Enhancing Vulnerable Road User Safety at Signalized Intersections Through Cooperative Perception and Driving Automation: Final Report

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Highway Research Center

FOREWORD

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

This project expands the CARMA Ecosystem by developing a cooperative perception (CP) functionality for detecting vulnerable road users to improve safety and mobility at signalized intersections. This report documents detailed information about the proposed CP algorithm, as well as the procedures and results of its testing. The intended audience for this report is CDA stakeholders, such as system developers, analysts, researchers, application developers, and infrastructure owners and operators.

John Harding, Director
Office of Safety and Operations
Research and Development

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16. Abstract
Walking and biking are increasingly popular modes of travel and exercise in urban and suburban areas and are promoted by initiatives from the U.S. Department of Transportation and other U.S. Government agencies, such as Complete Streets, to reduce congestion and emissions and foster a healthy lifestyle. However, despite a decline in overall transportation-related fatalities due to various safety strategies, the fatality rate for vulnerable road users (VRUs) continues to rise, highlighting the critical need to enhance VRU safety at urban signalized intersections. Emerging technologies in transportation, such as cooperative driving automation and cooperative perception (CP), present promising opportunities to improve VRU safety at intersections. This project capitalizes on these technologies by developing a CP VRU safety application to be applied at signalized intersections where information about the infrastructure detected VRUs is sent out to vehicles within communication range to increase their situational awareness and to ensure safety. This system focuses on data fusion (DF) and communication capabilities for both infrastructure and vehicles. By leveraging CP and DF from infrastructure and cooperative automated driving systems-equipped vehicles, the safety of all road users within the communication range is enhanced. This CP VRU safety application, evaluated in a simulation environment, demonstrated significant safety improvements for VRUs at signalized intersections. For the selected test scenarios, the application could prevent 98 percent of VRU crashes compared to the base scenario where no CP VRU safety application was used.

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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

AAA	American Automobile Association
AASHTO	American Association of State Highway and Transportation Officials
ADS	automated driving systems
API	application programming interface
AV	automated vehicle
BSM	basic safety message
C-ADS	cooperative automated driving systems
CDA	cooperative driving automation
COMM	communications (category)
CP	cooperative perception
CPA	cooperative perception application
CS	computer security
CV	constant velocity
DF	data fusion
FHWA	Federal Highway Administration
GNN	global nearest neighbor
HRSO	Office of Safety and Operations Research and Development
ID	identification
IEEE	Institute of Electrical and Electronics Engineers
ITE	Institute of Transportation Engineers
ITS	intelligent transportation systems
LiDAR	light detection and ranging
MOT	multiple object tracking
NCV	nonconnected vehicle
NEMA	National Electrical Manufacturers Association
NHTSA	National Highway Traffic Safety Administration
NIST	National Institute of Standards and Technology
NTCIP	National Transportation Communications for ITS Protocol
ODP	object detection and perception
OSS	open-source software
RC	radio communication
ROS	Robot Operating System
SAE	SAE International®
SDSM	sensor data sharing message
SIM	simulation (category)
SPaT	signal phase and timing
SUMO™	Simulation of Urban Mobility
TC	trajectory control
TMC	traffic management center
TSC	traffic signal controller
TTC	time to collision
UDP	user datagram protocol
USDOT	U.S. Department of Transportation
VRU	vulnerable road user

V2V	vehicle-to-vehicle
V2X	vehicle-to-everything
XiL	everything-in-the-loop
XML	Extensible Markup Language

EXECUTIVE SUMMARY

Traffic incidents at signalized intersections involving vulnerable road users (VRUs), such as pedestrians and cyclists, account for a disproportionate share of fatalities and serious injuries. The National Highway Traffic Safety Administration reports that these locations account for roughly 20 percent of pedestrian fatalities, 33 percent of bicyclist fatalities, 45 percent of pedestrian injuries, and 56 percent of bicyclist injuries (Brookshire et al. 2016). These findings highlight the need for innovative solutions to enhance safety at these critical junctures. This summary provides an overview of key findings from the Federal Highway Administration's (FHWA) report, *Enhancing Vulnerable Road User Safety at Signalized Intersections Through Cooperative Perception and Driving Automation*: *Final Report*. This study explores the potential of cooperative perception (CP) technology, which leverages communication between infrastructure (e.g., cameras installed on signal poles) and vehicles, to create a more comprehensive understanding of the traffic environment and to enable timely warnings and interventions to prevent crashes.

USE CASE AND SCENARIO OVERVIEW

The study focuses on improving safety at signalized intersections by detecting VRUs using CP technology and sharing this data with cooperative automated driving system (C-ADS)-equipped vehicles. In the test scenarios, infrastructure sensors detected VRUs and broadcasted this information to a vehicle through sensor data sharing messages (SDSMs). The goal was to enable the C-ADS-equipped vehicle to adjust its trajectories in realtime to avoid collisions, even when VRUs were occluded from the vehicle's line of sight.

Testing was conducted in CDASim, a simulated environment designed to enable the safe testing of Cooperative Driving Automation (CDA) technologies, including CP. Four different situations were tested, where the vehicle either turned left or drove straight through the intersection, with or without CP. The infrastructure's ability to detect occluded VRUs, and the vehicle's response to these warnings, was critical in assessing CP's effectiveness.

KEY RESULTS AND FINDINGS

The most significant outcome of this study was the ability of CP technology to prevent crashes in 98 percent of the test runs. That is, the research team broke down each of the four previously mentioned situations (straight through with CP, straight through without CP, left turn with CP, left turn without CP) into eight specific scenarios by changing different variables, such as vehicle speed and VRU speed, yielding a total of 32 different scenarios (16 with CP and 16 without CP). Each of these scenarios was repeated three times, to account for variability embedded in the simulation software, yielding a total of 48 test runs with CP and 48 test runs without CP. The no-CP scenarios resulted in a crash every single time (48 out of 48 runs). With CP turned on, only one crash occurred out of 48 test runs, resulting in a crash rate of approximately 2 percent and a crash avoidance rate of 98 percent.

This outcome clearly demonstrates the potential of CP to significantly improve safety by detecting VRUs and enabling vehicles to respond proactively. It is important to emphasize, however, that these results are specific to the scenarios tested under controlled conditions in

CDASim and should not be generalized to all traffic situations or environments without further validation.

POTENTIAL FOR VISION ZERO

These results suggest that CP technology could play a crucial role in advancing the U.S. Department of Transportation's goal of Vision Zero, which is to eliminate traffic fatalities and serious injuries (Vision Zero Network 2024). CP improves situational awareness by fusing data from infrastructure and vehicles, enabling timely interventions. The exact extent of CP's contribution toward Vision Zero still requires more research as real-world applications may present more complex challenges than what was tested in this study.

SOFTWARE ECOSYSTEM AND DEVELOPMENT

FHWA's CARMA Ecosystem℠ was a pivotal tool in this study (FHWA 2022b). As an open-source platform, CARMA℠ enables the development and testing of CDA applications. CARMA can operate in both physical systems and simulated systems. In this study, CARMA was used in simulation within the CDASim environment.

CARMA supported the exchange of critical data between vehicles and traffic signals to enhance VRU safety. By making CARMA open source, FHWA encourages the wider adoption of CP technology within the research community, fostering collaboration and accelerating progress toward safer roadways.

KEY ASSUMPTIONS AND LIMITATIONS

The simulations were conducted in CDASim under ideal conditions with perfect communication environments (i.e., no latency or packet loss) and optimal weather and road conditions. The results were highly promising, but real-world challenges such as weather variability, communication disruptions, and complex traffic environments still need to be addressed. Because of these assumptions and limitations, results should not be generalized without further validation.

FUTURE WORK AND RECOMMENDATIONS

While the study demonstrates the significant potential of CP to improve intersection safety, additional research and real-world testing are necessary. Future work should focus on the following:

- Expanding tests to real-world environments with diverse road types, weather conditions, and traffic patterns.
- Refining CP algorithms further to improve their robustness and accuracy.
- Exploring strategies for integrating CP technology into existing infrastructure to facilitate widespread adoption.

CONCLUSION

CP technology shows great potential for enhancing the safety of VRUs at intersections. However, CP should not be viewed as a standalone solution; it must be integrated into a broader strategy that includes infrastructure improvements, public education, and enforcement efforts. This study underscores the importance of continued research and investment in CP technology as part of a comprehensive approach to achieving Vision Zero and eliminating traffic-related fatalities and injuries.

CHAPTER 1. INTRODUCTION

BACKGROUND

Walking and biking are two common modes of travel and exercise in urban and suburban areas. Initiatives such as Complete Streets are enhancing and expanding transportation facilities for pedestrians and bicyclists (Federal Highway Administration (FHWA) n.d.a.). These initiatives are expected to increase the number of people opting to walk or bike instead of driving an automobile as their primary method of commuting. This shift is beneficial for reducing congestion and promoting the health and wellness of the U.S. population.

To support the increasing needs of these modes of transportation, the safety of vulnerable road users (VRUs), which includes pedestrians, bicyclists, and motorcyclists, needs to be enhanced. According to traffic safety facts from the National Highway Traffic Safety Administration (NHTSA), a 1.7-percent decrease in the fatality rate occurred from 2021 to 2022 (NHTSA 2024). However, pedestrian and motorcyclist fatalities increased by 0.7 and 1.2 percent, respectively (NHTSA 2024). Additionally, another NHTSA study, *Advancing Pedestrian and Bicyclist Safety: A Primer for Highway Safety Professionals*, identified conflicts at intersections and other crossing locations as major factors contributing to crashes in the United States (Brookshire et al. 2016). Approximately 20 percent of pedestrian and 33 percent of bicyclist fatalities, as well as an estimated 45 percent of pedestrian and 56 percent of bicyclist injuries, are due to intersection collisions. These numbers may be higher in urban areas due to increased crossing activities (Brookshire et al. 2016). Therefore, enhancing VRU safety at urban signalized intersections is critical.

Emerging transportation technologies, such as cooperative driving automation (CDA) and cooperative perception (CP), offer excellent opportunities to increase VRU safety at signalized intersections. To that end, FHWA's Office of Safety and Operations Research and Development (HRSO) has been building the CARMA Ecosystem℠, an open-source software (OSS) ecosystem used for CDA research (FHWA 2022b). The CARMA Ecosystem consists of four main systems: namely CARMA Platform℠, CARMA Cloud℠, CARMA Messenger℠, and CARMA Streets℠ (FHWA 2022a). Each of these four systems serves as a sandbox on top of which researchers may host their own CDA applications, such as the following:

- CARMA Platform is the OSS that can be installed on a vehicle (assuming proper hardware is available) to enable it to be a research cooperative automated driving system (C-ADS)-equipped vehicle. This software allows researchers to host and test their own custom-built C-ADS applications and use cases (FHWA 2022a).

- CARMA Cloud is the OSS that sits in the "cloud" (i.e., a remote server) to enable communication with vehicles. This software allows researchers to host and test their own custom-built applications that pertain to the network (or the traffic management center (TMC)) communicating with vehicles. For example, TMC implements a new speed limit due to bad weather, or vehicles request and receive information about modified lane configurations due to work zones (FHWA 2022a).

- CARMA Messenger is the OSS that can be installed on a vehicle to enable it to become connected (but fully human driven). This software allows researchers to host and test their own custom-built applications that enable human drivers to communicate with other vehicles, the infrastructure, and the cloud. Historically, this OSS has been used to support research for first responders. For example, a police vehicle pulled over on the side of the road communicates its presence and implements a geofence around it to close off a lane to ensure safety (FHWA 2022a).

- CARMA Streets is the OSS that can be installed on the infrastructure (i.e., the edge) to allow local infrastructure to communicate with vehicles and the cloud. This software allows researchers to host and test their own custom-built applications that pertain to local infrastructure sending and receiving messages from vehicles. Historically, this OSS has been used to support CP and communication and optimization with the traffic signal controller (TSC) (FHWA 2022a).

Although not required, generally, when researchers build and test their applications, the applications will reside in multiple complementary systems, as described in the preceding list. For example, an application that optimizes movement at a signalized intersection may have a component hosted on CARMA Streets to optimize the signal phase and timing (SPaT) plan and a second component hosted on CARMA Platform to enable the C-ADS-equipped vehicle to optimize the trajectory driving through the intersection based on the received optimized SPaT plan (FHWA 2022a).

In addition to these core CARMA℠ software systems, an everything-in-the-loop (XiL) simulation tool named CDASim is being developed to provide a low-cost and efficient approach for developing and testing CDA technology (FHWA 2023). Currently, CDASim integrates critical components of the CARMA Ecosystem (CARMA Platform, CARMA Streets, and CARMA Cloud), an open-source traffic simulator (Eclipse® Simulation of Urban Mobility (SUMO™)), an open-source vehicle driving simulator (CARLA®), and a communications simulator (ns-3) into a single platform (FHWA 2022b, 2023; Eclipse Foundation n.d.; CARLA Team 2024; nsnam 2024).

The CARMA Ecosystem and CDASim can be used to support CP research, which can support CDA technology, to improve transportation safety and mobility (FHWA 2022a, 2023). Equipped with sensors such as light detection and ranging (LiDAR), radar, and cameras, different entities (e.g., vehicles and infrastructure) can detect objects and share key safety and mobility information via vehicle-to-everything (V2X) communication. This feature enables entities to overcome sensor limitations like blind spots and limited detection ranges.

OBJECTIVE

This project aims to leverage CDA and CP technologies to enhance VRU safety at signalized intersections by using both infrastructure and vehicle sensors. Specifically, this project develops an application, called the CP VRU safety application, that enables data fusion (DF) and communication capabilities for both infrastructure and vehicles to support VRU perception at intersections. By facilitating CP, DF from infrastructure and C-ADS-equipped vehicles can improve the safety of all road users within the communication range.

AUDIENCE

The intended audience for this report includes:

- Federal, State, and local transportation agencies' CDA transportation stakeholders.
- Academia stakeholders, including universities and research institutions.
- 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 report.
- Analysts, researchers, and CDA application developers.

DOCUMENT STRUCTURE

The structure of this document is described as follows:

- Chapter 1 introduces the background and objective of this study.
- Chapter 2 describes the history of VRU safety and CP.
- Chapter 3 details the development of the CP VRU safety application.
- Chapter 4 presents the testing and evaluation process for the proposed CP VRU safety application.
- Chapter 5 summarizes this report and offers recommendations for future research.

CHAPTER 2. A BRIEF HISTORY OF VRU SAFETY AND CP RESEARCH IN TRANSPORTATION SYSTEMS

HISTORY OF VRU SAFETY IN TRANSPORTATION SYSTEMS

The safety of VRUs has evolved significantly over the past century as traffic systems have become more complex and urbanization has intensified. Initially, traffic safety measures were predominantly designed with motorists in mind. However, as traffic incidents involving VRUs have increased, dedicated efforts to enhance their safety emerged.

With the rise of automobiles in the early 1900s, urban areas started experiencing traffic-related injuries and fatalities among pedestrians and cyclists. By the 1920s, urban areas experienced a surge in traffic-related injuries and fatalities among pedestrians and cyclists. By 1923, more than 17,000 VRUs were being killed by cars each year, a significant 47-percent increase from 12,000 deaths in 1920 (Johnson 2013). The increasing number of pedestrian fatalities led to some of the first organized efforts to improve safety. For example, cities began passing laws establishing that pedestrians have the right-of-way under certain circumstances. When these measures proved insufficient, physical interventions such as barriers were implemented to prevent pedestrians from crossing in unsafe locations. The first pedestrian crosswalk signal was installed and tested on Fifth Avenue between 40th and 45th Streets in New York City between 1918 and 1926 (Weingroff 2017). The first crossing guard in the United States was implemented in Omaha, NE, in 1923 (RoadTrafficSigns 2024).

In the 1950s and 1960s, both governmental and nongovernmental organizations became actively involved in advocating for VRU safety measures through various activities and programs. The American Automobile Association (AAA) made significant contributions by publishing *Pedestrian Protection* in 1939, *Planned Pedestrian Program* in 1958, and *Manual on Pedestrian Safety* in 1964 (AAA 1939, 1958, 1964). Additionally, AAA sponsored school safety programs for children as well as other community safety initiatives. In April 1969, the NHTSA National Highway Safety Bureau released "Pedestrian and Bicycle Safety," volume 14 in its series of highway safety program manuals (NHTSA 1969). In 1964, the National Safety Council in the United States launched the country's first defensive driving course, in part to teach drivers how to better anticipate and avoid conflicts with VRUs and other vehicles (National Safety Council 2024).

The 1970s marked a pivotal shift toward a greater emphasis on designing urban infrastructure with the safety of VRUs, such as pedestrians and cyclists, as a priority. This trend reversed the previous approach of prioritizing motor vehicle traffic flow in urban areas at the expense of VRU safety and accessibility. As the fact became evident that the street networks of old towns and city centers could not sustainably accommodate indefinite increases in traffic, countries like France and the Netherlands implemented comprehensive traffic plans. These plans aimed to optimize the use of existing street space by reducing private car traffic in city centers and increasing dedicated facilities for pedestrians and cyclists. The emergence of pedestrianized streets, particularly in commercial or tourist areas, was an early manifestation of this shift (Organisation for Economic Co-operation and Development 1998).

During the 1970s, the situation became increasingly clear that public awareness campaigns and law enforcement efforts were not enough to induce appropriate speed behavior from motorists. Instead, safety experts focused on the physical design of the road environment to more effectively encourage lower speeds and safer driver behavior. The concept of "traffic calming"—the use of physical speed reduction measures like speed humps, chicanes, and narrowed streets—slowly gained traction to self-enforce lower vehicle speeds in urban areas, particularly in residential neighborhoods and areas with high pedestrian activity (Organisation for Economic Co-operation and Development 1998).

