U.S. Department of Transportation
Federal Highway Administration

cda ANNUAL REPORT

Publication No. FHWA-HRT-24-089

CDA Program Overview:[1]
https://www.youtube.com/watch?v=moxMSXyY8Rg

CARMA℠ Video Series YouTube link:[2]
https://www.youtube.com/playlist?list=PL5_sm9g9d4T2MK54sZh5iV0vKKFuvgzBH

WZM red light testing scenario:[3]
https://youtu.be/tZf2xE8tt10

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QR code for FHWA VOICES SIT-1 video:[5]
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<table>
<tr><td>1. Report No.
FHWA-HRT-24-089</td><td colspan="2">2. Government Accession No.</td><td colspan="2">3. Recipient’s Catalog No.</td></tr>
<tr><td colspan="3" rowspan="2">4. Title and Subtitle
2022 CDA Annual Report</td><td colspan="2">5. Report Date
April 2024</td></tr>
<tr><td colspan="2">6. Performing Organization Code</td></tr>
<tr><td colspan="3">7. Authors
Animesh U..Balse; Mitali Bellamkonda; Zachary R. Cooper; Amir Ghiasi; Zhitong Huang; Robin Laqui (ORCID: 0009-0004-8967-0699); Edward M. Leslie; Yingyan Lou; Shreekant V. Marwadi; Stephen Moyer; Francois P. Nieto; Osama Osman; Khandakar M. Rashid; Sujith K. Racha; Saeid Soleimaniamiri; Ankur Tyagi; Zachary W. Urban</td><td colspan="2">8. Performing Organization Report No.</td></tr>
<tr><td colspan="3" rowspan="2">9. Performing Organization Name and Address
Leidos Inc.
1750 Presidents Street
Reston, VA 20190</td><td colspan="2">10. Work Unit No.</td></tr>
<tr><td colspan="2">11. Contract or Grant No.
693JJ321D000010</td></tr>
<tr><td colspan="3" rowspan="2">12. Sponsoring Agency Name and Address
U.S. Department of Transportation
Federal Highway Administration
1200 New Jersey Avenue, SE
Washington, DC 20590</td><td colspan="2">13. Type of Report and Period Covered
Final report; January 2022–December 2022</td></tr>
<tr><td colspan="2">14. Sponsoring Agency Code
HRSO-40</td></tr>
<tr><td colspan="5">15. Supplementary Notes
The task order manager was Sudhakar Nallamothu (HRSO-40; ORCID: 0000-0002-7457-3704).</td></tr>
<tr><td colspan="5">16. Abstract
The Cooperative Driving Automation (CDA) Annual Report highlights the achievements of the CDA program and discusses the use cases that were created and researched to further overall CDA program objectives to enable a cooperative, safe, efficient, and sustainable transportation system for all users. This report also details engagement activities with stakeholders from academia, industry, and government through conferences, video, and publications.</td></tr>
<tr><td colspan="2">17. Key Words
CDA, cooperative driving automation, CARMA</td><td colspan="3">18. Distribution Statement
No restrictions. This document is available through the National Technical Information Service, Springfield, VA 22161.
https://www.ntis.gov</td></tr>
<tr><td>19. Security Classif. (of this report)
Unclassified</td><td colspan="2">20. Security Classif. (of this page)
Unclassified</td><td>21. No. of Pages
105</td><td>22. Price
N/A</td></tr>
</table>

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized.

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

ADS	automated driving system
AI	artificial intelligence
ARC-IT	Architecture Reference for Cooperative and Intelligent Transportation
ARPA-E	Advanced Research Projects Agency–Energy
AV	automated vehicle
C-ADS	cooperative automated driving system
CARLA	car learning to act
CAV	connected and automated vehicle
CAVe	CAV education
CDA	cooperative driving automation
CMV	commercial motor vehicle
ConOps	concept of operations
CP	cooperative perception
CTSE	critical time step estimation
CV	connected vehicle
C-V2X	cellular vehicle-to-everything
DSRC	dedicated short-range communication
ERV	emergency response vehicle
FHWA	Federal Highway Administration
GPS	Global Positioning System
HD	high definition
IHP	integrated highway prototype
ITS	intelligent transportation system
MOM	mobility operation message
NEXTCAR	NEXT-Generation Energy Technologies for Connected and Automated On-Road Vehicles
OBU	onboard unit
OEM	original equipment manufacturer
PoC	proof of concept
PSM	personal safety message
R&D	research and development
RSE	roadside equipment
RSU	roadside unit
RWM	road weather management
SAE	Society of Automotive Engineers
SPaT	signal phase and timing
STOL	Saxton Transportation Operations Laboratory
TCM	traffic control message
TCR	traffic control request
TFHRC	Turner-Fairbank Highway Research Center
TIM	traffic incident management
TOSCo	Traffic Optimization for Signalized Corridors
TS	trajectory smoothing

TSMO	transportation systems management and operations
USDOT	U.S. Department of Transportation
VRU	vulnerable road user
V2I	vehicle to infrastructure
V2V	vehicle to vehicle
V2X	vehicle to everything
WZM	work zone management
XiL	everything-in-the-loop

A MESSAGE FROM THE DIRECTOR

Source: FHWA.

It is my pleasure to introduce the first installment of the Federal Highway Administration's (FHWA's) *Cooperative Driving Automation (CDA) Annual Report*. This comprehensive document reflects thousands of hours of labor in 2022 by some of the brightest minds in all of transportation. The scope of work that goes into CDA advancement is truly impressive—from intricate test planning and delicate choreography among multiple vehicles, sensors, and infrastructure components to physical maintenance of high-end hardware and ongoing updates to critical software, to building relationships with other researchers, and to communicating our progress to the public.

