FHWA Cooperative Automation Research: CARMA Proof of-Concept TSMO Use Case Testing: CARMA Cooperative Perception Low-Level Concept of Operations

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U.S. Department of Transportation
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FOREWORD

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

In 2015, the FHWA's Office of Operations Research and Development developed a cooperative adaptive cruise control proof-of-concept prototype that was installed in five research vehicles. From there, the CARMA Ecosystem further evolved through testing and integration. At the time of this writing, the CDA Program is advancing into automated driving systems (ADS) that leverage infrastructure to support cooperative automation strategies. This project expands CARMA functionality to include transportation systems management and operations (TSMO) strategies on surface arterials with intersections. Along with new capabilities of CARMA Streets and TSMO use cases, this project is also conducting research on how cooperative perception can be used to improve the transportation network by increasing situational awareness.

This concept of operations (ConOps) is the last in a series of nine focused on transportation systems management and operations use cases and capabilities and is focused on cooperative perception (CP). It expands on the previous CP ConOps and provides additional details on the system framework and requirements of the CP feature in the CARMA Ecosystem for a particular scenario. The intended audience for this report is CDA stakeholders, such as system developers, analysts, researchers, application developers, and infrastructure owners and operators.

Brian Cronin, P.E.
Director, Office of Safety and Operations
Research and Development

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The Federal Highway Administration initiated the Cooperative Driving Automation (CDA) Program, formerly known as the CARMA Program, to advance the research and development of 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 cooperative perception (CP) is a feature of the CARMA Ecosystem that allows entities to share locally perceived data. CP is expected to improve perception performances of automated vehicles and CARMA Streets. The enhanced situational awareness is expected to enable more effective CDA safety and mobility applications This low-level concept of operations (ConOps) is published with the associated high-level ConOps.(1) This low-level ConOps focuses on the system framework and requirements of the CP feature in the CARMA Ecosystem for a particular scenario involving vulnerable road users crossing in controlled conflict areas.</td></tr>
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APPROXIMATE CONVERSIONS TO SI UNITS				
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		LENGTH		
in	inches	25.4	millimeters	mm
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yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
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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
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gal	gallons	3.785	liters	L
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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		
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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
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L	liters	0.264	gallons	gal
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m^3	cubic meters	1.307	cubic yards	yd^3
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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
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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

ADS	automated driving system
AV	automated vehicle
C–ADS	cooperative automated driving system
CAV	connected and automated vehicle
CDA	cooperative driving automation
COMM	communications
ConOps	concept of operations
CP	cooperative perception
CPA	cooperative perception application
CS	cybersecurity
DDT	dynamic driving task
DF	data fusion
FHWA	Federal Highway Administration
HRSO	Highway Research and Safety Operations
Hz	hertz
ITS	intelligent transportation system
LiDAR	light detection and ranging
NIST	National Institute of Standards and Technology
ODP	object detection and perception
OSS	open-source software
PoC	proof-of-concept
R&D	research and development
radar	radio detection and ranging
RSE	roadside equipment
SPaT	signal phasing and timing
TCD	traffic control device
TSMO	transportation systems management and operations
V2V	vehicle-to-vehicle
V2X	vehicle-to-everything
VRU	vulnerable road user

CHAPTER 1. INTRODUCTION

IDENTIFICATION

This document is a low-level concept of operations (ConOps) for cooperative perception (CP) in the CARMA Ecosystem, sponsored by the Federal Highway Administration's (FHWA) Office of Safety and Operations Research and Development (R&D), the Intelligent Transportation Systems Joint Program Office, and the Federal Transit Administration. This low-level ConOps is an initial step in the current CARMA development effort to define a particular scenario for proof-of-concept (PoC) demonstration and near-future development, as well as associated system requirements.

OBJECTIVE

This low-level ConOps is published with the associated high-level ConOps.[1] This low-level ConOps focuses on the system framework and requirements of the CP feature in the CARMA Ecosystem for a particular scenario. The particular scenario is Scenario 2 as defined in the high-level ConOps: vulnerable road users (VRUs) crossing in controlled conflict areas.[1] Three situations that fall into this scenario will be discussed in this low-level ConOps. All three situations involve a large vehicle (which can be a heavy vehicle, a transit vehicle, or an emergency response vehicle), a passenger vehicle equipped with cooperative automated driving systems (C–ADS), a VRU, and roadside sensing, computation, and communication infrastructure. This low-level ConOps will detail the operational needs and functional requirements of all CARMA components involved and serve as a reference document for algorithm development and implementation.

BACKGROUND

FHWA Cooperative Driving Automation (CDA) Program and CARMA Ecosystem

The Office of Safety and Operations R&D performs transportation operations R&D for FHWA. Onsite R&D is conducted at the Saxton Transportation Operations Laboratory for FHWA and operations R&D is conducted based on a national perspective of the transportation needs across the United States.

Since 2015, the Office of Safety and Operations R&D spearheaded FHWA's CDA Program, formerly known as the CARMA Program. The CDA Program is an FHWA initiative focused on transportation system improvements through research and testing for emerging automated driving and vehicle-to-everything (V2X) communication technologies.

Using V2X communications, CDA allows equipped vehicles to communicate with each other, with roadside equipment (RSE), and with other road users. SAE International has standardized the classification of cooperation between vehicles. Similar to the levels of automation defined in SAE J3016™, the new standard, SAE J3216™, defines the classes of cooperation.[2,3] Vehicles equipped with C-ADS can share their status and driving intent (classes A and B) and seek and enter cooperative driving agreements (classes C and D). Figure 1 summarizes the cooperation classes in relation to the levels of vehicle automation.

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

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

© 2020 SAE International.[(3)]
[1]Improved object and event detection prediction through CDA Class A and Class 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.
[2]Class A and B communications are one of many inputs to an ADS's object and event 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.

Figure 1. Chart. Overview of SAE cooperation classes and automation levels.

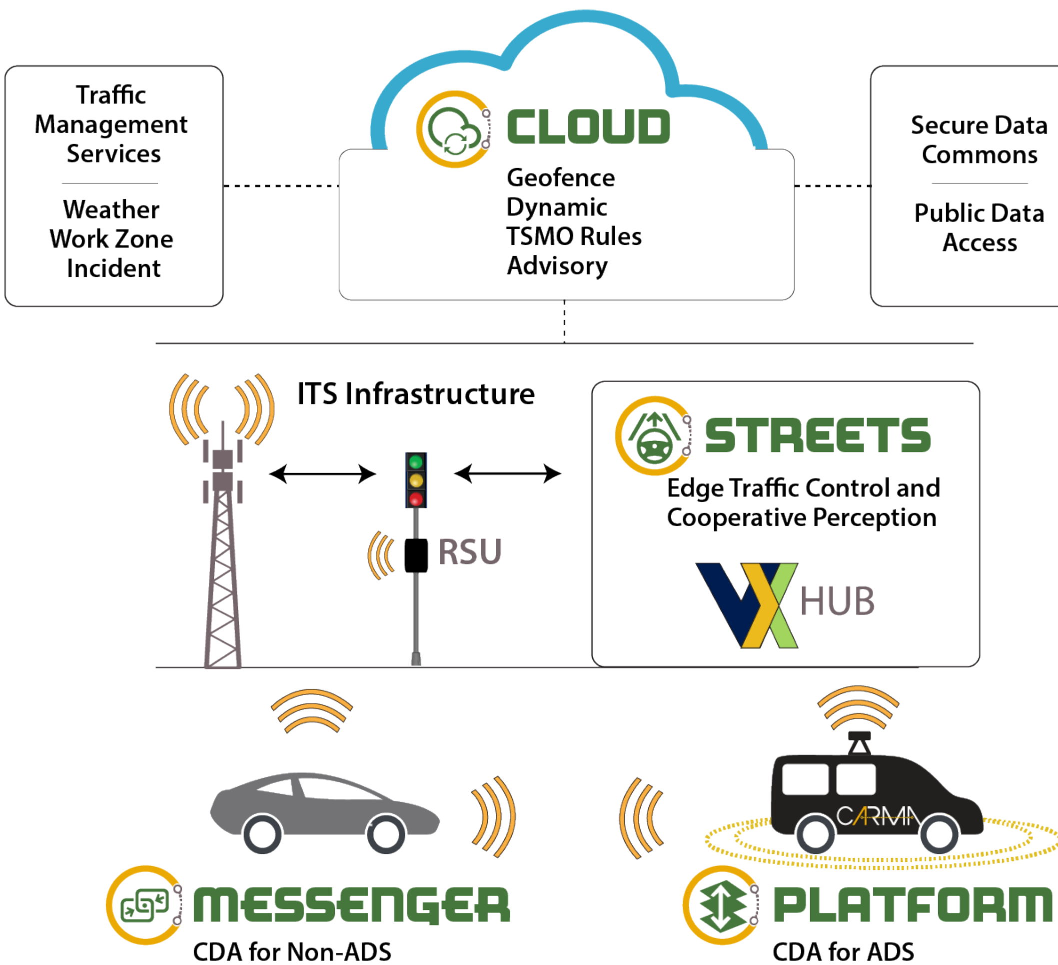
FHWA's CDA Program has led to a suite of open-source software (OSS) for CDA, referred to as the CARMA Ecosystem, including both vehicle and infrastructure technologies. The CARMA Ecosystem currently consists of four core products (figure 2): CARMA Platform, CARMA Messenger, CARMA Streets, and CARMA Cloud.

CARMA Platform is an automated driving system (ADS). In its third iteration, the current CARMA Platform achieves conditional driving automation (at SAE International Level 3) and enables ADS functionality to be used for cooperative automation strategies.

CARMA Messenger represents the capability of moving nonautomated entities (e.g., first-responder vehicles, pedestrians, buses) to communicate with the infrastructure and with vehicles equipped with CARMA Platform to improve transportation system performance.

CARMA Streets represents the infrastructure piece of CDA at conflict areas (e.g., intersections). It provides an interface to roadside units, supports two-way communication between vehicles and infrastructure, and supports CDA by using edge computing to optimize travel through conflict areas. A part of CARMA Streets is the V2X Hub, a set of software that facilitates data exchange needed in V2X communications by translating data elements into various standard protocols.