By the 1980s, the idea of comprehensive networks for pedestrians and cyclists began to take hold in some countries. Dedicated pedestrian footpaths were organized into continuous routes, often widened and resurfaced, while cycle tracks or lanes were implemented with varying levels of success from a safety standpoint. The integration of pedestrianized streets in city centers into larger mobility schemes aimed at reducing private car traffic and improving accessibility for all users became more widespread. The concepts of mixed traffic and traffic calming, achieved through self-enforcing speed reduction measures, extended from residential areas to the treatment of urban thoroughfares with heavy traffic. The notion that fast motorized traffic may need to yield priority to local traffic and VRUs in areas with high levels of street activity became more acceptable (Organisation for Economic Co-operation and Development 1998).

The late 1990s and early 2000s witnessed a paradigm shift in transportation safety philosophy, spearheaded by two complementary initiatives: Vision Zero and Complete Streets (Vision Zero Network 2024; FHWA n.d.a.). Originating in Sweden during the 1990s, Vision Zero adopted an ethical stance that no loss of life on roads is acceptable, catalyzing an integrated, multidisciplinary approach to proactively mitigate risk factors through vehicle design enhancements, infrastructure improvements, stringent enforcement mechanisms, and comprehensive public education campaigns (Vision Zero Network 2024).

Concurrently, the Complete Streets concept emerged as an urban planning model that challenged conventional vehicular-centric street design practices in the United States (FHWA n.d.a.). Grounded in sustainable safety principles, this concept advocated for accommodating all road users by incorporating multimodal facilities like sidewalks, bicycle lanes, accessible transit stops, and traffic calming elements into an interconnected transportation network. Both initiatives systematically contradicted the prevailing notion that casualties from traffic incidents were inevitable. Instead, they placed the onus on system designers and policymakers to prioritize VRU protection through a coordinated implementation of regulatory measures, infrastructural interventions, and behavioral modification strategies, thereby catalyzing a comprehensive reframing of how urban mobility is conceptualized and executed globally.

In recent years, the emergence of CDA technologies has introduced new opportunities to enhance VRU safety. By integrating advanced sensors, onboard systems, and V2X communication capabilities, these emerging technologies lay the foundation for improving VRU visibility, detecting potential conflicts, and actively intervening to prevent incidents (Weaver et al. 2022). For instance, pedestrian detection systems in vehicles, using cameras, radar, and other sensors, can identify nearby pedestrians and cyclists, alerting drivers through visual and auditory warnings. Some systems can automatically apply brakes if the driver fails to respond, thereby avoiding collisions. Automatic emergency braking technologies can decelerate or bring the vehicle to a complete stop in imminent crash situations, significantly reducing the risk of injury to VRUs (Saadé 2017). Additionally, V2X technology enables communication between vehicles and various elements of the road infrastructure, including traffic signals, pedestrian crosswalks, and other vehicles. This technology can enhance situational awareness for drivers and can provide warnings about potential hazards, such as approaching pedestrians or cyclists.

The journey toward enhancing VRU safety has been a continuous process of innovation, collaboration, and adaption, driven by a growing recognition of the need for more comprehensive and sustainable mobility solutions. From early advocacy efforts to modern intelligent transportation systems (ITS), prioritizing the safety of VRUs has become increasingly important. Trends in fatal and serious injuries are rising for VRUs. According to the statistics, in the United States, fatal crashes were relatively steady from 2017 through 2019 but then jumped by 7.4 percent in 2020 and then again by 14.5 percent in 2021. The rate of serious injuries was even higher in recent years. Serious injuries showed a substantial decrease of 15.4 percent from 2018 through 2020 before taking a major swing upward in 2021, with a 30-percent increase (Texas Department of Transportation 2023). Moving forward, a comprehensive, systemwide approach that harmonizes infrastructure design, vehicle technology, legislation, enforcement, and public education will be crucial. To that end, to contribute to a "vision zero" world, this project focused on using CDA and V2X technologies to develop technologies that could further improve VRU safety.

HISTORY OF CP RESEARCH IN TRANSPORTATION SYSTEMS

The development of CP has been a gradual process that spans the last few decades, driven by advances in sensing technologies, communication systems, and artificial intelligence. The initial work on CP suggests sharing raw sensory data between two mobile agents. These data may include images, LiDAR point clouds, a combination of images and point clouds, location information, and relative range measurements. (Shan, Worrall, and Nebot 2021). As the field progressed, the application of CP expanded into vehicular networks in recent years. Researchers started investigating vehicle-to-vehicle (V2V) communication systems, laying the groundwork for what would eventually become CP in autonomous driving. As automated driving technology gained momentum, researchers recognized the potential of sharing perceptual information between vehicles and between vehicles and other infrastructures to enhance overall safety and efficiency. Recent years witnessed rapid advancements in computer vision and sensor fusion techniques, which were crucial in enabling vehicles to interpret and integrate data from various sources.

The scope of CP has extended beyond vehicular application. Studies are now exploring its potential in smart cities and Internet of Things environments, where multiple sensors and devices can share information to create a comprehensive understanding of urban areas (Jandial et al. 2020; Shibo et al. 2022). Moreover, the application of CP can also expand to enhance the safety of VRUs by integrating data from various sources, such as vehicles and infrastructure sensors.

As the field continues to evolve and with ongoing advancements in artificial intelligence, edge computing, and communication technologies, CP is poised to play a crucial role in shaping the future of autonomous systems and smart environments.

CHAPTER 3. DEVELOPMENT OF THE CP VRU SAFETY APPLICATION FOR SIGNALIZED INTERSECTIONS

This chapter outlines the proposed VRU safety application using CP. It covers the proposed CP approach, operational framework, development and testing environment, and the high-level architecture of the CP VRU safety application.

PROPOSED CP APPROACH

For the past decade, CP use cases have included advanced pedestrian warning systems using infrastructure-based perception, advisory warning of opposing traffic for permissive left-turn vehicles, automated vehicle (AV) path planning using CP information, and enhanced awareness of obstructed objects in various scenarios (Seeliger et al. 2014; Günther et al. 2016; Kitazato et al. 2016; Deng, Di, and Song 2018). These scenarios include driving along a curved road with limited line of sight in overtaking scenarios and around an intersection.

Despite significant progress in the study of CP, the integration of CP with C-ADS has not been thoroughly tested and demonstrated on real platforms, particularly in complex scenarios such as signalized intersections. This report serves as a proof of concept, validating the benefits of CP in enhancing the safety of VRUs in signalized intersections. The report marks a crucial step toward field testing, which involves development and testing within the CARMA Ecosystem (FHWA 2022b). This ecosystem facilitates the seamless transfer from simulation to real-world applications, leveraging its existing V2X and connected and AV capabilities, which have been successfully demonstrated in real-life use cases. Furthermore, the advancements achieved within this ecosystem can be used by academia and third parties to test their own unique algorithms and solutions to similar problems. Developing and integrating CP into the CARMA Ecosystem meant exploring two areas of advancement: communication methods of detected objects in an intersection and processing those objects from multiple sources for tracking and fusing (FHWA 2022b).

Per SAE International® (SAE) J3224™ standard, the sensor data sharing message (SDSM) format enables the exchange of detailed sensor data between V2X participants. This format includes information about detected objects, such as VRUs, which help vehicles and infrastructure to collaboratively perceive and respond to the driving environment (SAE 2022).

Other messages such as basic safety messages (BSMs) and personal safety messages either lack the depth of sensor data sharing or require the objects that need to be detected to carry a transmitter device. SAE J3224 SDSM is best used to describe the state of the detected objects in combination with these messages (SAE 2022).

After detected objects are broadcast through SDSMs, CP users receiving the messages need an algorithm to keep track of and fuse the incoming detected object data with the existing data (SAE 2022). This algorithm is called a multisensor, multiple-objects tracking problem. The state-of-the-art techniques for this problem can generally be divided into four steps: time and spatial alignment, data association, track management, and DF. This four-step approach is mostly derived from the Institute of Electrical and Electronics Engineers (IEEE)-published "Object-Level Perception Sharing Among Connected Vehicles," which achieved a realistic performance measured by accuracy and credibility of the shared-obstacle fusion (Ambrosin et al. 2019).

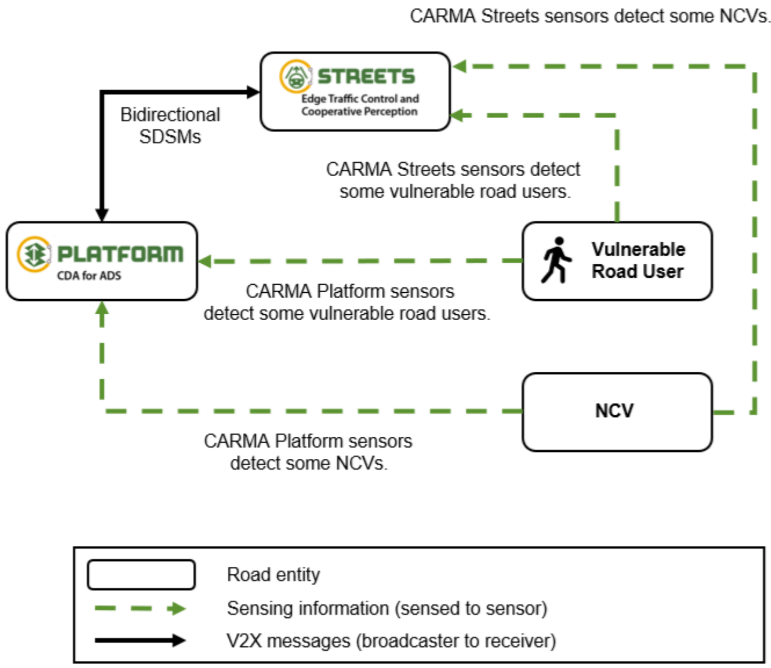
The research team's approach extends the work in Ambrosin et al. (2019) by implementing the architecture as submodule libraries, allowing for extensibility and replacement with different modules. The team also executes V2X capabilities, as opposed to the V2V approach shown in the research by Ambrosin et al., and demonstrates actual AV yielding capability by leveraging CARMA Platform (FHWA 2022a). Detailed explanations of each submodule are included in the following sections.

OPERATIONAL FRAMEWORK

This section illustrates the high-level operational framework of the CP VRU safety application, introducing the involved road users, data flow, and software architecture used on a high level. The CP VRU safety application aims to improve the safety of VRUs by leveraging CP in the signalized intersection. In other words, the infrastructure and C-ADS-equipped vehicles will detect all entities within a signalized intersection, no matter the occlusion or intersection geometry, through transmission and receipt of SDSMs (SAE 2022). Therefore, with the help of CP, the C-ADS-equipped vehicles can make safer trajectories that otherwise may have resulted in a crash or near miss.

The data flow for the CP VRU safety application is illustrated in figure 1 where detectable entities include the following:

- VRUs.
- Nonconnected vehicles (NCVs).
- C-ADS-equipped vehicles.



Source: FHWA.

Figure 1. Flowchart. Object detection and involved entities at traffic signal intersections (FHWA 2022a, 2022b).

VRUs and NCVs may be sensed by both the infrastructure and C-ADS-equipped vehicle sensors, although not necessarily at the same time. Sensor hardware systems of both infrastructure and C-ADS-equipped vehicle are both capable of preprocessing raw data to generate object list data, which is a list of detected objects' state information such as pose, heading, object type, and twist. Multiple products on the market have such capabilities (Lou et al. 2022). To avoid duplicating work associated with object detection algorithms and applications provided by the existing off-the-shelf sensors, this study only focuses on the DF of the object lists that are provided by one or more sensing agents. Based on that assumption, the simulation environment of CDASim is improved to generate such object list data from each agent individually. Then the agent with the CP algorithm developed in this use case applies the DF to get a more accurate object list (FHWA 2023).

Once VRUs and NCVs are sensed, these detections are communicated between infrastructure and the C-ADS-equipped vehicles using the SDSMs in a bidirectional message transfer. In this use case, although this step shows bidirectional communication, only C-ADS-equipped vehicles perform the DF step using the messages from infrastructure. Messages broadcast from the vehicles can be leveraged by other agents in future use cases, but the infrastructure is not doing the DF as the infrastructure is not making any safety decisions or calculations in this use case.

The CP modules, a library called multiple object tracking (MOT), are designed as a set of reusable agents' independent components. What this concept means in the CARMA Ecosystem is that the CP modules are middleware agnostic, whether using a Robot Operating System (ROS) or Kafka®, which are the middleware used by CARMA Platform and CARMA Streets, respectively (FHWA 2022a, 2022b; Open Robotics 2021; Apache Software Foundation 2014). These modules instead work off a standard CP object-tracking interface, which abstracts the data type from the different middleware used by the input sources. Therefore, multiple message conversion adapters were implemented to complete the CP stack, thus connecting MOT library modules to the rest of the CARMA Platform system (FHWA 2022a).

This approach keeps the application of CP more flexible, allowing it to function effectively in exclusively C-ADS-equipped vehicle contexts, infrastructure and C-ADS-equipped vehicle contexts, or the mixed users of NCV and C-ADS-equipped vehicle and infrastructure contexts. To supplement SDSMs, C-ADS systems also broadcast BSMs, per SAE standards (SAE 2020). All supported message types are broadcast at 10 Hz per their SAE standards, which is required to maintain operational safety in vehicle control (SAE 2020).

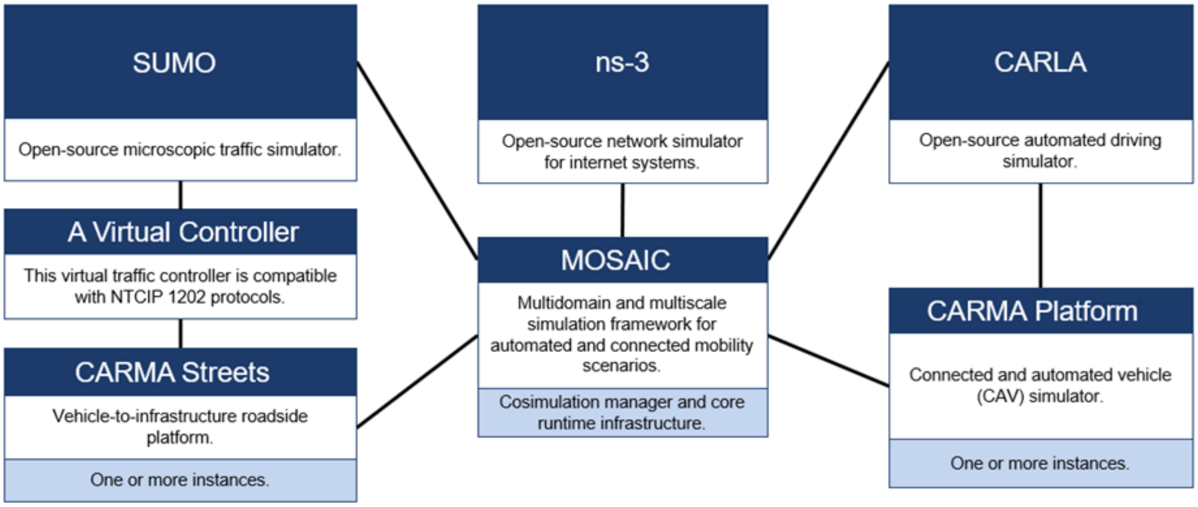
DEVELOPMENT AND TESTING ENVIRONMENT

CDASim is a cosimulation tool for advancing CDA development and evaluation by establishing XiL capabilities using OSS (FHWA 2023). This section describes the development environment of CDASim for testing VRU use cases (FHWA 2023). The section also provides the motivation for using simulations instead of field tests at this stage of the technology development.

CDASim High-Level Architecture

CDASim contains the following seven major components, as shown in figure 2:

- Traffic simulator: Eclipse SUMO (Eclipse Foundation n.d.).
- Communication simulator: ns-3 (nsnam 2024).
- Vehicle driving simulator: CARLA (CARLA Team 2024).
- Simulation manager: MOSAIC™ (Eclipse Foundation 2024).
- C-ADS-equipped vehicle simulator: CARMA Platform (FHWA 2022a).
- Vehicle-to-infrastructure roadside platform: CARMA Streets (FHWA 2022b).
- Traffic light operations: virtual TSC.



Source: FHWA.
See American Association of State Highway and Transportation Officials (AASHTO), Institute of Transportation Engineers (ITE), and National Electrical Manufacturers Association (NEMA) (2019) for National Transportation Communications for ITS Protocol (NTCIP) 1202 protocols.

Figure 2. Diagram. CDASim high-level architecture.

SUMO is an open-source traffic simulation suite generating background traffic and simulating connected and unconnected human driver behavior (Eclipse Foundation n.d.). SUMO also measures the benefits of CDA applications to traffic (e.g., travel time reduction and throughput increase). As a communication simulator, ns-3 simulates V2X communication (nsnam 2024). However, this study assumes a perfect communication medium (e.g., no latency and packet loss).

CARMA Streets runs the various roadside infrastructure application and generates the V2X messages such as SAE J2735™ MAP and SPaT or J3224 SDSM (FHWA 2022a; SAE 2020, 2022). CARMA Streets leverages V2X Hub℠ to broadcast its generated messages to other road users (FHWA 2024b). Both in field testing and in simulation, the V2X Hub acts as the data aggregator or disseminator and translator between the SAE format that C-ADS-equipped vehicles generate to National Transportation Communications for ITS Protocol (NTCIP) format that infrastructure components can understand (FHWA 2024b; American Association of State Highway and Transportation Officials (AASHTO), Institute of Transportation Engineers (ITE), and National Electrical Manufacturers Association (NEMA) 2019).