The nature of research is that, in large part, the work has never been done before. That fact alone can be a major hurdle. How do we arrive at a destination without a map, especially when the destination exists only in theory? I am excited to share this report with you and demonstrate the accomplishments of FHWA in 2022 to meet that challenge head-on. This report centers on eight key use cases that our team completed in 2022 to achieve holistic advancement of CDA in a diverse set of applications and conditions. In the following pages, you will learn how we performed the use cases by challenging previously accepted assumptions, experimenting with new technologies, bringing in experts from outside of Government, and ultimately developing new standards of practice that all parties interested in the advancement of CDA can benefit from.

Inside this report, you will find how CDA is transforming the future of transportation and adding value to the transportation system and the Department's mission by bringing safe, efficient, and equitable autonomous driving to the Nation's roadways. If you would like to know more about CARMA℠ outside of our CDA research, we have a plethora of videos, research, and reports for you to explore online at https://highways.dot.gov/research/operations/CARMA.[11]

Sincerely,

Carl Andersen
Acting Director, Office of Safety and Operations Research and Development
FHWA

ABOUT CDA AND RESEARCH AT TURNER-FAIRBANK HIGHWAY RESEARCH CENTER

Cooperative driving automation (CDA) facilitates communication and cooperation between properly equipped vehicles, infrastructure, and other road users. The SAE International J3216™ standard defines CDA as having four classes of cooperation—called Classes A–D—with increasing levels of cooperation in each successive class:[(12)]

- Class A: Status sharing.
- Class B: Intent sharing.
- Class C: Agreement seeking.
- Class D: Prescriptive.

Information shared among CDA participants can directly influence the dynamic driving task by one or more nearby vehicles with driving automation features engaged. Ultimately, CDA-enabled cooperation can facilitate safer and more efficient movement of road users, which can improve the overall performance of the transportation system—and at lower cost than traditional methods.

During the past 10 years, the Federal Highway Administration's (FHWA's) CDA program, based at Turner-Fairbank Highway Research Center (TFHRC) in McLean, VA, has shaped the future of transportation automation by strengthening infrastructure and developing platforms for collaborative research and development (R&D) of CDA to advance the safety, efficiency, and sustainability of the entire transportation system.

I am extremely proud of everything we accomplished in 2022. Not only did we make significant advances in CDA for light cars and freight operations, but we also prioritized ways to keep pedestrians and other vulnerable road users safe. We have done so much to establish a baseline of technologies and standard practices that I believe put us at a tipping point for even more exciting developments as we push toward CDA deployment.

—Carl Andersen, FHWA

Source: FHWA.

Source: FHWA.

ADVANCES IN CDA: AN OVERVIEW

The future of global CDA demands a secure and connected infrastructure capable of receiving and understanding valid messages and interpreting intended actions of connected and automated vehicles (CAVs). To that end, significant advances are recommended for key components of the infrastructure and for vehicles and their ability to communicate. Current research includes data analysis and observations of technology performance, interference performance, and adequacy of the 30-MHz frequency for safety-critical communications.

In 2022, FHWA achieved significant advances toward standardized message sets that inform CDA vehicles about their surroundings and environments to help make informed decisions. The achievements will ensure that CAVs can make safe movements in recognition of other vehicles and pedestrians.

Source: FHWA.

Another takeaway from 2022 is that for CDA to continue to advance, original equipment manufacturers (OEMs), advanced driver-assistance systems (ADAS), and connected infrastructure will have to develop their capabilities for improved behavior and operations.

A broad range of industry stakeholders that are interested in integrating CDA into their products includes a variety of vendors, developers, manufacturers, users, policymakers, and researchers. The various levels of driving automation are described and defined in figure 1. Successful integration of CDA into real-world infrastructure will rely on:

- More aggressive collaborations among OEMs, software developers, vendors, researchers, academia, vehicle manufacturers, and local, State, and national transportation collaborators.

- Accessible, transferable processes and methods for testing new applications of CDA technologies.
- A multiphase plan to build on public–private collaborations for testing of autonomous public transportation initiatives.
- Resolution of challenges associated with poor Global Positioning System (GPS) access and localization to help resolve light detection and ranging (LiDAR) and high-definition (HD) mapping limitations for isolated communities such as rural environments that lack access to infrastructure networks.
- Methods to adapt to climate change wherein roadway surfaces and infrastructure in situations affecting and requiring real-time route-change adjustments and assessments for alternative routes.

SAE® J3016™ Levels of Driving Automation

	SAE® Level 0	SAE® Level 1	SAE® Level 2	SAE® Level 3	SAE® Level 4	SAE® Level 5
What does the human in the driver's seat have to do?	You <u>are</u> driving whenever these driver support features are engaged – even if your feet are off the pedals and you are not steering			You <u>are not</u> driving when these automated driving features are engaged – even if you are seated in "the driver's seat"		
	You must constantly supervise these support features; you must steer, brake, or accelerate as needed to maintain safety			When the feature requests You must drive	These automated driving features will not require you to take over driving	
	These are driver support features			**These are automated driving features**		
What do these features do?	These features are limited to providing warnings and momentary assistance	These features provide steering **OR** brake/ acceleration support to the driver	These features provide steering **AND** brake/ acceleration support to the driver	These features can drive the vehicle under limited conditions and will not operate unless all required conditions are met		This feature can drive the vehicle under all conditions
Example Features	▪ automatic emergency braking ▪ blind spot warning ▪ lane departure warning	▪ lane centering OR ▪ adaptive cruise control	▪ lane centering AND ▪ adaptive cruise control at the same time	▪ traffic jam chauffer	▪ local driverless taxi ▪ pedals/ steering wheel may or may not be installed	▪ Same as level 4, but feature can drive everywhere in all conditions

Figure 1. Illustration. SAE J3016™ taxonomy and definitions for terms related to driving automation systems for on-road motor vehicles.[(13)]

This report is organized into two main sections. The first section, FHWA's CDA Use Cases, describes the use cases that have been demonstrated during the past year. These use cases aim to answer research questions such as how infrastructure can help improve pedestrian safety. They provide the basis for future research that advances the deployment of technologies that improve safety and efficiency in transportation.