CARMA Cloud further supports regional transportation systems management and operations (TSMO) through cloud-based management of transportation systems, data exchange, and multiple simultaneous remote services. CARMA Cloud also hosts CARMA Analytics, which supports the fusion, analysis, and management of cooperative automated vehicles (AVs) and traditional transportation data. CARMA Platform, CARMA Messenger, CARMA Streets, and CARMA Cloud are all OSS built to benefit CDA research.



Source: FHWA.[1]
ITS = intelligent transportation system; RSU = roadside unit.

Figure 2. Illustration. CARMA products.

Project Background

This project extends current efforts within the CARMA Program by enhancing the CARMA Ecosystem to enable CP capabilities. For this project, CP is defined as the sharing of a locally perceived driving environment—in particular, locally perceived road objects—by an equipped road entity through V2X communications. Such road entities could be a vehicle equipped with C–ADS or RSE with detection and perception capabilities. In the high-level ConOps, the project team has reviewed the CP state of the art and state of the practice, identified opportunities to incorporate CP into the CARMA Ecosystem, examined high-level system operational needs and functional requirements, and discussed 14 potential use case scenarios that belong to four application categories.(1)

AUDIENCE

The intended audience for this ConOps includes the following:

- U.S. Department of Transportation and CDA and arterial transportation stakeholders, including program managers, assistant managers, research engineers, and transportation technology specialists.
- Academia stakeholders, including faculty, researchers, and students.
- Private sector stakeholders, including consultant companies and original equipment manufacturers.
- System developers who will create and support CDA algorithms based on the system concepts described in this ConOps.
- Analysts, researchers, and CDA application developers.

DOCUMENT STRUCTURE

This document is organized as follows.

Chapter 1 defines the scope of this ConOps.

Chapter 2 summarizes key information from the high-level CP ConOps, including CP technical considerations, CP use cases, and high-level operational needs and functional requirements.(1)

Chapter 3 describes the three situations that this low-level ConOps will focus on, as well as their relationship with each other.

Chapter 4 details the following information for Situation 1: user-oriented operational description, associated entities and stakeholders, operational user needs, system functional requirements, and performance metrics.

Chapters 5 and 6 provide the same details for Situations 2 and 3.

The appendix includes the operational needs and functional requirements developed in the high-level CP ConOps.[1]

References provide a list of reference documents.

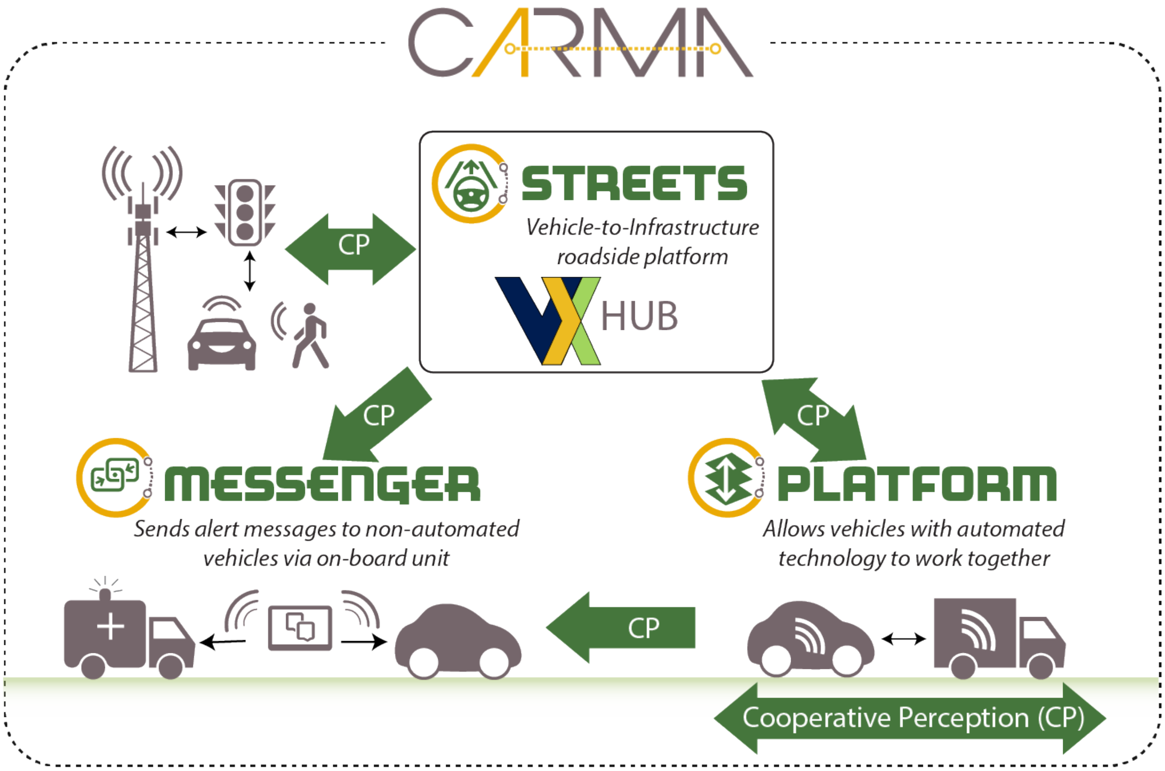
CHAPTER 2. CP OVERVIEW

Sharing "what I see" is the concept of CP in its most intuitive sense. Standards developing organizations, such as SAE International and the European Telecommunication Standards Institute, and the research community have reached a consensus on the concept of CP.[4,5,6,7] More specifically, CP is the sharing of a locally perceived driving environment—in particular, locally perceived road objects—by an equipped road entity through V2X communications. Such road entities could be a vehicle equipped with C–ADS or an RSE with detection and perception capabilities.

CP could be a valuable feature of CDA. In addition to enhancing situational awareness when some road users and road objects are not capable of machine-to-machine communications, CP could also supplement basic safety messages or personal safety messages defined in SAE J2735, in the case where the range and quality of V2X communication are limited.[8] Even when the shared CP information is redundant (but not complete duplication), for example, perceived objects in the mutual field of view of two C–ADS-equipped vehicles, such redundancy could reduce uncertainty in both vehicles' local perception. The enhanced situational awareness is expected not only to improve safety performance in immediate collision avoidance scenarios but also to enable safer motion planning. Moreover, enhanced performances of connected and automated vehicles' (CAVs') perception systems could also support path and trajectory planning for improved mobility and energy performances.

CP IN CARMA ECOSYSTEM

The CP feature can be integrated into all four core products in the CARMA Ecosystem. As illustrated in figure 3, CARMA Platform is a candidate to incorporate CP. Vehicles equipped with CARMA Platform are expected to have advanced sensing and perception systems and can initiate the sharing of CP information. Although CARMA Messenger currently does not have perception capabilities and is not able to generate original CP information (as indicated by the one-way arrows pointing toward Messenger in figure 3), it is able to receive CP information, process it for human driver consumption, and relay CP information to other entities with communication capabilities. Additionally, applications could be developed to further process the CP information received for consumption by human drivers (e.g., advisory warning). CARMA Streets could use CP information received directly from road objects or relayed through CARMA Cloud to obtain a more comprehensive picture of the driving environment and possibly improve solutions to relevant TSMO use cases. RSEs equipped with CARMA Streets could also serve as a relay for CP information. Moreover, if an RSE equipped with CARMA Streets can access existing or newly installed infrastructure-based sensors (e.g., cameras and light detection and ranging (LiDAR)), it could provide original CP information to connected road entities. CARMA Cloud could be a hub where all CP information is consolidated into a global map of road objects.



Source: FHWA.[1]

Figure 3. Illustration. CP in the CARMA Ecosystem.

CP TECHNICAL CONSIDERATIONS

Extensive research has been performed in the past decade on various technical aspects of CP. Five categories of technical considerations have been identified in the high-level CP ConOps.[1] They are: enhanced object detection and perception (ODP), communication issues, cyber security (CS) issues, data fusion (DF) algorithms, and the effective application of information obtained through CP. This section briefly provides an overview of these technical considerations. Interested readers are referred to the high-level CP ConOps, and the references cited therein, for details.[1]

Enhanced ODP primarily deals with extracting a perceived object's center and dimensions, which is often relevant to CP applications. Once the objects are detected and perceived, CP messages will be generated and disseminated through V2X communications. A large body of literature exists on CP communication issues, such as CP message content, as well as CP message generation and dissemination rules. CS issues are intrinsic to V2X communications. In addition to known security threats to general V2X communications, falsifying perception data is a CS threat specific to CP.[9] Once a vehicle has received CP information, DF algorithms are needed to combine peer data with locally perceived data. Finally, the effective use of CP information to improve safety and mobility, or CP applications (CPA) is an issue that should not be overlooked.

CP USE CASES

In the literature, use cases of CP experiments include advanced pedestrian warning using infrastructure-based perception, advisory warning of opposing traffic for permissive left-turn vehicles, enhanced awareness of obstructed objects in various scenarios (e.g., along a horizontal curve, in overtaking scenarios, and around an intersection, and AV path planning using CP information. (See references 7, 10, 11, 12, 13, and 14.)

The high-level CP ConOps identified 14 CP use case scenarios (see table 1). The scenarios are bracketed into four application groups.[(1)] The first application involves VRUs. The second application focuses on safety, namely collision avoidance. The third application extends beyond safety into increased mobility. The fourth application introduces scenarios in which CP provides a general increase in situational awareness.

This low-level ConOps focuses on the system framework and requirements of the CP feature in the CARMA Ecosystem for Scenario 2 as defined in the high-level ConOps: VRUs crossing in controlled conflict areas.[(1)]

Table 1. Summary of CP operational scenarios.[(1)]

Application	Scenario	Description
VRUs	Basic road segment	Vehicles on the same side of the road should be aware of VRUs, anticipate the VRUs' movements, and adjust trajectories accordingly.
VRUs	Controlled crossing areas	Various vehicle-pedestrian conflicts at controlled intersections.
VRUs	Nondesignated crossing areas (i.e., midblock)	Vehicles unable to detect VRUs at nondesignated midblock crossing.
VRUs	Boarding and alighting transit	Pedestrians cross the road to board transit or after disembarking from a transit vehicle. Pedestrians step in front of a transit vehicle to load/unload a bicycle from a bike rack. CP improves perception performance of other vehicles in the vicinity of the stopped transit vehicle.
Collision avoidance	Car-following	Vehicles need to act (e.g., braking) automatically when an imminent collision is perceived and communicate upstream to relevant following vehicles.
Collision avoidance	Wrong-way driving	Wrong-way vehicle entering a highway from a right-way off-ramp.
Conflict avoidance and cooperative driving	Intersections	Vehicle turning left at signalized intersection with opposing left-turning and through-moving vehicle.
Conflict avoidance and cooperative driving	Around business access areas	Vehicles coming out of a business driveway have potential conflict with oncoming traffic.