CARLA provides three-dimensional driving environments, such as roads, buildings, pedestrians, and other simulated vehicles, to develop and test different plugins of CARMA Platform (CARLA Team 2024). Furthermore, while CARMA Platform provides the C-ADS capability and generates trajectory commands, CARLA carries out the actual physical vehicle simulation, such as breaking and throttling or vehicle inertia (FHWA 2022a; CARLA Team 2024). MOSAIC is the simulation manager that synchronizes data and time among different simulators for each simulation step (Eclipse Foundation 2024). Lastly, a virtual controller drives the virtual traffic signal in the simulation environment.

Motivation Behind Using a Simulation Environment

Testing the development of CP in a signalized intersection use case in simulation before field implementation offers the following advantages:

- Safety: Eliminates the risk of incidents or malfunctions in test track setup, ensuring the safety of drivers, pedestrians, and researchers.
- Cost-effectiveness: Minimizes the expenses associated with field tests, such as equipment and test track use, fuel, and labor costs.
- Controlled environment: Allows precise control over variables and conditions, facilitating relatively consistent and repeatable experiments.
- Scenario versatility: Enables quick testing of multiple scenarios and edge cases, which might be impractical to replicate on a test track.
- Rapid iteration: Speeds up the development cycle by allowing quick modifications and immediate testing without the logistical constraints of field testing.
- Data collection: Provides extensive and detailed data collection capabilities, essential for thorough analysis and debugging. Test track tests can also provide extensive and even irreplaceable data if the right conditions are met. However, the right conditions may be harder to achieve.
- Initial validation: Helps validate algorithms and systems in a risk-free environment before subjecting them to the complexities of field tests.
- Early detection of issues: Facilitates early identification (ID) and resolution of potential issues, reducing the likelihood of encountering significant problems during field tests.

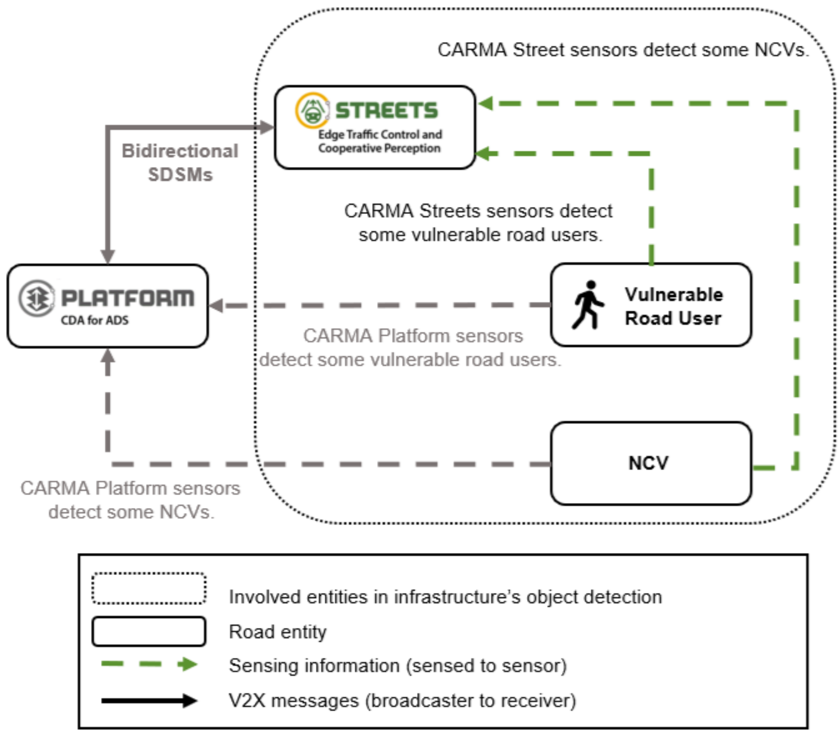
HIGH-LEVEL ARCHITECTURE OF CP VRU SAFETY APPLICATION

This section provides a high-level overview of the main components and data flows of the CP VRU safety application, including the following subsections: Infrastructure Detection Data Flow, C-ADS-Equipped Vehicle Detection Data Flow, CP Stack, MOT, and the High-Level Design of the CARMA Platform's Object Avoidance.

Infrastructure Detection Data Flow

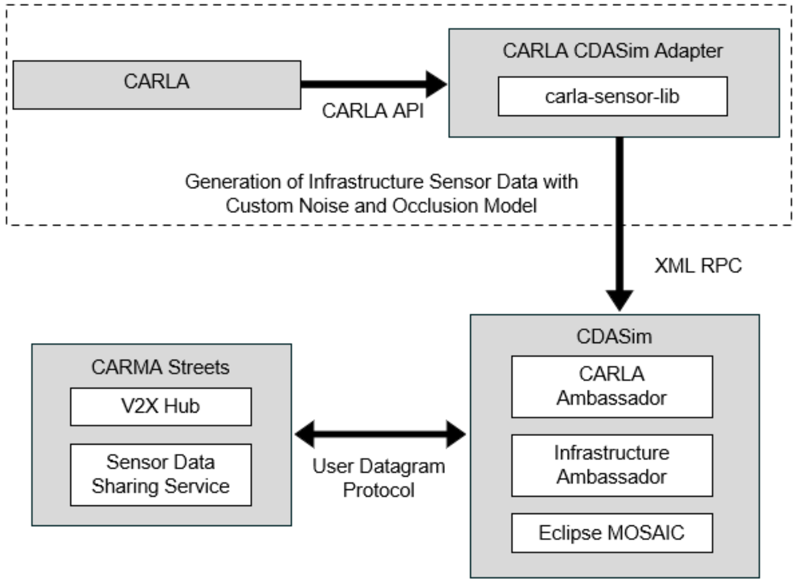
This subsection illustrates the infrastructure-side data flow for the CP VRU safety application. The road entities involved in the infrastructure object detection are highlighted in figure 3, and its architectural data flow is shown in figure 4. While CARLA has been integrated into CDASim, figure 4 shows them as separate components to better illustrate the data flow (CARLA Team 2024; FHWA 2023).

First, in figure 4, to simulate real-world data, configurable noise and line-of-sight occlusion models are applied to the sensor detection data sent from CARLA (CARLA Team 2024). This step is done through a wrapper library for the CARLA application programming interface (API), called carla-sensor-lib. The CARLA-CDASim adapter uses this library to simulate infrastructure sensor data and forward it to CDASim through an Extensible Markup Language (XML) remote procedure call (FHWA 2023; tutorialspoint 2024). CARMA Streets then converts incoming sensor-detected data from CDASim into an SDSM for broadcast to other connected actors within a signalized intersection (FHWA 2022a, 2023). CARMA Streets uses V2X Hub to convert the SAE-formatted messages into NTCIP-formatted messages and broadcasts them back to CDASim, using the user datagram protocol (UDP). UDP is used in other simulation components, such as ns-3, simulating roadside unit broadcasting in the field testing (FHWA 2024b; SAE 2020; AASHTO, ITE, and NEMA 2019; nsnam 2024).



Source: FHWA.

Figure 3. Flowchart. Involved entities highlighted in infrastructure's object detection at the signalized intersection.



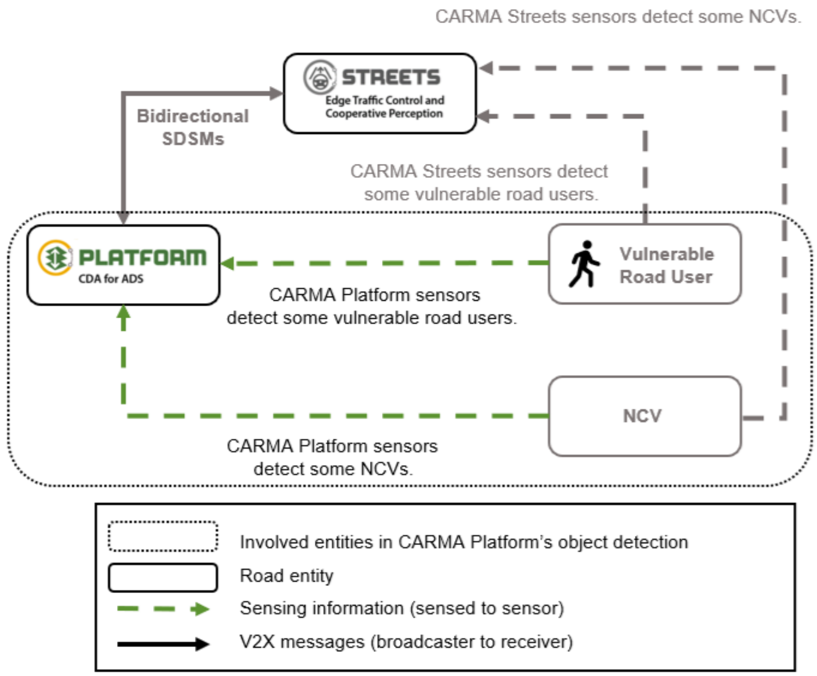
Source: FHWA.
RPC = remote procedure call.
Note: CARLA is part of the CDASim tool. The figure intentionally separates the components for better data flow illustration.

Figure 4. Flowchart. Infrastructure detection data flow.

C-ADS-Equipped Vehicle Detection Data Flow

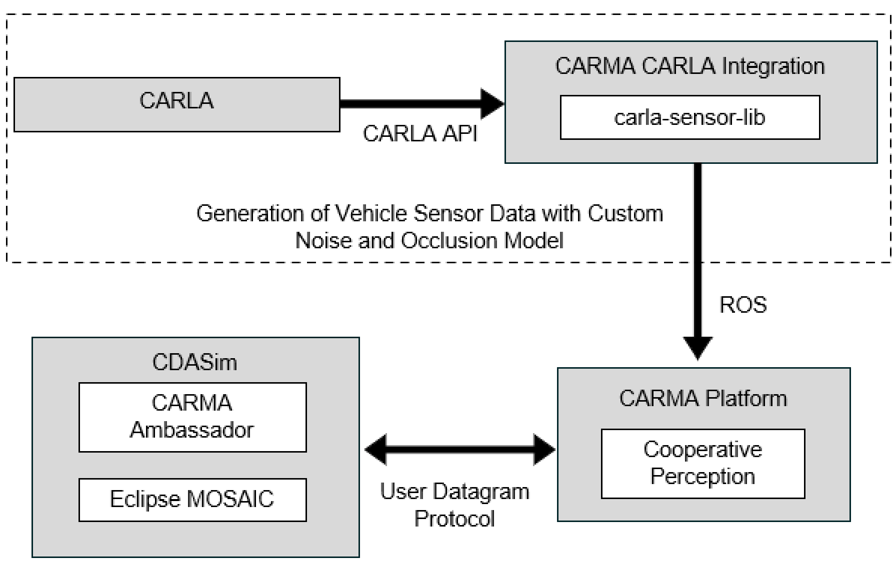
This subsection illustrates the vehicle side data flow for the CP VRU safety application. The road entities involved in CARMA Platform's object detection data are highlighted in figure 5, and the corresponding architectural data flow for CARMA Platform detection is shown in figure 6 (FHWA 2022a). Similar to the infrastructure side, sensor detection data from CARLA are modified to emulate real-world vehicles' onboard sensors by carla-sensor-lib using the CARMA CARLA integration tool. These modified data are then sent to CARMA Platform via ROS to use in its CP stack (FHWA 2023; Open Robotics 2021).

CDASim sends SDSM messages from the infrastructure to provide additional detections of occluded VRUs (VRUs outside of the CARMA Platform-equipped vehicle's perception zone) to CARMA Platform through UDP (FHWA 2022a, 2023). CDASim also takes the SDSMs generated from CARMA Platform to broadcast to other agents (FHWA 2022b). CARMA Platform uses the data received from CDASim, along with its CP stack, to detect occluded VRUs to adjust its planned trajectory accordingly to ensure safe driving (FHWA 2022a).



Source: FHWA.

Figure 5. Flowchart. Involved entities highlighted in CARMA Platform's object detection at traffic signal intersection.

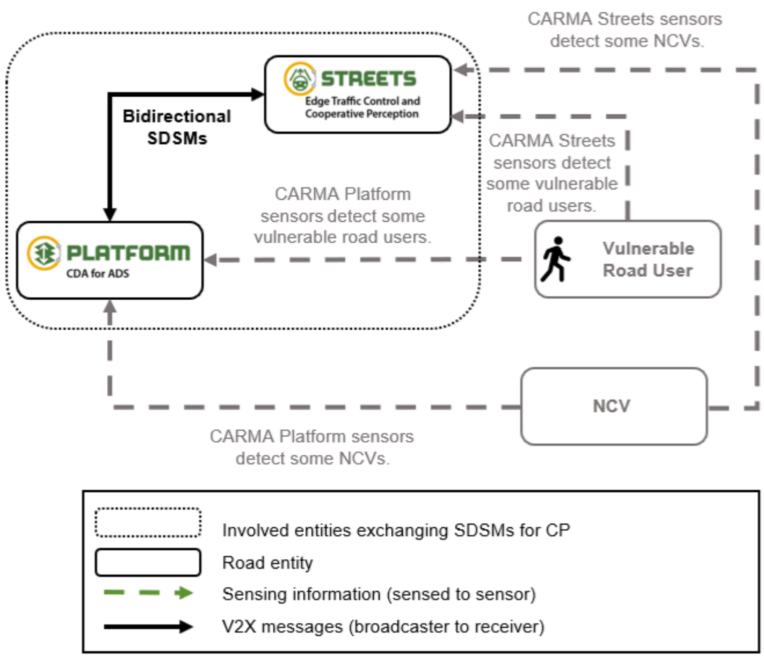


Source: FHWA.
Note: CARLA is part of the CDASim tool. The figure intentionally separates the components for better data flow illustration.

Figure 6. Flowchart. CARMA Platform detection data flow.

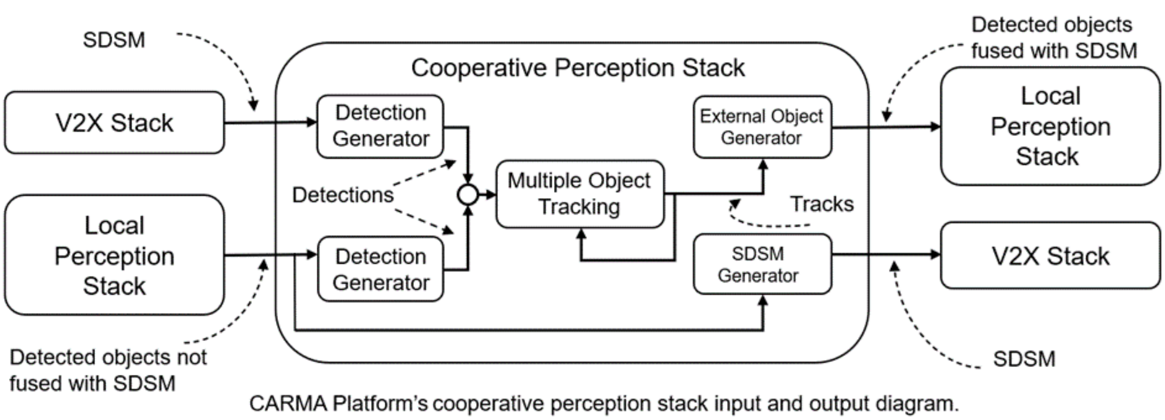
CP Stack

This subsection illustrates the CP stack and the DF components of the CP VRU safety application. The road entities involved in performing the CP are highlighted in figure 7. The corresponding CP stack developed on the vehicle is shown in figure 8, which comprises the main DF algorithm and message type conversions, each tailored to varying system stack requirements of CARMA Platform. The DF algorithm, MOT, is implemented as a deployable library suitable for use in both vehicles and infrastructure. In this use case, the CP stack is only integrated into the CARMA Platform due to reasons mentioned in the Operational Framework (FHWA 2022a).



Source: FHWA.

Figure 7. Flowchart. Involved entities highlighted in CP at traffic signal intersection.



Source: FHWA.

Figure 8. Flowchart. CP data flow in CARMA Platform.

In the CP stack, the input to the MOT algorithm is a data structure, called detection, which has common CP object detection properties. For example, CP object detection properties used are constant velocity (CV) model for pedestrians and constant turn rate and velocity model for vehicles. Moreover, detections specifically represent object-level sensor detections that are directly from the sensors and not yet fused or tracked. Tracks, on the other hand, are the output of the MOT algorithm that represent the object-level detection that is fused and tracked by the system over time. Track represents the best previously known states of the detections and is used to fuse with incoming detections to get the current, most accurate states. Therefore, detection generator nodes for V2X and local perception stacks convert from SDSMs and onboard sensor detected objects to common detection objects in a map frame that can be readily ingested by MOT API. Tracks generated by the MOT algorithm, on the other hand, are fed into MOT itself for the next time step, which is fusing and external object generator to be used by the downstream CARMA Platform components to generate safe trajectories (FHWA 2022a). As the SAE J3224 SDSM standard requires that SDSMs only contain nonfused object lists, onboard sensor-detected objects are directly fed into the SDSM generator to be broadcast to other road users (SAE 2022).