The second section, FHWA's CDA Program Activities, discusses additional FHWA research and technologies that are not directly related to the CDA use cases. The section also summarizes

FHWA-funded grants, along with high-level program metrics such as how many miles were logged in testing. The section includes communications message sets developed during testing. Finally, the section discusses publications and stakeholder engagement activities such as workshops.

FHWA'S CDA USE CASES

FHWA objective is to improve transportation through research into CDA technologies, and the work that TFHRC performs helps accomplish that objective. This work involves maintaining a fleet of CDA-equipped vehicles, as shown in figure 2.

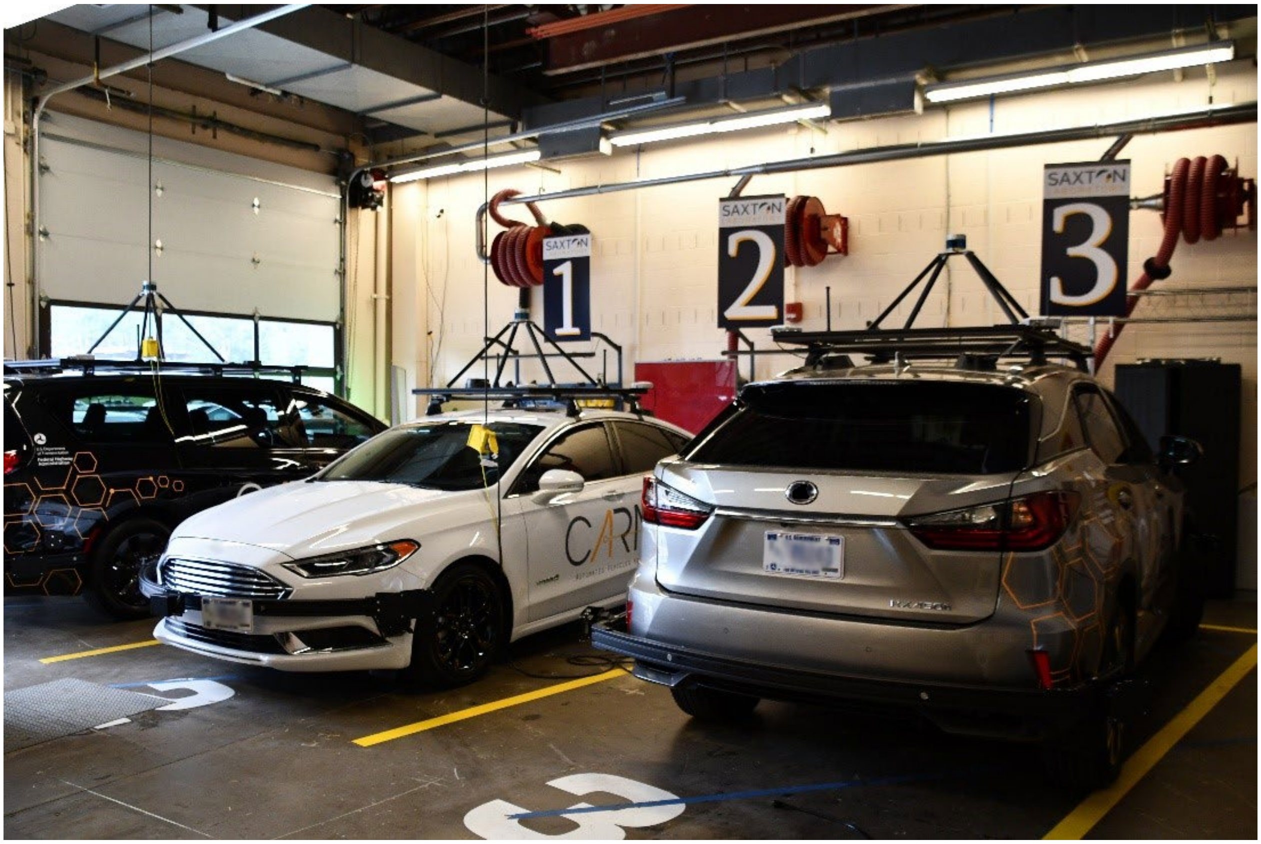
Vehicle-to-Everything (V2X) Communication

All of the following use cases were developed and tested using dedicated short-range communication (DSRC). With the V2X communication spectrum moving from DSRC to cellular vehicle to everything (C-V2X), and the radioagnostic nature of the software, the same tests may be repeated using C-V2X radios that follow the roadside unit (RSU) 4.1 specification.(14)

As research continues into CAVs, FHWA must answer such questions as follows: How will infrastructure communicate with vehicles for safe navigation through a work zone? and How can infrastructure help improve pedestrian safety? The questions have been answered through research conducted at the Saxton Transportation Operations Laboratory (STOL).

This section presents some of the CDA use cases that have been demonstrated and that answered the questions with the help of connected infrastructure.

Each case was developed at STOL in collaboration with FHWA and university research stakeholders. The use cases provide the future FHWA work that will advance industry closer to deployment of technologies that will improve safety and efficiency in transportation.