Application	Scenario	Description
Conflict avoidance and cooperative driving	Two-lane, two-way roads	Vehicle is trying to pass a slow-moving vehicle in front on a two-lane, two-way road with oncoming traffic in the opposite direction.
Conflict avoidance and cooperative driving	Lane changing	Vehicles upstream of an abrupt lane-changing event could adjust their trajectories preemptively.
General enhanced situational awareness	Behind large vehicles	Vehicles traveling behind large vehicles have limited line of sight.
General enhanced situational awareness	Horizontal or vertical curves	Vehicle's line of sight could be limited due to roadway geometry, particularly horizontal and vertical curves.
General enhanced situational awareness	Adverse weather	Vehicle's line of sight is limited in adverse weather, such as fog, snow, and rain, which negatively affects driver visibility, situational awareness, and performance.
General enhanced situational awareness	Work zone	Vehicles approaching a work zone with a closed lane segment, overlaid scheduled lanes, and stop lines.

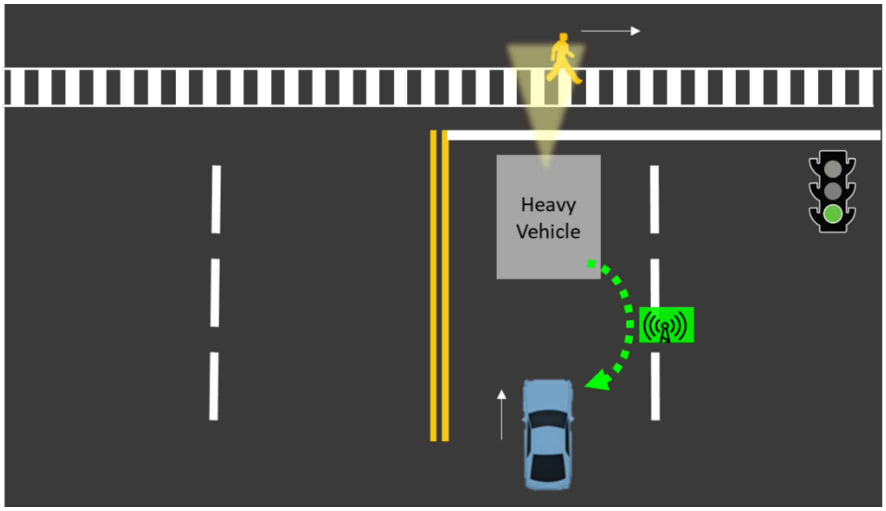
CHAPTER 3. CP USE CASE: VRU CROSSING IN CONTROLLED CONFLICT AREAS

This low-level ConOps focuses on the system framework and requirements of the CP feature in the CARMA Ecosystem for a particular scenario. The scenario is the second scenario in the VRU application group as defined in the high-level ConOps: VRUs crossing in controlled conflict areas.(1)

In controlled conflict areas, such as pedestrian crossings, intersections, roundabouts, and ramps, VRUs should have higher priority when crossing the road. When traffic volume is relatively high, or when the number of conflict points is large, human drivers could easily miss VRUs. Autonomous vehicles could also have limited line of sight and may be unable to detect VRUs sufficiently early. CP supported by both infrastructure- and vehicle-based sensors, as well as V2X communications, could significantly increase road vehicles' awareness of VRUs and thus improve VRU safety. Additionally, with proper design of CAV path-planning algorithms and infrastructure-based intersection management algorithms that fully take advantage of CP information, mobility and energy consumption improvements could also be possible in controlled conflict areas.

Several representative situations that fall into the use case of VRUs crossing in controlled conflict areas are discussed in the high-level CP ConOps.(1) The representative situations include multiple examples of turning vehicles conflicting with crossing VRUs, as well as an edge case in which vehicles that have the right-of-way conflict with pedestrians who have not cleared the intersection (e.g., due to the pedestrian's slow-moving speed).

Figure 4 depicts this edge case, in which a westbound pedestrian is clearing the intersection out of the designated signal phase. A heavy (or large) vehicle is the first vehicle stopped at the intersection on its northbound approach with a clear line of sight of the pedestrian. The vehicle remains stopped to allow the pedestrian more time to cross. A passenger vehicle (the bottom vehicle in figure 4) is approaching northbound behind the heavy (or large) vehicle. The approaching vehicle may be unable to detect the pedestrian due to the vehicle's obstructed front view. The approaching vehicle could have a collision with the pedestrian if the vehicle tries to change lanes and drive through the intersection in the adjacent lane. Through CP, the vehicle can potentially avoid this collision. Figure 4 illustrates the case in which the heavy vehicle waiting at the intersection is equipped with C–ADS and shares its perception with surrounding vehicles through V2V communications. Additionally, infrastructure-based sensing, detection, and communications could be an integral part of CP in controlled conflict areas.



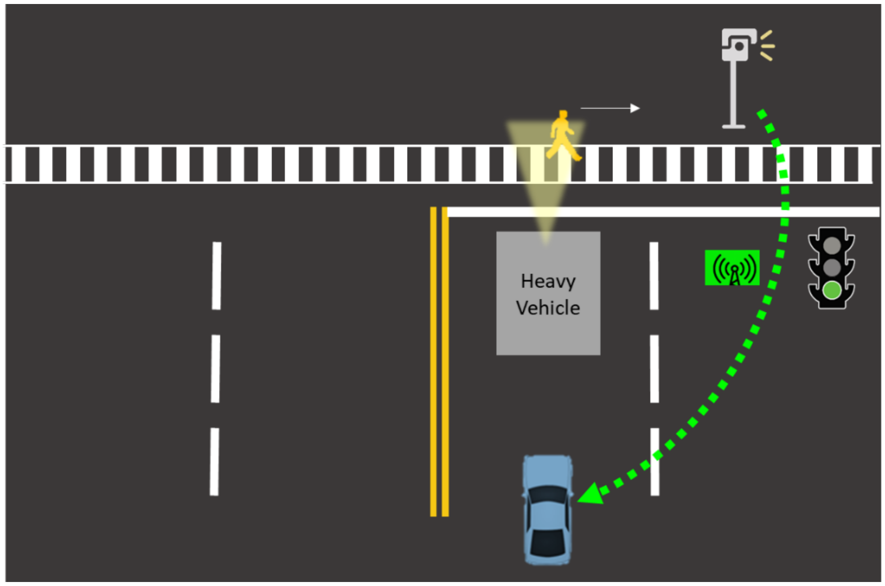
Source: FHWA.[(1)]

Figure 4. Illustration. CP through V2V communications to improve situational awareness: VRUs clearing intersection outside of allocated phase.

This low-level ConOps expands the edge case depicted in figure 4 into three related situations. All three situations involve a large vehicle (which can be a heavy vehicle, a transit vehicle, or an emergency response vehicle), a passenger vehicle equipped with cooperative ADS (C–ADS), a pedestrian, and roadside sensing, computation, and communications infrastructure. The three situations are the following:

- Situation 1. Both vehicles are stopped; CP is enabled by infrastructure technologies.
- Situation 2. Both vehicles are stopped; CP is enabled by both vehicle-based and infrastructure-based technologies, as well as DF.
- Situation 3. The heavy vehicle is stopped, and the passenger vehicle is approaching; CP is enabled by both vehicle-based and infrastructure-based technologies, as well as DF; the passenger vehicle incorporates CP information in its trajectory planning.

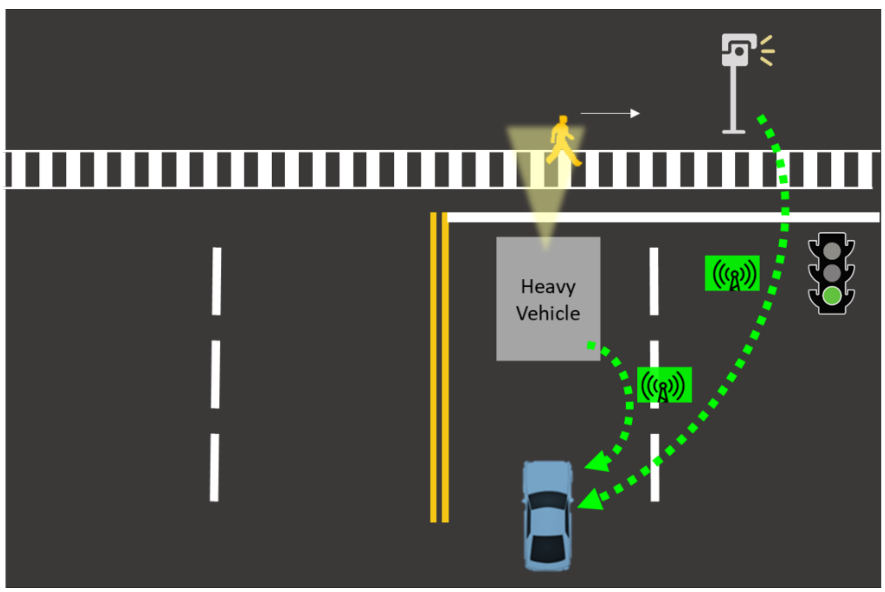
In Situation 1 (see figure 5), the two vehicles are stopped in the same lane behind the stop line at a signalized intersection when the light has just turned green for their approach. The pedestrian is crossing the road in front of the two vehicles outside of the designated pedestrian phase (e.g., due to the pedestrian's slow-moving speed). The heavy vehicle is the first vehicle behind the stop line and remains stopped to allow the pedestrian to cross the intersection safely. The passenger vehicle does not have direct line of sight of the pedestrian, as the large vehicle blocks its view. A set of RSE detects and perceives the pedestrian and sends an object-based CP message to the passenger vehicle through vehicle-to-infrastructure communications (represented by a dashed arrow). The passenger vehicle receives the CP message, processes it, and adds the pedestrian to its own object list. With the CP information, the passenger vehicle stays in place and does not use the adjacent lane to drive around the heavy vehicle.