MOT

MOT is the most complex piece of the CP stack and involves multiple subcomponents. Due to MOT's modularity, each of the following steps can be replaced or extended with alternative algorithms if desired. Since all detection objects are spatially aligned to a common map frame by this point, this stage largely consists of an architecture similar to the global objects manager mentioned in Ambrosin et al. (2019). The team's approach has the following steps:

1. Temporal alignment and prediction: All detected objects and existing tracks must be brought to a common time stamp before fusion. This stage performs the alignment method presented in Allig and Waneilik (2019), which uses an unscented Kalman filter to predict the detected object's and track's state at the next time step (Wan and Van Der Merwe 2000).

2. Detection-to-track scoring: A measurement of how close detected objects are to each track is needed to associate them with existing tracks (or to create new tracks). Multiple metrics are included in the library, such as simple Euclidean distance, semantic distance that takes into account classifications such as vehicle or pedestrian, Mahalanobis distance that takes into account probability, or special Euclidean space measurement (SE2) (Mahalanobis 1936). Semantic distance is used in this scenario as it offers the best performance.

3. Gating: A small optimization step is next to prune associations that are improbable based on the scores calculated in the previous step. That is, only the improbable association of detection to track is pruned, and detections that have no probable associations due to this gating step are handled in the track maintenance step described in step 5.

4. Detection-to-track association: This step, once the scores are calculated, can be formulated as a matching problem that can be solved by global nearest neighbor (GNN), where each detection is associated with a single track. The Hungarian algorithm is also a

commonly used algorithm that can be replaced here, but for an uncongested intersection with a small number of road users in this use case, GNN works well (Kuhn 1955).

5. Track maintenance: Some detections and existing tracks without matches may still be present after detections are associated with existing tracks. This step handles creating a new track or removing the old one. Unassociated detections are clustered to create a "tentative" track. Upgrading a "tentative" to a "confirmed" track and removing old tracks that did not get an association are handled by a simple counter-based algorithm with adjustable thresholds. For example, the algorithm decreases the counter of a track if it did not get any association in this iteration and increases the counter if it did. The algorithm readjusts the counters every iteration to remove tracks that have zero counts or upgrades those to "confirmed" so those tracks can be used by the downstream components. Tentative tracks are tracked inside the MOT and not passed to downstream components yet.

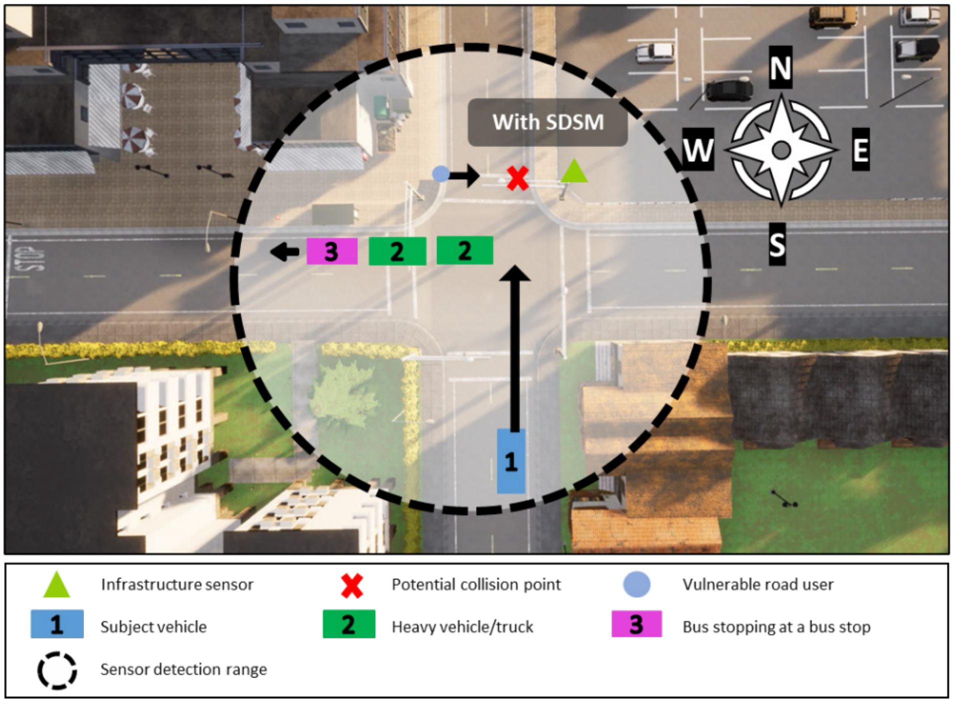
6. Detection-to-track fusion: The last step is to fuse the detections with existing tracks to create new ones. A common method of covariance intersection method is used here (Julier and Uhlmann 1997; Liggins et al. 2017).

Indepth notations and a data flow diagram can be found in the CP stack of the carma-platform GitHub page. The source code and API documentation for the MOT implementation can also be found on GitHub (FHWA n.d.b.).

High-Level Design of CARMA Platform Object Avoidance

Using the latest tracks that surround the vehicle, CARMA Platform modifies its trajectory to make the vehicle yield before potential collision points (FHWA 2022a). CARMA Platform accomplishes this objective by assuming a simple CV model for the VRU and generating a linear trajectory for 10 s (adjustable) based on the extrapolation of the VRU's velocity and heading (FHWA 2022a). This scenario is a simplified approach of VRU behavior, which is a whole research field on its own, that can be improved in later works. For now, this approach will suffice as the primary purpose is to showcase the potential of CP to improve safety and not to perfect the automated driving systems (ADS) response.

Figure 9 shows an example of a potential collision detection in an intersection where a vehicle equipped with CARMA Platform (the subject vehicle) is traveling north and a pedestrian is crossing the road west to east (the circle) (FHWA 2022a). Two heavy vehicles (i.e., trucks) are behind a bus that has stopped at a bus stop to the west. One of the vehicles is occluding the pedestrian from the CARMA Platform-equipped vehicle (FHWA 2022a). However, the infrastructure sensor, to the northeast of the intersection, detects the pedestrian and sends the information to the CARMA Platform-equipped vehicle through an SDSM (FHWA 2022a). Once the CV model detects a potential collision (shown in figure 9 as an x), CARMA Platform's yielding functionality modifies its original trajectory to a safer one along its originally intended route with a certain safety gap distance with the least amount of jerk possible (FHWA 2022a). If stopping is unnecessary when yielding to an obstacle, CARMA Platform adjusts its speed to maintain the safety gap without coming to a full stop (this function applies to other general cases, for example, when driving behind another moving vehicle) (FHWA 2022a).



Source: FHWA.

Figure 9. Illustration. Trajectory intersection visualization for collision avoidance.

This approach is chosen because minimizing jerk in the vehicle is one of the common methods in the industry to ensure a comfortable traveling experience. This problem of trajectory generation can be solved by the minimum jerk polynomial trajectory method, which can generate a trajectory by solving a quintuple polynomial system of equations derived from kinematic equations and constrained known initial and end conditions of location, speed, and acceleration (Flash and Hogan 1985). Although the algorithm is written to prioritize minimizing the jerk, it also has parameters to target comfortable deceleration of 3.0 m/s^2. This feature is why the performance metrics discussed in chapter 4, in the subsection titled TC, evaluate deceleration rate during the run as opposed to jerk.

More documentation and source code pertaining to how a trajectory is modified based on CP data is available on GitHub (FHWA n.d.c.).

CHAPTER 4. TESTING AND EVALUATING THE PROPOSED APPLICATION

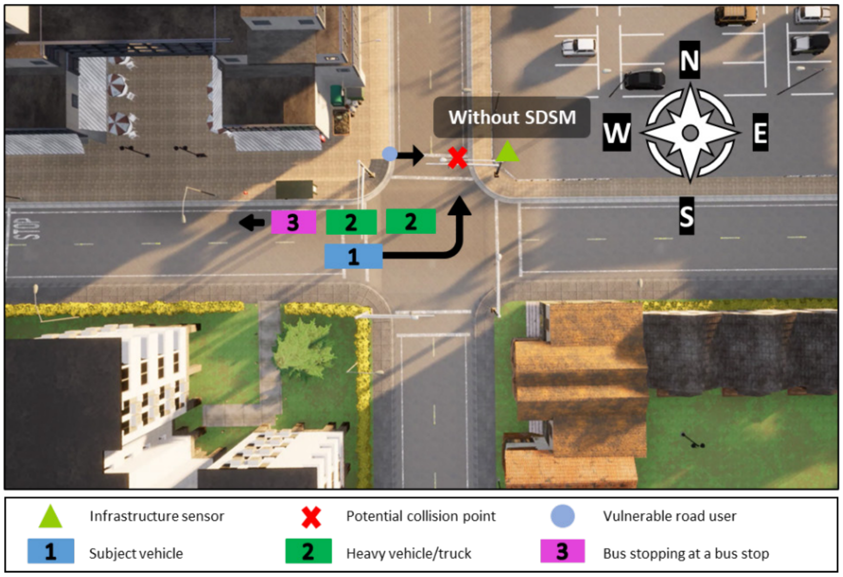
This chapter illustrates the test and evaluation process of the CP VRU safety application and presents the corresponding results.

OPERATIONAL SCENARIOS

This section outlines four distinct test scenarios designed to evaluate the effectiveness of CP under conditions of blocked line of sight while a vehicle traverses an intersection. These scenarios are divided into two main categories: those without CP and those with CP, with each further subdivided by the direction of the vehicle through the intersection (left turn or straight through). Namely, the four distinct test scenarios are the following:

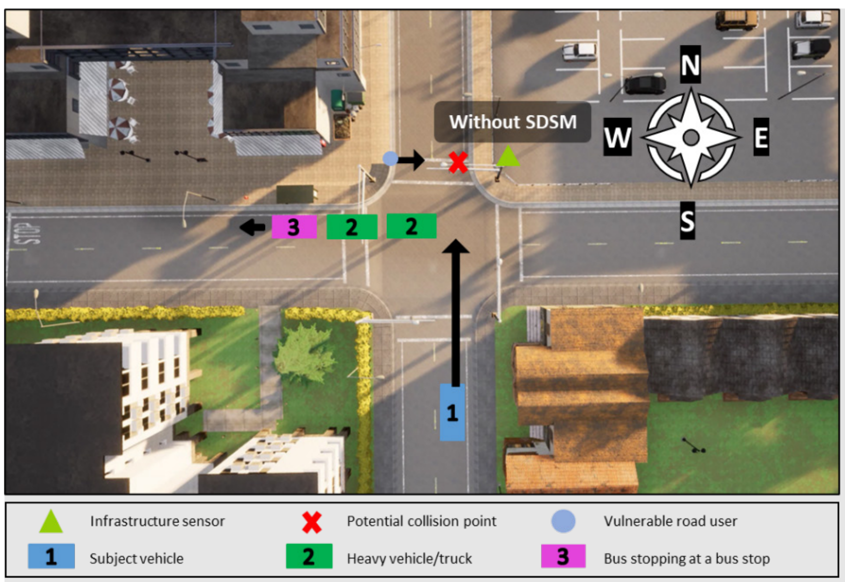
- Scenario 1: Left-turn direction without CP (figure 10–A).
- Scenario 2: Straight through without CP (figure 10–B).
- Scenario 3: Left-turn direction with CP (figure 11–A).
- Scenario 4: Straight through with CP (figure 11–B).

In these test scenarios, the C-ADS-equipped vehicle starts from a predetermined point and completes its route through the intersection. The chosen starting location ensures the vehicle can accelerate to the designated speed limit before reaching the intersection box. The C-ADS-equipped vehicle goes through the intersection with a configured speed limit. In these scenarios, a pedestrian starts crossing the intersection when the vehicle is within a specific distance of the intersection, creating a potential crash risk due to conflicting paths. The C-ADS-equipped vehicle's line of sight is blocked by three stopped trucks or buses, and the vehicle cannot detect the pedestrian by itself until it passes the last truck or bus. In scenarios 3 and 4, where the infrastructure broadcasts SDSMs, the C-ADS-equipped vehicle is expected to detect the pedestrian using the received SDSMs, come to a full stop, and avoid hitting the pedestrian. These four scenarios simulate common VRU crossing scenarios in urban areas.



Source: FHWA.

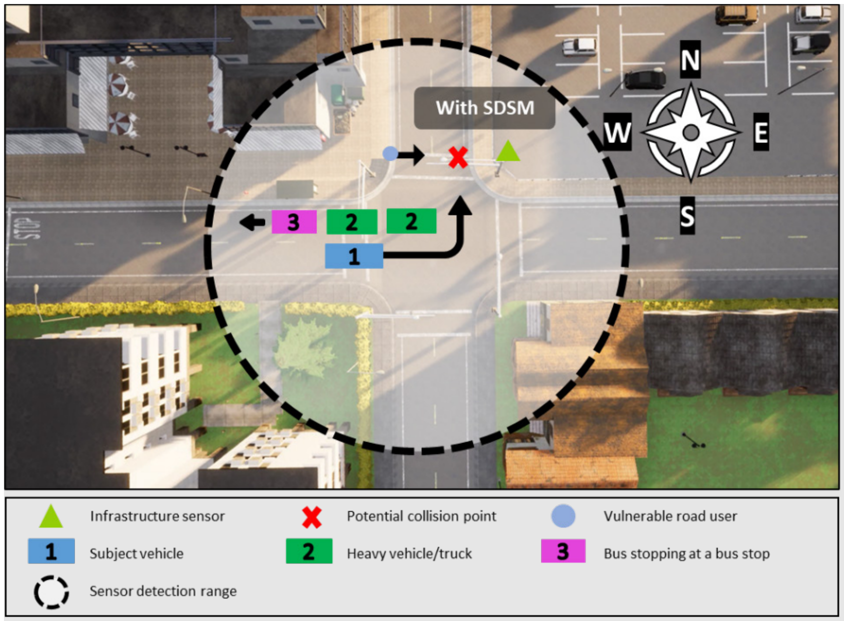
A. Scenario 1: Left-turn direction without CP.



Source: FHWA.

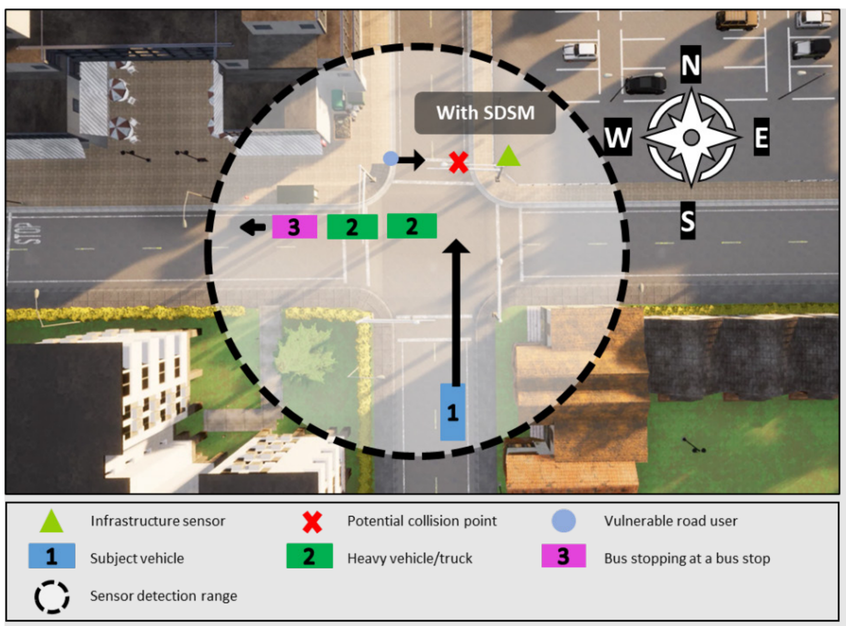
B. Scenario 2: Straight through without CP.

Figure 10. Illustrations. Test scenarios without CP enabled (scenarios 1 and 2).



Source: FHWA.

A. Scenario 3: Left-turn direction with CP.



Source: FHWA.
Note: Figure 11-B is the same as figure 9 and is duplicated here for clarity.

B. Scenario 4: Straight through with CP.

Figure 11. Illustrations. Test scenarios with CP enabled (scenarios 3 and 4).

The meticulously crafted scenarios evaluate both the presence and absence of CP, focusing on CP's role in enhancing safety at intersections. The objective in these scenarios is for the vehicle to yield to the pedestrian as soon as a conflict in their paths is detected.

To effectively evaluate the capabilities and benefits of CP in avoiding crashes, the initial conditions and test parameters are structured. Structuring initial conditions and test parameters ensured that a minimum of 75 percent of tests without CP resulted in a crash or near-miss incident (see the Test Parameters and Number of Runs subsection) and preferably even a higher percentage. This act allowed for simple analysis to see how safety was improved in these scenarios when CP was turned on.

TEST AND EVALUATION PROCESS

The following subsections contain the overall test approach for the CP VRU use case. They detail the specific test approach the project team used for testing. The project team worked with the FHWA team and project stakeholders to identify and agree on the performance metrics and valid run criteria during the test plan development.

Testing Process

The standard engineering processes employed at the Saxton Transportation Operations Laboratory involve several levels of testing to help verify the system correctness (FHWA 2024d). The first level is automated unit testing. Project teams targeted unit tests that exercise at least 80 percent of the code, as individual modules, often with mocked-up interfaces to enable testing in isolation. The researchers ran a full suite of unit tests on every build, and the status is reported continuously on the GitHub website (FHWA 2024e).