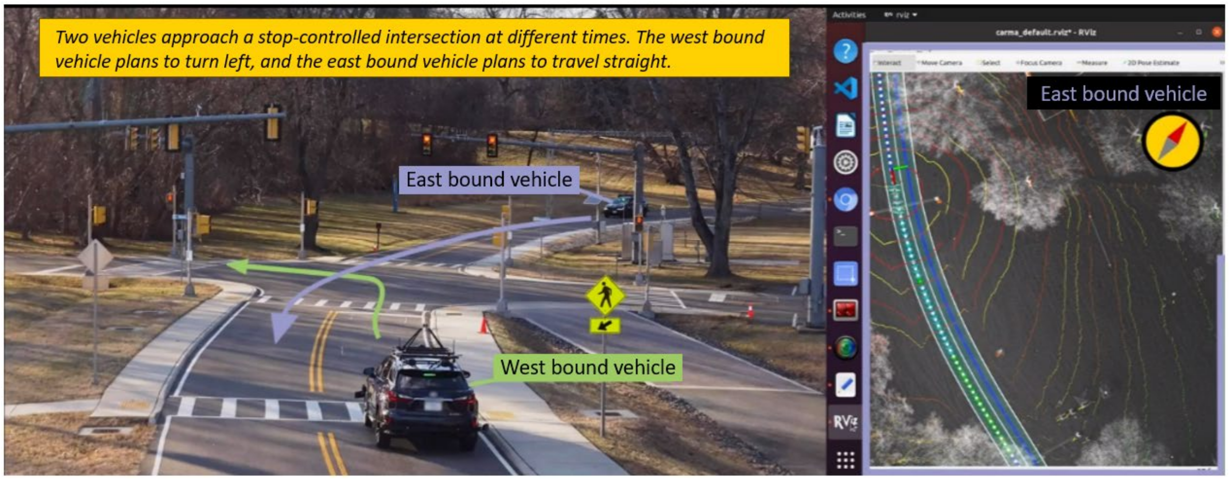
Source: FHWA.

Figure 2. Photo. CARMA vehicles parked in the Saxton Transportation Operations Laboratory garage.

STOP-CONTROLLED INTERSECTIONS

Objective

The goal of transportation systems management and operations (TSMO) use case 1 is to demonstrate the use of CDA and its benefits for stop-controlled intersections. The objective is to further improve traffic safety, throughput, and energy efficiency by enabling vehicles and infrastructure to work together to coordinate movement through a stop-controlled intersection. Figure 3 shows testing for TSMO use case 1.



Source: FHWA.

Figure 3. Photo. Transportation systems management and operations use case 1 testing at TFHRC.

Description

In this use case, cooperative automated driving system (C-ADS)-equipped vehicles inside the communication area of the intersection broadcast to infrastructure certain real-time information about their operating states (e.g., location, speed, and acceleration) and intents (e.g., direction—entry lane, target exit lane). The infrastructure uses the information to calculate a set of schedules that optimize system performance. The infrastructure then transmits the necessary information (e.g., the first available time to enter the intersection box) to the vehicles. With that, each vehicle smooths its own trajectory based on the schedule it received. The vehicle makes a full stop when it arrives at the intersection and departs the intersection after receiving permission from the infrastructure. The permission the infrastructure provides is calculated based on the first-come-first-served rule and each vehicle's route.

Benefits for Transportation

The developed algorithm contains a set of hard safety constraints that avoid potential crash risks and uncomfortably high accelerations and decelerations. For example, the infrastructure does not enable multiple vehicles with conflicting directions to simultaneously depart the intersection. Also, the algorithm maximizes intersection throughput and minimizes overall travel delay at intersections by enabling vehicles with nonconflicting directions (e.g., two right turns) to simultaneously pass through the intersection. Finally, the use case seeks to smooth vehicle trajectories, which in turn minimizes energy consumption and improves riding comfort.

State of Practice

From an operations perspective, the proposed CDA framework for this use case presents changes to the ways traffic can be operated at stop-controlled intersections. With proper upgrades in intelligent transportation infrastructure systems (e.g., by equipping such systems with roadside equipment (RSE) and edge-computing devices), information exchanges can be supported to accommodate the needs for such CDA use cases.

Technical Specifications

Parts of CARMA Ecosystem Used

To enable TSMO use case 1, the following technology is used:

- Stop-controlled intersection.
- CARMA Platform℠.[158]
- CARMA Streets℠.[15]
- Vehicle-to-Everything (V2X) Hub.[16]

The implemented cooperative framework for this use case has two main components:

- Critical time step estimation (CTSE).
- Trajectory smoothing (TS).

First, the CTSE component estimates a set of critical time steps (e.g., stopping time at the stop bar and entry time) to the intersection box for each C-ADS-equipped vehicle. This component is called at CARMA Streets in a centralized manner.[15] The outcome of this component is broadcast to the CARMA Platform℠ installed in C-ADS-equipped vehicles via V2X Hub.[16,17] Second, the TS component is called at CARMA Platform in a decentralized manner to control C-ADS-equipped vehicle trajectory based on the estimated critical time steps.

Hardware and Software

The following technology is used on the infrastructure side in this use case:

- CARMA Streets release 3.11 and above.[15]
- V2X Hub release 7.1 and above.[16]

The following technology is used on the vehicle side in this use case:

