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

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Turner-Fairbank Highway Research Center
6300 Georgetown Pike
McLean, VA 22101-2296

FOREWORD

The Federal Highway Administration's (FHWA) Cooperative Driving Automation (CDA) Program, formerly known as the CARMA℠ Program, is an initiative to enable collaboration for research and development of CDA technologies. The CDA Program develops and maintains an ecosystem of open-source software tools, which together are known as the CARMA Ecosystem, to enable CDA research. The CARMA Ecosystem uses 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, FHWA's Office of Operations Research and Development developed a cooperative adaptive cruise control proof-of-concept prototype that was installed in five research vehicles. From there, the CARMA Ecosystem further evolved through testing and integration. At the time of this writing, the CDA Program is advancing into automated driving systems that leverage infrastructure to support cooperative automation strategies.

This concept of operations is the eighth in a series of nine focused on transportation systems management and operations use cases and capabilities, and is focused on cooperative perception. The intended audience for this report is CDA stakeholders such as system developers, analysts, researchers, application developers, and infrastructure owners and operators.

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

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16. Abstract 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 safety and mobility applications of CDA. This document presents a concept of operations for the CARMA CP feature to support 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

ACC	adaptive cruise control
ADS	automated driving system
ASN.1	Abstract Syntax Notation One
AV	automated vehicle
BSM	basic safety message
CACC	cooperative adaptive cruise control
C-ADS	cooperative ADS
CAV	connected and automated vehicle
CDA	cooperative driving automation
CNN	convolutional neural network
COMM	communications
ConOps	concept of operations
CP	cooperative perception
CPA	cooperative perception application
CS	cybersecurity
DF	data fusion
DSRC	dedicated short-range communication
ETSI	European Telecommunication Standards Institute
FHWA	Federal Highway Administration
GPS	global positioning system
HRSO	Office of Safety and Operations R&D
Hz	hertz
IOO	infrastructure owner and operator
ITS	intelligent transportation system
LiDAR	light detection and ranging
NHTSA	National Highway Traffic Safety Administration
ODP	object detection and perception
R&D	research and development
RADAR	radio detection and ranging
RSE	roadside equipment
STOL	Saxton Transportation Operations Laboratory
TSMO	transportation systems management and operations
V2I	vehicle-to-infrastructure
V2V	vehicle-to-vehicle
V2X	vehicle-to-everything
VRU	vulnerable road user

CHAPTER 1. INTRODUCTION

IDENTIFICATION

This document is a 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 R&D (HRSO), the Intelligent Transportation Systems Joint Program Office, and the Federal Transit Administration. This ConOps is an initial step in the current CARMA development effort to define a set of testable use cases that demonstrate how CP can be used to improve traffic safety and mobility.

DOCUMENT OVERVIEW

Background

HRSO performs transportation operations R&D for FHWA at the Saxton Transportation Operations Laboratory (STOL). HRSO conducts operations R&D based on a national perspective of the transportation needs of the United States.

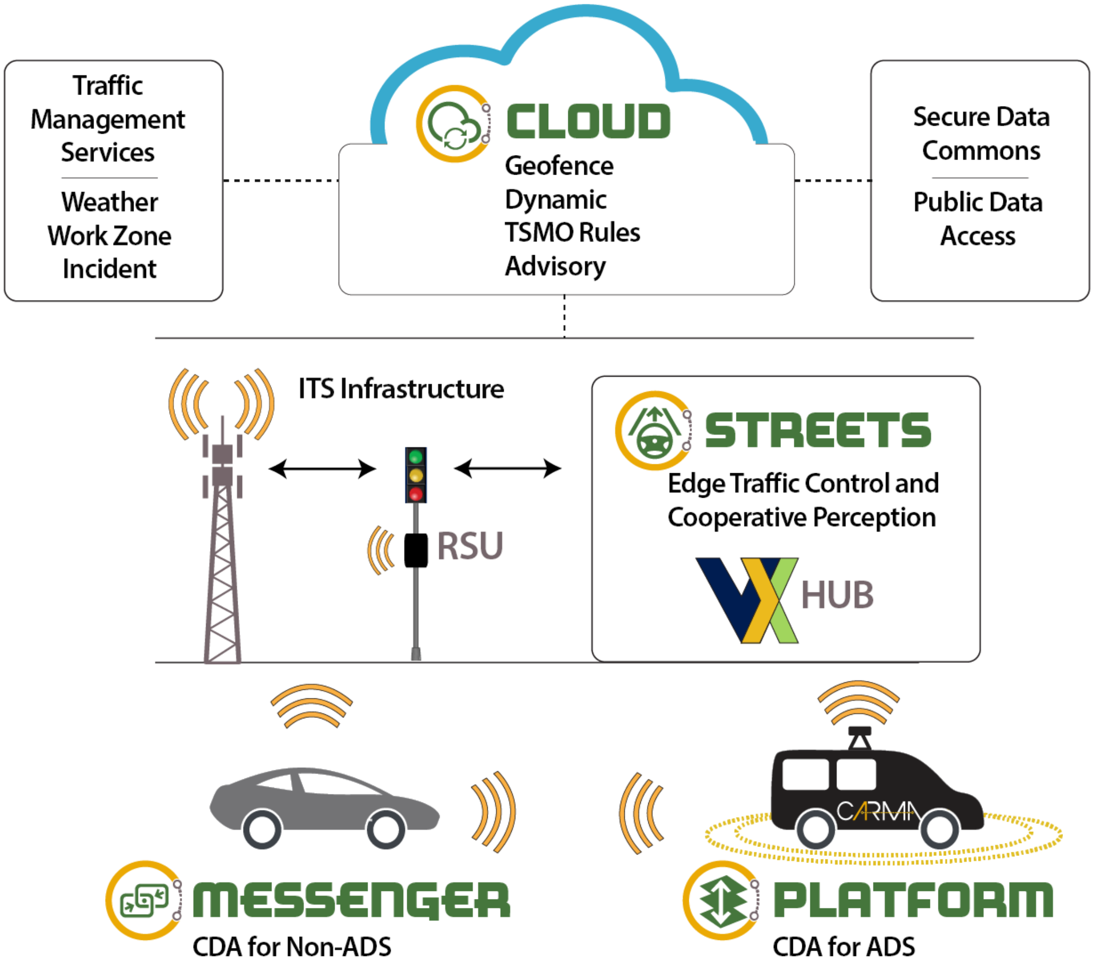
In 2015, FHWA designed, built, and installed a cooperative adaptive cruise control (CACC) proof-of-concept prototype system in a fleet of five research vehicles. The CACC system was built on the CARMA Platform℠ as an advancement of standard adaptive cruise control (ACC) systems by utilizing vehicle-to-vehicle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

A new reference platform, CARMA2, was developed using the Robot Operating System™ to enable easy sharing and integration of research into industry research vehicles. CARMA2 advanced the 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. CARMA2 also developed the Integrated Highway Prototype I, which combined speed harmonization, lane change/merge, and platooning into one trip. An associated research effort focused on developing the understanding of negotiations between entities and how they can be done efficiently to help improve traffic flow based on cooperative tactical maneuvers.

The third iteration of CARMA is currently being produced. CARMA3 takes the platform into automated driving systems (ADS) with SAE International Level 3, and above, driving automation. CARMA 3 enables ADS functionality to be used for cooperative automation strategies using Autoware®, an open-source ADS platform.

CARMA Cloud℠, CARMA Messenger, and CARMA Streets are also being developed. CARMA Cloud represents the infrastructure piece of cooperative driving automation (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 and buses) to communicate with the infrastructure and with CARMA Platform-equipped vehicles to improve network performance. CARMA Streets enables vehicles to communicate with the infrastructure at conflict areas (e.g., intersections) and provides an interface to roadside units. CARMA Streets uses edge computing to optimize travel through conflict areas. CARMA Platform, CARMA Cloud, CARMA Messenger, and CARMA Streets are all open-source software products built to benefit CDA research and implementation.

CARMA products are developed using an agile software development process to facilitate collaboration with the stakeholder community. Figure 1 illustrates the four open-source software products of the CARMA Ecosystem. The development of the CP use cases is a part of the CARMA effort.



Source: FHWA.

ITS = intelligent transportation system; RSU = roadside unit;
TSMO = transportation systems management and operations.

Figure 1. Illustration. CARMA^{SM} products.

Table 1 lists other projects associated with the development of the CARMA Ecosystem.

Table 1. Other projects associated with the development of the CARMA Ecosystem.

Task Order	Product	Title
STOL I T-13005	CARMA	Development of platform technology for automated vehicle research
STOL II 0013	CARMA2	Development of connected and automated vehicle (CAV) capabilities: Integrated Prototype I
STOL II 693JJ318F000225	CARMA3	Development of cooperative automation capabilities: Integrated Prototype II
STOL II 693JJ319F000369	CARMA Integrated Highway Prototype II	ADS Original Equipment Manufacturer-Industry Research Collaboration and Integrated Highway Prototype
FHWA Office of Operations (OPS) IV 693JJ318F000327	V2X Hub	Integrated Data Exchange Hub for Modular Operational Data Environment

Objective

This project extends the research from the development of cooperative automation capabilities: Integrated Prototype II by enhancing the CARMA Ecosystem to enable CP capabilities. This ConOps focuses on the high-level system framework of the CP feature in the CARMA Ecosystem, its requirements, and the potential impacts on transportation systems. A team of CARMA participants supports this project through development and testing.

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

The structure of this ConOps is generally consistent with the outline of a System Operational Concept document described in “Annex A” of *ISO/IEC/IEEE 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 more specifically capture those enhancements.

Chapter 1 defines the scope of the ConOps.

Chapter 2 describes the current situation and identifies the need for changes with respect to processes and systems to be affected by the ConOps.

Chapter 3 describes the concept for the CP feature in the CARMA Ecosystem, its capabilities, infrastructure configuration and needs, and CP system performance metrics.

Chapter 4 provides examples of operational scenarios that may be impacted by the CP feature of the CARMA Ecosystem. This chapter also presents descriptions of operational needs and functional requirements.

Chapter 5 summarizes the proposed ConOps of the CP feature and provides recommendations on the next steps, including a high-level system validation plan.

References provides a list of reference documents.

CHAPTER 2. CURRENT SITUATION AND OPPORTUNITIES FOR CHANGES

This chapter provides an overview of existing efforts to develop CP from the connected and automated vehicle (CAV) technology industries and the research communities. Opportunities for CP to enhance CDA and to be incorporated into the CARMA Ecosystem are discussed. This chapter also briefly describes the proposed CARMA CP features, their designed usage, and their expected benefits in addressing relevant needs of transportation system users and infrastructure owners and operators (IOOs).

AUTOMATED DRIVING, CDA, AND CP

Automated driving technologies, such as computer vision, sensor fusion algorithms, vehicle motion planning, and actuation, are cornerstones of automated driving. These are self-contained, stand-alone technologies that can enable automated driving without the need of any additional inputs, as a human driver would require, from other road users or infrastructure operators. While the focus of CAV development in the United States has been on stand-alone automated driving technologies, recent consensus has emerged that CDA could further the safety and mobility benefits of CAVs.

Using vehicle-to-everything (V2X) communications, CDA allows equipped vehicles to communicate with each other, with roadside equipment (RSE), and other road users. SAE International has standardized how cooperation between vehicles is regarded. 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 cooperative automated driving systems (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 2 summarizes the cooperation classes in relation to the levels of vehicle automation.

As shown in figure 2, the short description for CDA class A (status sharing) includes “here I am” and “what I see.” A well-known “here I am” status information is the basic safety message (BSM) defined in SAE J2735.(4) 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 (ETSI),(5,6,7) and the research community(8) have reached consensus on the concept of CP. 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 RSE with detection and perception capabilities.

CP could be a valuable feature of CDA. It could enhance situational awareness when some road objects are unable to share their own statuses through V2X communications. This situation, indeed, would be the case in the short-to-medium-term future, where a mixed traffic of CAVs and human-driven nonconnected vehicles still prevails. Additionally, static or foreign objects in the driving environment, and some road users, such as pedestrians, are not currently expected to be required to have machine-to-machine communication capabilities. In this case, road entities with CP capabilities that also have the line of sight of these static or foreign objects could share perception information with other RSEs and C–ADS-equipped vehicles to improve RSE and vehicle perception performance. CP could also supplement BSM in the case where the range and quality of V2X communication are limited. For example, consider a two-lane, two-way road with light traffic where the BSM from a C–ADS-equipped vehicle is unable to reach a group of approaching vehicles in the opposite direction due to limited communication range. If the leading vehicle in the opposite direction can perceive the C–ADS-equipped vehicle, the leading vehicle could share its perception with the rest of the vehicles in the group. Even when the shared perception information is redundant (but not complete duplication) from one C–ADS-equipped vehicle to another (e.g., perceived objects in the mutual field of view of both 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 perception performances could also support path and trajectory planning for improved mobility and energy performances.