Source: FHWA.

Figure 5. Illustration. Situation 1.

Situation 2 (figure 6) adds some complexity to Situation 1 by highlighting DF, one of the five CP technical considerations. If the large vehicle is also equipped with C–ADS that supports CP, it could detect and perceive the pedestrian and send a CP message to the passenger vehicle through V2V communications. The passenger vehicle receives CP messages about the same object (the pedestrian) from both the RSE and the large vehicle and needs to fuse data from both CP messages before adding the pedestrian to its own object list.



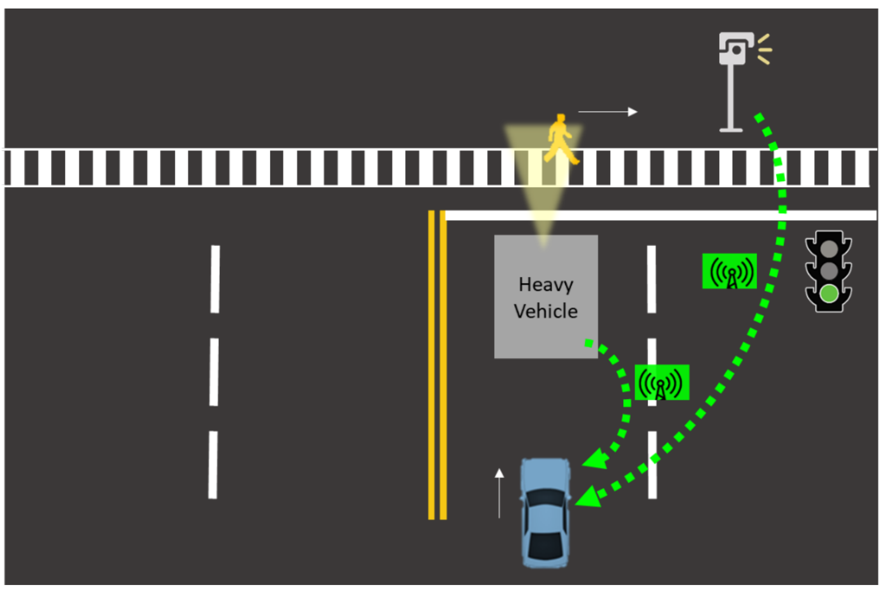
Source: FHWA.

Figure 6. Illustration. Situation 2.

Situation 3 (figure 7) explores improvements to CDA features that effectively use CP information. In addition to ODP and DF, CPA is an essential consideration in Situation 3. Unlike

Situations 1 and 2, the passenger vehicle in Situation 3 is approaching the intersection, unaware of the pedestrian due to its obstructed front view. Without CP, the passenger vehicle could decide to drive around the stopped heavy vehicle as it approaches the intersection during the traffic signal's green phase. Such a maneuver could lead to a collision between the passenger vehicle and the pedestrian. Through CP, the passenger vehicle receives information about the pedestrian from both the RSE and the large vehicle, becomes aware of the pedestrian and their status after fusing perception data shared by multiple sources, and adjusts its own trajectory to avoid conflict with the pedestrian. For example, the passenger vehicle may do one of the following:

- Come to a full stop behind the large vehicle.
- Slow down sufficiently behind the heavy vehicle in anticipation that the heavy vehicle will start to move after the pedestrian clears the lane that the two vehicles are in (traffic laws permitting).
- Change lanes and slow down to allow the pedestrian to safely cross before speeding up again (traffic laws permitting).



Source: FHWA.

Figure 7. Illustration. Situation 3.

The three situations have increasing complexities. In Situation 1, two of the five CP technical considerations, ODP and communication issues, are relevant to system functions. DF becomes relevant in Situation 2, in addition to the two technical considerations in Situation 1. Finally, in Situation 3, the effective use of CP information becomes more relevant as the passenger vehicle is moving. Note that although CS considerations are critical to the viability of the CP feature in actual deployment, they are beyond the scope of the functional requirements of a PoC system. Therefore, this low-level ConOps will not include CS requirements.

The next three chapters will detail operational user needs and system functional requirements for the three situations. Note that this low-level ConOps and its associated high-level ConOps are both focused on CP in the CARMA Ecosystem.[1] Therefore, the system requirements discussed in the next three chapters are specific to CARMA products. This low-level ConOps serves as a reference document for algorithm development and implementation.

CHAPTER 4. SITUATION 1

This chapter analyzes Situation 1, described in chapter 3. In Situation 1, both vehicles are stopped behind the stop line while a pedestrian clears the intersection out of the designated pedestrian phase. CP in Situation 1 is enabled by infrastructure sensing, computing, and communication technologies. The large vehicle in Situation 1 is assumed to be a manually driven vehicle that does not support V2X communications. The passenger vehicle in Situation 1 is assumed to be capable of V2X communications at a minimum. The pedestrian in Situation 1 is assumed to be nonconnected. Situation 1 exhibits two of the five CP technical considerations, namely ODP and communication issues.

USER-ORIENTED OPERATIONAL DESCRIPTION

This section describes Situation 1 (figure 5) from the perspectives of the road users involved.

Driver Perspective (connected but nonautomated vehicle)

At a signalized intersection, a passenger vehicle driver is stopped at a red light on the northbound intersection approach. The northbound intersection approach has two lanes. The driver's vehicle is second in the median-lane queue, behind a large vehicle. The curbside lane has no visible queued vehicles or arriving vehicles.

On the vehicle's dashboard, the driver notices an alert of a pedestrian in a "conflicting crosswalk" (i.e., a crosswalk where a pedestrian could conflict with the car). The alert could be in audio, visual, or haptic format, or a combination of those formats. The dashboard could also provide a countdown clock, which would provide real-time updates of the northbound signal phase. For example, the dashboard countdown clock could show that the northbound signal will turn green after a certain amount of time (e.g., 15 s). The driver may not yet see the conflicting pedestrian with their own eyes due to the blocked line of sight. However, the dashboard continues to warn of a conflicting pedestrian, and the countdown clock (to the next green phase) continues to display a decreasing number of seconds remaining in the interval. If adaptive pedestrian phase is enabled at the intersection, the driver may notice that the countdown clock time displays a higher number of remaining seconds, due to extensions of the current (east-west) green pedestrian phase.

As the signal phases change, the driver sees the northbound signal turn green as expected. However, the dashboard still warns of a conflicting pedestrian. By now, the driver may or may not have seen the conflicting pedestrian at the crosswalk. The large vehicle (first in queue) continues to remain motionless for an unusually long time (e.g., more than 5 s) after the northbound signal turns green. Normally in such a situation, the driver would change lanes to drive past the large vehicle. However, because of the conflicting pedestrian warning, the driver continues to wait.

The driver may notice the conflicting pedestrian appear just to the right of the large vehicle, within the crosswalk. The driver may then see the pedestrian complete their walking trip past the crosswalk and onto the sidewalk. The pedestrian alert then disappears from the dashboard. The large vehicle then drives ahead northbound and through the intersection. The passenger vehicle driver then drives ahead northbound as well.

Vehicle Perspective (CAV)

The description in this subsection assumes that the passenger vehicle (second in queue) is an SAE Level 3 vehicle that supports at least CDA Class A capabilities.

At a signalized intersection, a passenger car waits behind a large vehicle stopped at a red light on the northbound intersection approach. The vehicle's virtual environment indicates that the northbound intersection approach has two lanes. The virtual environment indicates that the vehicle is second in the median lane queue and that the curbside lane has no queued vehicles or incoming vehicles. The passenger car is receiving and processing both CP messages and signal phasing and timing (SPaT) messages from the infrastructure.

The CP messages begin to indicate the presence of a pedestrian who may conflict with the northbound signal phases and traffic movements. At approximately this same time, the SPaT messages could also indicate an expected duration of the current (east-west) signal phase (e.g., 15 s). At some point during the east-west signal phase, the vehicle may directly sense the same conflicting pedestrian through its own detection capabilities when the vehicle's line of sight of the pedestrian is not blocked. Also, at some point during the east-west signal phase (e.g., 10 s), the SPaT messages may indicate that the current (east-west) signal phase will extend by an additional few seconds (e.g., 5 s) if the intersection runs adaptive pedestrian phases.

Some amount of time after the east-west signal phase began (e.g., 20 s), the SPaT messages indicate that a new north-south signal phase has begun. However, the CP messages continue to indicate the presence of a pedestrian who may conflict with the northbound traffic movements. The large vehicle (first in queue) continues to remain motionless for an unusually long time (e.g., more than 5 s) after the northbound signal turns green. Normally in such a situation, the passenger vehicle would change lanes to drive past the large vehicle. However, because of the conflicting pedestrian presence, the vehicle continues to wait. Some amount of time later (e.g., 10 s), the CP messages then cease to contain any pedestrian information. At the same time, the large vehicle (which was first in queue) then starts to drive ahead northbound and through the intersection. The vehicle then drives ahead northbound in the same lane, after assessing that the right-of-way of the current lane is cleared.

VRU Perspective

The pedestrian approaches a signalized intersection, with queued vehicles waiting at multiple approaches. The pedestrian pushes a button to request crossing the intersection in the eastbound direction. Once the traffic signal turns green in the eastbound direction, the pedestrian enters the intersection crosswalk and walks across four northbound lanes of traffic. Due to her slow walking speed, the pedestrian is not able to clear the intersection within the allocated pedestrian green phase. The pedestrian sees the pedestrian signal turn red ("do not walk") when she is in the middle of the crosswalk. The pedestrian continues to cross the intersection as the northbound vehicles wait for her to clear the intersection. The pedestrian completes her crossing, exits the eastbound crosswalk, and enters a sidewalk on the far side of the intersection.