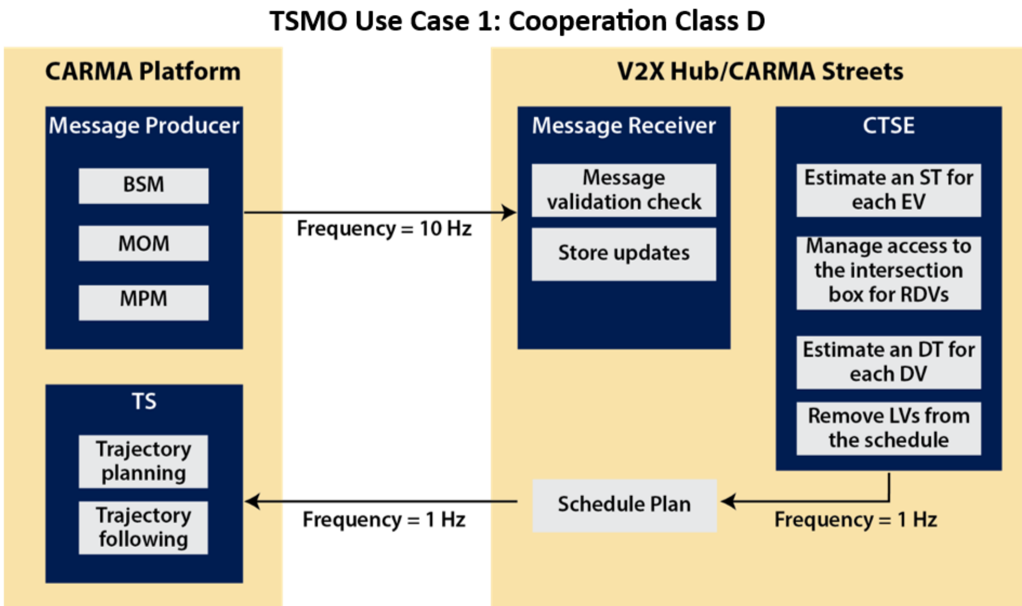
- CARMA Platform vehicles.[15]
- CARMA Platform release 3.11 and above.[18]

The following standards are used in this use case:

- SAE Taxonomy and Definitions for Terms Related to CDA for On-Road Motor Vehicles: J3216_202107.[12]
- SAE Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles: J3016_202104.[13]
- SAE V2X Communications Message Set Dictionary: J2735_202211.[19]

Architecture, Logic, Connectivity, and Communication

The architecture for TSMO use case 1 is illustrated in figure 4.



Source: FHWA.
BSM = basic safety message; DT = departure time; DV = departing vehicle; EV = entering vehicle; LV = leaving vehicle; MOM = mobility operation message; MPM = mobility path message; RDV = ready-to-depart vehicle; ST = stopping time.

Figure 4. Diagram. TSMO stop-controlled intersections architecture.

Results

Testing Overview

To evaluate and fine-tune the developed algorithms, the research team conducted simulation experiments in a microscopic traffic simulator. The experiments included several scenarios to replicate real-world traffic conditions such as various traffic demand levels and different intersection geometries.

For the experiments, the team considered a set of objective measures:

- Throughput.
- Average delay.
- Level of service at the intersection.
- Average fuel consumption.
- Average stopping time.

The simulation results showed that the developed algorithms improved almost all the objective measures, which generally get improved with vehicles' cooperation classes. Additionally, the team performed several levels of proof-of-concept (PoC) testing (i.e., integration, verification, and validation). The intent of the test-revision cycles is to move the research closer to deployment.

The test plan documents define test acceptance criteria, which decide whether a test scenario is successful or not. The criteria have various operational aspects:

- Communication.
- Safety.
- Mobility.
- Trajectory smoothness.

To analyze the test results, the team collected and processed log files from CARMA Streets and CARMA Platform.(18) Initial analyses from the verification and validation testing show that the PoC frameworks improved most of the metrics identified in the test plans.

Verification Testing

Verification testing took place at TFHRC in McLean, VA. Two test scenarios were defined for the verification testing: conflicting and nonconflicting. Each scenario used two CARMA vehicles. For both scenarios, the team determined the vehicles' starting times such that the two vehicles arrived at the intersection at nearly the same time.

In the first scenario:

- Two vehicles approached a stop-controlled intersection.

- One of the vehicles had a straight direction inside the intersection box in its path, while the other one had a left-turn direction inside the intersection box in its path. Therefore:
    - The vehicles had directions that conflicted with each other inside the intersection box.
    - One of the vehicles had to stop at the stop bar and receive access to the intersection box earlier than the other.

In the second scenario:

- Both vehicles had right-turn directions inside the intersection box.
- Therefore, the vehicles did not have conflicting directions with each other inside the intersection box, and both vehicles could:
    - Stop at the stop bar.
    - Receive access to the intersection box.
    - Enter the intersection box at the same time.

For both scenarios, the tests passed the test acceptance criteria. In the way that PoC test standards require, the research team marked a test successful when the team observed at least four successful runs out of every five consecutive runs. When unsuccessful runs occurred, they were due to localization issues. That criterion implies that the system has been implemented to an acceptable level for a PoC test. However, more efforts, including implementation and testing, may be needed to improve the system for real-world deployments—and especially to evaluate the safety impacts of this algorithm. Unsuccessful runs due to localization issues are disregarded from the analyses for two reasons:

- Localization issues have nothing to do with use case algorithms and performance.
- Improper localization that the inputs required for use case algorithms are not valid, and so the analyses are not conclusive.

Validation Testing

Validation testing also took place at TFHRC. An independent evaluator developed and executed the validation test plan. The evaluation defined three scenarios in the test plan:

- Scenarios 1 and 2 were similar to those completed for verification testing.
- Scenario 3 had conflicting directions at the intersection, but the difference was that the vehicles' initial positions and/or start times were different. The intent of this scenario was to check whether the system would enable access to a vehicle arriving at the intersection stop line while the other vehicle was still approaching the intersection from the opposite side.

For each scenario, the test demonstrated functionality per the test plan.

Test Results and Level of Performance and Advancement

To evaluate the system's performance, the team collected data and defined and calculated 11 performance metrics. Evaluation of the metrics showed that all performance metrics were passed in representative test runs that were reviewed (not all test runs were completely processed due to limited resources). However, the team faced a few issues relevant to vehicle control performance. In addition, vehicle-to-vehicle (V2V) communication—especially between vehicles in the same lane or approach—was not considered in the testing, and so additional work was needed for full realization of the use case. Testing and demonstration of the use case showed no safety concerns that would prevent further development.

