR MANAGEMENT

This scenario focuses on maximizing corridor capacity through improved vehicle trajectories and signal timing. Most corridor management practices apply an integrated corridor management (ICM) system to actively monitor and react to nonrecurring events that impact highway or freeway corridors. Traditional ICM systems include various traffic management strategies such as modifying signal timing and dynamic message sign information, redistributing congestion between a paired freeway and arterial along a single corridor, modifying toll rates, changing ramp meters, and promoting transit alternatives. Therefore, this group of scenario may include several subscenarios depending on the specific ICM system strategy and roadway geometry.

Since a typical ICM system integrates with several infrastructure devices, CARMA Streets can improve the overall system performance by collecting, processing, and sharing real-time information from and to different devices and surrounding traffic. Since a corridor might include several conflict areas, more than one CARMA Streets units may need to coordinate with each other via CARMA Cloud or other communication approaches (e.g., cellular network). Further, a set of algorithms can sit at each CARMA Streets and CARMA Cloud components to obtain arterial and freeway congestion data from infrastructure sensors (e.g., RSE, loop detectors) and influence congestion levels by adjusting signal timing and dynamic message signs. Additionally, with the information shared by CARMA Streets and/or CARMA Cloud and received by CARMA Platform and CARMA Messenger, vehicle trajectories along the corridor can be adjusted to improve the traffic performance. However, given the expanded spatial scope of corridors, the signal-timing modifications may have a greater impact on corridor-wide mobility, in comparison to the vehicle trajectory modifications.

This use case scenario is not considered for CARMA Streets development and testing in the "CARMA Proof-of-Concept TSMO Use Case Testing" project. However, to guide the further development of the CARMA Streets system, table 14 provides a list of operational needs that are pertinent to this use case scenario.

Table 14. CARMA Streets operational needs for Scenario 8.

ID#	Relevant Component	Need Statement
N01	CARMA Streets	Needs to store static infrastructure data (e.g., map, speed limits, and lane restrictions).
N02	RSE	Needs to communicate with one or more RSE unit(s).
N02.01	RSE	Needs to relay all or part of the current and processed information.
N03	CARMA Platform	Needs to communicate with CARMA Platform installed in all surrounding C-ADS-equipped vehicles.
N03.01	CARMA Platform	Needs to receive CARMA Platform data including vehicle status and intent information.
N03.02	CARMA Platform	Needs to send the use case-specific variables (e.g., signal-timing plan information).
N03.03	CARMA Platform	Needs to send vulnerable user information (e.g., type, location, heading, and speed) determined by fusing data received from different sources (i.e., vehicles and infrastructure units).
N04	CARMA Messenger	Needs to communicate with CARMA Messenger installed on all surrounding non-ADS connected vehicles.
N04.01	CARMA Messenger	Needs to receive CARMA Messenger data including vehicle status information.
N04.02	CARMA Messenger	Needs to send the use case-specific variables (e.g., signal-timing plan information).

ID#	Relevant Component	Need Statement
N04.03	CARMA Messenger	Needs to send vulnerable user information (e.g., type, location, heading, and speed) determined by fusing data received from different sources (i.e., vehicles and infrastructure units).
N04.04	CARMA Messenger	For transit bus, need to receive scheduling information (i.e., whether it is delayed, on-time, or ahead of the schedule).
N05	CARMA Cloud	Needs to communicate with CARMA Cloud.
N05.01	CARMA Cloud	Needs to relay all or part of the current and processed information.
N05.02	CARMA Cloud	Needs to receive signal-timing information from neighboring intersections.
N05.03	CARMA Cloud	Needs to send the current local aggregated traffic status information.
N05.04	CARMA Cloud	Needs to receive the current traffic status information from different areas of the corridor.
N06	Signal controller	Needs to communicate with a signal controller.
N06.01	Signal controller	Needs to send SPaT data.
N06.02	Signal controller	Needs to adapt the signal-timing plan (e.g., signal coordination).
N06.03	Signal controller	Needs to receive and process the requests from pedestrian mobile devices and send a pedestrian call to the signal controller.
N07	Camera	Needs to receive and temporarily store camera data in real time.
N07.01	Camera	Needs to process camera videos to detect presence of vulnerable users (e.g., pedestrians and bicyclists).
N08	Mobile Device	Needs to communicate with pedestrian cell-phone devices that have required communication hardware and software requirements.
N08.01	Mobile Device	Needs to receive and process pedestrian crossing requests for both intersections and mid-block crossing points.
N09	CARMA Streets	Needs to temporarily store and process the data received from all components in real time.
N09.01	CARMA Streets	Needs to estimate near future vehicle trajectories.
N09.02	CARMA Streets	Needs to compute the optimal vehicles schedule sequence according to specific use case or a policy.