ENTITIES AND STAKEHOLDERS

The following entities and their associated minimum configurations should be considered when executing the operational situation for research and development purposes:

- The pedestrian crossing the road could be a real human because the safety risk in this situation is low since neither vehicle is moving. Alternatively, a programmable articulation pedestrian dummy could be used. Depending on the infrastructure-sensing technologies used, the pedestrian dummy may need to be outfitted with additional equipment. For example, if infrastructure sensors are based on thermal technologies, heating pads could be mounted on the pedestrian dummy.

- The first vehicle behind the stop line could be any large vehicle if it is able to block the line of sight of the passenger vehicle behind it.

- The passenger vehicle behind the large vehicle should have machine-to-machine communication capabilities, at a minimum. It does not have to have any driving automation (SAE Level 0), but it should have onboard computing capabilities that can process CP information and convert it for human driver consumption. Alternatively, a vehicle with SAE Level 3, or above, driving automation could be used.

- Infrastructure sensing, computing, and communication technologies are necessary to execute this operational situation.

Stakeholders of this operational situation include the following:

- VRUs, including pedestrians, bicyclists, motorcyclists, and micromobility users.
- Drivers of connected but nonautomated passenger vehicles.
- Passenger vehicles equipped with C–ADS.
- Researchers and developers.
- Original equipment manufacturers.
- Infrastructure owners and operators.

OPERATIONAL USER NEEDS

Table 2 summarizes the operational user needs specific to CP in Situation 1.

Table 2. Operational user needs for Situation 1.

Mode/Vehicle Type	Automation	Connectivity/ CDA	User Characteristics and Needs	ID Number
Passenger vehicle driver	Human driving	Connected	Receive real-time updates from the connected vehicle about VRUs within the controlled conflict area (e.g., a warning message designed for human driver consumption) at a reasonable frequency.	CP-UN-S1-01
Passenger vehicle	Automated driving	Vehicles equipped with C–ADS	Receive real-time updates from the infrastructure about VRU locations, headings, speeds, etc.	CP-UN-S1-02
VRU	Nonmotorized/ human driving	Nonconnected	Need continuous attention from other users on the road.	CP-UN-S1-03

SYSTEM FUNCTIONAL REQUIREMENTS

In correspondence with the high-level CP ConOps, this low-level ConOps uses CARMA Ecosystem as an example CDA system to explore incorporating the CP feature.(1) Table 3 summarizes the system functional requirements of relevant CARMA products for Situation 1. These system requirements support the user needs discussed in table 2. It should be noted that the system functional requirements in this low-level ConOps are developed based on the assumption that infrastructure-based sensors have onboard computation capabilities to detect and perceive pedestrians. If infrastructure-based sensors do not have detection and perception capability, such capabilities should be required to reside in CARMA Streets. The high-level CP ConOps includes discussions on system functional requirements for both cases.(1) The last column of table 3 traces these system requirements to the high-level system operational needs and functional requirements defined in the high-level CP ConOps.(1) The high-level system operational needs and functional requirements are also provided in the appendix of this document.

Table 3. System functional requirements for Situation 1.

ID Number	Relevant Component	Functional Requirements Statement	Traces To
CP-S1-SR01	Infrastructure-based smart sensors	Infrastructure-based smart sensors (sensors with onboard computation capability) installed at an intersection detect and classify pedestrians within predefined detection zones (e.g., crosswalks). A smart sensor perceives the following minimal attributes of a detected pedestrian: location, speed, and heading.	CP-SR-09; CP-N-ODP03a
CP-S1-SR02	Infrastructure-based smart sensors	Infrastructure-based smart sensors (sensors with onboard computation capability) installed at an intersection transmit processed object-based perception data to CARMA Streets. Processed object-based perception data should be continuously transmitted at a consistent frequency while a pedestrian is in a predefined detection zone. A typical transmission frequency is 10 Hz. Accounting for fluctuation in the communication network, the average transmission frequency during a continuous detection session should be 10 Hz $\pm$ 1 Hz.	CP-SR10; CP-N-ODP03b
CP-S1-SR03	CARMA Streets	An infrastructure computer with CARMA Streets installed wirelessly transmits processed object-based perception data as a CP message at a frequency between 10 and 1 Hz according to a ruleset that specifies conditions to determine transmission frequency and object inclusion.	CP-SR12; CP-N-COMM02; CP-N-COMM05

ID Number	Relevant Component	Functional Requirements Statement	Traces To
CP-S1-SR04	CARMA Platform	A CDA vehicle equipped with CARMA Platform receives and processes CP messages sent by CARMA Streets. Each CP message should be processed before the next message is received. Objects that are not currently in the CDA vehicle's world model will be added to the object list. Attributes of existing objects created from previous CP messages should be updated according to received perception data.	CP-SR14; CP-N-COMM03
CP-S1-SR05	CARMA Messenger	CARMA Messenger installed in a display system for connected non-AV receives and processes object-based perception data sent by CARMA Streets. Each CP message should be processed before the next message is received. Objects that are not currently in the vehicle's world model will be added to the object list. Attributes of existing objects created from previous CP messages should be updated according to received perception data.	CP-SR17; CP-N-COMM03
CP-S1-SR06	CARMA Messenger	CARMA Messenger installed in a connected non-AV notifies the human driver (e.g., through visual and/or audio alerts) about conflicting VRUs derived from object-based perception data at a reasonable frequency.	CP-SR19; CP-N-CPA02

COMM = communication.

PERFORMANCE METRICS

Key performance metrics for monitoring and evaluating operations during execution of this situation should include the following:

- Object detection and perception data frequency is the frequency at which the infrastructure-based smart sensor transmits object detection and perception data to CARMA Streets.

- Object detection and perception accuracy is the accuracy of the infrastructure-based smart sensor in detecting, perceiving, and locating the VRU.

- CP message latency is the time difference between origination of the CP message from CARMA Streets and the receipt by the vehicle. Total end-to-end latency could include the time to compose, transmit, and decompose the message.

- CP message drop rate is the number of CP messages not received divided by the total number of CP messages sent.

CHAPTER 5. SITUATION 2

This chapters analyzes Situation 2, described in chapter 3. In Situation 2, both vehicles are stopped behind the stop line while a pedestrian clears the intersection out of the designated pedestrian phase. CP in Situation 2 is enabled by both vehicle- and infrastructure-based sensing, computing, and communication technologies. The large vehicle in Situation 2 is assumed to be a vehicle equipped with detection, perception, and V2X communication capabilities. The passenger vehicle in Situation 2 is assumed to be capable of V2X communications, at a minimum. The pedestrian in Situation 2 is assumed to be nonconnected. Situation 2 exhibits three of the five CP technical considerations. In addition to ODP and communication issues discussed in Situation 1 (see chapter 4), DF is essential in Situation 2.

USER-ORIENTED OPERATIONAL DESCRIPTION

This section describes Situation 2 (figure 6) from the perspectives of the road users involved. Compared with Situation 1 (figure 5), DF is now an additional system functionality. In Situation 2, the passenger vehicle fuses CP data from two sources (both the large vehicle and the infrastructure).

Driver Perspective (connected but nonautomated vehicle)

From the perspective of the driver of the passenger vehicle (second in queue), Situation 2 is not significantly different from Situation 1 as described in chapter 4. The passenger vehicle receives CP messages from both the large vehicle (first in queue) and the infrastructure and fuses the data to synthesize information. This process runs within the passenger vehicle's software and is not visible to the driver.

If the large vehicle detects the pedestrian before the infrastructure does, the passenger vehicle may receive CP information about the pedestrian earlier than it would have in Situation 1. The passenger vehicle's dashboard pedestrian warning (alert) may appear earlier as a result.

Vehicle Perspective (CAV)

The description in this subsection assumes that the passenger vehicle (second in queue) is an SAE Level 3 vehicle that supports at least CDA Class A capabilities.

At a signalized intersection, a passenger vehicle waits behind a large vehicle at a red light on the northbound intersection approach. The vehicle's CDA software indicates that the northbound intersection approach has two lanes. The CDA software indicates that the vehicle is second in the median lane queue and that the curbside lane has no queued vehicles or incoming vehicles. The passenger vehicle is receiving and processing both CP messages and SPaT messages from the infrastructure. The SPaT messages indicate that all northbound signal phases are currently red.

The CP messages from the infrastructure begin to indicate the presence of a pedestrian who may conflict with the northbound signal phases and traffic movements. Also, at approximately the same time, the passenger vehicle (second in queue) starts to receive CP messages from the large vehicle (first in queue) about a pedestrian who may conflict with the northbound signal phases and traffic movements. The passenger vehicle executes internal logic to determine and confirm that the CP messages from both the infrastructure and the large vehicle are related to the same pedestrian. Once confirmed, the passenger vehicle's internal logic reconciles any discrepancy in object attributes (e.g., location, speed, heading) in the CP messages from both sources and registers the pedestrian and her attributes in the vehicle's world model.

At approximately this same time, the SPaT messages could also indicate an expected duration of the current (east-west) signal phase (e.g., 15 s). At some point during the east-west signal phase, the vehicle may directly sense the same conflicting pedestrian through its own detection capabilities when the vehicle's line of sight of the pedestrian is not blocked. Also, at some point during the east-west signal phase (e.g., 10 s), the SPaT messages may indicate that the current (east-west) signal phase will extend by a few seconds (e.g., 5 s) if the intersection runs adaptive pedestrian phases.

Some amount of time after the east-west signal phase began (e.g., 20 s), the SPaT messages indicate that a new north-south signal phase has begun. However, the CP messages continue to indicate the presence of a pedestrian who may conflict with the northbound traffic movements. The large vehicle (first in queue) continues to remain motionless for an unusually long time (e.g., more than 5 s) after the northbound signal turns green. Normally in such a situation, the passenger vehicle would change lanes to drive past the large vehicle. However, because of the conflicting pedestrian presence, the vehicle continues to wait. Some amount of time later (e.g., 10 s), the CP messages then cease to contain any pedestrian information. At the same time, the large vehicle (which was first in queue) then starts to drive ahead northbound and through the intersection. The passenger vehicle then drives ahead northbound in the same lane after assessing that the right-of-way of the current lane is cleared.

VRU Perspective

From the pedestrian's perspective, Situation 2 is identical to Situation 1. The pedestrian remains unaware of how other road users are sensing their movements or about what measures the other road users are taking to avoid a potential conflict.