The next level is component integration testing. This testing typically involves all the software for a given system (e.g., CARMA Platform, CARMA Streets) being executed together, either in the simulation environment or on a live vehicle or device. The test exercises the real-time interactions among the various software components with all real internal interfaces in place. Sometimes component integration testing is applied to a subset of the full system to better study a few key interactions. The test also makes isolating issues early easier to ensure the smoothness of future full scenario integration testing. As simulation capabilities are added and enhanced for the CARMA suite of software, integration testing will begin in simulation, including small- and full-scale scenarios (FHWA 2022a).

Once integration testing is successful, the snapshot of the code is branched into a candidate release branch in GitHub to isolate it from ongoing feature development. This code is then packaged as candidate distributable Docker® images and published on the Docker hub (Docker, Inc. 2024). At this point, the team performs a formal system-level verification test, which may involve multiple systems interacting (e.g., CARMA Platform and CARMA Streets). Only independently controlled (by configuration management processes and staff) Docker images are used for this level of testing. The testing follows a formal, peer-reviewed test plan, and all results are documented and shared with the U.S. Government. Verification is not considered complete until all essential anomalies are addressed and retested when changes occur. On acceptance, the release candidate becomes a formal release with a numbered version ID number. Similar to integration testing, simulation capabilities are leveraged to improve the efficiency, quantity, and complexity of verification test scenarios.

New releases are normally subjected to the final round of smoke testing and validation. Validation testing is focused on suitability for the intended purpose, rather than detailed functional correctness. After all testing is passed, the developed application will be released to the public to support their own CDA research.

Test Scope

The procedures outlined for this testing serve the following three main purposes:

- To verify that the functionality developed for this use case was properly implemented on CARMA Streets, V2X Hub, and CARMA Platform within the CDASim virtual environment (FHWA 2022a, 2023, 2024b).
- To verify that the developed functionality meets the metrics and requirements agreed on by both the project team and FHWA.
- To verify that the functionality is properly integrated with the resulting CARMA Platform, CARMA Streets, V2X Hub, and CDASim releases (FHWA 2022a, 2023, 2024b).

On the completion and passing of all test cases documented in this plan, these three purposes are considered met.

Testing Environment, Related Assumptions, and Constraints

The general setting for the testing environment and related assumptions and constraints are as follows:

- Testing environment general setting and major notes are as follows:
    - The test is conducted in a controlled simulation environment.
    - CARMA Platform vehicles, CARMA Streets, V2X Hub, and CDASim are in working order with up-to-date software and configuration (FHWA 2022a, 2023, 2024b).
    - Only one CARMA Platform vehicle is present in all test cases, and no messages are generated from other vehicles (FHWA 2022a).
    - Up to three nonmoving and non-C-ADS-equipped vehicles and one VRU can be created and used in all test cases.
    - One infrastructure sensor has an unobstructed view of all road participants in the intersection in all test cases.
    - The clocks from different simulators in CDASim are synchronized (FHWA 2023).

The use case uses a slightly altered version of the SAE J3224 SDSM standard (SAE 2022). The standard specifies that the sender of the SDSMs should filter out the data about C-ADS-equipped vehicles as the vehicles are capable of broadcasting more accurate information about themselves using their BSM. In the current CARMA Streets release, the ability to filter out C-ADS-equipped vehicles does not yet exist and will be part of a future work. However, this situation does not impact the results of the tests because only one C-ADS-equipped vehicle is present in the test scenarios (FHWA 2022b).

- The assumptions are as follows:
  - This use case emphasizes DF and CP based on these object lists to prevent duplicated efforts, given the availability of numerous off-the-shelf sensors capable of providing detected object lists. Consequently, sensor detections are simulated at an object level rather than a sensor level. The simulated objects incorporate a noise model (Gaussian noise specifically for this test), with the tuning parameters of this model reported and configurable for future research. However, this test does not anticipate an exhaustive exploration of various sensor noise variations, as its primary aim is to demonstrate information sharing between the CARMA Platform and CARMA Streets (FHWA 2022b).
  - The V2X communication environment is considered perfect (e.g., no latency and package drops). A future effort will need to evaluate how performance is impacted when this assumption is relaxed.
  - The performance metrics and data analysis focus on the traffic benefits of CP.
  - The signalized intersection is under fixed-time traffic signal control.
  - Tests are performed under ideal weather and road conditions.
- The constraints are as follows:
  - Road users and test object models used in the CARLA environment to simulate the scenarios are selected from the best available options to serve their respective purposes (CARLA Team 2024). While their models do not exactly mimic real-life scenarios, their functionality provides similar scenarios for testing and research.
  - CARMA Platform has a constraint of a maximum 8.0 m/s^2 deceleration rate (FHWA 2022b). To replicate a high emergency break scenario in the field, this use case uses 8.0 m/s^2 as the highest possible emergency break. The team chose this value because the literature review indicated that this value is a conservative deceleration rate most vehicles can achieve (De Ceunynck 2017). CARLA simulator also comes with 8.0 m/s^2 as its highest deceleration rate by default (CARLA Team 2024).
  - The use case is constrained to a signalized intersection with fixed signal and timing phases.

- Vehicle speed limits at turns are bounded based on the road geometry and cannot exceed a certain threshold. However, the pedestrian and vehicle speeds are designed to closely resemble real-life situations.
- The initial conditions of the CARMA Platform-equipped vehicle are designed so that it arrives at the intersection during a green phase (FHWA 2022b). This feature ensures that the vehicle's speed and trajectory are influenced only by the presence of pedestrians and not by the signal status. This setup allows the vehicle to achieve its test speed parameters reliably.
- The current CARLA simulator version in the use case is limited to 0.9.10, although newer versions exist. This limitation results in a limited selection of CARLA simulator models (e.g., only a heavy truck is available, instead of a bus). This limitation also required in-house patch fixes for some CARLA features (e.g., developing a wrapper library called carla-sensor-lib to fix and improve faulty semantic LiDAR sensor feature offered by CARLA) (CARLA Team 2024).
- VRU behavior is simulated using a CV model.

Test Requirements and Performance Metrics

This subsection outlines the test requirements and performance metrics for this use case. As shown in table 1, four categories of requirements and performance metrics are defined for evaluating the testing outcomes. Table 2 provides descriptions of the pertinent requirements within each category, and table 3 presents and describes the chosen performance metrics. The naming convention in these tables uses the format “R-category-number” for requirements (e.g., R-SIM-01) and “M-category-number” for performance metrics (e.g., M-RC-01). Overall, the requirements are defined to ensure that the testing system performs as designed and intended, and the performance metrics are defined to evaluate the system’s performance.

Table 1. Categories of requirements and performance metrics for the CP VRU use case.

Requirements and Performance Metrics Categories	Description
SIM	This category specifies the requirements and evaluates the efficiency and effectiveness of the SIM environment.
RC	This category outlines the requirements for communication and performance metrics that measure the reliability and consistency of RC among various equipped services and objects.
CP	This category details the requirements for CP functionalities and pertains to performance metrics that evaluate the precision and reliability of detection, track maintenance, and DF within an environment enhanced by CP capabilities.
TC	This category sets the requirements for vehicle TC and centers on assessing the performance of vehicle trajectory planning and control, as well as the use of an implemented yield model, and other related factors.

SIM = simulation; RC = radio communication; TC = trajectory control.

Table 2. Requirements for the CP VRU use case.

ID No.	Requirement Text
R-SIM-01	The simulation environment should include infrastructure equipped with CARMA Streets and V2X Hub, a vehicle equipped with CARMA Platform, one VRU, and three non-C-ADS-equipped heavy vehicles (FHWA 2022a, 2024b).
R-SIM-02	The infrastructure in the simulation environment should be equipped with a LiDAR to detect the objects and classify them if they are within the visible line of sight* of the infrastructure.
R-SIM-03	The CARMA Platform-equipped vehicle should be equipped with a LiDAR and should be able to detect objects and classify them if they are within the visible line of sight of the vehicle (FHWA 2022b).
R-SIM-04	The simulation environment should integrate a remotely hosted virtual TSC to control a traffic signal in CARLA (CARLA Team 2024).
R-SIM-05	The infrastructure clock should be synchronized with the simulation clock.
R-SIM-06	The CARMA Platform clock should be synchronized with the simulation clock (FHWA 2022b).
R-SIM-07	The CARLA clock should be synchronized with the simulation clock (CARLA Team 2024).
R-SIM-08	The SUMO clock should be synchronized with the simulation clock (Eclipse Foundation n.d.).
R-SIM-09	The TSC clock should be synchronized with the simulation clock.
R-SIM-10	The simulation environment should collect all data for postanalysis of simulation accuracy and performance.
R-RC-01	The infrastructure within the simulation environment should generate and broadcast SDSMs through the V2X Hub when an object is within its visible line of sight (FHWA 2024b).

ID No.	Requirement Text
R-RC-02	The CARMA Platform in the simulation environment should broadcast its local perception data through SDSMs (FHWA 2022b).
R-RC-03	The CARMA Platform in the simulation environment should receive and process SDSMs from the V2X Hub (FHWA 2022b, 2024b).
R-RC-04	The infrastructure in the simulation environment should receive NTCIP SPaT messages from the TSC and broadcast valid SAE J2735 SPaT messages (AASHTO, ITE, and NEMA 2019; SAE 2020).
R-RC-05	CARMA Platform should receive and process SPaT messages (SAE 2020).
R-RC-06	The infrastructure in the simulation environment should broadcast valid SAE J2735 MAP messages (SAE 2020).
R-RC-07	CARMA Platform should receive and decode MAP messages (FHWA 2022b).
R-CP-01	All CP-related plugins within CARMA Platform should be active and operational (FHWA 2022b).
R-CP-02	In the presence of the VRU within the line of sight and detection range of the infrastructure or vehicle, the CP stack should report a tracked object for the received detection.
R-TC-01	The yield plugin, the basic-travel plugins, and the SPaT-related plugins† within CARMA Platform should be active and operational (FHWA n.d.c., 2022a).
R-TC-02	CARMA Platform should use SPaT information, and the vehicle should avoid entering the intersection box during the red or yellow phases (FHWA 2022b).
R-TC-03	CARMA Platform must consistently adhere to its predefined route‡ to reach its destination (FHWA 2022b).

*The area within the detection range of the LiDAR on the infrastructure or vehicle that is not occluded by any other object. In this use case, the LiDAR detection is set to 50 m.

†Implementation of the plugins can be found on the GitHub page (FHWA 2024c), where yield plugin information is in the yield_plugin folder. Basic-travel plugins are route_following_plugin, pure_pursuit_wrapper, inlanecruising_plugin, and SPaT-related plugins are lci_strategic_plugin, light_controlled_intersection_tactical_plugin, and intersection_transit_maneuvering.

‡A sequence of roadway segments to move from origin to destination.

Table 3. Performance metrics for the CP VRU use case.

ID No.	Performance Metric	Description
M-SIM-1	Simulation speed	The speed at which the simulation progresses.
M-RC-1	SPaT message frequency	The frequency at which the infrastructure disseminates SPaT messages.
M-RC-2	SDSM frequency	The frequency at which the infrastructure disseminates SDSMs.
M-RC-3	MAP message frequency	The frequency at which the infrastructure disseminates MAP messages.
M-CP-1	SDSM positional accuracy	The accuracy of the VRU position reported in the SDSM.
M-CP-2	Track fusion accuracy	The accuracy of the VRU position derived from the associated fused track.

ID No.	Performance Metric	Description
M-CP-3	Track stability (missing track)	The stability and quality of associating detections to tracked objects and maintaining fused tracks, measured by the frequency and impact of missing objects in the detection process.
M-CP-4	Track stability (duplicated track)	The stability and quality of associating detections to tracked objects and maintaining fused tracks, measured by the frequency and impact of duplicated objects in the detection process.
M-CP-5	Application latency	The processing time and application latency of the carma_cooperative_perception stack to fuse the information from any incoming messages and updating the existing information in its object list.
M-TC-1	Near-miss or collision percentage	The ratio of simulation runs with near misses* or collisions to the total number of simulation runs for a specific scenario, expressed as a percentage.
M-TC-2	Travel experience	The comfort experienced by the vehicle passengers. In this use case, the acceleration magnitude of the vehicle defines the level of comfort.
M-TC-3	Conflict clearance delay	The time delay for the vehicle in passing through the conflict point after the conflicting object (e.g., VRU in this use case) has passed the conflict point.

*In this use case, a near miss occurs when the time to collision (TTC) is below a certain threshold. TTC is calculated based on the vehicle's and the VRU's locations, speeds, and maximum accelerations and decelerations. In this study, for a test run to be counted as a near miss, the TTC value must be less 1.5 s in this use case, which is a commonly accepted TTC threshold (Fu et al. 2019; Haleem, Alluri, and Gan 2015).

Valid Run Criteria

This subsection defines the criteria for a valid run that apply to all test cases. The valid run criteria determine what must occur and what can cause a test to be invalid or fail once a test run has begun. The valid and invalid runs for this use case are defined as follows:

- Valid run: A simulation run that satisfies all the requirements defined for this use case in table 2.
- Invalid run: A simulation run that does not satisfy at least one of the requirements defined for this use case in table 2.

Test Parameters and Number of Runs

The testing encompasses various combinations of test parameters. Table 4 lists the test parameters identified for CP VRU use case testing. The initial two parameters pertain to the speeds of the CARMA Platform-equipped vehicle and the VRU (FHWA 2022b). Varying these parameters generates distinct conflict scenarios and affects how the CARMA Platform-equipped vehicle yields (FHWA 2022b). The third parameter, the minimum safety yielding gap, is a configurable setting for the implemented yield functionalities, dictating the desired stopping distance between the CARMA Platform-equipped vehicle and the VRU (FHWA 2022b). Each of these test parameters can assume one of two different values, resulting in eight possible combinations of parameter values (parameter set A, B, C, D, E, F, G, and H), as presented in table 4. These values are chosen to ensure that the percentage of near-miss or collision events in the scenarios without CP activation is projected to be 75 percent or higher.

Table 4. Test parameters for the CP VRU use case (FHWA 2022b).

Parameter Index	Left Turn			Straight Through		
	Vehicle Target Speed (m/s (km/h))	VRU Speed (m/s)	Minimum Safety Yielding Gap (m)	Vehicle Target Speed (m/s (km/h))	VRU Speed (m/s)	Minimum Safety Yielding Gap (m)
A	5.0 (18)	1.0	4	13.4 (48.24)	1.4	4
B	5.0 (18)	1.2	4	13.4 (48.24)	1.8	4
C	5.0 (18)	1.0	10	13.4 (48.24)	1.4	10
D	5.0 (18)	1.2	10	13.4 (48.24)	1.8	10
E	4.0 (14.4)	1.0	4	8.9 (32.04)	1.4	4
F	4.0 (14.4)	1.2	4	8.9 (32.04)	1.8	4
G	4.0 (14.4)	1.0	10	8.9 (32.04)	1.4	10
H	4.0 (14.4)	1.2	10	8.9 (32.04)	1.8	10

To verify the effectiveness of the developed functionalities under randomness, on top of varying the parameter combinations, the team has run the same combination and scenario multiple times. The randomness can come from the noise model for adding noises to the detection or from the differences when engaging the vehicle after starting the simulation. Given four scenarios, three parameters described in the preceding paragraphs, two values for each parameter, and three runs for each scenario and parameter set, the testing team aimed to conduct and use 96 runs in total (4 scenarios×(2 parameter values^{3})×3 runs=96). If a given scenario and parameter set resulted in an invalid run, the research team conducted more runs to achieve three valid runs for each scenario and parameter set.

RESULTS ANALYSIS

This section provides the analysis of the CP VRU use case test data. The defined performance metrics are measured, and the analysis data are obtained by using and processing data from CARMA Platform rosbags, CARMA Streets Kafka data, log files, and through observations. Table 5 presents a summary of the conducted simulation runs (FHWA 2022b; Apache Software Foundation 2014).

Table 5. Test summary.

Left Turn			Straight Through		
Parameter Index	**Valid Runs (No.)**	**Invalid Runs (No.)**	**Parameter Index**	**Valid Runs (No.)**	**Invalid Runs (No.)**
Without CP					
A	3	0	A	3	0
B	3	0	B	3	0
C	3	0	C	3	0
D	3	0	D	3	0
E	3	0	E	3	0
F	3	1	F	3	1
G	3	1	G	3	1
H	3	0	H	3	1
With CP					
A	3	0	A	3	0
B	3	3	B	3	0
C	3	0	C	3	0
D	3	0	D	3	0
E	3	0	E	3	0
F	3	0	F	3	0
G	3	0	G	3	0
H	3	0	H	3	0
Total	48	5	Total	48	3

The reasons for the eight invalid runs are the following:

- Four runs were impacted because the CARMA Platform was configured to down sample the road centerline too aggressively, causing the vehicle to lose critical points needed to generate a trajectory (FHWA 2022b). This situation resulted in the vehicle either driving off the road due to lack of any planning or not moving at all after yielding to a pedestrian. Although this issue demonstrates an area for potential future improvement in the CARMA Platform stack, the issue is independent of the CP VRU safety application, and therefore these runs were not considered valid.

- Two runs were affected by a known issue in the CARMA Platform where sometimes some plugins fail to activate at startup. The issue is exacerbated by another known issue where CARMA Platform fails to recognize deactivation of these plugins and requests maneuvers from them too frequently, thus freezing normal operations and causing the vehicle to deviate from its route (FHWA 2022b).

- Two runs were caused by incorrect simulation vehicle dimensions, which mistakenly shut down the CARMA Platform by incorrectly determining the vehicle was not on the road (FHWA 2022b).