Next Steps

This use case proved the benefits that could be realized through the application of CDA at stop-controlled intersections. While a few limitations were identified through data collection and analysis, the scenarios raised no safety concerns, and high potential for future work remains intact.

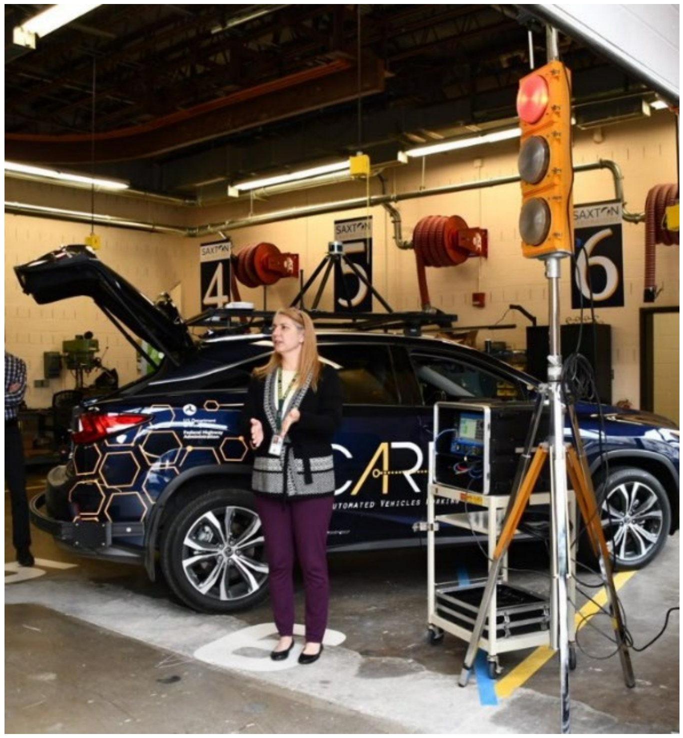
In particular, the developed framework can be improved in three ways:

- Applying V2V communications in this framework can enable this use case for higher scale deployments and thus can potentially realize the benefit demonstrated in simulation experiments.
- Extending this use case to a mixed traffic environment, wherein only a portion of traffic consists of C-ADS-equipped vehicles can facilitate faster and more realistic deployments.
- Improving this use case to consider vulnerable road users (VRUs) in the system will make the use case more realistic and more reliable and move it closer to future deployments.

FIXED-TIME TRAFFIC SIGNALS

Objective

This use case demonstrates CDA and its benefits for signalized intersections with fixed-time settings. The objective is to improve traffic throughput and energy efficiency by providing CAVs with signal timing information about signalized intersections. Figure 5 shows a fixed-time signal and CARMA-equipped car used in testing.



Source: FHWA.

Figure 5. Photo. CARMA vehicle used for a demonstration parked in the STOL garage.

Description

In this use case, automated driving system (ADS)–equipped vehicles inside the communication area of the intersection receive signal phase and timing (SPaT) messages from the infrastructure. With that information, each vehicle smooths its own trajectory to either pass through the intersection during a green interval if possible or minimize its stopping time. The anticipated vehicles' speeds passing through the intersection will increase. Also, due to less stop-and-go traffic, the startup delay will be reduced, which in turn increases intersection throughput and vehicle fuel efficiency.

Benefits for Transportation

This use case is designed to improve throughput and the energy efficiency of traffic at signalized intersections with fixed-time settings while maintaining safety. The framework maximizes intersection throughput and minimizes overall travel delay at intersections by enabling vehicles to pass through the intersection with minimum stops or no stops. These trajectories minimize energy consumption and improve riding comfort.

State of Practice

From an operations perspective, the proposed CDA framework for this use case presents changes to the ways traffic can be operated at signalized intersections. This use case relies on RSE to generate standard SPaT inputs to the use case algorithm that consider existing standards and practices except for a few limitations (e.g., excluding pedestrian calls).[1,2,3] Therefore, as standards and practices evolve, FHWA researchers upgraded RSE accordingly. With proper upgrades in intelligent transportation infrastructure systems (e.g., equipped with RSE), vehicles can be provided with sufficient information to accommodate the needs for such CDA use cases. Agencies also need to evaluate and build capabilities for operating such emerging systems. The conventional process of transportation system performance monitoring and reporting would be revolutionized with the prevalence of C-ADS-equipped vehicles and advanced sensors. Conventional strategies for implementing signalized intersections, which agencies are already familiar with, can be significantly enhanced by CDA technologies.

Technical Specifications

Parts of CARMA Ecosystem Used

CARMA Platform and V2X Hub enable TSMO use case 2—DA Vehicle Optimization at Fixed-Time Traffic Signals.(18,19) This framework broadcasts SPaT messages via the V2X Hub, and then the CTSE component at CARMA Platform estimates the time the vehicle can enter the intersection based on the received SPaT information.(18) Afterward, the TS component at CARMA Platform controls the C-ADS-equipped vehicle trajectory accordingly to minimize the vehicle's stopping time and optimize the vehicle's energy and fuel efficiency.(18) This use case is like a past use case called ecoapproach and departure, wherein an SAE Level 1 vehicle equipped with a previous CARMA software version reacts to the received SPaT messages.(13) The new use case is extended to accommodate multiple SAE Level 3+ vehicles approaching a fixed-time signalized intersection to optimize their trajectories.