ENTITIES AND STAKEHOLDERS

When executing this operational situation (Situation 2) for research and development purposes, the entities and their associated minimum configurations are mostly identical to those in Situation 1 (as described in chapter 4). The following minimum configurations required for the large vehicle and the passenger vehicle in Situation 2 are slightly different from those in Situation 1:

- As in Situation 1, the large vehicle used in executing Situation 2 needs to be able to block the line of sight of the passenger vehicle behind it. Additionally, the large vehicle should have sensing, perception, and machine-to-machine communication capabilities, at a minimum. It does not have to have any driving automation (SAE Level 0), but it needs to be able to detect and perceive the pedestrian and generate and broadcast CP messages. Alternatively, a vehicle with SAE Level 3, or above, driving automation could be used.

- In addition to the minimum requirements discussed in Situation 1, the passenger vehicle needs new computation capabilities to fuse CP messages from multiple entities. Such computation capabilities may include object localization, object association, and state (attribute) estimation.

The stakeholders for Situation 2 are identical to those for Situation 1, which were described in chapter 4.

OPERATIONAL NEEDS

Table 4 summarizes the operational user needs specific to CP in Situation 2. Note that the operational needs of the passenger vehicle driver (when the passenger vehicle is connected but not automated) and those of the pedestrian in table 4 are identical to CP-UN-S1-01 and CP-UN-S1-03 in table 2. The operational user needs of the passenger vehicle (when the passenger vehicle is connected and automated) in table 4 are slightly different from CP-UN-S1-02 in table 2.

Table 4. Operational user needs for Situation 2.

Mode/Vehicle Type	Automation	Connectivity/ CDA	User Characteristics and Needs	ID Number
Passenger vehicle driver	Human driving	Connected	See CP-UN-S1-01 in table 2.	CP-UN-S1-01
Passenger vehicle	Automated driving	Vehicles equipped with C–ADS	Receive real-time updates from both the infrastructure and other road vehicles equipped with C–ADS about VRU locations, headings, speeds, etc.	CP-UN-S2-01
VRU	Nonmotorized/ human driving	Nonconnected	See CP-UN-S1-03 in table 2.	CP-UN-S1-03

SYSTEM FUNCTIONAL REQUIREMENTS

In correspondence with the high-level CP ConOps, this low-level ConOps uses CARMA Ecosystem as an example CDA system to explore incorporating the CP feature.(1) The system functional requirements of relevant CARMA products for Situation 1 (table 3) are still relevant for Situation 2. It should be noted that the system functional requirements in this low-level ConOps are developed based on the assumption that infrastructure-based sensors have onboard computation capabilities to detect and perceive pedestrians. If infrastructure-based sensors do not have detection and perception capability, such capabilities should be required to reside in CARMA Streets. The high-level CP ConOps includes discussions on system functional requirements for both cases.(1) Additional system functional requirements specific to Situation 2 are detailed in table 5. These system requirements support the user needs discussed in table 4. The last column of table 5 traces these system requirements to the high-level system operational needs and functional requirements defined in the high-level CP ConOps.[(1)] The high-level system operational needs and functional requirements are also provided in the appendix of this document.

Table 5. System functional requirements for Situation 2.

ID Number	Relevant Component	Functional Requirements Statement	Traces To
CP-S1-SR01	Infrastructure-based smart sensors	See CP-S1-SR01 in table 3.	CP-SR-09; CP-N-ODP03a
CP-S1-SR02	Infrastructure-based smart sensors	See CP-S1-SR02 in table 3.	CP-SR10; CP-N-ODP03b
CP-S1-SR03	CARMA Streets	See CP-S1-SR03 in table 3.	CP-SR12; CP-N-COMM02; CP-N-COMM05
CP-S2-SR01	CARMA Platform	A CDA vehicle equipped with CARMA Platform detects and classifies pedestrians within its field of view and detection range and perceives the following minimal attributes of a detected pedestrian: location, speed, and heading.	CP-SR02; CP-N-ODP01
CP-S2-SR02	CARMA Platform	A CDA vehicle equipped with CARMA Platform wirelessly transmits locally perceived object data as a CP message at a frequency between 10 and 1 Hz according to a ruleset that specifies conditions to determine transmission frequency and object inclusion.	CP-SR11; CP-N-COMM01; CP-N-COMM05
CP-S2-SR03	CARMA Platform	A CDA vehicle equipped with CARMA Platform receives and processes CP messages sent by CARMA Streets and other CARMA Platform instances. Each CP message should be processed before the next message is received.	CP-SR14; CP-N-COMM03

ID Number	Relevant Component	Functional Requirements Statement	Traces To
CP-S2-SR04	CARMA Platform	A CDA vehicle equipped with CARMA Platform, in realtime, fuses object-based perception data received from CARMA Streets and other CARMA Platform instances and produces a merged world model. Objects that are not currently in the CDA vehicle's world model will be added to the object list. Attributes of existing objects created from previous CP messages will be updated according to newly received and fused perception data.	CP-SR15; CP-N-DF01
CP-S2-SR05	CARMA Messenger	CARMA Messenger installed in a connected non-AV receives and processes object-based perception data sent by CARMA Streets and other CARMA Platform instances. Each CP message should be processed before the next message is received.	CP-SR17; CP-N-COMM03
CP-S2-SR06	CARMA Messenger	CARMA Messenger installed in a connected non-AV, in realtime, fuses object-based perception data received from CARMA Streets and other CARMA Platform instances and produces a merged world model. Objects that are not currently in the vehicle's world model will be added to the object list. Attributes of existing objects created from previous CP messages will be updated according to newly received and fused perception data.	CP-SR18; CP-N-DF01
CP-S1-SR06	CARMA Messenger	See CP-S1-SR06 in table 3.	CP-SR19; CP-N-CPA02

PERFORMANCE METRICS

All performance metrics for Situation 1 discussed in chapter 4 are still relevant in Situation 2. Additional performance metrics should be considered to assess the effectiveness of the object-level data fusion required in Situation 2. These additional performance metrics could include the following:

- Accuracy of object association is the accuracy of the data fusion algorithms in matching objects detected and perceived by multiple entities.
- Accuracy of the fused object detection and perception is the accuracy of the fused data in VRU detection and attributes perception.
- Computational time of data fusion algorithms is the time it takes to fuse CP data from multiple entities into one set of object-based perception data.

CHAPTER 6. SITUATION 3

This chapters analyzes Situation 3 described in chapter 3. In Situation 3, a large vehicle is stopped behind the stop line (first in queue) with a passenger vehicle approaching the intersection behind the large vehicle, while a pedestrian clears the intersection out of the designated pedestrian phase. CP in Situation 3 is enabled by both vehicle- and infrastructure-based sensing, computing, and communication technologies. The large vehicle in Situation 3 is assumed to be equipped with detection, perception, and V2X communication capabilities. The passenger vehicle in Situation 3 is assumed to be capable of V2X communications at a minimum. The pedestrian in Situation 3 is assumed to be nonconnected. Situation 3 exhibits four of the five CP technical considerations. In addition to ODP, communication issues, and DF required in Situation 2 (see chapter 5), the effective use of CP information in vehicle trajectory planning and control is more relevant in Situation 3 as the passenger vehicle equipped with C–ADS approaches the intersection.

USER-ORIENTED OPERATIONAL DESCRIPTION

This section describes Situation 3 (figure 7) from the perspectives of the road users involved. Compared with Situation 2 (figure 6), CPA is now an additional system functionality. In Situation 3, the passenger vehicle uses the fused CP data from two sources (both the large vehicle and the infrastructure) in its trajectory planning and control algorithms.

Driver Perspective (connected but nonautomated vehicle)

At a signalized intersection, a passenger vehicle driver approaches a green light on the northbound intersection approach. The northbound intersection approach has two lanes. A large vehicle remains motionless at the northbound intersection stop bar in the median lane. The curbside lane has no visible queued vehicles or incoming vehicles.

As the vehicle gets closer to the intersection (but is still relatively far from the large vehicle), the driver notices, on the vehicle's dashboard, an alert of a pedestrian in a "conflicting crosswalk" (i.e., a crosswalk where a pedestrian could conflict with the vehicle's path). The driver may not yet see the conflicting pedestrian with their own eyes. The large vehicle remains motionless for an unusually long time (e.g., more than 5 s) during the northbound green phase as the passenger approaches the green light. Normally in such a situation, the driver would maintain speed and change lanes to drive past the large vehicle. However, because of the conflicting pedestrian warning, the driver slows down to wait behind the large vehicle. Alternatively, the driver may change lanes and slow down at the same time when the vehicle is still relatively far from the stop bar (at a sufficient distance to make a full stop at the speed of travel).

As the passenger vehicle stops behind the large vehicle, or as the passenger vehicle changes to the curbside lane, the driver may notice the conflicting pedestrian appear just to the right of the large vehicle within the crosswalk. If the vehicle has changed lanes and is in the curbside lane approaching the intersection, the driver further slows down and stops at the stop bar to wait for the pedestrian to clear the intersection. The driver may then see the pedestrian complete their walking trip past the crosswalk and onto the sidewalk. The pedestrian alert then disappears from the dashboard. The large vehicle then drives ahead northbound and through the intersection. The passenger vehicle driver drives ahead northbound as well, following the large vehicle (if the passenger vehicle has stopped behind the large vehicle) or at the same time as the large vehicle (if the passenger vehicle has changed lanes and stopped behind the stop bar in the curbside lane).

Vehicle Perspective (CAV)

At a signalized intersection, a passenger vehicle approaches a green light on the northbound intersection approach. The vehicle's CDA software indicates that the northbound intersection approach has two lanes. The virtual environment indicates that a nearby vehicle remains motionless at the northbound intersection stop bar, in the median lane, and that the curbside lane has no queued vehicles or incoming vehicles. The passenger vehicle is receiving and processing both CP messages and SPaT messages from the infrastructure. The SPaT messages indicate that all northbound signal phases are currently green. The SPaT messages may indicate an expected duration of the current (north-south) signal phase (e.g., 90 s).