CP LITERATURE REVIEW

Technical Considerations in CP

Extensive research has been performed in the past decade on various technical aspects of CP. This section describes the following five categories of technical considerations examined in the literature: enhanced object detection and perception (ODP), communication issues, security issues, data fusion (DF) algorithms, and the effective application of information obtained through CP.

Enhanced ODP

While convolutional neural networks (CNN) have been successfully applied to detecting common road objects for ADS (including vehicles, motorcycles, bicycles, and pedestrians), enhancements are still actively being proposed and tested as new datasets become available. Wei et al. proposed three CNN enhancements to specifically address relevant challenges in the driving environment, such as the significantly varying scale of objects, occlusion, and inferior lighting conditions.(9,10) More specifically to CP, the received CP information of an object that is otherwise obstructed from the subject vehicle should include the object's location (usually of a certain point) and dimensions in order for the subject vehicle to take appropriate actions, especially in safety-critical applications. However, extracting the center and the dimensions of a perceived object could be challenging, depending on the viewing angle. Rawashdeh and Wang proposed a solution that involves two neural networks: using YOLO object detection software and DenseNet for classifying the make and model of a vehicle (and hence estimated dimensions).(11) Their work has trained a DenseNet on 196 vehicle classes from the Stanford Cars Dataset and fine-tuned on 13 common vehicle classes in the Midwest.(12)

Communication Issues

Once the objects are detected and perceived, CP messages will be generated and disseminated through V2X communications. CP research has quickly converged on sharing object-based messages (i.e., processed object information) from its brief early exploration of sharing raw sensory data.(8) Nonetheless, naïve broadcasting of processed object information could still result in excessive redundancy and cause congestion of the communication networks, which will lead to data package drops and long communication delays. Therefore, the format of CP messages and the message generation and dissemination rules have received considerable attention in the literature.

Early work in this area was spearheaded by researchers in the Ko-FAS initiative around 2010.(13) As a part of the research initiative, an early version of CP message specification using the Abstract Syntax Notation One (ASN.1) was developed in 2012.(14) In 2016, Günther et al. proposed a new CP message specification called environmental perception message, which improved the earlier CP message specification by removing unnecessary data fields.(14) More recent research has also proposed to include the probability of existence, correlation, and higher-order derivatives of a detected object (e.g., acceleration and yaw rate) when needed, to improve the global fusion accuracy.(15)

To reduce communication overhead, some researchers have suggested appending CP information to an existing BSM, instead of a distinct message with additional header information, wherever possible.(16) Others have proposed dynamic CP message generation rules, where only a subset of objects detected by an entity is included in the CP message. The transmitting entity determines which objects to include based on how many times they have been detected, their status changes, the level of confidence of the perception, whether the detected objects have V2X capabilities, their distances to the sender, and the anticipated value of the information. (See references 7, 14, 17, 18, and 19.) For example, Gani et al. has determined that when message length must be limited due to observed channel load, prioritizing objects located closer to the edge of the sender's perception range is more beneficial to global awareness.(18) A similar idea is to include only a subset of attributes of a detected object based on its predicted mode of motion.(15) Additionally, the transmission rate of CP messages could also be adaptive in response to observed communication channel load.(18) Existing research has also suggested utilizing different channels (e.g., control versus service) and different transmission methods (e.g., cellular versus Wi-Fi®) for dissemination of CP messages of varying priority and impacts, and adopting peer-to-peer protocols to widely circulate the availability of information but only send/retrieve the actual information when needed. (See references 16, 20, 21, and 22.)

Cybersecurity (CS) Issues

CS issues are intrinsic to V2X communications. However, CS has not received much attention compared to the operational aspects of V2X communications. Known security threats to general V2X communications include eavesdropping, modification of a V2X message, impersonating the sender, and jamming the communication channels.(23) More specific to CP, it is also possible to falsify perception data.(23) In this case, noncryptographic security mechanisms are needed to identify false perception data. The literature suggests this could be possible if a vehicle receives redundant perception information from various sources.(23,24) Additionally, some rule-of-thumb verifications can also be applied, such as checking that the received information is within a reasonable range and tracks reasonably with respect to certain motion prediction models.(24)

DF

Once a vehicle has received CP information, DF algorithms are needed to combine peer data with locally perceived data. The receiving vehicle first needs to localize peer-detected objects in its own map using the sender's global positioning system (GPS) and its own GPS. Object association is performed next, matching the two sets of objects. Distance-based methods are commonly used for track-to-track association. (25,26) Special attention should be given to objects that are only detected by peer vehicles, especially when the detection and perception capabilities of the host vehicle and peer vehicles are not comparable (e.g., low- versus high-fidelity sensors).(27) Finally, DF is performed to combine peer and host data to update the attributes of objects that are detected by both the host and peer vehicles. This can be achieved through extended Kalman filtering, covariance intersection methods, and information matrix fusion.(26,28,29)

Application of CP Information

The use cases of CP experimented in the literature 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 automated vehicle (AV) path planning using CP information. (See references 8, 14, 30, 31, 32, and 33.) While these works have reported mostly positive impacts of CP, some late warnings were observed by Seeliger et al.(30) Kim et al. revealed the need for a new and improved path planning methods to fully take advantage of CP. (33) Another unique study has conducted driver simulator experiments with human subjects to investigate how effective CP-based warning messages are for human drivers in various driving scenarios.(34) The study found that CP-based warnings are as effective when the potential conflict is occluded as when it is visible to the driver. Moreover, CP-based warnings are more effective when anticipation is low.

CP State of Practice

While many CP technical considerations are still being actively researched, progress has also been made in the state of practice.

ETSI published its first draft report of collective perception message in 2019 based on results from numerous research projects.(7) The report focuses on communication issues related to CP. It defines the general CP message structure, which includes mandatory data package header, mandatory information about the sender, and optional data containers describing sensor information, perceived object(s), and free space. The report has proposed a message syntax and coding rules for CP following the ASN.1 standards.(35,36) The ETSI report recommends a CP message generation frequency between 1 and 10 hertz (Hz), proposes two sets of rules to include objects in a CP message (one for objects that belong to person or animal classes and the other for the rest), and discusses various dynamic redundancy management rules to reduce communication load (see the "Communication Issues" section earlier in this chapter). The ETSI report presents results from two simulation studies.(7) It found that the dynamic message generation rules can achieve the same level of general awareness but causes less congestion of the communication network.

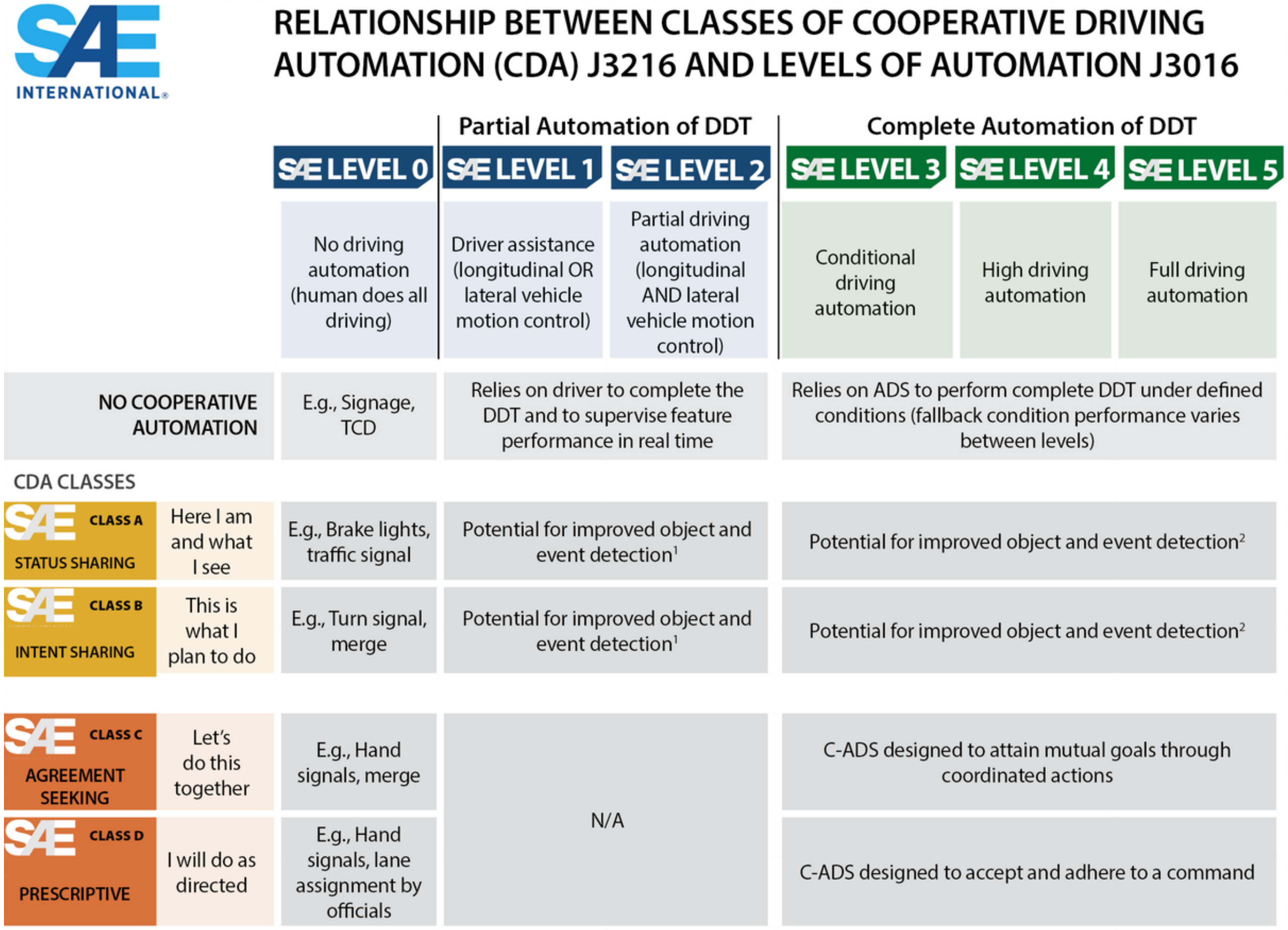
Relevant products have started to emerge as well. One new system integrates a roadside vehicle-to-infrastructure (V2I) communication unit with an Internet Protocol (IP) camera that has video analytics capability.(37) Another example is demonstrating how infrastructure-based perception could help enhance CAVs' situational awareness.(8,38)

OPPORTUNITIES FOR CHANGES

Existing research has demonstrated the benefits of CP in safety applications and its potential in CDA applications. CAV-based and infrastructure-based CP have both been investigated. The majority of experiments conducted involve infrastructure-based CP. Among the various CP technical considerations, research on object detection and DF algorithms is relatively mature. Further exploration is still needed on communication and security issues, some of which are also expected to be use case-specific.

Given the potential benefits of CP and the relatively mature operational technologies, the authors of this ConOps propose to integrate CP into the CARMA Ecosystem (figure 1). The CP feature can be integrated into all four products in the CARMA Ecosystem. The CARMA Platform is a candidate to incorporate CP. Vehicles equipped with the CARMA Platform are expected to have advanced sensing and perception systems and can initiate the sharing of CP information. Road users equipped only with CARMA Messenger may or may not generate original CP information (depending on their sensing and perception capabilities) but will be able to relay CP information they have received. 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 transportation systems management and operations (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 is able to 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.

This ConOps focuses on defining high-level use cases and related functional needs of CP. It serves as the basis to further define detailed perception and fusion algorithms, communications protocol, and security measures.



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

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

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[1] Improved object and event detection and 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.

[2] 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.

Figure 2. Chart. Overview of SAE cooperation classes and automation levels.

STAKEHOLDER NEEDS AND FEEDBACK

Stakeholders are entities and people whose actions influence travel in the transportation environment. These may include individual transportation users traveling on publicly accessible roadways, public transportation service providers, emergency responders, and IOOs. This section describes the stakeholders and their needs. This section also describes an effort to seek stakeholder feedback through a workshop.