Hardware and Software

On the infrastructure side, V2X Hub release 7.2 and above is used.(16)

On the vehicle side, the following technology is used:

- CARMA Platform vehicles.(15)
- CARMA Platform release 4.0.3 and above.(18)

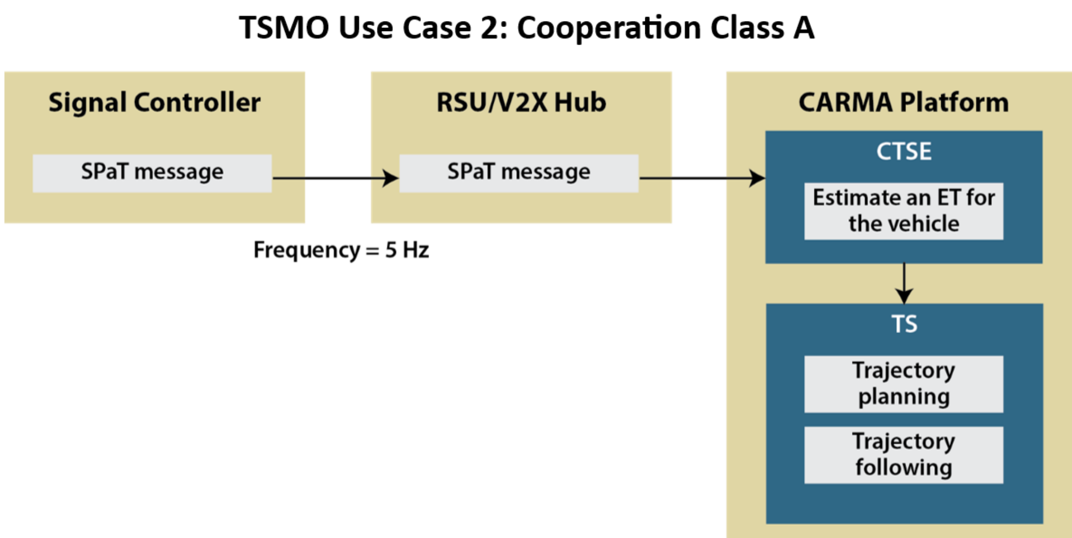
[1]National Electrical Manufacturers Association signal phasing.(20)
[2]National Transportation Communication for Intelligent transportation systems (ITS) Protocol 1202.(10)
[3]SAE J2735.(19)

Standards:

- SAE Taxonomy and Definitions for Terms Related to CDA for On-Road Motor Vehicles: J3216_202107.[12]
- SAE Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles: J3016_202104.[13]
- SAE V2X Communications Message Set Dictionary: J2735_202211.[19]

Architecture, Logic, Connectivity, and Communication

The architecture for the fixed-time traffic signals CDA use case is illustrated in figure 6.



Source: FHWA.

Figure 6. Diagram. TSMO fixed-time traffic signals architecture.

Results

Testing Overview

To evaluate and fine-tune the developed algorithms, the research team conducted simulation experiments in an open-source traffic simulator. For the experiments, the team considered a set of objective measures as follows:

- Throughput.
- Average delay.
- Level of service at the intersection.
- Average fuel consumption.
- Average stopping time.

The simulation results showed that the developed algorithms improved almost all the objective measures, some of which generally get improved with vehicles' cooperation classes.

The team performed several levels of PoC tests (i.e., integration, verification, and validation). The intent of the test-revision cycles is to move the research closer to deployment. The test plan documents define the test acceptance criteria, which decide whether a test scenario is successful or not. The criteria include various operational aspects such as communication, safety, mobility, and trajectory smoothness. To analyze the test results, the team collected and processed log files from CARMA Platform.(18) The results of analyses from the verification and validation testing show that the PoC frameworks improved most of the metrics identified in the test plans.

Verification Testing

The verification testing took place at TFHRC. It was conducted by testing of the two major signal transition ranges: the green to yellow to red transition and the red to green transition, as shown in figure 7. The team tested each signal transition range with a starting position within the trajectory planning range (close) and outside the trajectory planning range (far) as shown in the following figure. These combinations create four scenarios for verification testing.