These eight invalid runs did not satisfy at least one of the requirements noted in table 2. Although these eight invalid runs demonstrate areas for potential future improvement in the CARMA Platform stack, they are independent of the CP VRU safety application.

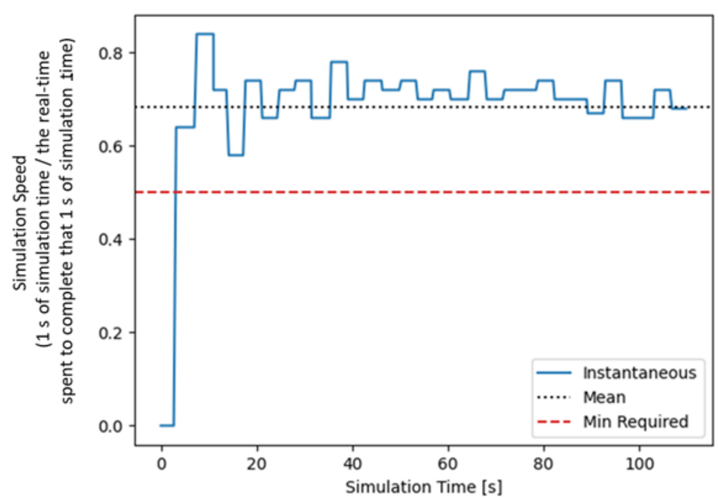
Performance Analysis

This subsection provides a detailed analysis of the performance metrics and requirements for various components of the system, including the simulation environment, RC, CP, and trajectory control (TC). Each subsection describes the specific metrics used to evaluate the performance and the results obtained from the simulation experiments.

During the simulation experiment, eight runs were invalid due to failures on the CARMA Platform (FHWA 2022b). As a result, the team conducted 104 total runs to achieve 96 valid runs, as presented in table 5.

Simulation Environment (SIM)

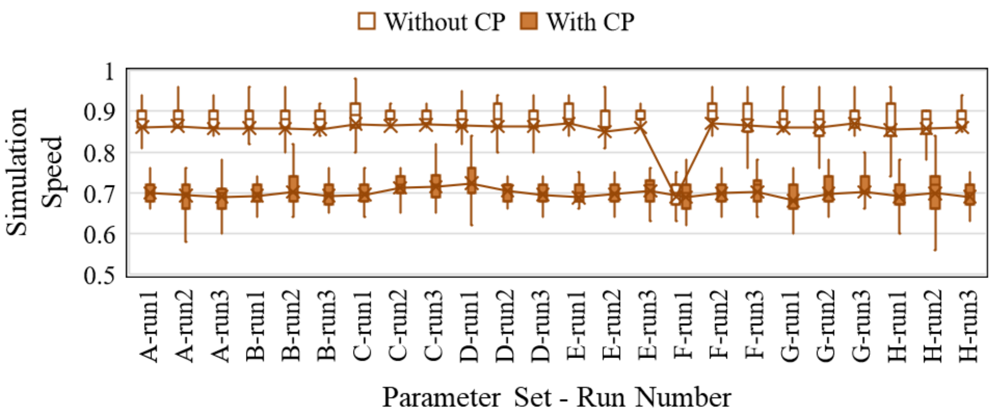
The performance of the simulation environment is tested by the speed at which the simulation progresses. This measure is called simulation speed (see performance metric M-SIM-1 in table 3) and is calculated by dividing 1 s of simulation time by the realtime spent to complete that 1 s of simulation time. In this testing, the minimum acceptable simulation speed is set to 0.5. Figure 12 shows an example of simulation speed over time for a CP scenario where the vehicle goes straight through the intersection, and the box plots in figure 13 show the quartiles of the simulation speeds at different simulation time steps across all runs. The slow simulation time evident at the beginning of the simulation, as seen in figure 12, is common to all runs and is due to the simulation starting at zero speed, followed by a sudden increase to the average simulation speed.



Source: FHWA.
Min = minimum.

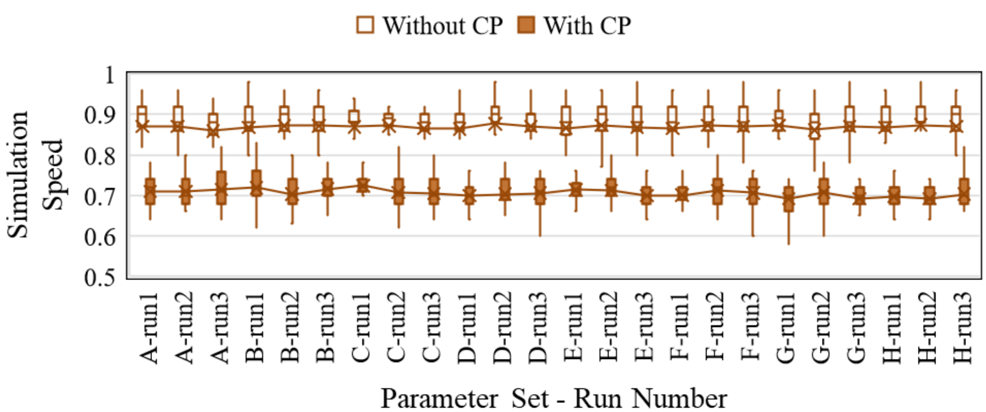
Figure 12. Graph. Example of the simulation speed over time.

As shown in figure 13, the simulation speed remains fairly constant across all runs for a given scenario. This figure also indicates that in scenarios without CP, the simulation speed stays close to 1, meaning that each second of simulation progresses almost as fast as 1 s of realtime. However, when CP is involved, the simulation environment must process more plugins and functions, causing the simulation speed to decrease to around 0.7 (reduced by approximately 18.5 percent on average). This situation demonstrates that, with all plugins active, the simulation speed decreases slightly but does not require extensive time to conduct simulations. Future work can consider how simulation speed can be further increased and what this finding may indicate about real-world performance. Figure 13-A shows that F-run1 without CP resulted in slower simulation speed than all the other runs without CP. The data seem to be an outlier and currently have no explanation, but the data are still valid for this use case.



Source: FHWA.

A. Simulation speeds for left-turn runs.



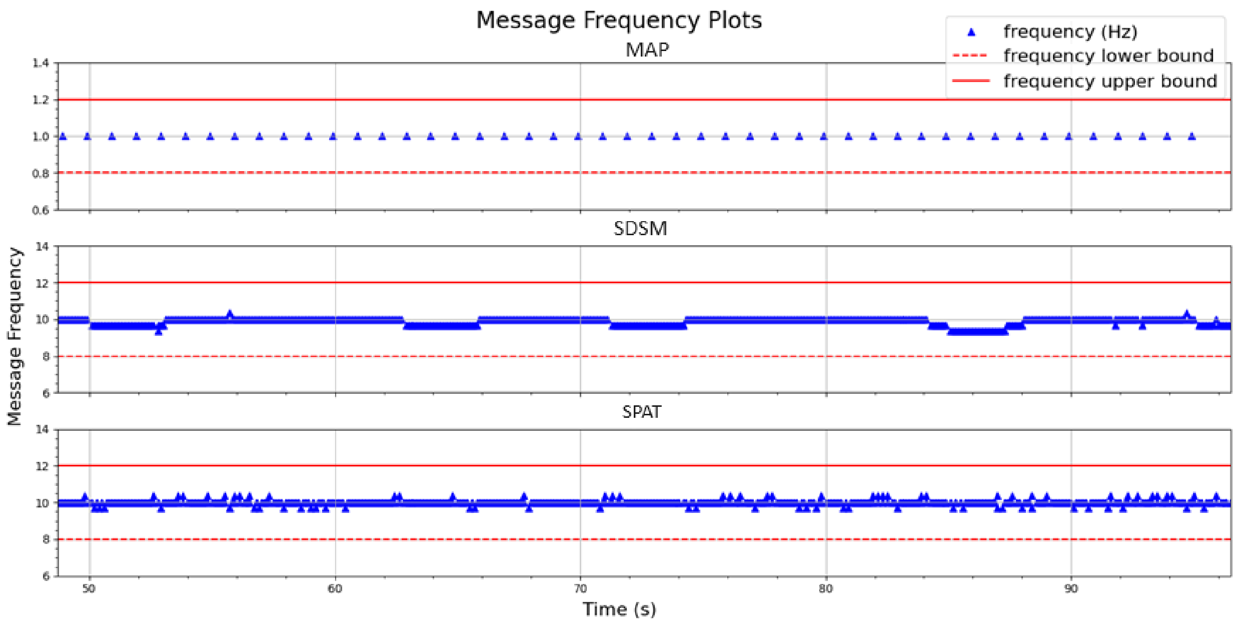
Source: FHWA.

B. Simulation speeds for straight-through runs.

Figure 13. Graphs. Simulation speed.

RC

In terms of RC, the researchers plotted and investigated the frequencies of the broadcast messages. Figure 14 presents an example of message frequency plots for a CP scenario with the vehicle going straight through. Across all runs, the observed minimum and maximum frequencies for the MAP message are 0.97 Hz and 1.03 Hz, for SDSMs are 8.11 Hz and 10.34 Hz, and for the SPaT message are 9.68 Hz and 10.71 Hz, respectively. As shown in figure 14, all broadcast messages remained stable and within the required frequency bounds (shown by frequency lower and upper bounds labeled in figure 14), consistent across all conducted runs.



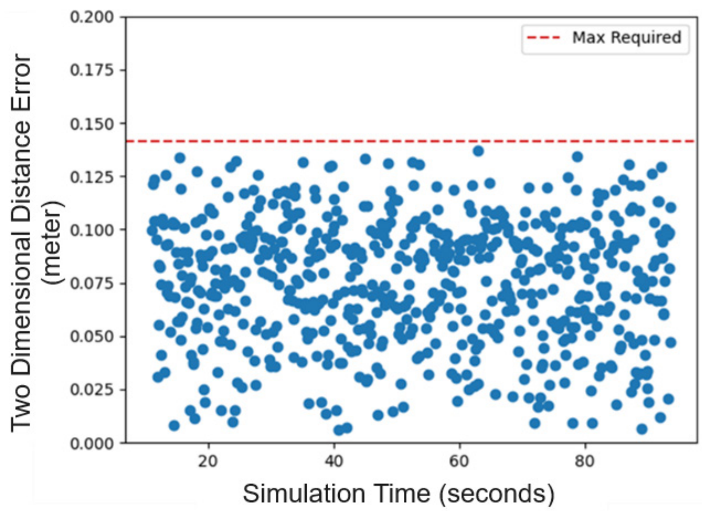
Source: FHWA.

Figure 14. Graph. Example of message frequency plots.

CP

The performance of the implemented CP algorithms and plugins is evaluated by assessing the precision and reliability of detection, track maintenance, and DF within the simulation environment.

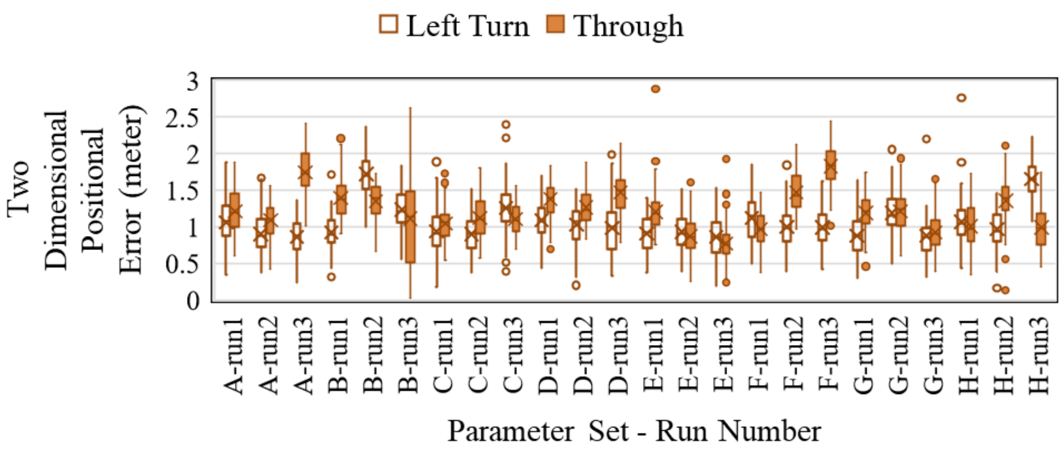
First, to evaluate the precision and reliability of detection in the reported SDSM, the researchers plotted and investigated the two-dimensional distance (considering the latitudinal and longitudinal distances) errors between the actual VRU positions and the reported VRU positions in the SDSM. To introduce some randomness, an implemented noise model adds noises to the actual VRU positions when reporting them in the SDSM. The noise added to each directional position is bounded by 0.1 m. Therefore, the two-dimensional distance error between the actual VRU position and the reported VRU position in the SDSM should be bounded by $\sqrt{0.12+0.12} \approx 0.14$ m, which is the case for all the conducted runs. By ensuring that the two-dimensional distance error is 0.14 m or less, the researchers are confident that the SDSM conversion did not introduce any additional error into the system besides what is already there due to sensor noise. Figure 15 presents an example plot of this error for a CP scenario with the vehicle going straight through.



Source: FHWA.
Max = maximum.

Figure 15. Graph. Example of the VRU positional error in the reported SDSM.

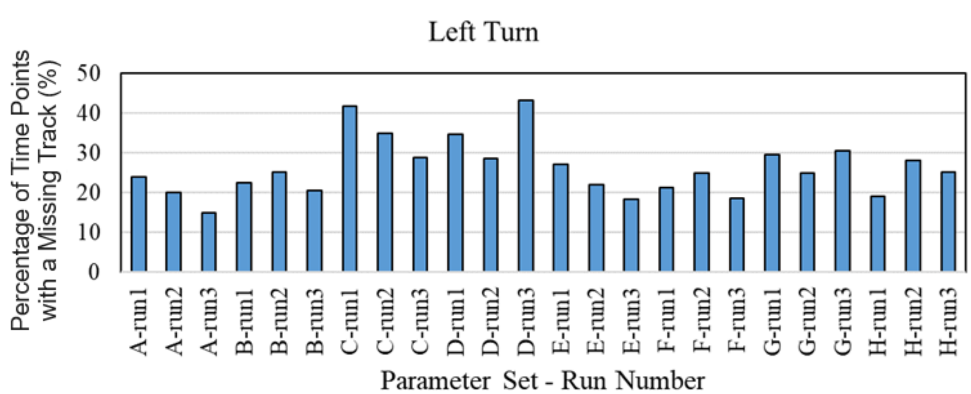
Next, the precision and reliability of the predicted tracks from the received SDSMs are tested by calculating the two-dimensional distance error between the tracks and the VRU positions in the reported SDSMs. Figure 16 presents a box plot of this error for when the VRU is moving in the CP scenarios. As shown in this figure, the two-dimensional error remains less than 2 m in most of the conducted runs and is unaffected by the vehicle's direction at the intersection (left turn or straight through). This observation demonstrates that the track error remains stable across various tested parameter sets. However, the observation also indicates that the implemented algorithms for updating the tracks can be further refined to reduce the introduced error. A 2-m error margin, while stable, is relatively high for applications such as pedestrian detection in autonomous vehicles, where precision needs to be within 0.5 to 1.5 m to ensure safety and reliability (Jiménez et al. 2011). Future studies and improvements are necessary to reduce this error margin, which will enhance system performance and safety in complex environments.



Source: FHWA.

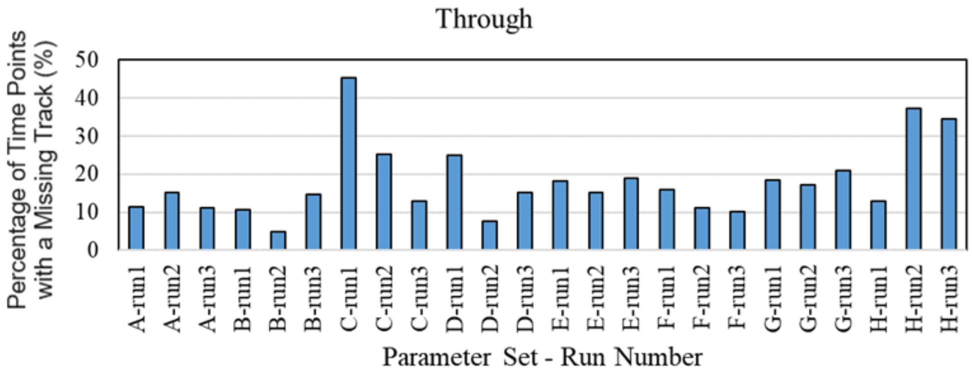
Figure 16. Graph. Track errors while the VRU is moving for the CP scenarios.

The researchers further evaluated the reliability of the implemented track fusion algorithm by checking for missing and duplicated tracks while the VRU was moving. The evaluation of the tracks shows that while no duplicated tracks are observed in any of the conducted simulation runs, most runs do experience a missing track for a certain amount of time. Figure 17 presents the percentage of simulation time points with a missing track for simulation runs with CP enabled. As depicted in figure 17, each simulation run, on average, misses a track for between 20 to 50 percent of simulation time points when the VRU is moving. In all but one of the CP scenario runs, the missed track did not impact vehicle operations in terms of yielding to the pedestrian during testing. However, these results demonstrate that more improvements are needed to address the issue of missing tracks.



Source: FHWA.