Stakeholder Needs

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 passenger and freight vehicles—human-driven or automated—constitute the majority of road users. Other road users include pedestrians, bicyclists, motorcyclists, transit vehicles, and emergency responders. The general needs of transportation users include smooth, low-stress, and fast travel, reliable travel times energy-efficient and safe trips, and accurate information to help transportation users make optimal decisions about driving tasks (decision support systems).

Nonmotorized transportation users are particularly vulnerable, and their safety needs should be given the highest priority. Motorcyclists can also be considered vulnerable road users (VRUs), as their collision protection is minimum. Special motorized vehicles, such as transit and emergency responders, may also have higher demands on safety, reliability, and accurate information of the driving environment.

As a valuable feature of CDA, CP is expected to support all of the transportation user needs through improved situational awareness. Improved situational awareness could lead to improved safety performances. The National Highway Traffic Safety Administration (NHTSA) estimates that the combined use of V2V and V2I communications has the potential to significantly reduce unimpaired light vehicle crashes.(39) For VRUs and special motorized vehicles, CP could significantly improve their safety by making more vehicles aware of their presence. Conversely, special motorized vehicles could also extend their awareness of their surroundings through CP information received from other road entities. CP is expected to provide additional perception information to vehicles equipped with C–ADS, enabling them to make more informed decisions when planning their own trajectories and when engaged in class C and class D cooperative driving. This advanced trajectory planning with enhanced situational awareness could lead to smoother trajectories and more energy-efficient trips. CP can also supply CARMA Streets with a more comprehensive understanding of the traffic conditions. Improved situational awareness by CARMA Streets is expected to enhance cooperative coordination of vehicles at intersections, leading to increased throughput of intersections and reduced friction and energy consumption in traffic flow by improving vehicle-following stability. A traffic flow that is more stable overall is expected to lead to more reliable travel times.

Table 2 identifies 13 categories of transportation users based on their mode/vehicle type and their ADS capabilities and connectivity and defines the characteristics and needs of each category.

Table 2. Transportation user characteristics and needs.

Mode/Vehicle Type	Automation	Connectivity/CDA	User Characteristics and Needs
Passenger vehicle	Human driving	Nonconnected	Regular human drivers have neither connectivity nor automation capability, and they have uncertain driving behaviors. Needs align with general user needs.
Passenger vehicle	Human driving	Connected	Connected human drivers receive additional traveler information and can make better informed travel decisions. Connected human drivers can avail improved mobility and efficiency through advanced traffic operation strategies such as variable speed limit, queue warning, collision warning, and guided approach to intersections. Needs align with general user needs.
Passenger vehicle	Automated driving	Nonconnected	Nonconnected vehicles equipped with ADS operate independently, relying on local sensor information and automated control software, and usually have conservative behavior to provide increased comfort and safety margin. Needs include accurately sensing local traffic conditions and actuating control of vehicles to ensure safety and travel efficiency. Need to learn how to solve the trolley problem (i.e., how to minimize injury to CAV passengers and other road users in unavoidable crashes).

Mode/Vehicle Type	Automation	Connectivity/CDA	User Characteristics and Needs
Passenger vehicle	Automated driving	Vehicles equipped with C-ADS	CDA participants in the traffic stream to improve overall traffic performance. Needs include the availability of other vehicles to perform cooperative actions, improving overall system safety and efficiency while guaranteeing individual vehicle travel experiences. Need timely information on any infrastructure change, especially those relevant to VRU safety. Need timely updates to respond to evolving behaviors of other road users around CAVs. Need to learn how to solve the trolley problem (i.e., how to minimize injury to both CAV passengers and other road users in unavoidable crashes).
Transit vehicle	Human driving	Nonconnected	Regular human drivers have neither connectivity nor automation capability, and they have uncertain driver behavior. Need coordination with transit center to operate timely and efficiently and to improve safety and reliability. Require signal priority to enhance the operational efficiency and safety. Needs align with general user needs.
Transit vehicle	Human driving	Connected	Connected human transit drivers can have improved service through transit signal priority, dynamic transit vehicle scheduling, and dispatching and routing capabilities. Connected human transit drivers receive coordinated information among public transportation providers and travelers that helps in successful transit transfers. Needs align with general user needs.

Mode/Vehicle Type	Automation	Connectivity/CDA	User Characteristics and Needs
Transit vehicle	Automated driving	Nonconnected	Nonconnected vehicles equipped with ADS operate independently, relying on local sensor information and automated control software, and usually have conservative behavior to provide increased comfort and safety margin. Needs include accurately sensing local traffic conditions and actuating control of vehicles to ensure safety and travel efficiency. Need to distinguish between bystanders and would-be passengers who are actively walking toward the vehicle or waiting at a designated stop. Need to learn how to solve the trolley problem (i.e., how to minimize injury to both CAV passengers and other road users in unavoidable crashes).
Transit vehicle	Automated driving	Vehicles equipped with C–ADS	CDA participants in the traffic stream to improve overall traffic performance. Needs include coordination with other modes of traffic, such as passenger vehicles, bicyclists, and pedestrians, to perform cooperative actions and improve overall system safety and efficiency. Needs include coordination with would-be passengers/bystanders near bus stops to ensure safety during approach/departure and boarding/alighting and to improve scheduling, reliability, and the overall transit experience. Need to learn how to solve the trolley problem (i.e., how to minimize injury to both CAV passengers and other road users in unavoidable crashes).

Mode/Vehicle Type	Automation	Connectivity/CDA	User Characteristics and Needs
Emergency vehicle	Human driving	Nonconnected	Require signal preemption through equipped intersections as early as necessary to ensure the safety of all vehicles, including the emergency vehicle. Needs align with general user needs.
Emergency vehicle	Human driving	Connected	Connected human drivers receive additional traveler information and can make better informed travel decisions. Need basic emergency vehicle preemption control for connected emergency response vehicles (police, fire, ambulance, etc.) to improve emergency response efficiency and reliability. Needs align with general user needs.
Emergency vehicle	Automated driving	Nonconnected	Nonconnected 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 margin. Needs include accurately sensing local traffic conditions and actuating control of vehicles to ensure safety and travel efficiency. Need collaboration between the signal preemption and the automated driving control to achieve better efficiency. Need to learn how to solve the trolley problem (i.e., how to minimize injury to both CAV passengers and other road users in unavoidable crashes).

Mode/Vehicle Type	Automation	Connectivity/CDA	User Characteristics and Needs
Emergency vehicle	Automated driving	Vehicles equipped with C–ADS	CDA participants in the traffic stream to improve overall traffic performance. Needs include coordination with other modes of traffic, such as passenger vehicles, bicyclists, and pedestrians, to perform cooperative actions and improve overall system safety and efficiency. Needs include coordination between emergency dispatchers and other vehicles so that incident data could be transmitted directly to emergency dispatchers for emergency response. Need timely information on any infrastructure change, especially those relevant to VRU safety. Need timely updates to respond to evolving behaviors of other road users around emergency CAVs. Need to learn how to solve the trolley problem (i.e., how to minimize injury to both CAV passengers and other road users in unavoidable crashes).

Mode/Vehicle Type	**Automation**	**Connectivity/CDA**	**User Characteristics and Needs**
VRU	Nonmotorized/human driving	Nonconnected	VRUs, such as pedestrians, cyclists, and motorcyclists, are generally not expected to have any connectivity or automation capability, and they have uncertain behaviors. Need continuous attention from other users on the road, including, but not limited to, the following scenarios: • Signalized and unsignalized intersections when VRUs are crossing the road. • Vehicles turning or merging into traffic. • Midblock crossing. • Walking or biking along the edge of a highway or on the shoulder. Need to coordinate with transit vehicles to board the bus. Need to activate traffic signal to cross a signalized intersection or activate a rectangular rapid flashing beacon to cross midblock or an unsignalized intersection when available.
VRU	Nonmotorized/human driving	Connected	While VRUs are generally not expected to have connectivity or automation, it is possible in the future for VRUs' handheld devices to communicate through V2I and V2V technologies for safe crossing of the road. Need continuous attention from other users on the road, even with connected handheld devices, due to highest safety priority. Needs align with general user needs.

IOOs

IOOs are traffic participants who provide, operate, and maintain roadways and supporting infrastructure for the safety and mobility needs of transportation users. IOOs include public, public-private, or private sector entities that operate in accordance with applicable laws at the Federal, State, or local level.

TSMO is a standard practice of IOOs, including monitoring and managing traffic and the factors affecting traffic flow, such as incidents, weather, intersections, dissemination of routing information, and other actions that increase traffic flow efficiency. The goals of IOOs may include the following:

- Reducing recurring congestion.
- Improving reliability and safety.
- Reducing travel times, fuel consumption, and emissions.
- Maintaining and increasing the use of alternative and emerging transportation modes, such as car-sharing options (CAVs are considered as a separate mode by travelers(40)).

From the perspective of IOOs, CP could support the following benefits:

- Faster realization of efficiency goals. Adopting CP as a feature of CARMA Streets at intersections may enable greater congestion management abilities to increase throughput, enhance safety, and improve driver experience. If infrastructure-based sensing and perception is adopted, these benefits could be realized even when the percentage of road users equipped with advanced sensing and perception systems is low. These benefits may increase as the percentage of vehicles equipped with C–ADS increases.

- Maximized resource utilization for more efficient solutions. Traditional approaches to managing congestion, such as capacity expansion, are increasingly facing funding constraints and inherent limitations in alleviating transportation problems. The CP feature enhances the capabilities of CARMA Streets to optimize operational strategies that offer the potential for innovative solutions to congestion and travel time variability problems.

- Organizational evolution to accommodate the future of mobility technology. Organizations that respond to rapid technological change may be more likely to thrive in this era of rapid technological change in the transportation field.

CARMA CP Workshop Stakeholder Feedback

An online workshop hosted by FHWA's STOL for stakeholders held on May 4, 2021, helped identify their needs and expectations and what factors and use case scenarios matter to them.(41). Hosted by FHWA, the workshop provided more than 25 participants with an overview of the CP concept, CP use cases, and how CP can be incorporated into the CARMA Ecosystem. Participants included stakeholders from academia, State public transit authorities, port authorities, regional transportation authorities, and the Federal Government.

To collect feedback about the described systems, participants were asked poll questions during the workshop. Some questions related to the concept of CP that had been described in the workshop. The expected system presented in the workshop included high-level system architecture diagrams that had been prepared by the research team. A number of use case applications that could be impacted by the CARMA CP were also presented at the workshop. The poll questions asked during the workshop are summarized as follows:

- Do you have any questions and/or comments about this intuitive example of the CP?
- Do you have any questions and/or comments about the proposed system architecture?
- Do you have any questions and/or comments about the use cases involving VRUs and additional use cases that you would like to see? Which ones seems the most relevant?
- Which use case seemed most important to you?

Participant responses included the following:

- "Use cases that provide awareness of pedestrians/VRUs."
- "Use cases that include lateral conflict scenarios (e.g., cut-ins)."
- "Would like to see more of the intelligent transportation system (ITS) infrastructure-to-vehicle use case in the urban setting."
- "How long the messages will be valid."

Additional poll questions included:

- "Can you think of any other use case where CP will help?"
- "What are some challenges of the CP concept for CDA communication, in your opinion?"

Some of the participant's responses include comments such as the following:

- "Impact on traffic due to emergency vehicles."
- "CS/spoofing."
- "Resolution of conflicting messages from multiple sources."
- "We have a concurrent program on Infrastructure Perception and Control at the National Renewable Energy Laboratory that we want to coordinate with FHWA on."

The feedback received from this workshop helped develop the CARMA CP operational needs and functional requirements, presented in chapter 4 of this ConOps.

JUSTIFICATION FOR AND NATURE OF CHANGES

The transportation industry is moving toward improving safety with ADS by enhancing various vehicle technologies (i.e., levels of automation and ubiquitous sensing using AV). While more advanced sensing and computing capabilities are integrated with ADS, the performance of the perception system of an individual vehicle is always limited by its line of sight and detection range. CP could be a valuable feature of CDA to enhance situational awareness, improve safety, and enhance mobility. Key considerations are what changes must take place to enable CP in the CARMA Ecosystem, and what additional capabilities and possibilities can be expected. The

CARMA Ecosystem includes technologies for vehicles (CARMA Platform and CARMA Messenger) and the infrastructure (CARMA Streets and CARMA Cloud). This section discusses the nature of the changes needed to enable CP in CAVs and in the roadside infrastructure.