The CP messages from the infrastructure begin to indicate the presence of a pedestrian who may conflict with the northbound signal phases and traffic movements. At approximately the same time, the passenger vehicle (second in queue) starts to receive CP messages from the large vehicle (first in queue) about a pedestrian who may conflict with the northbound signal phases and traffic movements. The passenger vehicle executes internal logic to determine and confirm that the CP messages from both the infrastructure and the large vehicle are related to the same pedestrian. Once confirmed, the passenger vehicle's internal logic reconciles any discrepancy in object attributes (e.g., location, speed, heading) in the CP messages from both sources and registers the pedestrian and her attributes in the vehicle's world model.

The vehicle's CDA software indicates that the large vehicle (at the stop bar) has remained motionless for an unusually long time (e.g., more than 5 s) during the northbound green signal. Normally in such a situation, the passenger car would maintain speed and change lanes to drive past the large vehicle. However, because CP messages from at least one of the data sources indicate that a pedestrian remains within the conflict area, the passenger vehicle exercises its internal maneuver and trajectory planning logic to determine the best course of action. It could slow down to wait behind the large vehicle or change lanes and come to a full stop in the curbside lane. Some amount of time later (e.g., 10 s), the CP messages then cease to contain any pedestrian information. If the passenger vehicle has changed lanes and is the first vehicle stopped behind the stop bar in the curbside lane, the vehicle's own sensors may have also observed the pedestrian clearing the intersection and confirmed that the pedestrian is no longer present in the conflict area. At approximately the same time, the large vehicle (which was first in queue) starts to drive northbound and through the intersection. The passenger vehicle drives ahead northbound as well, following the large vehicle (if the passenger vehicle has stopped behind the large vehicle) or at the same time as the large vehicle (if the passenger vehicle has changed lanes and stopped behind the stop bar in the curbside lane).

VRU Perspective

From the pedestrian's perspective, Situation 3 is identical to Situations 1 and 2. The pedestrian remains unaware of how other road users are sensing them or about what measures the other road users are taking to avoid a potential conflict.

ENTITIES AND STAKEHOLDERS

When executing this operational situation (Situation 3) for research and development purposes, the entities and their associated minimum configurations are mostly identical to those in Situations 1 and 2 (as described in chapter 4), with the following differences:

- Because Situation 3 presents more potential safety risks to the pedestrian during testing, a pedestrian dummy should be used instead of a human. The use of a pedestrian dummy would allow for safe experimentation with the passenger vehicle's safety/mobility application that uses CP information, whether the application is a driver warning system (for connected but nonautomated vehicles) or maneuver and trajectory planning logic (for CAVs).

- For the passenger vehicle, in addition to the minimum requirements discussed in Situations 1 and 2, the vehicle should have a safety/mobility application that uses CP information to improve safety when approaching controlled VRU crossing areas. The warning system (for connected but nonautomated vehicles) should provide alert information in the form and frequency that are appropriate for human consumption and allow sufficient time for the human driver to react. If the passenger vehicle is connected and automated, the vehicle's maneuver and trajectory planning logic that uses CP information should compute a smooth trajectory that ensures pedestrian safety.

The stakeholders for Situation 3 are identical to those for Situation 1, which were described in chapter 4.

OPERATIONAL NEEDS

The operational needs for Situation 3 are identical to those for Situation 2, which were summarized in table 4.

SYSTEM FUNCTIONAL REQUIREMENTS

In correspondence with the high-level CP ConOps, this low-level ConOps uses CARMA Ecosystem as an example CDA system to explore incorporating the CP feature.(1) The system functional requirements of relevant CARMA products for Situation 2 (table 5) are still relevant for Situation 3. It should be noted that the system functional requirements in this low-level ConOps are developed based on the assumption that infrastructure-based sensors have onboard computation capabilities to detect and perceive pedestrians. If infrastructure-based sensors do not have detection and perception capability, such capabilities should be required to reside in CARMA Streets. The high-level CP ConOps includes discussions on system functional requirements for both cases.(1) Additional system functional requirements specific to Situation 3 are detailed in table 6. These system requirements support the user needs discussed in table 4. The last column of table 6 traces these system requirements to the high-level system operational needs and functional requirements defined in the high-level CP ConOps.(1) The high-level system operational needs and functional requirements are also provided in the appendix of this document.

Table 6. System functional requirements for Situation 3.

ID Number	Relevant Component	Functional Requirements Statement	Traces To
CP-S1-SR01	Infrastructure-based smart sensors	See CP-S1-SR01 in table 3.	CP-SR-09; CP-N-ODP03a
CP-S1-SR02	Infrastructure-based smart sensors	See CP-S1-SR02 in table 3.	CP-SR10; CP-N-ODP03b
CP-S1-SR03	CARMA Streets	See CP-S1-SR03 in table 3.	CP-SR12; CP-N-COMM02; CP-N-COMM05
CP-S2-SR01	CARMA Platform	See CP-S2-SR01 in table 5.	CP-SR02; CP-N-ODP01
CP-S2-SR02	CARMA Platform	See CP-S2-SR02 in table 5.	CP-SR11; CP-N-COMM01; CP-N-COMM05
CP-S2-SR03	CARMA Platform	See CP-S2-SR03 in table 5.	CP-SR14; CP-N-COMM03
CP-S2-SR04	CARMA Platform	See CP-S2-SR04 in table 5.	CP-SR15; CP-N-DF01
CP-S2-SR05	CARMA Messenger	See CP-S2-SR05 in table 5.	CP-SR17; CP-N-COMM03
CP-S2-SR06	CARMA Messenger	See CP-S2-SR06 in table 5.	CP-SR18; CP-N-DF01
CP-S3-SR01	CARMA Platform	A CDA vehicle equipped with CARMA Platform uses fused perception data from multiple sources, as well as static data such as maps and driving rules, to plan and control a smooth trajectory that avoids conflict with pedestrians clearing the intersection outside of their designated phase.	CP-SR16; CP-N-CPA01
CP-S3-SR02	CARMA Messenger	CARMA Messenger installed in a connected non-AV notifies the human driver (e.g., through visual or audio alerts or both) about conflicting VRUs derived from object-based perception data at a reasonable frequency. The notification should be given well before the passenger vehicle gets too close to the intersection (within the stopping distance at the vehicle's current speed) to allow for sufficient time for the human driver to react.	CP-SR19; CP-N-CPA02

PERFORMANCE METRICS

All performance metrics for Situations 1 and 2 are still relevant in Situation 3. Additional performance metrics that should be considered in Situation 3 to assess the effectiveness of the passenger vehicle's safety/mobility application that uses CP information could include the following:

- Travel speeds driven are the speeds a vehicle drives during the tests, which will be used to evaluate the driving smoothness within the control area.
- Acceleration profile is the acceleration of a vehicle at different time steps during the tests. The magnitude of deceleration could be used as a surrogate for safety-critical encounters.
- Timeliness of CP messages refers to whether the approaching passenger vehicle has sufficient distance to make a full stop when it first receives CP messages from other entities and registers the conflicting pedestrian.
- Timeliness of relevant safety/mobility applications that use CP information refers to whether the approaching passenger vehicle has sufficient distance to make a full stop when its safety/mobility applications first alert the driver or first start to replan its trajectory by using CP information.
- Reaction time of human driver refers to the time it takes for a human driver to react and reduce speed after receiving the first in-vehicle warning about a conflicting pedestrian. This measure could be used as a surrogate for the effectiveness of the in-vehicle warning.

CHAPTER 7. CONCLUSION

CDA technologies enable mobility and safety applications that individual ADS-operated vehicles cannot achieve. Such CDA applications are achieved by roadway entities communicating and working with each other. CP further enhances CDA by extending the perception range and performance of relevant CDA entities, such as roadside infrastructure and vehicles equipped with C–ADS. Such increased perception performance is expected to improve situational awareness, safety, mobility, and reliability of the transportation system.

This low-level ConOps discusses the system framework and requirements of three situations that fall into a particular CP scenario identified in the high-level ConOps: VRUs crossing in controlled conflict areas.(1) All three situations involve a large vehicle (which can be a heavy vehicle, a transit vehicle, or an emergency response vehicle), a passenger vehicle equipped with C–ADS, a VRU, and roadside sensing, computation, and communication infrastructure.
In these situations, autonomous vehicles could easily miss VRUs due to limited line of sight. CP supported by both infrastructure- and vehicle-based sensors, as well as V2X communications, could significantly increase road vehicles' awareness of VRUs and thus improve VRU safety. This ConOps defines the stakeholders, operational needs, system functional requirements, and performance metrics for each of the three situations.

Although CP provides great potential to improve safety and mobility of transportation systems, there are a few technical challenges that need to be further addressed before deploying CP applications. One of the most important requirements of a safe and effective CP application is the timeliness and accuracy of the information shared with different components of the system. The latency of VRU detection and perception, as well as the communication latency, must be sufficiently small to mitigate or eliminate possible conflicts. In addition, false or erroneous CP data may cause safety-critical concerns or lead to diminished trust among transportation users. Cybersecurity is another vital challenge that needs further attention in implementing and deploying CP applications. Loopholes in CP systems could cause severe safety and mobility issues in transportation networks.

The system functional requirements defined in this ConOps will guide the development of a PoC CP feature in the CARMA Ecosystem. To verify and validate the PoC system, a set of field tests can be conducted on a closed test track. As a PoC, the testing criteria should be first limited to the communication pipeline for VRU detection through CP. The purpose of the testing will be to verify the software, collect data for defined performance metrics, and validate that the implemented software meets the defined operational needs and functional requirements. Because many factors contribute to CP data accuracy, the testing will not focus on verifying or validating the accuracy aspect of the PoC CP feature in the CARMA Ecosystem. However, the data collected during testing may provide some insights that could help further development of CP applications in future studies.

APPENDIX. HIGH-LEVEL SYSTEM REQUIREMENTS

This appendix summarizes the high-level operational needs (table 7) and the functional requirements (table 8) of CARMA CP features, based on the generic use cases discussed in the high-level ConOps.[1] Based on the five CP technical considerations (see the CP Technical Considerations section), the functional requirements and operational needs are classified into five categories: ODP, COMM, CS, DF, and CPA. Infrastructure-based ODP could be performed by CARMA Streets (CP-N-ODP02a and CP-N-ODP02b) or by smart sensors that also have computation capabilities (CP-N-ODP03a and CP-N-ODP03b). These operational needs and functional requirements will inform future development of the system requirements of the CARMA CP features.