ID#	Relevant Component	Need Statement
N09.03	CARMA Streets	Needs to fuse data from different sources (i.e., vehicles and infrastructure units) to determine vulnerable user information (e.g., type, location, heading, and speed).
N09.04	CARMA Streets	Needs to aggregate traffic information received from individual vehicles and sensors.
N09.05	CARMA Streets	Needs to compute the optimal signal-timing plan according to specific use case or a policy.
N11	CARMA Streets, CARMA Platform, CARMA Messenger, CARMA Cloud	Needs to have proper cybersecurity platforms and strategies to protect and recover from cyber threats.

SCENARIO 9: AUTOMATED PORT DRAYAGE

This scenario is executed within a somewhat different domain than the others. While most CARMA Streets use case research focuses on city and highway traffic, this scenario focuses on interactions between an intermodal terminal operating system and automated freight vehicles at a port facility. The automated port drayage scenario uses automated trucks to transport loads between a port area and a staging area, where a staging area is defined as a location where a manual driving environment transitions to an automated driving environment. As automated freight driving systems expand in capability, loads could be staged at the origin or destination facility. All pickups and drop-offs by the human shipper/receiver are then done at the staging area. Automated trucks move through port area gates with minimal screening, while manual drayage trucks move through staging area gates with normal screening.(27)

In a use-case port management scenario, a route is developed for heavy vehicles to navigate from a starting-point lot to a location for loading and unloading containers to and from chassis, stop at an inspection point passage whereby vehicles "passing" inspection continue onward with the route (and vehicles "failing" inspection navigate to a holding area for further inspection), traverse gate passage, emulate a short-haul drayage before returning to the starting location, and loop around into an unloading and loading area at the starting-point lot. CARMA Cloud may be used to manage the rules of this fleet as it drives through each of the activities. CARMA Streets would facilitate navigational communication between the terminal operating system and the fleet.

The combination of the terminal operating system and CARMA Streets provides up-to-date control and location data to the trucks over the air at a rate that avoids collisions or frequent rerouting. The data include:

- Origin, destination, content, and ownership data of relevant containers.
- Weight and loading patterns of containers.
- Mapping and port layout data, updated immediately following any change.
- Crane location and status of container loading.

- Factors affecting trajectory plans such as the locations and quantities of other vehicles in the port.

This use case scenario is not considered for CARMA Streets development and testing in the "CARMA Proof-of-Concept TSMO Use Case Testing" project. However, to guide the further development of the CARMA Streets system, table 15 provides a list of operational needs that are pertinent to this use case scenario.

Table 15. CARMA Streets operational needs for Scenario 9.

ID#	Relevant Component	Need Statement
N01	CARMA Streets	Needs to store static infrastructure data (e.g., map, speed limits, and lane restrictions).
N02	RSE	Needs to communicate with one or more RSE unit(s).
N02.01	RSE	Needs to relay all or part of the current and processed information.
N03	CARMA Platform	Needs to communicate with CARMA Platform installed in all surrounding C-ADS-equipped vehicles.
N03.01	CARMA Platform	Needs to receive CARMA Platform data including vehicle status and intent information.
N03.02	CARMA Platform	Needs to send the use case-specific variables (e.g., location, route, and schedule).
N03.03	CARMA Platform	Needs to send vulnerable user information (e.g., type, location, heading, and speed) determined by fusing data received from different sources (i.e., vehicles and infrastructure units).
N03.08	CARMA Platform	Needs to receive port drayage vehicle status information such as location and lading status.
N03.09	CARMA Platform	Needs to communicate container pickup and drop-off locations to port vehicles.
N04	CARMA Messenger	Needs to communicate with CARMA Messenger installed on all surrounding non-ADS connected vehicles.
N04.01	CARMA Platform	Needs to receive CARMA Messenger data including vehicle status information.
N04.02	CARMA Messenger	Needs to send the use case-specific variables (e.g., location, route, and schedule).
N04.03	CARMA Messenger	Needs to send vulnerable user information (e.g., type, location, heading, and speed) determined by fusing data received from different sources (i.e., vehicles and infrastructure units).
N04.10	CARMA Messenger	Needs to provide inspection status information to and from a human-controlled port inspection system.
N05	CARMA Cloud	Needs to communicate with CARMA Cloud.
N05.01	CARMA Cloud	Needs to relay all or part of the current and processed information.