Organizational/Institutional Changes

The following organizational/institutional changes support the development and deployment of CP:

- Adopt a traffic engineering process approach. A traffic engineering process takes into consideration the design and operational aspects of transportation infrastructure, as well as user characteristics, in developing operational strategies for transportation safety and mobility. It is important to keep this traffic engineering context in mind when developing CP operational scenarios where the technology could be applicable and beneficial. Low-level ConOps can be developed for specific operational scenarios at the regional or local level and for the facility in question.

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

- Develop a performance management system. Identifying the 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 the various vehicles, onboard sensors, wireless devices, roadside units, roadway traffic sensors, weather systems, message boards, and other related systems. These data can be placed in, or be accessible from, a common data environment.

- Include rich, accurate data sources from a variety of sources. Those sources include the following types of data:
    - Real-time traffic data: vehicle speed and location data collected and disseminated by vehicles as part of a connected system. They also include traditional detection sources (e.g., inductive loop detectors, overhead radio detection and ranging (RADAR), closed-circuit television cameras) that provide traffic data for the system.

    - Traffic signal plan data: the planned signal phase and timing at a signalized intersection from the signal.

    - Weather condition data: infrastructure-based road weather information systems 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, iced, salted) can be provided by in-pavement sensors.

  - Crowdsourced data: collected from platforms that have large installed user bases that can supplement data from other sources.

  - Historical data: improves the accuracy of traffic analysis and the prediction of traffic conditions.

Technical/Technological Changes

The following technical/technological changes enable the development and deployment of CP in the CARMA Ecosystem:

- Procure new hardware to support technology.
  - Increase the CP capabilities of the CARMA Ecosystem through infrastructure-based sensing and perception systems.
  - Equip vehicles with C–ADS that includes camera, LiDAR, RADAR, and other computational resources to implement algorithms needed for CP.
- Develop/acquire new software.
  - Implement relevant algorithms to achieve CP.
  - Use CP information effectively for safety and mobility applications.

Operational Policy Changes

Operational policies of a facility or service are designed to accommodate traffic operations that meet the goals of the operators.

Key questions to determine proper operational policies include the following:

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

All stakeholders should have clear expectations and incentives to participate. Improved facility safety and mobility performances are the goals of IOOs. Users can also create agreements or compacts to set expectations, encourage investments, and measure performance.

Facility Infrastructure Changes

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

- Communication equipment (e.g., roadside units) to enable two-way communication with equipped road entities within the communication range.

- Roadside sensors (e.g., video cameras, RADAR, LiDAR) to detect and estimate real-time trajectories of nonequipped vehicles and other road users.

CHAPTER 3. OPERATIONAL CONCEPT OF THE PROPOSED SYSTEM

This chapter details the operational concept of the CP feature. It describes how CP can be implemented in the CARMA Ecosystem to improve safety and efficiency.

TECHNOLOGICAL FRAMEWORK FOR CP

This section describes the CP system framework in the CARMA Ecosystem. The CP feature provides the possibility for different CDA participants (e.g., vehicles and infrastructure) to exchange information about external objects detected in the surrounding environment. These external objects include VRUs and obstructions on the roadway. The external objects can be detected by vehicles' extrospective onboard sensors (e.g., cameras and LiDAR) or similar infrastructure-based sensors.

At this initial feature development stage, two of the five technical considerations of CP—communication protocols and DF algorithms (see the "Technical Considerations in CP" section in chapter 2)—are identified as key to achieving a minimum viable product. They are relevant because a substantial amount of new software is needed in these two areas that are the fundamental ingredients of CP. Relatively mature production software exists for ODP. While ODP algorithms can be further enhanced, existing technologies are sufficient to support a minimum viable CP feature.(10,11) CS improvements and strategies to boost the effectiveness of CP at the application level should come after the development of the CP feature. This section focuses on the communication protocols and DF algorithms needed to implement CP in the CARMA Ecosystem.

Communication Protocols

As identified in the literature review, two general approaches have been considered for CDA participants to share perception information. First, CDA participants can directly broadcast raw sensor information. In this approach, each recipient should be able to receive, temporarily store, and process this information to detect the external objects. However, broadcasting raw sensor data or video footage requires substantial communication resources and may not be a feasible solution. The second approach is that each CDA participant processes their own raw data to extract a set of attributes for each external object. This set may include a vector of information that specifies the object, such as the object type (e.g., pedestrian), dimensions, location, speed, or the direction of movement (if it is a moving object). For the CP feature in the CARMA Ecosystem, the object-based approach will be adopted.

It is possible that a CDA participant sends redundant and unnecessary frequent updates for the same object, which may increase the communication load. An overloaded communication network may cause some other necessary object updates to be missed, which may decrease the performance of the CP feature. A methodology to mitigate or ignore redundant messages is important. Another issue that may arise in sharing perception information is communication latency. As a result of communication latency, information may not arrive in a timely manner. In such cases, the received information is outdated and may not be valuable, and might even be harmful to use (especially if the detected object is moving). To mitigate this issue, a time-stamp field should be included in the object attributes, which represents the time at which the observers detect objects. Recipients can take special considerations when the received information contains time stamps that are relatively old.

DF Algorithms

Different sources may have slightly different inferences of object attributes. For example, for an object that is visible to both a vehicle and a roadside camera, the vehicle and infrastructure may process their own sensor information and obtain somewhat different attribute values of the same object. This may occur due to the different viewing angles, capabilities, and accuracies of the sensors. In such cases, each CDA participant should decide to use the perception information from a single entity or a combination of multiple entities. For example, it may make sense to rely on a sensor that is closer to the object or has higher accuracy. To make such a decision, a DF method will need to be developed, which may reside inside each CDA participant to properly fuse object attributes received from different sources.

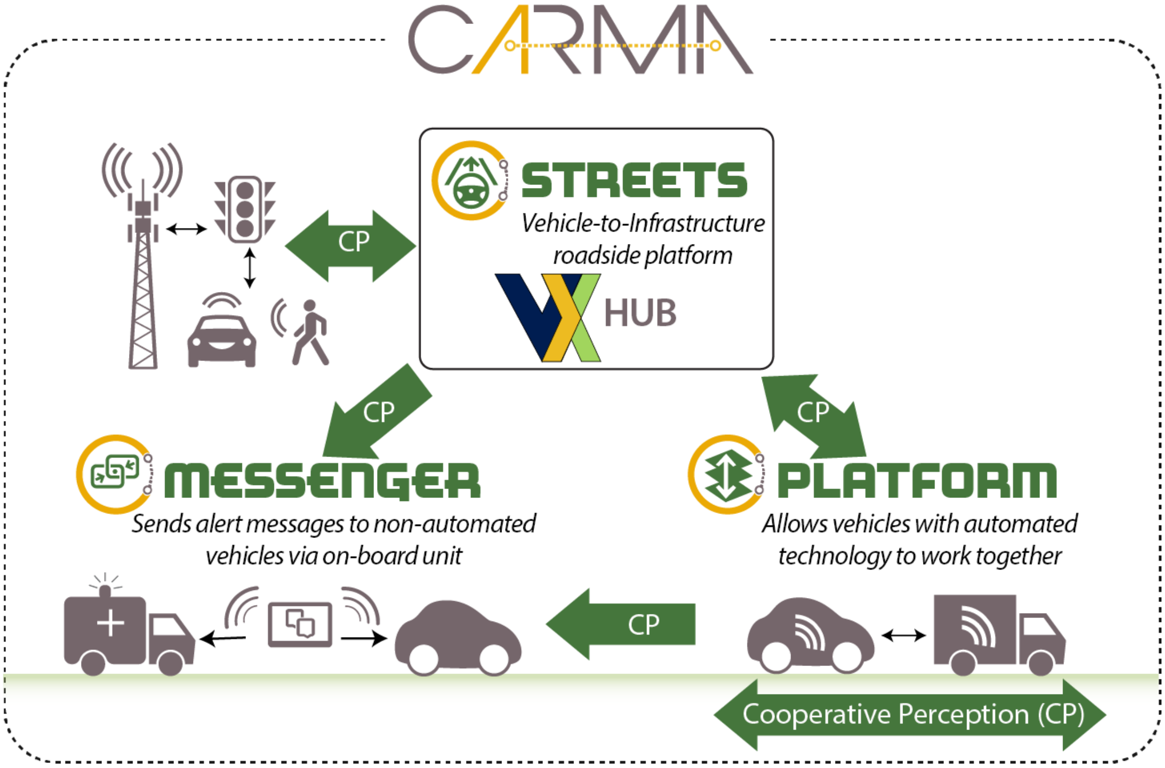
In designing the DF element, errors in object detections are inevitable. It is also possible that a recipient receives multiple contradictory messages of the same object. One way to mitigate these errors is to define a confidence level for each object attributes sent by each CDA participant to be able to fuse them and come up with a final solution, similar to the approaches adopted in Allig and Wanielik, Ambrosin et al., and Gabb et al.(15,25,28) For example, map matching algorithms are required to match the object location with the map geometry. It is possible that the mapping algorithm cannot accurately identify the object's location on the map. Therefore, having an object confidence level methodology will be helpful so the information recipients know how and to what level they can rely on the received information.

CP in the CARMA Ecosystem

Figure 3 illustrates the connection among different components of the CARMA Ecosystem that enables CP. Components of the CARMA Ecosystem can exchange real-time information about their own information as well as their perceptions about the surrounding environment. In this ecosystem, CARMA Streets plays the role of an edge processor on the infrastructure side. CARMA Streets is a roadside interface and an edge computing device that enables communication between infrastructure and different transportation users. CARMA Streets can be connected to different traffic control devices, sensors, and mobile devices (e.g., RSE, signal controllers, cameras, and cellular phones) to send and receive necessary information in realtime. CARMA Streets can receive perception information from roadside sensors (e.g., cameras and LiDAR) and CARMA Platform-equipped vehicles. CARMA Streets can store, process, and send the processed information to all vehicles equipped with CARMA Platform and CARMA Messenger within the RSE communication radius. Communication between CARMA Streets and vehicles can be enabled by the RSE equipped with broadcast- or network-based communication technologies.

In addition, vehicles equipped with CARMA Platform can directly exchange perception information between each other and vehicles equipped with CARMA Messenger. This information exchange can happen via V2V communication channels without engaging CARMA Streets. CARMA Streets can also provide additional information to the vehicles. Therefore, each vehicle equipped with CARMA Platform should be able to create, maintain, and update a list of external objects with their fused attributes.

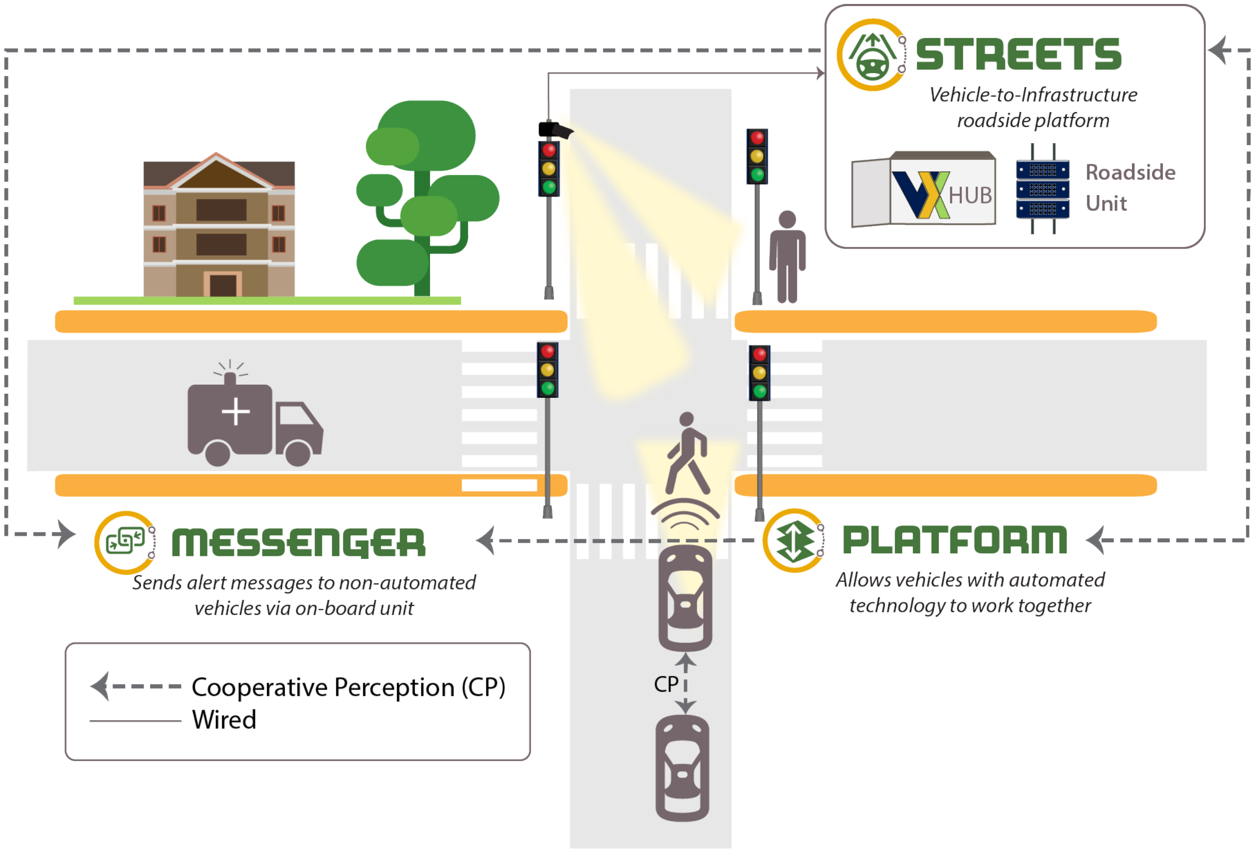
While CARMA Messenger currently does not have perception capabilities and is not able to generate original CP information (as indicated by the one-way arrows pointing toward Messenger in Figure 3), it can receive CP information. CARMA Messenger can also process received CP information for human driver consumption, and relay CP information to other entities with communication capabilities.