Table 7. CARMA CP operational needs.

Category	ID	Relevant Component	Operational Needs Statement
ODP	CP-N-ODP01	CARMA Platform	Need to process and fuse calibrated raw data received from different local onboard extrospective sensors (e.g., LiDAR and cameras) and produce object-based perception information in realtime. The process should detect external objects and perceive their status, such as location, speed, heading, dimensions, acceleration, and yaw rate.
ODP	CP-N-ODP02a	Infrastructure-based roadside sensors–CARMA Streets	Need to transmit raw sensor data from infrastructure-based roadside sensors to CARMA Streets in realtime.
ODP	CP-N-ODP02b	CARMA Streets	Need to process calibrated raw sensor data from infrastructure-based roadside sensors in realtime to detect road objects and produce object-based perception information.
ODP	CP-N-ODP03a	Infrastructure-based roadside smart sensors	Need to process calibrated raw sensor data from infrastructure-based roadside sensors in realtime to detect road objects and produce object-based perception information.
ODP	CP-N-ODP03b	Camera infrastructure-based roadside smart sensors–CARMA Streets	Need to transmit object-based perception data produced by infrastructure-based roadside smart sensors to CARMA Streets in realtime.

Category	ID	Relevant Component	Operational Needs Statement
COMM	CP-N-COMM01	CARMA Platform	Need to temporarily store and broadcast processed perception data from local onboard extrospective sensors.
COMM	CP-N-COMM02	CARMA Streets	Need to temporarily store and broadcast processed perception information generated from infrastructure-based roadside sensor data.
COMM	CP-N-COMM03	CARMA Platform–CARMA Messenger–CARMA Streets	Need to receive and temporarily store processed perception information generated by other entities.
COMM	CP-N-COMM04	CARMA Platform–CARMA Messenger–CARMA Streets	Need to rebroadcast perception information received from other entities.
COMM	CP-N-COMM05	CARMA Platform–CARMA Messenger–CARMA Streets	Need to employ communication management strategies to reduce congestion in the communication channels. These strategies could include dynamic generation and dissemination rules.
CS	CP-N-CS01	All	Need to have proper CS platforms and strategies to protect and recover from cyber threats.
DF	CP-N-DF01	CARMA Platform–CARMA Messenger–CARMA Streets	Need to combine perception information from multiple sources and produce a merged world view for local applications. Needed DF algorithms include localization, track-to-track association, and attributes update.
CPA	CP-N-CPA01	CARMA Platform	Need to update relevant ADS and C–ADS features to effectively use CP to improve safety and efficiency.
CPA	CP-N-CPA02	CARMA Messenger	Need to have applications that convert CP data to information appropriate for human consumption.
CPA	CP-N-CPA03	CARMA Streets	Need to update relevant CDA applications to effectively use CP to improve safety and efficiency.

Table 8. CARMA CP functional requirements.

ID	Relevant Component	Functional Requirements Statement	Traces To
CP-SR01	CARMA Platform	A CDA vehicle processes and fuses calibrated raw data received from local onboard extrospective sensors, including LiDAR, visible spectrum camera, and radar.	CP-N-ODP01
CP-SR02	CARMA Platform	A CDA vehicle detects external objects such as vehicles, motorcycles, cyclists, and pedestrians. A CDA vehicle perceives the following attributes of detected external objects: absolute location, location relative to the subject vehicle, speed, heading, and size (length, width, height).	CP-N-ODP01
CP-SR03	Infrastructure	Infrastructure-based sensors, including LIDAR, visible spectrum cameras, and radar installed at static locations, such as an intersection, transmit calibrated raw sensor data to infrastructure computers, including CARMA Streets, at a frequency of at least 10 Hz.	CP-N-ODP02a
CP-SR04	CARMA Streets	An infrastructure computer provides physical interfaces for connecting to LiDAR sensors.	CP-N-ODP02a
CP-SR05	CARMA Streets	An infrastructure computer provides physical interfaces for connecting to radar sensors.	CP-N-ODP02a
CP-SR06	CARMA Streets	An infrastructure computer provides physical interfaces for connecting to visible spectrum camera sensors.	CP-N-ODP02a
CP-SR07	CARMA Streets	An infrastructure computer consumes and processes calibrated raw sensor data from infrastructure-based roadside sensors at a frequency greater than or equal to the transmission frequency of the infrastructure sensors.	CP-N-ODP02b

ID	Relevant Component	Functional Requirements Statement	Traces To
CP-SR08	CARMA Streets	From calibrated raw data from infrastructure sensors, an infrastructure computer detects and classifies objects such as vehicles, motorcycles, cyclists, and pedestrians. An infrastructure computer perceives the following attributes of detected external objects: absolute location, speed, heading, and size (length, width, height).	CP-N-ODP02b
CP-SR09	Infrastructure	Infrastructure-based smart sensors (that also have computation capability), including LiDAR, visible spectrum cameras, and radar installed at static locations, such as an intersection, detect and classify detected objects such as vehicles, motorcycles, cyclists, and pedestrians. A smart sensor perceives the following attributes of detected external objects: absolute location, speed, heading, and size (length, width, height).	CP-N-ODP03a
CP-SR10	Infrastructure	Smart sensors (sensors with computation capability), including LiDAR, visible spectrum cameras, and radar installed at static locations, such as an intersection, transmit processed object-based perception data to infrastructure computers, including CARMA Streets at a frequency of at least 10 Hz.	CP-N-ODP03b
CP-SR11	CARMA Platform	A CDA vehicle wirelessly transmits processed object-based perception data from local sensors at a frequency between 10 and 1 Hz according to a ruleset that specifies conditions to determine transmission frequency and object inclusion.	CP-N-COMM01; CP-N-COMM05
CP-SR12	CARMA Streets	An infrastructure computer wirelessly transmits processed object-based perception data at a frequency between 10 and 1 Hz according to a ruleset that specifies conditions to determine transmission frequency and object inclusion.	CP-N-COMM02; CP-N-COMM05

ID	Relevant Component	Functional Requirements Statement	Traces To
CP-SR13	CARMA Streets	An infrastructure computer transmits processed object-based perception data to wired clients such as CARMA Cloud or other instances of CARMA Streets at a frequency between 10 and 1 Hz.	CP-N-COMM02
CP-SR14	CARMA Platform	A CDA vehicle consumes object-based perception data received from other entities at a frequency greater than or equal to the transmission frequency.	CP-N-COMM03
CP-SR15	CARMA Platform	A CDA vehicle fuses local and received object-based perception data at a frequency greater than or equal to the transmission frequency of CP messages.	CP-N-DF01
CP-SR16	CARMA Platform	A CDA vehicle plans and controls its trajectory based on fused local and received perception data and static data such as maps and driving rules.	CP-N-CPA01
CP-SR17	CARMA Messenger	A display system for connected, nonautomated vehicles consumes object-based perception data received from other entities at a frequency greater than or equal to the transmission frequency of CP messages.	CP-N-COMM03
CP-SR18	CARMA Messenger	A display system for connected, nonautomated vehicle fuses received object-based perception data at a frequency greater than or equal to the transmission frequency of CP messages.	CP-N-DF01
CP-SR19	CARMA Messenger	A display system for connected, nonautomated vehicles displays relevant information derived from object-based perception data for human consumption at a reasonable frequency.	CP-N-CPA02
CP-SR20	CARMA Streets	An infrastructure computer consumes object-based perception data received from other entities at a frequency greater than or equal to the transmission frequency.	CP-N-COMM03

ID	Relevant Component	Functional Requirements Statement	Traces To
CP-SR21	CARMA Streets	An infrastructure computer fuses object-based perception data received from other entities to produce at least the following functions: localization of entities within the operational domain, and assignment and update of attributes of detected entities.	CP-N-DF01
CP-SR22	CARMA Platform	A CDA vehicle rebroadcasts object-based perception information received from other entities according to a ruleset that specifies rebroadcasting frequency and conditions for choosing whether to rebroadcast or not.	CP-N-COMM04; CP-N-COMM05
CP-SR23	CARMA Messenger	A display system for connected, nonautomated vehicles rebroadcasts object-based perception information received from other entities according to a ruleset that specifies rebroadcasting frequency and conditions for choosing whether to rebroadcast or not.	CP-N-COMM04; CP-N-COMM05
CP-SR24	CARMA Streets	An infrastructure computer rebroadcasts object-based perception information received from other entities according to a ruleset that specifies rebroadcasting frequency and conditions for choosing whether to rebroadcast or not.	CP-N-COMM04; CP-N-COMM05
CP-SR25	CARMA Platform	A CDA vehicle monitors the quantity of data being broadcast and received wirelessly and dynamically reduces the broadcasting frequency of perception messages to reduce radio interference.	CP-N-COMM05
CP-SR26	CARMA Messenger	A display system for connected, nonautomated vehicles monitors the quantity of data being broadcast and received wirelessly and dynamically reduces the broadcasting frequency of perception messages to reduce radio interference.	CP-N-COMM05
CP-SR27	CARMA Streets	An infrastructure computer monitors the quantity of data being broadcast and received wirelessly and dynamically reduces the broadcasting frequency of perception messages to reduce radio interference.	CP-N-COMM05

ID	Relevant Component	Functional Requirements Statement	Traces To
CP-SR28	CARMA Platform	A CDA vehicle satisfies CS requirements set forth in National Institute of Standards and Technology (NIST) 800-series publications.(15)	CP-N-CS01
CP-SR29	CARMA Messenger	A display system for connected, nonautomated vehicles satisfies CS requirements set forth in NIST 800-series publications.(15)	CP-N-CS01
CP-SR30	CARMA Streets	An infrastructure computer satisfies CS requirements set forth in NIST 800-series publications.(15)	CP-N-CS01
CP-SR31	Infrastructure	Infrastructure-based smart sensors that include computational platforms, such as infrastructure-based sensors that can detect and classify objects, satisfies CS requirements set forth in NIST 800-series publications.(15)	CP-N-CS01

radar = radio detection and ranging.

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