A. Percentage of simulation time points with missing tracks while the VRU is moving for the left-turn simulation runs.

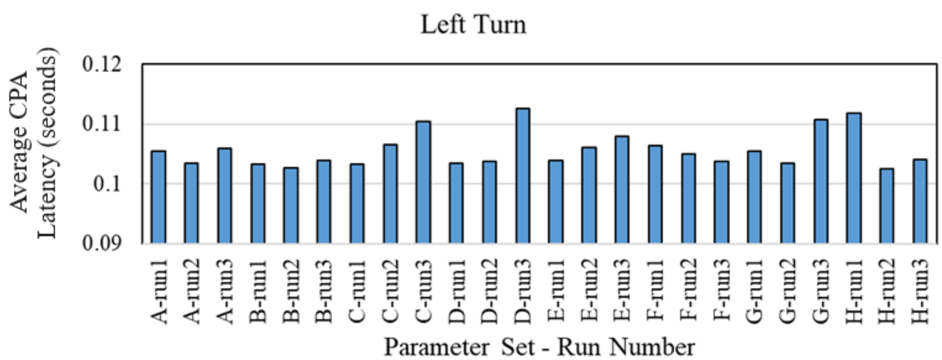


Source: FHWA.

B. Percentage of simulation time points with missing tracks while the VRU is moving for the straight-through simulation runs.

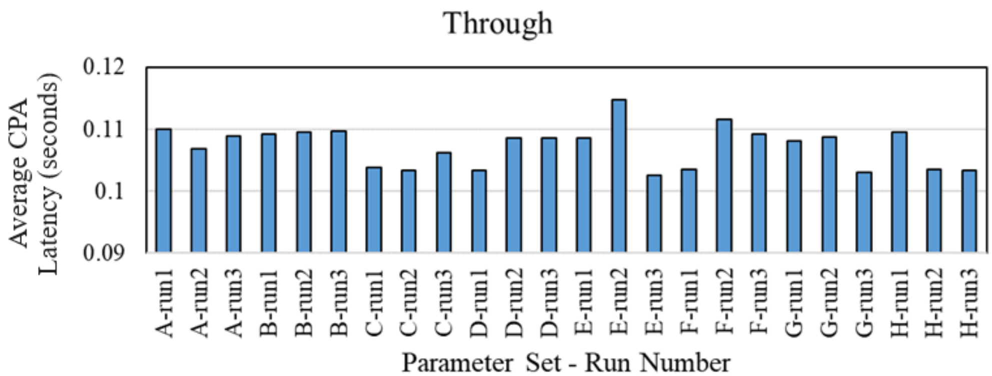
Figure 17. Graphs. Percentage of simulation time points with missing tracks while the VRU is moving for the CP scenarios.

Finally, figure 18 presents the average CP application (CPA) latency for simulation runs with CP enabled. Because each simulation step is 0.1 s (10 Hz), representing periods shorter than this measurement is not possible. The CP stack also operates at 10 Hz, contributing to application latency. Even slight latencies caused by factors such as computation load or resource contention can delay data publication by one time step, resulting in a 0.1-s delay. All runs had a maximum of 0.2-s latency. Increasing the simulation step frequency would resolve this issue, allowing for more precise time representation and reducing latency.



Source: FHWA.

A. CPA latency for the left-turn simulation runs.



Source: FHWA.

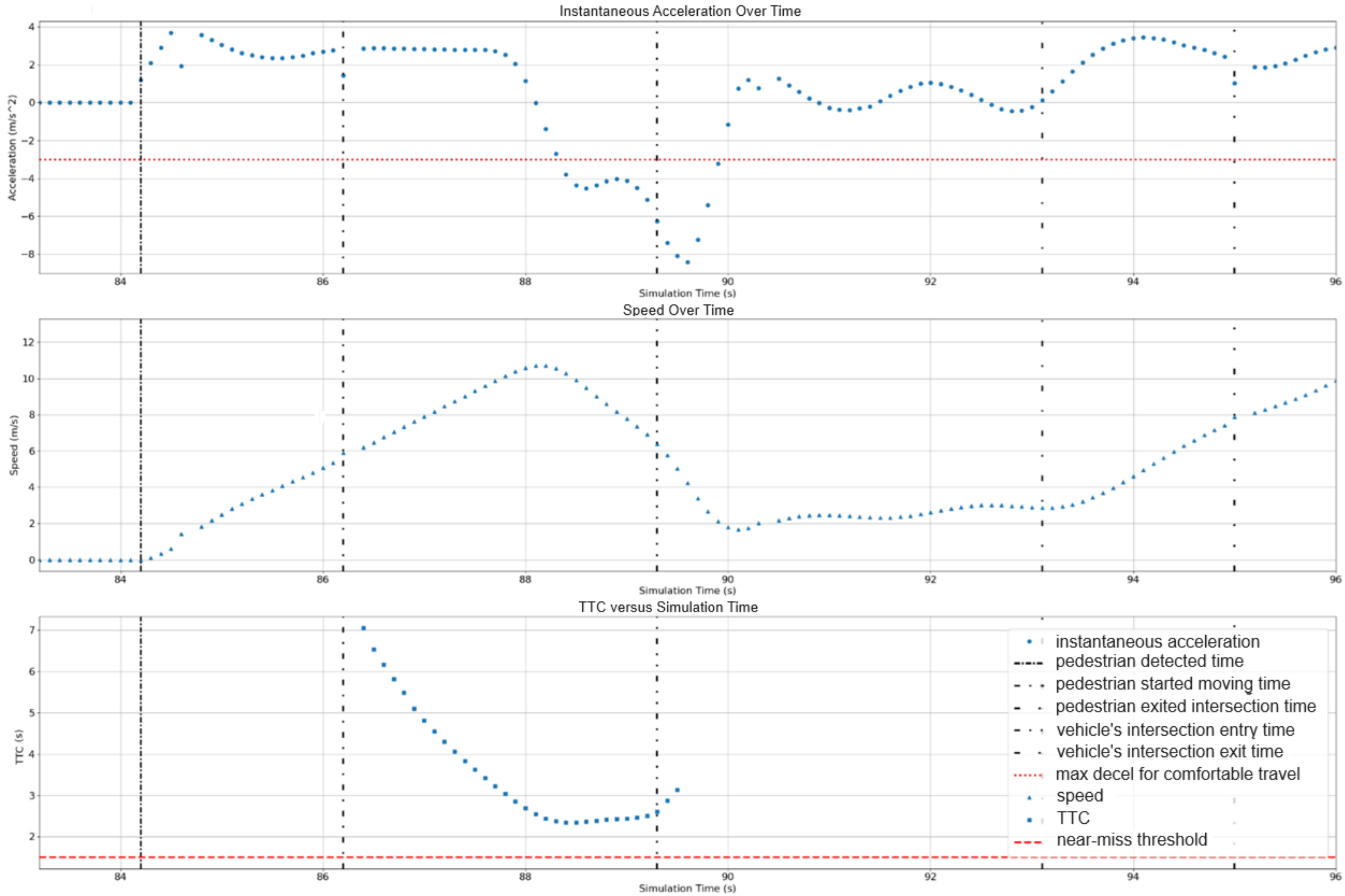
B. CPA latency for the straight-through simulation runs.

Figure 18. Graphs. CPA latency.

TC

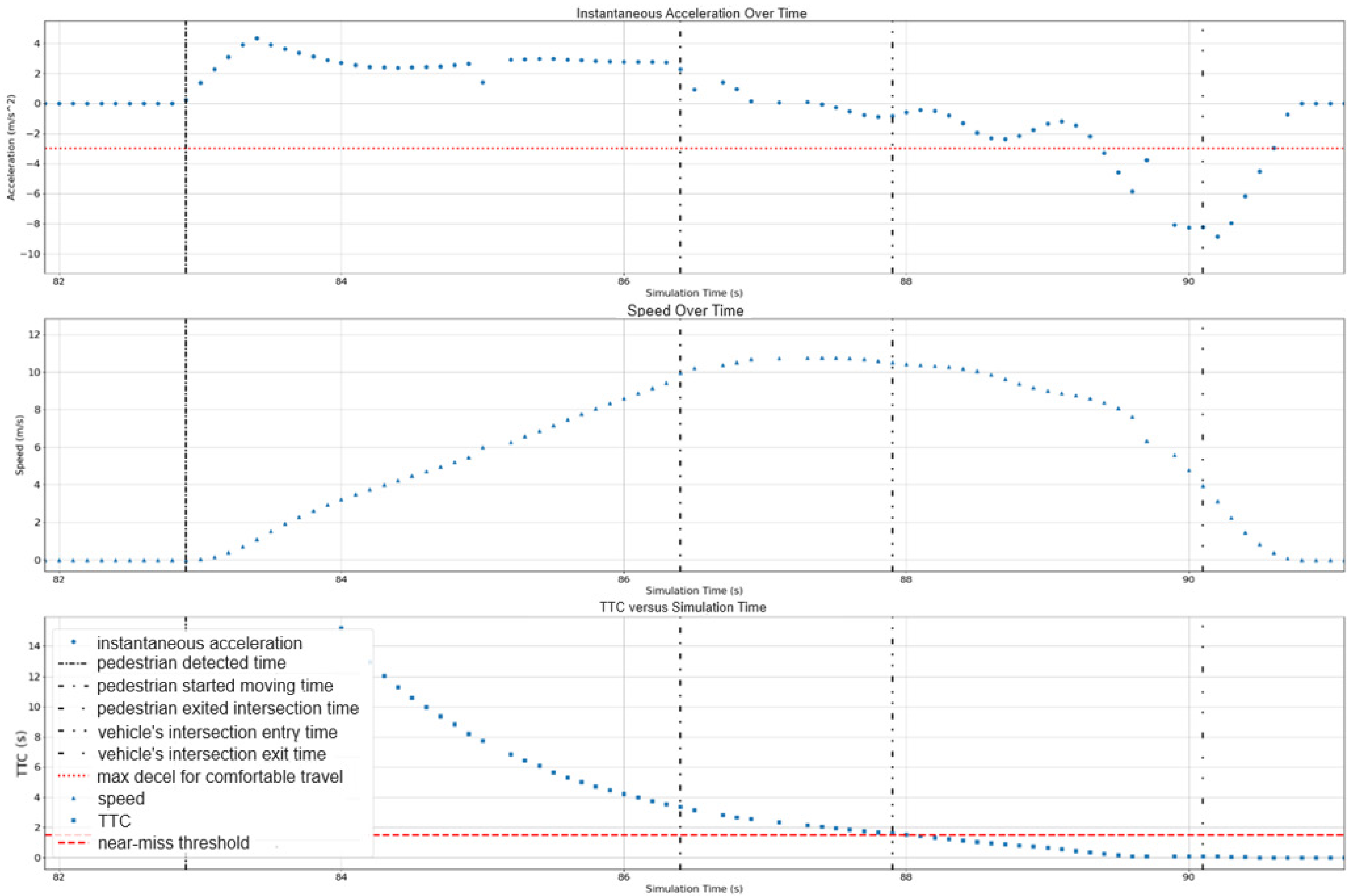
One of the most important performance metrics defined for this use case is the near-miss or collision percentage (see performance metric M-TC-1 in table 3), which assesses the level of safety improvement by enabling CP capabilities. In this use case, a near miss occurs when the time to collision (TTC) at any simulation time step is below a certain threshold. TTC is calculated based on the location, speed, and maximum acceleration and deceleration of the vehicle and the VRU. In the literature, a commonly accepted threshold for considering an event a near miss is a TTC value less than 1.5 s. Events with TTC values below this threshold are indicative of high-risk situations where immediate action is required to avoid a collision (Fu et al. 2019; Haleem, Alluri, and Gan 2015). Lowering the TTC threshold to 1.5 s allows for the ID of near misses that demand prompt, evasive maneuvers, thereby enhancing the safety protocols in autonomous vehicle systems. In this use case, the TTC threshold is set to 1.5 s.

The simulation results show that 100 percent of the simulation runs without CP enabled ended in a crash. The results also show that while all left-turn simulation runs with CP enabled resulted in a safe event where the vehicle yields to the VRU, one straight-through simulation run with CP enabled out of 24 simulation runs resulted in a crash, and 5 of them ended up with a near miss (i.e., a TTC value less than 1.5 s before the vehicle passed the conflict point). Figure 19 presents vehicle acceleration, speed, and TTC values over time for straight-through simulation runs for the following situations: one example test run without a crash or a near miss (parameter A), one test run that did have a crash (parameter B), and one example test run that did have a near-miss event (out of five runs total that had a near-miss event) (parameter C).



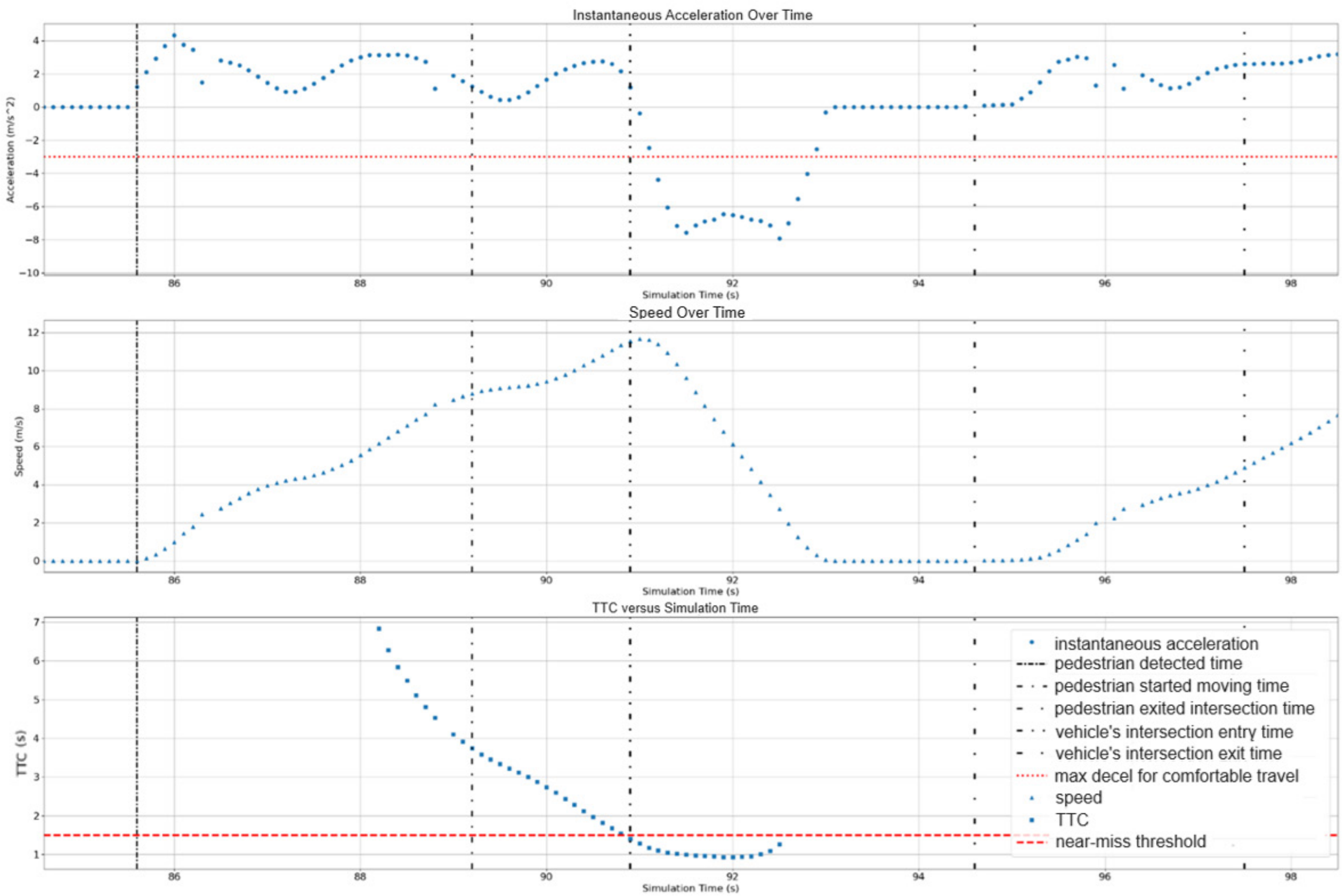
Source: FHWA.
decel = deceleration.

A. Example of a simulation run without a crash or near-miss event.



Source: FHWA.

B. Example of a simulation run with a crash event.



Source: FHWA.

C. Example of a simulation run with a near-miss event.

Figure 19. Graphs. Vehicle acceleration and speed profiles for straight-through simulation runs with CP enabled.

The crash event occurred due to a series of small deviations from the intended plan, with each contributing incrementally to the incident (the TTC value equal to zero at simulation time of approximately 89.5 s in figure 19-B indicates a crash event). Specifically for the crash event, there were only 3.6 s between the pedestrian starting to walk and the crash, primarily due to the high speed of the vehicle in the straight-through scenario. A potential collision detection can only be measured when a pedestrian starts walking because, despite the vehicle detecting the VRU long before through SDSMs, the vehicle can only estimate the VRU's trajectory once the VRU starts moving. The sequence of events unfolded as follows:

- The CARLA simulator, despite the pedestrian starting to walk when the vehicle was 40 ms away, gradually increased the pedestrian's speed, taking 0.7 s to reach the target speed, which reduced the vehicle's detection range to about 32 m (CARLA Team 2024)—2.9 s until the crash.