Source: FHWA.

Figure 3. Illustration. CP in the CARMA Ecosystem.

Figure 4 illustrates some general scenarios where CP is enabled by V2I and V2V communications. In Figure 4, a pedestrian on the intersection crosswalk and another pedestrian waiting to cross are both captured by a mounted camera. If the camera has ODP capabilities, it sends a processed list of objects to CARMA Streets. If the camera does not have processing capabilities, it sends the raw video to CARMA Streets in realtime via wired connection. CARMA Streets could perform video analytics to detect the pedestrians and perceive their relevant attributes. If a proper application is installed and activated in the pedestrians' mobile devices, the pedestrians' attributes can be sent to CARMA Streets through the RSE via the cellular network. (Note that this is not expected or required for CP.) CARMA Streets processes, detects, and estimates/fuses the pedestrians' attributes. It then sends information about the pedestrians to vehicles equipped with CARMA Platform and CARMA Messenger within the RSE's communication radius. The pedestrian on the crosswalk is also captured by the first vehicle stopped at the intersection in the northbound approach. As a vehicle outfitted with CARMA Platform, this vehicle detects and perceives the pedestrian and broadcasts its own CP message. The CP message is received by the surrounding vehicles equipped with either CARMA Platform or CARMA Messenger, as well as the RSE. The RSE can pass this CP message to CARMA Streets for further object-level fusion. Other surrounding vehicles may receive information about the pedestrian on the crosswalk from either the first stopped vehicle in the northbound approach, CARMA Streets, or both. If vehicles receive the perception information from multiple sources, they will need to fuse the object attributes to improve accuracy/precision and remove redundant information.



Source: FHWA.

Figure 4. Illustration. CP enabled by V2I and V2V communications in the CARMA Ecosystem.

OPERATIONAL NEEDS AND FUNCTIONAL REQUIREMENTS

This section describes the operational needs (table 3) and the functional requirements (see table 4) of CARMA CP features, based on the generic use cases discussed in the previous section. Based on the five CP technical considerations (see the "Technical Considerations in CP" section), the functional requirements and operational needs are classified into five categories: ODP, communications (COMM), CS, DF, and CP application (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 guide future development of the system requirements of the CARMA CP features.

Table 3. 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.
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.

Category	**ID**	**Relevant Component**	**Operational Needs Statement**
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 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, but are not limited to, 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 4. 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 but not limited to, 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 but not limited to, LiDAR, visible spectrum cameras, and RADAR installed at static locations, such as an intersection, transmit calibrated raw sensor data to infrastructure computers including, but not limited to, CARMA Streets at a frequency of no less than 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
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

ID	Relevant Component	Functional Requirements Statement	Traces To
CP-SR09	Infrastructure	Infrastructure-based smart sensors (that also have computation capability) including, but not limited to, 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, but not limited to, LiDAR, visible spectrum cameras, and RADAR installed at static locations, such as an intersection, transmit processed object-based perception data to infrastructure computers including, but not limited to, CARMA Streets at a frequency of no less than 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
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

ID	Relevant Component	Functional Requirements Statement	Traces To
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, non-AVs 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, non-AV 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, non-AVs 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
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, non-AVs 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

ID	Relevant Component	Functional Requirements Statement	Traces To
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 in order to reduce radio interference.	CP-N-COMM05
CP-SR26	CARMA Messenger	A display system for connected, non-AVs 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
CP-SR28	CARMA Platform	A CDA vehicle satisfies CS requirements set forth in National Institute of Standards and Technology (NIST) 800-series publications.(42)	CP-N-CS01
CP-SR29	CARMA Messenger	A display system for connected, non-AVs satisfies CS requirements set forth in NIST 800-series publications.(42)	CP-N-CS01
CP-SR30	CARMA Streets	An infrastructure computer satisfies CS requirements set forth in NIST 800-series publications.(42)	CP-N-CS01
CP-SR31	Infrastructure	Infrastructure-based smart sensors that include computational platforms, such as infrastructure-based sensors that are capable of detecting and classifying objects, satisfy CS requirements set forth in NIST 800-series publications.(42)	CP-N-CS01

ID = identity.

INFRASTRUCTURE CONFIGURATION AND NEEDS

This section describes technological and institutional infrastructure and explains the role of IOOs in preparing a CDA environment that supports the CP feature.

A 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. The CP feature for a local transportation network (e.g., an intersection) may require RSE that includes one or multiple RSEs, an edge processor, and probably roadside sensors (e.g., cameras and LiDAR). The presence of roadside sensors is optional but helpful. If the area is not equipped with roadside sensors, the CP feature can still be achieved by vehicles equipped with C–ADS. The RSE can communicate to vehicles equipped with C–ADS, irrespective of the particular communication technologies, using the appropriate protocols. Vehicles equipped with C–ADS can also share what they sense about the surroundings. The two-way information exchange constitutes the foundation of CDA, which includes CP.

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 RSE or multiple RSEs will relay the 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 process and share the perception information with the vehicles via the RSEs inside the communication radius. This communication can happen using broadcast- or network-based communication technology with appropriate protocols.

FUNCTIONAL PERFORMANCE METRICS

The CP feature in the CARMA Ecosystem needs to be evaluated for its effectiveness in positively impacting three performance metrics: traffic performance, vehicle behaviors (vehicle operations during execution of different use case scenarios), and communication, each of which may include a number of subcategories that are discussed in the following sections.

Metrics for Traffic Operations

This section identifies performance measures on traffic performance to be used to evaluate the impact of the CP feature in the CARMA Ecosystem on traffic flow. The following five categories of impacts are identified: safety, throughput and delay, flow stability, flow breakdown and reliability, and sustainability.(43)

Safety

Safety is a key factor in evaluating the impacts of new technologies on transportation systems. Because the majority of crashes are due to human errors, connected vehicles have the potential to significantly decrease the number of crashes, specifically at high market penetration levels.(44) With the CP feature, further safety improvements can be expected because each connected vehicle can rely not only on its own sensor information, but also on received perception information from other vehicles or infrastructure. One way to quantify safety improvements is by calculating safety surrogate measures for a given facility. These measures include:

- Metrics for situational awareness.(16,18)
- Frequency of critical encounters.(34)
- Space and time headway distributions.
- Time to collision distribution.

Throughput and Delay

With connected vehicles and CP technologies, infrastructure will be informed about the presence of all connected vehicles within the communication radius, and thus can optimize operations of the traffic control devices in realtime (e.g., signal adaptations). Traffic operations optimized with enhanced situational awareness will increase flow throughput and decrease travel delay. Additionally, vehicles equipped with C–ADS could also further optimize their path and trajectories based on extended perception data for mobility improvements. However, such impacts are dependent on the market penetration 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.

Flow Stability

CP information can potentially contribute to more stabilized traffic flows. Several stability indices developed in the literature can be used.(See references 45, 46, 47, and 48.) 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 CP technologies are expected to improve traffic flow reliabilities by providing safer, smoother, and more responsive vehicle operations. The use case can employ multiple measures to quantify impacts on flow breakdown and reliability, such as the occurrence of shock waves and the severity of shock waves formed.

Sustainability

The environmental impacts of CDA and CP are uncertain. Smoother operations associated with CDA and CP can potentially lead to lower greenhouse gas emissions and energy consumption. Calculating emissions and energy consumption is usually an offline process that uses observed data or data previously obtained by simulation.(49) Several methods are available in the literature for that purpose at different data aggregation levels.(50,51,52) For 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 CP features may include the following:

- Space headway. Space headway is the longitudinal distance between two consecutive 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. Acceleration profile is the accelerations of each vehicle at different time steps during the tests. The magnitude of deceleration could be used as a surrogate for safety-critical encounters.

Additional metrics can be calculated from space headway and travel speeds, such as time headway and time to collision. Space headway, travel speed, and acceleration of the immediate downstream vehicle are also independent variables in typical car-following models.

Performance Metrics for Communication

To quantify communication performance and to determine if communication and the maneuver negotiations took place as designed, data exchanges from V2V and V2I can be evaluated using the following metrics:

- Length/size of the perception message.
- Message dissemination frequency.
- Observed communication channel load.
- Data packet drops.
- Communication latency.

CHAPTER 4. OPERATIONAL SCENARIOS

This section describes 14 operational scenarios where CP could be employed to improve traffic safety and mobility. The scenarios are bracketed into four application groups. 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 where CP provides a general increase in situational awareness. All subject vehicles receiving CP information are depicted as generic vehicles in this chapter. However, the subject vehicles could very well be transit and emergency vehicles equipped with C–ADS.

APPLICATION 1: INTERACTING WITH VRUS

This set of scenarios focuses on VRUs who are at higher risk of severe injury if involved in a road incident. VRUs include pedestrians, bicyclists, motorcyclists, scooter riders, and people who use manually operated or power-driven mobility devices, such as wheelchairs and scooters. Compared to passenger vehicles, crash protection of VRUs is minimal, and often nonexistent. VRUs are harder to see on the road because they are much smaller objects compared to passenger vehicles, and can easily be occluded. It is also more difficult to predict VRUs' movements due to a higher level of uncertainty. CP could significantly increase road vehicles' awareness of VRUs; thus, improving VRU safety.

Scenario 1: Basic Road Segment

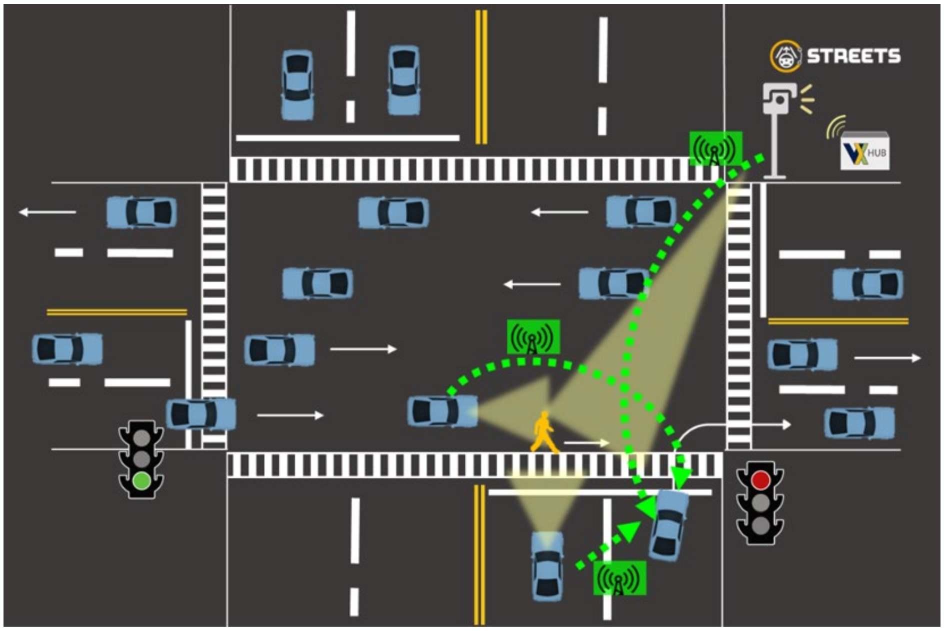
When VRUs share the right-of-way with automobiles (e.g., in the case of motorcyclists), or are present on the side of a basic road segment, vehicles on the same side of the road should be aware of the VRUs, anticipate the VRUs' movements, and adjust their vehicle trajectories accordingly. Through CP, vehicles that would otherwise be unaware of VRUs due to a limited line of sight are now informed about VRUs. In this scenario, the CP should not be limited to vehicles in the immediate vicinity of VRUs. This is because increased awareness would also prepare vehicles that are farther away from the VRUs for any maneuvers taken by those who are immediately adjacent to the VRUs.