ID#	Relevant Component	Need Statement
N05.03	CARMA Cloud	Needs to send the current local aggregated traffic status information.
N05.04	CARMA Cloud	Needs to receive the current traffic status information from different areas of the corridor.
N06	Signal controller	Needs to communicate with a signal controller.
N06.01	Signal controller	Needs to send SPaT data.
N06.02	Signal controller	Needs to adapt the signal-timing plan (e.g., placing green extension calls).
N06.03	Signal controller	Needs to receive and process the requests from pedestrian mobile devices and send a pedestrian call to the signal controller.
N07	Camera	Needs to receive and temporarily store camera data in real time.
N07.01	Camera	Needs to process camera videos to detect presence of vulnerable users (e.g., pedestrians and bicyclists).
N08	Mobile Device	Needs to communicate with pedestrian cell-phone devices that have required communication hardware and software requirements.
N08.01	Mobile Device	Needs to receive and process pedestrian crossing requests for both intersections and mid-block crossing points.
N09	CARMA Streets	Needs to temporarily store and process the data received from all components in real time.
N09.03	CARMA Streets	Needs to fuse data from different sources (i.e., vehicles and infrastructure units) to determine vulnerable user information (e.g., type, location, heading, and speed).
N09.04	CARMA Streets	Needs to aggregate traffic information received from individual vehicles and sensors.
N10	Terminal Operating System	Needs to communicate with a terminal operating system.
N11	CARMA Streets, CARMA Platform, CARMA Messenger, CARMA Cloud	Needs to have proper cybersecurity platforms and strategies to protect and recover from cyber threats.

FUNCTIONAL REQUIREMENTS

To summarize the discussion on key CARMA Streets features and guide the future development of the CARMA Streets system's requirements, this section describes the functional requirements of CARMA Streets. Table 16 lists the CARMA Streets functional requirements. For each functional requirement, the relevant operational needs are also presented in this table.

Table 16. CARMA Streets functional requirements and corresponding operational needs.

ID#	Requirement Statement	Relevant operational needs
F01	Sufficient storage and computing capabilities: CARMA Streets should have an appropriate operating system, be able to store different algorithm codes and required parameters determined by the managerial agency, store raw video footage, be able to run a few algorithms at the same time according to real-time inputs, and temporarily store the outcomes.	N01, N07, N08, N09, N10
F02	Wired communication capabilities to communicate with different components such as V2X Hub, signal controller, RSE, and camera. The communication frequency should be approximately 10 Hz or more, if broadcast-based communication.	N02, N06, N07, N10
F03	Wireless communication capabilities to communicate with different components such as CARMA Cloud, CARMA Platform, and CARMA Messenger. The communication frequency should be approximately 10 Hz or more, if broadcast-based communication.	N03, N05, N04
F04	Wireless communication and software capabilities to communicate with cellphones, receive, and process pedestrian crossing requests.	N08
F05	Exchange and decode various messages received from different components in real time.	N02, N06
F06	Process and analyze various information data received from different components to compute use case-specific variables.	N09, N10
F07	Relay information between RSE within certain geo-fenced area in real time through broadcast-based and/or network-based communication technology. The connection between the CARMA Streets and the RSE should have minimum latency.	N02, N10
F08	Ability to adapt signal-timing plan, interfere with signal actuation, place or end green time extension, and place or end pedestrian calls via the signal controller.	N06
F09	Implement security measures to prevent access to the physical interfaces of a CARMA Streets installation.	N11
F10	Implement protocol-level security measures to mitigate interference with corridor and cloud communication.	N11
F11	Encrypt data at rest to protect PII.	N07, N09, N11

PII = Personally Identifying Information; Hz = hertz.

CHAPTER 5. CONCLUSIONS

This chapter summarizes the objectives, major features, and benefits of the CARMA Streets system and provides high-level recommendations for the development of CARMA Streets.