- A slight imperfection is known to be in the collision detection algorithm of the CARMA Platform, where the algorithm searches for potential collisions using the commanded trajectory rather than the trajectory that the vehicle can follow more reasonably (FHWA 2022b). This situation occurs because, at times, the commanded trajectory may have target speeds that are different than the vehicle can actually achieve at that time (e.g., continuously commanding 13.4 m/s for target speed although vehicle's speed only gradually changing from 10.0 m/s to 13.4 m/s) This problem is present only in certain segments of a trajectory, and CARMA Platform calculates collision risk imperfectly by operating under the assumption that what was planned was actually executed (FHWA 2022b). This calculation took about 0.6 s early in the run, with no potential collision detected—2.3 s until the crash.

- CARMA Platform lost the critical last few points needed to generate a trajectory for 0.4 s (until the vehicle travels more and new points become available on the road) due to aggressive down sampling of the road's centerline (FHWA 2022b)—1.9 s until the crash.

- CARMA Platform, after this event, could detect the potential collision and commanded a stop for 0.4 s, but this duration was not significant enough for the CARLA controllers to take effect, and the speed did not change much (FHWA 2022b; CARLA Team 2024)—1.5 s until the crash.

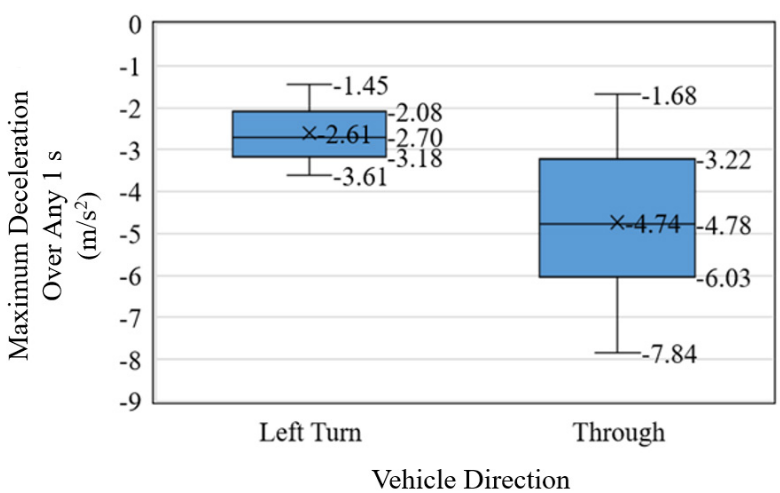
- The SDSM did not include the pedestrian at this time stamp and forced the CP to drop the track due to aggressive tuning. CP tuning should have been such that it would withstand such drops. CP is also tuned to take 0.3 s to confirm new tracks, so that period was also lost—1.2 s until the crash.

- CARMA Platform, at this point, detected the potential collision again and started decelerating (FHWA 2022b). However, the vehicle was only 10 m away at 9.6 m/s with 1.2 s left until the crash. Even with an emergency deceleration of 8.0 m/s² commanded, the CARLA controllers could only reduce its speed to 4.0 m/s when the crash happened. This circumstance is because 8.0 m/s² commanded is not an instantaneous deceleration due to the physical simulation model of vehicles in CARLA. In other words, in CARLA, 8.0 m/s² is achievable (and is the limit) but not instantaneously when commanded (CARLA Team 2024).

- These procedures effectively simulate the scenario where, even if a C-ADS platform detects a potential collision and provides counteractions, the physical vehicle still requires time to respond.

According to the results from 48 simulation runs with CP for both left-turn and straight-through movement scenarios, the developed CP VRU safety application could prevent 47 crashes (including 5 near-miss events); 1 actual crash occurred. The developed application could prevent 98 percent of crashes (albeit 10 percent were near-miss events). Therefore, for the tested scenarios, the developed application significantly enhances the safety of VRUs at signalized intersections.

Another measure for evaluating the performance of the TC algorithms is the smoothness of the vehicle trajectory when yielding to the VRU. To evaluate the vehicle trajectory smoothness, the vehicle's maximum deceleration rate over any 1-s interval of the simulation is calculated and stored. Figure 20 presents the box plot of the maximum deceleration rates for the left-turn and straight-through simulation runs with CP enabled. As shown in this figure, due to the imposed maximum lateral acceleration and deceleration and lower speed limits, vehicles can maintain smoother trajectories when turning left compared to traveling straight through the intersection. That is, the maximum deceleration rates of the straight-through simulation runs are much higher than the expected and comfortable deceleration rates, even though the vehicles are aware of the VRU presence at the intersection well in advance. This detail indicates that the implemented algorithms do not perform as expected and require future improvements.

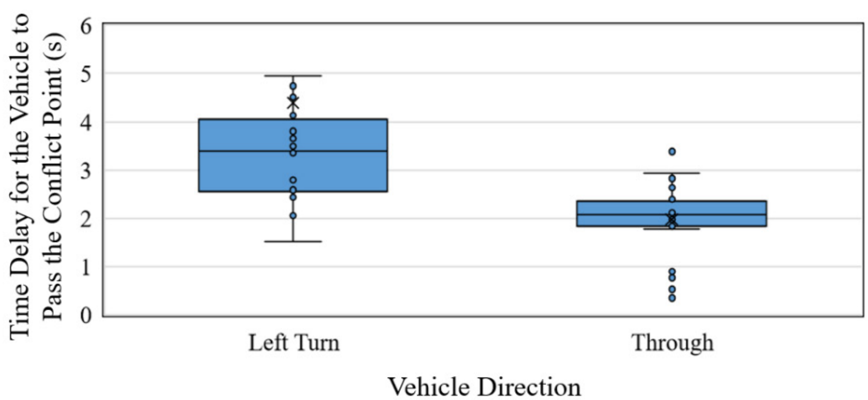


Source: FHWA.

Figure 20. Graph. Maximum deceleration rates over any 1-s interval for scenarios with CP enabled.

Specifically, further improvements are required for the yield plugin of CARMA Platform. This plugin uses the jerk-minimizing trajectory algorithm to generate a trajectory with minimum jerk, which means the plugin aims to minimize sudden changes in acceleration. Although comfortable deceleration is not the primary goal, given sufficient planning time and runway, this trajectory should naturally result in a comfortable deceleration for the vehicle. However, the current implementation does not account for situations in which the vehicle has already started decelerating and is experiencing a nonzero deceleration. Instead, during each iteration of trajectory generation, the algorithm mistakenly assumes a starting deceleration of zero and generates a new trajectory as if the deceleration were starting from scratch. This approach overlooks the previous trajectory, which would have resulted in a more accurate path if reused or refined more.

The last performance measure for the TC category focuses on the time delay for the vehicle in passing through the conflict point after the conflicting VRU has passed the conflict point. This measure is calculated by subtracting the minimum required time for the vehicle to pass the conflict point after the VRU has passed the conflict point from the actual time the vehicle took to pass the conflict point. The minimum required time for the vehicle to pass the conflict point is calculated based on the vehicle’s current speed, distance to the conflict point, and maximum acceleration rate, assuming the vehicle will aim to pass the conflict point as quickly as possible. As shown in figure 21, the vehicle experiences less time delay in straight-through scenarios compared to left-turn scenarios. This result is expected since the speed limit for the straight-through direction is relatively higher. Also, the vehicle's maximum acceleration during a left turn is lower than when going straight. Therefore, the vehicle requires more time to pass the conflict point. Overall, the time delay results show that the vehicle can quickly identify when the VRU has passed the conflict point and can accelerate and pass the conflict point with minimal delay.



Source: FHWA.

Figure 21. Graph. Time delay for the vehicle in passing through the conflict point.

High-Level Analysis Summary

Overall, the simulation results of this VRU use case reveal the following key findings:

- The simulation environment maintains consistent speed with CP enabled, and operating speed decreased by 18.5 percent on average, compared with no CP.

- RC remains stable and reliable across all runs in terms of the reliability and consistency of RC among various equipped services and objects.

- The CP system effectively maintains a low positional error due to controlled sensor noise, but the track fusion algorithm needs improvement to reduce its 2-m error margin to the ideal range of 0.5 to 1.5 m for better safety in autonomous vehicle applications. Despite no duplicated tracks, occasional missing tracks occur for short durations, indicating stable but improvable performance.

- The TC analysis shows relatively smooth vehicle trajectories during left turns compared to the straight-through scenario. The algorithm has room for improvements in straight-through scenarios to address higher deceleration rates.

- The time delay for vehicles passing through conflict points is minimal, especially in straight-through scenarios, showcasing effective conflict resolution after the VRU has passed the conflict point.

- The developed application significantly enhances the safety of VRUs at signalized intersections. According to the simulation results, the developed application prevented 98 percent of VRU crashes at the signalized intersection. Additional testing would be needed to extend the result to other scenarios and to make strong statements regarding the likely safety improvements in a real-world deployment.

Key improvements identified from the testing that need to be addressed in the future include the following:

- Improve CDASim's stability and efficiency to ensure it runs faster on machines other than the one used in testing. This action would lower the entry barrier as much as possible for other parties by enabling them to run CDASim on less powerful and, therefore, more cost-efficient machines (FHWA 2023).

- Increase the time step frequency of CDASim above that of its simulation tool components to minimize data delays, thus preventing CDASim from accidentally invoking the tool later than the time stamp when the tool was supposed to process the data (FHWA 2023).

- Upgrade CARLA and its related components in CDASim to a newer version than CARLA 0.9.10 (CARLA Team 2024). This action would help to improve sensor data results as 0.9.10 had faulty logic associated with the semantic LiDAR sensor, where the sensor provided erroneous actor IDs for the objects it was sensing.

- Improve sensor data sharing service time synchronization so that the sensor data sharing service never intermittently loses data.
- Improve the DF accuracy of the CP stack and its analysis method, especially for moving objects.
- Improve the track maintenance step of the CP stack so that it does not miss tracks as often (figure 17).
- Improve CARMA Platform's yielding behavior so that the vehicle comfortably decelerates under 3.0 m/s^2, still with the least amount of jerk as possible, with CP enabled (FHWA 2022b).
- Fix issues discovered in CARMA Platform during the testing that affect trajectory generation (FHWA 2022b).

CHAPTER 5. SUMMARY AND RECOMMENDATIONS FOR FUTURE RESEARCH

Walking and biking are two common modes of travel and exercise in urban and suburban areas. Supported by initiatives from the U. S. Department of Transportation (USDOT) and other transportation agencies, these activities are promoted to reduce congestion and ensure the health and wellness of the U.S. public (FHWA 2024a).

Despite the overall decline in transportation-related fatalities due to various safety strategies, the fatality rate for VRUs continues to rise (USDOT 2023). This trend underscores the critical need to enhance VRU safety at urban signalized intersections to accommodate the large demand for walking and biking. Emerging technologies in transportation, such as CDA and CP, offer promising opportunities to improve VRU safety at such intersections.

The recent research activities at FHWA's HRSO have laid a strong foundation for leveraging CDA and CP technologies to enhance VRU safety. This project builds on that foundation by developing a CP VRU safety application designed to use both CDA and CP technologies to improve safety at signalized intersections.

The CP VRU safety application focuses on DF and communication capabilities for both infrastructure and vehicles to support VRU perception at intersections. By facilitating CP, DF from infrastructure and C-ADS-equipped vehicles can enhance the safety of all road users within the communication range.

Evaluated within a simulation environment, the CP VRU safety application demonstrated significant safety enhancements for VRUs at signalized intersections. For the specific simulations that the researchers conducted, the application could prevent 98 percent of VRU crashes. Additionally, the application shows promising levels of precision and reliability in detection and track maintenance. The TC analysis in CP scenarios reveals that vehicle trajectories during left turns are smoother and closer to a comfortable deceleration level compared to straight-through scenarios, with a mean deceleration of less than 3.0 m/s^2 within any given second of the run. However, future improvements could potentially achieve even smoother and more comfortable deceleration, particularly in straight-through scenarios where higher deceleration rates were observed.

Several key opportunities for future improvements exist as well. First, the MOT algorithm can be improved for greater accuracy and reliability by more sophisticated association methods and track maintenance policies. Second, known imperfections in the CARMA Platform's yield plugin should be fixed to eliminate the current latency in detecting the collisions and use more sophisticated behavior prediction for both static and dynamic VRUs. Third, trajectory generation for obstacle avoidance should be improved for higher speed scenarios to provide smoother stops using a comfortable deceleration rate (less than 3.0 m/s^2) as well as minimize jerk as much as possible. Given the significant safety benefits demonstrated by the developed application, currently known issues need to be addressed first, and then further evaluation through field experiments is recommended.

APPENDIX. HIGH-LEVEL SYSTEM REQUIREMENTS

This appendix summarizes the high-level operational needs and the functional requirements of CP features for the four scenarios discussed in chapter 3. The operational needs and functional requirements are classified into five categories: object detection and perception (ODP), communications (COMM), computer security (CS), DF, and CPA.

Table 6 provides information about CP operational needs. ID numbers provide the following information: CP (to distinguish from other features being developed within the CDA Program)-N (operational need to distinguish from system function requirement (SR))-ODP, COMM, CS, DF, or CPA (categories)-*X* (number). For example, the vehicle-based ODP operation need is represented by CP-N-ODP-01, while the infrastructure-based need is represented by the next number, CP-N-ODP-02 (FHWA 2022a). These operational needs and functional requirements inform the development of the system requirements of the CARMA CP features in this use case.

Table 6. CP operational needs.

Category	ID	Relevant Component	Operational Needs Statement
ODP	CP-N-ODP01	CARMA Platform, CDASim (FHWA 2022b, 2023)	Need to receive and process object-level perception data from different local onboard extrospective sensors (e.g., LiDAR or cameras) in realtime. The process should detect external objects—such as location, speed, heading, dimensions, acceleration, and yaw rate—and perceive their status.
ODP	CP-N-ODP02	CARMA Streets, CDASim (FHWA 2022b, 2023)	Need to receive and process object-level perception data from infrastructure-based roadside sensors in realtime.
COMM	CP-N-COMM01	CARMA Platform, CDASim (FHWA 2022b, 2023)	Need to temporarily store and broadcast processed perception data from local onboard extrospective sensors.
COMM	CP-N-COMM02	CARMA Streets, CDASim (FHWA 2022b, 2023)	Need to temporarily store and broadcast processed perception data generated from infrastructure-based roadside sensor data.
COMM	CP-N-COMM03	CARMA Platform, CDASim (FHWA 2022b, 2023)	Need to receive and temporarily store processed perception data generated by other agents.
CS	CP-N-CS01	All	Need to have proper CS platforms and strategies to protect and recover from cyber threats.

Category	ID	Relevant Component	Operational Needs Statement
DF	CP-N-DF01	CARMA Platform (FHWA 2022b)	Need to combine perception data 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 updates.
CPA	CP-N-CPA01	CARMA Platform (FHWA 2022b)	Need to update relevant ADS and C-ADS features to effectively use CP to improve safety and efficiency.

Table 7 provides information on CP functional requirements. ID numbers provide the following information: CP-SR (system functional requirement)-*X* (number).

Table 7. CP functional requirements.

ID	Relevant Component	Functional Requirements Statement	Traces To
CP-SR01	CDASim (FHWA 2023)	Sensors mounted on C-ADS-equipped vehicle detect and transmit external objects, such as vehicles, motorcycles, cyclists, and pedestrians at frequency of no less than 10 Hz. Sensors perceive the following attributes of detected external objects: absolute location, location relative to the subject vehicle, speed, heading, and size (i.e., length, width, height).	CP-N-ODP01
CP-SR02	CARMA Platform, CDASim (FHWA 2022b, 2023)	CDASim provides interfaces for connecting to virtual sensors such as LiDAR, camera, or radars to CARMA Platform.	CP-N-ODP01
CP-SR03	CDASim (FHWA 2023)	Infrastructure sensors, including, but not limited to, virtual LiDAR, visible spectrum cameras, or radar installed at static locations (such as an intersection) transmit object-level sensor data to infrastructure computers, including, but not limited to, CARMA Streets, at a frequency of no less than 10 Hz. Sensors perceive the following attributes of detected external objects: absolute location, location relative to the subject vehicle, speed, heading, and size (i.e., length, width, height).	CP-N-ODP02
CP-SR04	CARMA Streets, CDASim (FHWA 2022b, 2023)	CDASim provides interfaces for connecting to virtual sensors such as LiDAR, camera, or radars to CARMA Streets.	CP-N-ODP02

ID	Relevant Component	Functional Requirements Statement	Traces To
CP-SR05	CARMA Platform, CDASim (FHWA 2022b, 2023)	A C-ADS-equipped vehicle wirelessly transmits processed object-level perception data from local sensors at a 10-Hz frequency.	CP-N-COMM01
CP-SR06	CARMA Streets, CDASim (FHWA 2022b, 2023)	An infrastructure computer wirelessly transmits processed object-level perception data at a 10-Hz frequency.	CP-N-COMM02
CP-SR07	CARMA Platform (FHWA 2022b)	A C-ADS-equipped vehicle consumes object-level perception data received from other entities at a frequency greater than or equal to the transmission frequency.	CP-N-COMM03
CP-SR08	CARMA Platform (FHWA 2022b)	A C-ADS-equipped vehicle fuses local and received object-level perception data at a frequency greater than or equal to the transmission frequency of CP messages.	CP-N-DF01
CP-SR09	CARMA Platform (FHWA 2022b)	A C-ADS-equipped 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-SR10	CARMA Platform (FHWA 2022b)	A C-ADS-equipped vehicle satisfies CS requirements set forth in NIST 800 series publications (NIST n.d.).	CP-N-CS01
CP-SR11	All	Simulation computer running the cosimulation tool meets the CS requirements set forth in NIST 800 series publications (NIST n.d.).	CP-N-CS01

NIST = National Institute of Standards and Technology.

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