Scenario 2: VRU Crossing at Controlled Conflict Areas

At controlled conflict areas, such as pedestrian crossings, intersections, roundabouts, and ramps, VRUs should be given higher priority when crossing the road. When traffic volume is relatively high, or when the number of conflict points is large, VRUs could easily be missed by human drivers. Autonomous vehicles could also have limited line of sight and may be unable to detect VRUs sufficiently early.

Figure 5 shows an example of this scenario. Consider a northbound vehicle waiting to turn right on red at a signalized intersection. A human driver may pay the most attention to eastbound vehicular traffic, and may not notice a VRU moving toward the vehicle on the east-west crossing. This vehicle could be made aware of the pedestrian if the vehicle is equipped with communication capabilities. At the same time, some vehicles around the intersection must be equipped with the CP feature of C–ADS, or the RSE capable of detection and perception. In

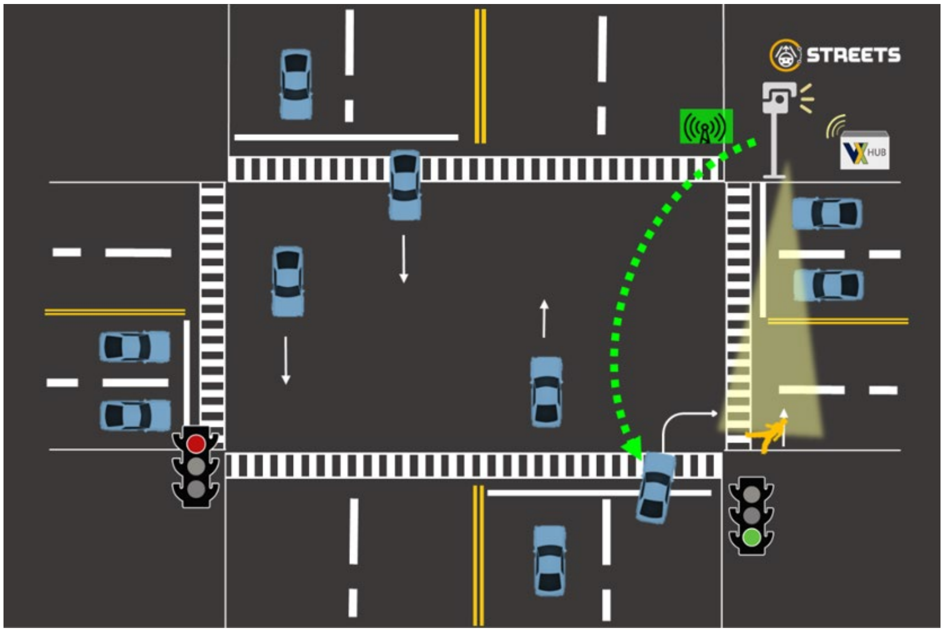
Figure 5, three entities around the intersection detect and perceive the pedestrian (represented by the triangles): one of the eastbound vehicles, the stopped northbound vehicle in the left lane of the northbound approach, and the RSE. All three entities could then share their perception with the northbound right-turn vehicle using V2V and V2I communications as indicated by the dotted arrows.



Source: FHWA.

Figure 5. Illustration. CP through V2V and V2I communications to improve situational awareness: potential conflict with VRUs during right-turn-on-red.

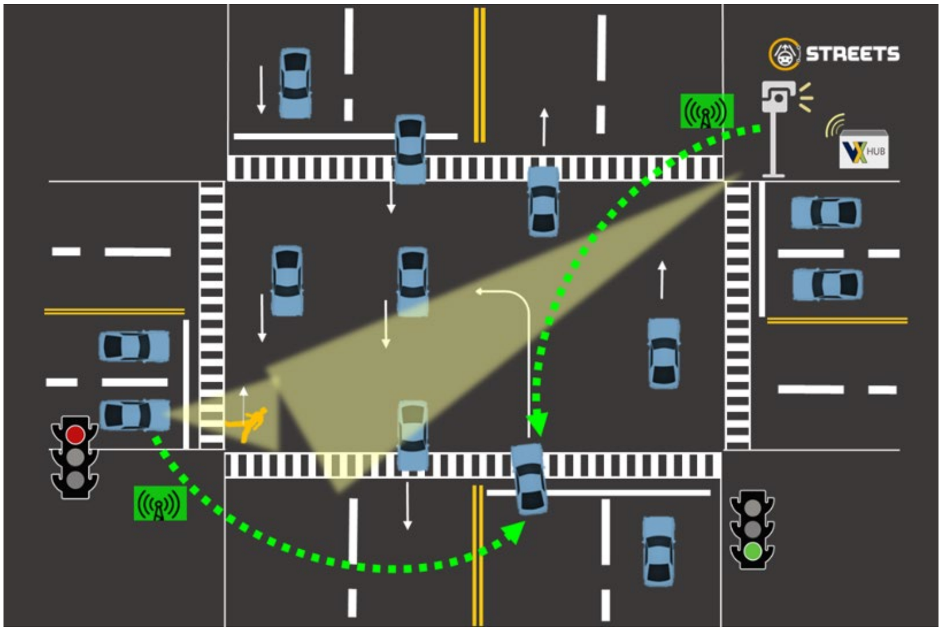
If the northbound right-turn vehicle in figure 5 is unable to find a gap during the east-west phase, and gets to turn right when the north-south traffic is given the right-of-way, the vehicle could also miss a VRU crossing the road at the north-south crossing (figure 6). CP supported by either infrastructure-based perception (as shown in figure 6) or C–ADS-equipped vehicles could enhance the situational awareness of this vehicle.



Source: FHWA.

Figure 6. Illustration. CP through V2I communications to improve situational awareness: potential conflict with VRUs during right turn.

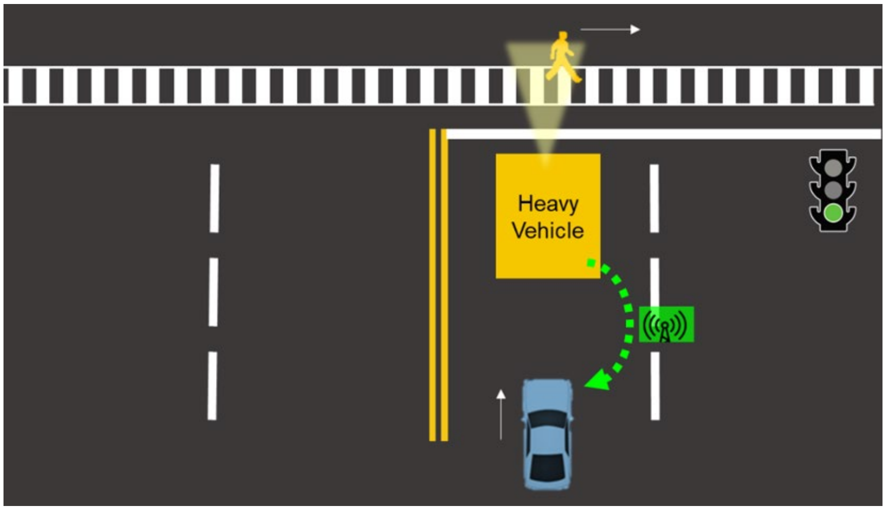
Similarly, a northbound vehicle waiting for a gap to turn left during a permitted left-turn phase may be unaware of a VRU crossing the road behind the southbound through traffic (Figure 7). In this case, the first vehicles stopped at the intersection in the westbound approach are best positioned to detect the VRUs. Infrastructure-based detection and perception systems could be useful in this scenario as well. Through CP using V2V and V2I communications, the northbound vehicle can become aware of the VRUs and, thus, significantly mitigate (or even eliminate) potential collisions.



Source: FHWA.

Figure 7. Illustration. CP through V2V and V2I communications to improve situational awareness: potential conflict with VRUs during permitted left turn.

Figure 8 shows another example of this scenario, where the line of sight of a vehicle traveling northbound (vehicle in Figure 8) approaching at a signalized intersection is blocked by a heavy (or large) vehicle and a westbound pedestrian is crossing the intersection. In this edge case, the vehicles have the right-of-way, but the pedestrian has not cleared the intersection (e.g., due to the pedestrian's slow-moving speed). The large vehicle is the first vehicle stopped at the intersection, and has a clear line of sight of the pedestrian. The vehicle remains stopped to allow the pedestrian more time to cross. The approaching vehicle, however, may be unable to detect the pedestrian due to the vehicle's obstructed front view, and could have a potential collision with the pedestrian if the vehicle tries to drive through the intersection in the adjacent lane. Through CP, the vehicle can potentially avoid this collision. If the heavy vehicle waiting at the intersection is equipped with C-ADS, it would be able to share its perception with surrounding vehicles through V2V communications.

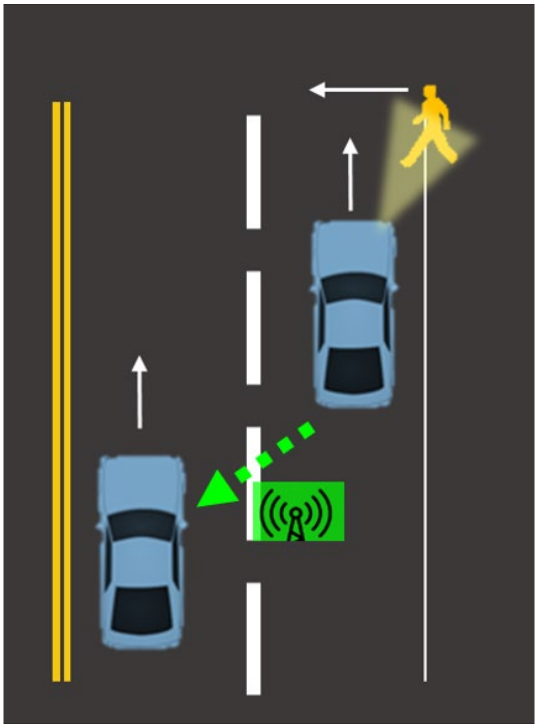


Source: FHWA.

Figure 8. Illustration. CP through V2V communications to improve situational awareness: VRUs clearing intersection outside of allocated phase.

Scenario 3: VRU Crossing at Nondesignated Areas

A dangerous scenario is when VRUs cross the road at nondesignated areas where traffic control devices are not installed. Human drivers are likely to react more slowly in this scenario due to the unexpected VRU crossing, even if they manage to spot the VRUs. While AVs' detection and reaction performances can be expected to remain at their normal levels, limited line of sight could prevent AVs from detecting the VRUs. For example, as shown in Figure 9, a vehicle in the outer-most lane may be able to detect a VRU who is crossing the road, and slow down to avoid collision. Vehicles in inner lanes behind the slowing vehicle in the outer-most lane may not have a direct line of sight of the VRU. CP will enable improved coordination among vehicles in this scenario to avoid collision with a VRU.

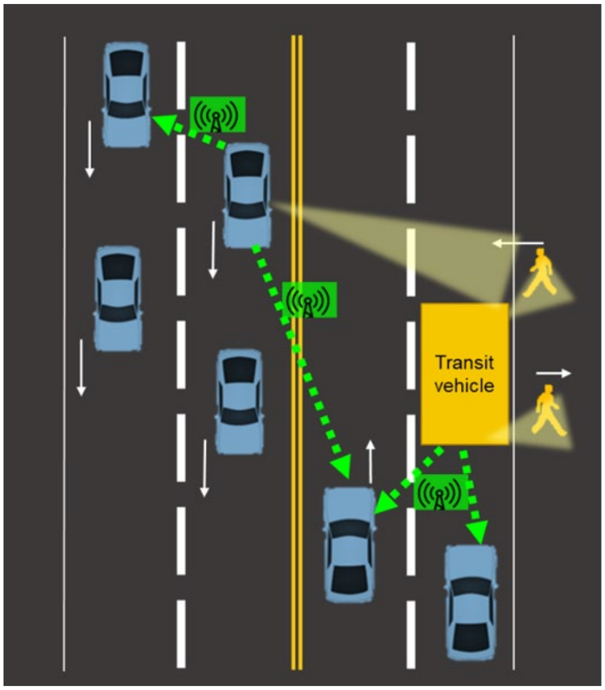


Source: FHWA.