BACKGROUND AND OBJECTIVE OF CARMA STREETS

The third iteration of CARMA, CARMA3, takes the platform into the world of ADSs with SAE Level 3 and up automation. The approach takes advantage of an open-source ADS platform, Autoware, to enable the use of ADS functionality for cooperative automation strategies. Additionally, CARMA Streets is being developed to enhance the capabilities of the CARMA ecosystem by enabling CDA participants with further capabilities with which to interact with road infrastructure. CARMA Streets is a roadside interface and edge-computing device that enables communication between infrastructure and various transportation modes and users. CARMA Streets enables vehicles to communicate with infrastructure at conflict areas (e.g., intersections) and provides an interface to roadside units, supporting edge computing to optimize travel through conflict areas. CARMA Streets aims to enhance TSMO strategies to improve transportation efficiency and safety. It is open source and is being built with the goal of benefiting the CDA research of universities and other research groups.

SUMMARY OF FEATURES AND EXPECTED BENEFITS OF CARMA STREETS

CARMA Streets serves as an edge-computing traffic device that may be connected to different traffic control devices, sensors, and mobile devices (e.g., RSE units, signal controllers, cameras, and cell phones) to send and receive necessary information in real time. CARMA Streets can send all or part of this information to other components of the CARMA ecosystem, i.e., CARMA Cloud, CARMA Platform, and CARMA Messenger. CARMA Streets can also receive other information from these components and then store, process, and send the processed information to the connected devices in real time. These information exchanges constitute the foundation of CARMA CDA applications, which include both cooperative perception and cooperative vehicle control/traffic management. CDA participants, vehicles, and infrastructure may use this information to improve situational awareness and expand their operational design domain.

In addition, CARMA Streets will provide an interface and an edge-computing framework that will significantly contribute to the sensor data fusion exchange. With the help of relevant algorithms, CARMA Streets can process real-time data from various sources, process and fuse them, and detect all surrounding external objects in the area. Then, CARMA Streets can share the location and types of these objects with all surrounding vehicles (through CARMA Platform and CARMA Messenger). If needed, each vehicle can then combine the received information with the detected objects from their own sensors to improve their detection accuracy and thus enhance travel safety and efficiency.

PERFORMANCE MEASURES OF CARMA STREETS

The effectiveness of CARMA Streets in the transportation system needs to be evaluated for its capability to positively affect performance metrics at a functional level from the following three perspectives:

1. Traffic performance that can be measured using safety, throughput, delay, flow stability, flow breakdown and reliability, and sustainability.

2. Vehicle behavior that can be measured using separation distance, travel speeds driven, acceleration profile and speed control error.

3. Communications using data exchanges during communication/negotiation.

RECOMMENDATIONS FOR CARMA STREETS DEVELOPMENT

This subsection suggests the steps that need to be taken to develop the CARMA Streets system. These steps are summarized as follows:

- In the CARMA Streets architecture, V2X Hub plugins are expected to be used to convert messages to appropriate standards (e.g., National Transportation Communications for NTCIP 1202 to SAE J2735 standards) to send to the other participating components. Therefore, integrating V2X Hub with CARMA Streets is among the first steps that needs to be taken.

- Simulation tools can be used to support advanced testing of CDA research efforts. To simulate both traffic dynamics and vehicle dynamics for CDA technology, a co-simulation tool that includes both microscopic traffic and vehicle dynamic simulators needs to be developed. Afterward, to support implementation of CDA technology in scenarios that involve CARMA Streets, an interface between CARMA Streets and the co-simulation tool will be developed.

- Algorithms may be developed or implemented to support specific CARMA Streets operational scenarios. With the co-simulation tool, one can study CARMA Streets impacts on transportation system performance, as measured by traffic performance metrics such as safety, efficacy, stability, and sustainability.

To develop and test the CARMA Streets system, the "CARMA Proof-of-Concept TSMO Use Case Testing" project is developing separate low-level ConOps documents for two of the use cases scenarios defined in Chapter 4: Signal Priority for Transit and Signal Preemption for Traffic Incident Management.

Finally, another separate low-level ConOps is being developed as part of the "CARMA Proof-of-Concept TSMO Use Case Testing" project efforts that will address the cooperative perception feature descriptions, requirements, and potential impacts on transportation systems. It is expected that the CARMA Streets system will support the feature development and testing.

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