Figure 9. Illustration. CP through V2V communications to improve situational awareness: VRUs crossing at nondesignated areas.

Scenario 4: VRU Boarding and Alighting Transit

Another scenario involving VRUs is when a surface transit vehicle (e.g., a bus) is stopped for passenger boarding and alighting, as shown in figure 10. Surface transit stops are located at a certain distance from the intersection, or even midblock. It is possible some VRUs would try to cross the road to catch the transit, or right after they have disembarked the transit vehicle. Other vehicles in the vicinity should be aware of the VRUs to avoid possible collision. CP would greatly enhance such awareness due to the relatively complex environment and the limited line of sight in the presence of larger transit vehicles.



Source: FHWA.

Figure 10. Illustration. CP through V2V communications to improve situational awareness: VRUs boarding and alighting transit.

In this scenario, the stopped transit vehicle is a good candidate to share its perception with the surrounding vehicles. Even if the transit vehicle is not equipped with exteroceptive sensors, the number of passengers getting off the transit vehicle is a piece of valuable information to share with vehicles in its vicinity. Such information could potentially be obtained through the transit vehicle's onboard internal cameras or other sensors. Vehicles with a better view of the transit stop area (e.g., from the opposite direction) may also share their perception with those behind the transit vehicle and those farther upstream in the opposite direction. Infrastructure-based service is another option to provide CP in this scenario.

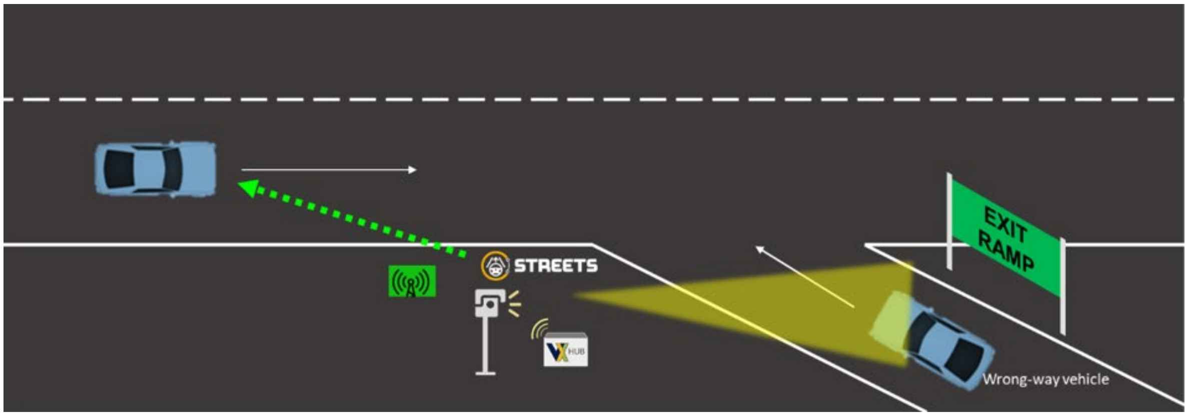
APPLICATION 2: COLLISION AVOIDANCE

Scenario 5: Car-Following Scenarios

In car-following scenarios, collision avoidance refers to the ADS feature where vehicles take action (e.g., braking) automatically when an imminent collision is perceived. There is consensus that forward collision avoidance (e.g., emergency braking systems) should be a standard feature on all new vehicles. With CP, the situation that first triggers forward collision avoidance could be communicated upstream to relevant following vehicles to avoid possible secondary critical situations. It might also be possible to extend forward collision avoidance to rear-end collision avoidance through CP. Currently, the exteroceptive sensors of a CAV largely focus on the view ahead of the vehicle. Through CP, a CAV would be able to register a vehicle fast approaching from behind (if the approaching vehicle is not equipped with forward collision avoidance), and take possible actions to avoid or mitigate the potential rear-end collision.

Scenario 6: Wrong-Way Driving

Wrong-way driving can lead to one of the most severe traffic incident scenarios. Figure 11 illustrates a wrong-way driving scenario where a vehicle enters a highway from a right-way off-ramp.



Source: FHWA.

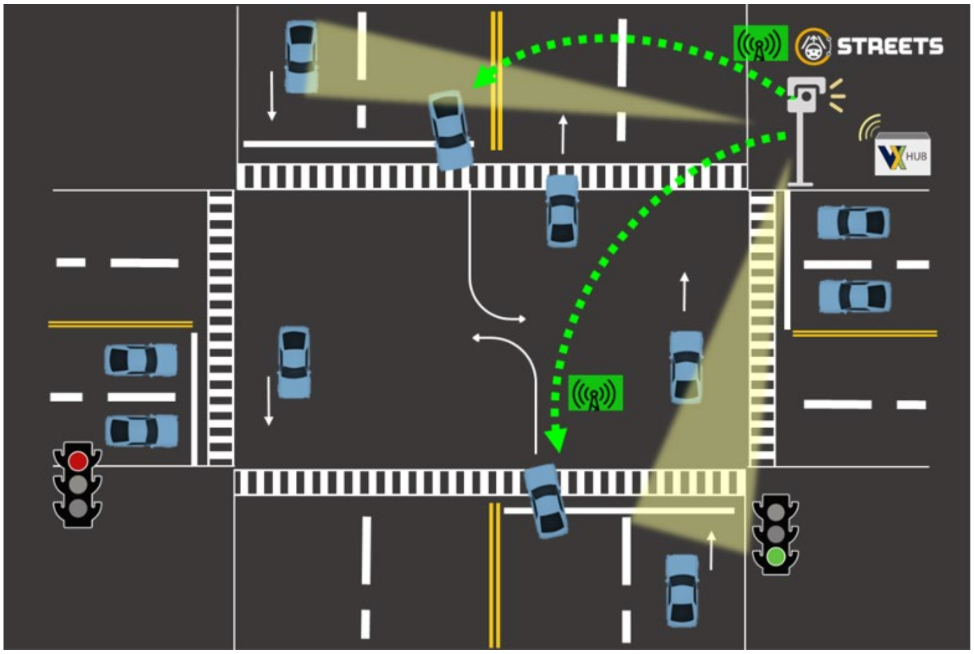
Figure 11. Illustration. CP through V2I communications to avoid wrong-way driving collision.

Current solutions to detect such wrong-way vehicles include in-pavement sensors and roadside cameras (often infrared cameras because a large percentage of wrong-way driving occurs at night). Such existing detection systems are typically connected to a TSMO center, which then broadcasts a wrong-way driver warning through established communication channels such as radio, dynamic message signs, and the internet. If right-way vehicles in the impact area are equipped with the cooperative driving feature of C-ADS, the perceived wrong-way driving event could be directly communicated to those right-way vehicles through V2I communications. The C-ADS-equipped vehicles could also automatically take preventative maneuvers (e.g., pull over), if necessary.

APPLICATION 3: CONFLICT AVOIDANCE AND COOPERATIVE DRIVING

Scenario 7: Intersections

Intersections consist of a large number of conflict points across various movements. Stop-controlled intersections fully eliminate conflicts at the cost of traffic efficiency. At signalized intersections, conflicts often exist between turning movements and associated conflicting traffic. For example, permitted left-turn movement conflicts with opposing through movement, and right-turn-on-red conflicts with the through movement heading to the same departure leg. Such turning movements are often subject to limited line of sight. Figure 12 shows that northbound and southbound left-turn vehicles during a permitted left-turn phase may block each other’s views of the opposing through vehicles. In this situation, the permitted left turns could be made safer if the turning vehicles are provided with traffic information. Figure 12 demonstrates an example where an RSE detects northbound and southbound through vehicles and communicates this perceived information to the turning vehicles.



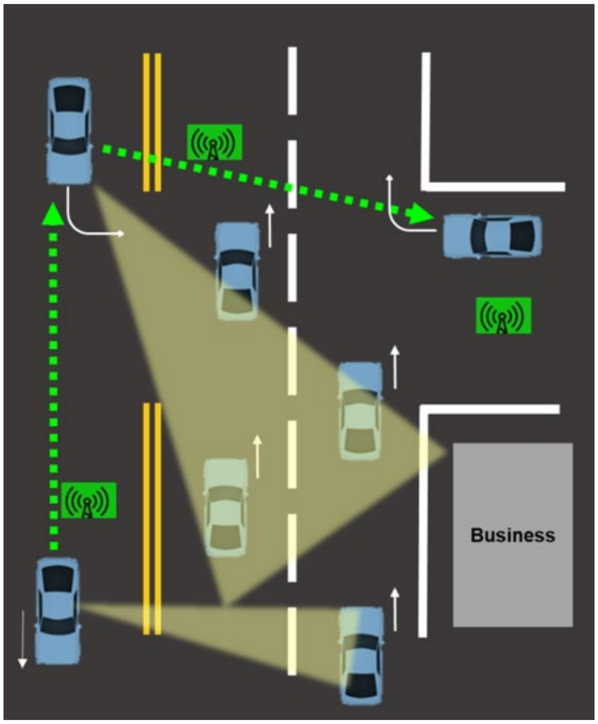
Source: FHWA.

Figure 12. Illustration. CP through V2V and V2I communications at controlled intersections for enhanced situational awareness and cooperative driving for conflicting movements.

In addition to enhanced situational awareness for the subject vehicle, CP could also enable mobility improvement at intersections. Using figure 12 as an example, if some other vehicles around the intersection are equipped with C–ADS, cooperative driving of Class B and higher could also benefit from CP. In applications where vehicles negotiate trajectories by themselves, enhanced perception performance of these vehicles could lead to safer and more efficient trajectories. When RSE prescribes trajectories for participating CAVs, relevant algorithms could further optimize the trajectories based on a more comprehensive picture of the driving environment, including status of the vehicles that are not connected, made possible by CP created collectively by C–ADS-equipped vehicles (and possibly also the RSE).

Scenario 8: Around Business Access Areas

Midblock business access areas (e.g., driveways) represent a relatively complex environment for vehicles heading into or out of the business establishments (figure 13). For vehicles turning left into a business driveway, potential conflicts with oncoming traffic may be mitigated with CP, especially for wide roads with multiple lanes in one direction. For a vehicle leaving the driveway, CP could assist the vehicle make a safer turn, either to the left or right. Additionally, CP could enable cooperative driving around the access area to improve overall mobility.

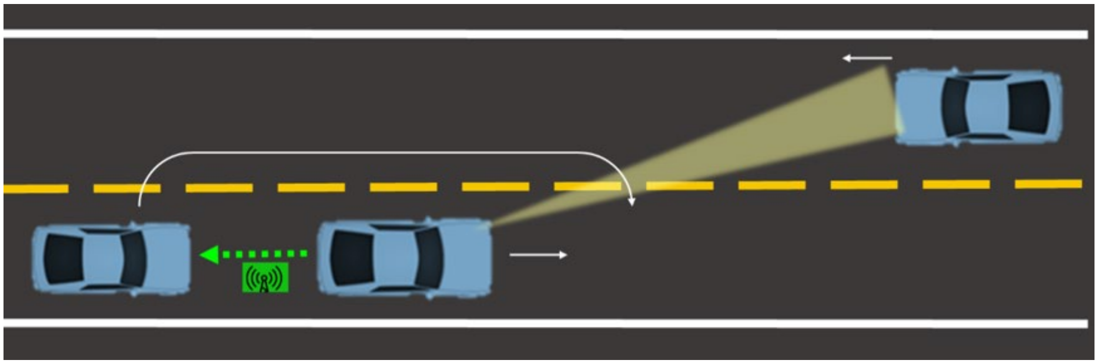


Source: FHWA.

Figure 13. Illustration. CP through V2V communications for enhanced situational awareness and cooperative driving of conflicting movements at midblock access areas.

Scenario 9: Overtaking on Two-Lane, Two-Way Roads

Overtaking maneuvers on two-lane, two-way roads require vehicles to use the lane in the opposite direction during the course of the action. Such maneuvers are subject to relatively high risk. The maneuvers require the overtaking vehicles to accurately estimate the amount of time they need to drive in the opposite direction, the distance to any oncoming vehicle in the opposition direction, and the time to possible collision when there is a potential conflict. In the overtaking scenario on two-lane, two-way roads, a vehicle should be aware of the number of vehicles ahead in its travel direction and the spacing and travel speeds of those vehicles, and the same set of information about oncoming traffic. The line of sight of an overtaking vehicle is typically obstructed by its immediate downstream vehicles. CP, together with V2V communication, could help facilitate a safe overtaking maneuver. As shown in figure 14, the first eastbound vehicle, if equipped with C-ADS, could share its perception of the westbound traffic through V2V communications with following vehicles that may attempt overtaking.



Source: FHWA.

Figure 14. Illustration. CP through V2V communications for enhanced situational awareness and cooperative driving during overtaking on two-lane, two-way roads.

Scenario 10: Lane-Changing Scenarios

In lane-changing scenarios, existing technologies (e.g., lane-change warning and blind-zone alerts) have largely addressed the safety concern caused by blind zones. CP could provide redundancy to existing blind-zone warning technologies. Additionally, CP could make vehicles further upstream aware of the lane-changing event. This could be especially valuable if the lane-changing vehicle is not connected and the lane change is abrupt and could disturb traffic. If vehicles with line of sight of the lane-changing event are equipped with C-ADS, they could share their perception data with other C-ADS-equipped vehicles farther upstream of the lane-changing event. Those vehicles could adjust their trajectories accordingly and preemptively to minimize jerky movements that could degrade both riding comfort and traffic stability.

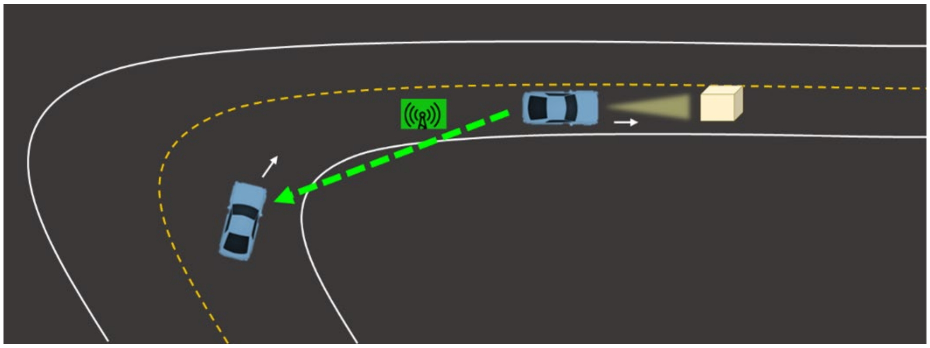
APPLICATION 4: GENERAL ENHANCEMENT OF SITUATIONAL AWARENESS

Scenario 11: Behind Large Vehicles

When a vehicle is traveling behind a large vehicle (e.g., transit vehicle or truck), its line of sight is significantly more obstructed than when following a passenger vehicle. Such obstruction could affect a vehicle's lane-changing maneuvers. Additionally, limited awareness of the downstream traffic condition could hinder the vehicle's ability to anticipate and react to other road users' maneuvers. Around intersections, limited awareness of downstream traffic could lead to a vehicle entering but unable to clear the intersection during the allocated green time and, thus, blocking traffic. CP, together with V2V and V2I communications, could improve the safety and mobility in such scenarios. Infrastructure-based perception could be a possible solution near intersections as well.

Scenario 12: Roadway Geometry Obstructing Line of Sight

A vehicle's line of sight could be limited due to roadway geometry, particularly horizontal and vertical curves. While the roadway geometric design guidelines ensure sufficient stopping sight distance for nominal conditions, limited line of sight could lead to potential critical situations in edge cases. Examples of edge cases include vehicles traveling above speed limit, adverse surface conditions, and unexpected objects in the middle of the road. As shown in figure 15, CP could extend the perception range of equipped vehicles, allow the vehicle to take proactive measures to avoid potential conflicts, and enable more effective path planning with less uncertainty.



Source: FHWA.

Figure 15. Illustration. CP through V2V communications to improve situational awareness: roadway geometry obstructing the line of sight.

Scenario 13: Adverse Weather Limiting Line of Sight

Adverse weather such as fog, snow, and rain negatively impact visibility, and thus a vehicle's situational awareness and safety performance. Vehicles equipped with CP technologies could both send and receive perception data, including the position and speed of surrounding vehicles, speed, and road condition data through V2V and V2I communications. Although the perceptions of all entities are limited by adverse weather, CP created collectively by multiple entities would still enhance the perception of each individual vehicle. The vehicles can then further communicate this perception of the traffic and roadway environment to upstream vehicles, which could improve arriving vehicles' situational awareness of the driving environment.

Scenario 14: Work Zone Posing Uncertainty to Driving Environment

Work zones represent a departure from normal driving, and can be difficult to navigate safely. Work zones might consist of a closed lane segment, overlaid scheduled lanes (for signaling reversal of travel direction), and stop lines at the approaches. The reduced capacity of work zones can lead to large queues of slow or stopped vehicles. Drivers approaching the queues are at increased risk of rear-end collisions. Changing traffic patterns beginning within the transition area can sometimes result in risky or aggressive behaviors as drivers try to negotiate right-of-way. Moreover, because work zones are temporary environments, the exact configuration of the environment often changes over time as initial work is completed and new work begins. The variable nature of work zones put them outside of the operating domain of lower-level automated systems. Through CP, vehicles farther upstream with limited line of sight of the work zone can potentially benefit from updated information of the upcoming work zone environment. This may be especially valuable in active work zones involving workers and moving equipment.

Table 5 provides a summary of CP operational scenarios.

Table 5. Summary of CP operational scenarios.

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 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 take action (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.
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 impacts 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 5. ANALYSIS OF THE PROPOSED SYSTEM

This chapter provides an analysis of the benefits, impacts, and limitations of CARMA CP. A high-level system validation plan is also discussed for this particular scenario.

SUMMARY OF POTENTIAL BENEFITS AND OPPORTUNITIES

CDA technologies enable mobility applications that are not achievable by individual ADS-operated vehicles. They do so by sharing information that can be used to increase the safety, efficiency, and reliability of the transportation system. 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 safety, mobility, situational awareness, and operations.

This ConOps has examined the idea of incorporating CP into the CARMA Ecosystem. The CP feature can be integrated in all four products in the CARMA Ecosystem (i.e., CARMA Platform, CARMA Messenger, CARMA Streets, and CARMA Cloud). CAVs operated on CARMA Platform are expected to have advanced sensing and perception systems, and can initiate the sharing of CP information. Such vehicles can also use CP data received from other road users to improve their own perception of the driving environment, which could lead to safer and smoother trajectories. Road users who are equipped only with CARMA Messenger may or may not generate original CP information (depending on their sensing and perception capabilities), but will be able to relay CP information they have received. 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. If an RSE equipped with CARMA Streets is able to access existing or newly installed infrastructure-based sensors (e.g., cameras and LiDAR), the RSE could generate original CP information and supply to connected road entities. CARMA Cloud could be a hub where all CP information is consolidated into a global map of road objects.

EXPECTED IMPACTS

The proposed CARMA CP feature can have an impact on research and operations of future C-ADS.

Research is still needed on several aspects of CP, especially in communication protocols, CS, and effective application of CP. Various strategies designed to balance the improved perception performance and the increased communication burden caused by CP need to be validated. New strategies may be needed, depending on the application. CS is of significant importance for CP to function properly in practice. Research in this area is relatively scarce and the gap needs to be bridged. The benefits of CP can only be achieved by well-designed applications that effectively use CP information. These applications could include enhanced path and trajectory planning algorithms, new CDA algorithms, and applications geared toward human users.

From an operations perspective, the proposed CP feature presents changes to existing ADS and CDA applications. ITS infrastructure would need to be upgraded to enable CP. For example, advanced communication infrastructure needs to be in place to handle the increased communication load. The CP feature for a local transportation network (e.g., an intersection) may require RSE that includes one or multiple RSEs, an edge processor, and probably roadside sensors (e.g., cameras and LiDAR). The conventional process of transportation system performance monitoring and reporting could be revolutionized with the prevalence of vehicles equipped with C–ADS and advanced sensors. Conventional strategies for transportation safety and TSMO that agencies are already familiar with may be enhanced by CP and other CDA technologies.

POSSIBLE LIMITATIONS AND DISADVANTAGES

While the proposed CP feature in the CARMA Ecosystem has the potential to improve safety and mobility of transportation systems, it might face limitations that could be further investigated. This section uses Application 1: Interacting with VRUs to discuss possible limitations and disadvantages of the proposed CARMA CP feature.

The timeliness and accuracy of CP information are key to CDA applications built on CP data, especially in safety-critical applications. The latency of VRU detection and perception, as well as the communication latency, must be sufficiently small in order to mitigate or eliminate possible conflicts. Real-time safety-critical applications of CP raise a high bar for the capabilities and performances of computation and communication infrastructure, algorithms, and protocols. Erroneous CP data of a VRU who is out of sight of an approaching vehicle that receives the information may cause the vehicle (and/or its human driver) to reduce trust in future CP data it receives. Worse, erroneous CP data could lead to possible collision involving the VRU.

CS issues left unaddressed could result in severe system loopholes that could be exploited. CP poses additional CS issues compared to general V2X communications. This is because falsified CP content is more difficult to identify (especially when the sender is out of sight of the receiving entity). CS attacks of CDA could lead to severe traffic congestion or deadly traffic incidents.

The effective use of CP information, especially in scenarios that involve human drivers, could be the bottleneck of reaping CP benefits. Even with fully autonomous vehicles, if the corresponding actions taken based on CP are too abrupt (e.g., hard deceleration) or extreme (e.g., complete stop in front of a pedestrian crossing the street at an undesignated location), it could cause ripple effects and lead to induced incidents or unstable traffic flow.

SYSTEM VALIDATION PLAN

This section describes potential methods to validate the developed algorithms and software systems for the CARMA CP feature. The purpose of validation testing is to ensure the developed software can meet the operational needs listed in table 5, or a subset of the operational needs depending on the application and operational scenario.

Using Scenario 4: VRU boarding and alighting transit as an example, this section describes the corresponding validation testing. In scenario 4, two types of road users are considered to have

CP capabilities: transit vehicles and passenger vehicles equipped with CARMA Platform. Road users with CP capabilities are designed to send perception information about VRUs boarding and alighting the transit bus to approaching vehicles equipped with CARMA Platform or CARMA Messenger that do not have direct line of sight.

Simulation Testing

Simulations can be designed to test the developed algorithm CP. The testing platform should include computers running CARMA Platform with CP and software to simulate actual V2X communications. Artificial data feeds can be sent to the computers emulating the vehicles equipped with CARMA Platform with CP. Such data feeds could include images, video streams, or LiDAR point clouds that include pedestrians. The computer emulators should be able to identify the pedestrians and produced object-based perception information. The transmission of the perception data could then be simulated using computer networking simulators.

Before evaluating the developed CP algorithms using any performance metrics, the functionality of the feature should be verified first. In other words, it should be verified that CP data are generated and transmitted to other vehicles in the surrounding area. To evaluate the performance of the developed CP feature, latency (both computation and communication) and accuracy of the CP data should be analyzed. Safety performance metrics identified in chapter 3 can be used to further estimate the benefits of CP in this scenario.

Field Testing

To ensure the developed algorithms can be reliably and easily implemented into CARMA Platform, a set of proof-of-concept tests can be conducted on a closed test track. This can be demonstrated onsite with a larger vehicle acting as a stopped transit vehicle. This vehicle should be equipped with necessary sensors, a vehicle personal computer loaded with CARMA Platform and the prototype CP software, and communication capabilities. Since the transit vehicle in this scenario is stopped, the testing criteria for this vehicle focuses on ODP, together with CP message generation and dissemination tasks. Multiple passenger vehicles equipped with CARMA Platform loaded with necessary feature groups can be instructed to approach the stopped shuttle bus (see figure 10). The purpose of the testing is to verify the software, collect vehicle behavior performance measures with existing path and trajectory planning algorithms, and validate that software meets the operational needs and functional requirements described in table 5. Communication metrics will be computed from field data. Vehicle motion data collected from the test track can be used not only to calculate vehicle behavior performance metrics, but also to estimate safety metrics, and possibly to infer traffic stability performance. This will provide insight into how path and trajectory planning algorithms can be further improved to use the CP information more effectively.

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