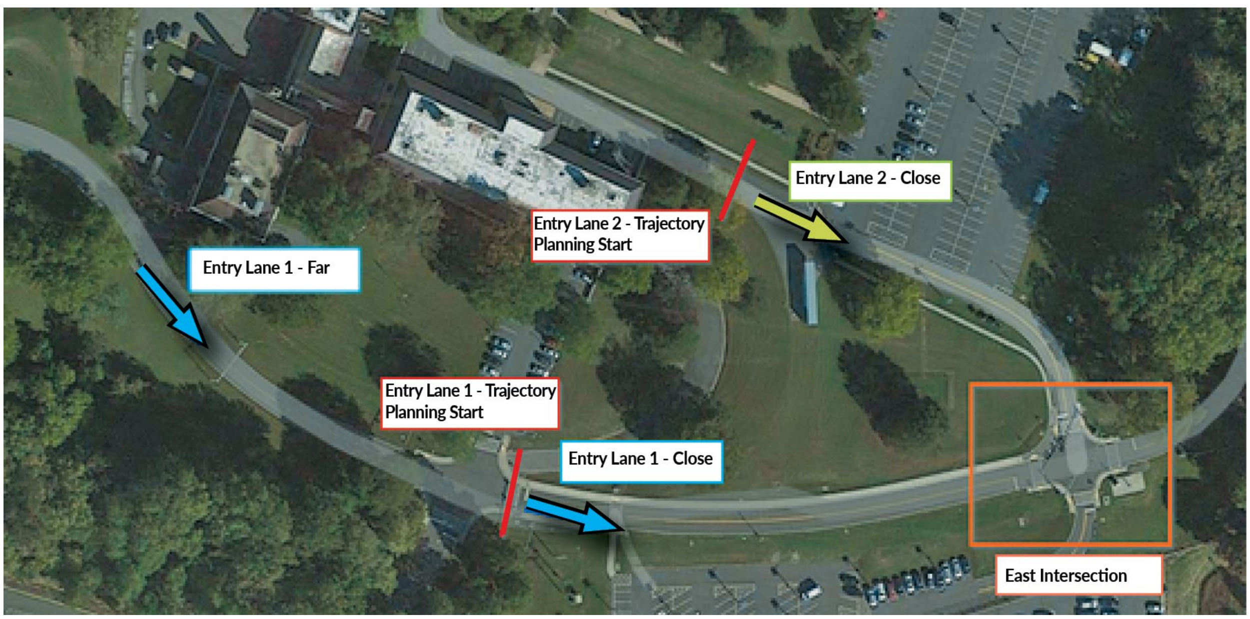


Figure 7. Map. Fixed-time traffic signals verification testing setup.(21)

Validation Testing

The validation testing also took place at TFHRC. An independent evaluator in developed and executed the validation test plan. The evaluation used five scenarios in the test plan:

- The first two scenarios specify signal status at the time of the vehicles' engagements.
- The third scenario characterizes the behavior of the vehicle under test when the vehicle is in a lane controlled by a SPaT message plan that is different from a SPaT message plan in an adjacent and parallel lane.
- The fourth scenario tests vehicle behavior when vehicle is traveling in a lane not under the control of a SPaT message being applied to an adjacent and parallel lane.
- The last scenario tests vehicle behavior when vehicle engages the route while already stopped within the configurable range of the intersection stop line.

For all the scenarios, the tests passed the test acceptance criteria defined in the test plan.

Source: FHWA.

Test Results and Level of Performance and Advancement

To evaluate the system's performance, the team collected data and calculated several performance metrics. The metrics included mobility, environmental, and communication performances. The evaluation showed that most of the performance metrics were passed in all test runs. The team faced a few issues relevant to vehicle control. In addition, V2V communication—especially for vehicles in the same lane or approach—was not considered in the testing, and so additional work is needed for the use case to be fully ready. Testing and demonstration of the use case showed no safety concerns in the laboratorial operational domain that would prevent further development. However, further safety analyses and operational investigation may be needed before deployment of the system in a real-world environment. The results of this test are shown in table 1.

Table 1. Traffic signal transition range and vehicle starting distance.

Test ID	Vehicle 1 Starting Direction	Vehicle 1 Starting Distance	Vehicle 2 Starting Direction	Vehicle 2 Starting Distance	Signal Transition Range
CC-RG	Entry lane 1	Close	Entry lane 2	Close	RG range
CC-GYR	Entry lane 1	Close	Entry lane 2	Close	GYR range
FC-RG	Entry lane 1	Far	Entry lane 2	Close	RG range
FC-GYR	Entry lane 1	Far	Entry lane 2	Close	GYR range

CC = close-close; FC = far-close; GYR = green to yellow to red; RG = red to green.

Next Steps

This use case proved the benefits that could be realized through the application of CDA in signalized intersections with fixed-time settings. Although a few limitations were identified through data collection and analysis, no safety concerns were raised, and high potential for future work remains intact. In particular, the developed framework can be improved in three ways:

- Applying V2V communications in this framework can enable this use case for higher-scale deployments and thus can potentially realize the benefit demonstrated in simulation experiments.
- Extending this use case to a mixed traffic environment wherein only a portion of traffic consists of C-ADS-equipped vehicles can facilitate faster and more realistic deployments.
- Testing this use case in two stages is needed prior to a large-scale deployment. In the first stage, cosimulation testing, it is recommended using a multitude of vehicles to replicate real-world traffic scenarios in a controlled environment. After identifying and addressing potential safety issues and addressing the use case's practicality and robustness under various dynamic traffic conditions, testing in real-world environments such as traffic corridors with mixed environments can begin. The testing would serve to further evaluate performance and ensure the system is fully optimized and safe for future deployment.

COOPERATIVE PERCEPTION

Objective

Cooperative perception (CP) is expected to improve perception performances of automated vehicles (AVs) and CARMA Streets.[(15)] CARMA CP is a feature of the CARMA Ecosystem that enables entities to share locally perceived data. The enhanced situational awareness is expected to facilitate more effective safety and mobility applications of CDA. Figure 8 shows CP testing at FHWA STOL. The goal of this use case is to verify and validate CP based on five key criteria:

- Detection, perception, and classification.
- Localization and tracking accuracy.
- Message latency.
- Message frequency.
- Message drop rate.

Source: FHWA.

A. A man walks across a crosswalk in front of a CARMA passenger vehicle stopped at the stop bar.(22)

Source: FHWA.

B. STOL engineers presenting CP testing at a TFHRC event.

Figure 8. Photos. FHWA STOL CP testing.

Description and Benefits for Transportation

CP would be helpful when some road objects are unable to share their own statuses through V2X communications, which would be the case in the short-to-medium-term future, which will see mixed traffic consisting of CAVs and human-driven, nonconnected vehicles.

CP has the potential to improve perception of road infrastructure (CARMA Streets) and road users (e.g., AVs) by extending their lines of sight.(15) The following items summarize the potential benefits of CP:

- Static or foreign objects in the driving environment—and some road users such as pedestrians—are not currently expected to be recommended to have machine-to-machine communication capabilities.
- Even when the shared perception information is redundant but not completely duplicated from one entity to another, such redundancy could reduce uncertainty in both entities' local perceptions.
- CP enhances situational awareness that could facilitate more effective safety and mobility applications of CDA. CP not only improves safety performance in immediate collision avoidance scenarios but also enables safer motion planning.
- Enhanced perception performances could also support path and trajectory planning for improved mobility and energy performances.

State of Practice

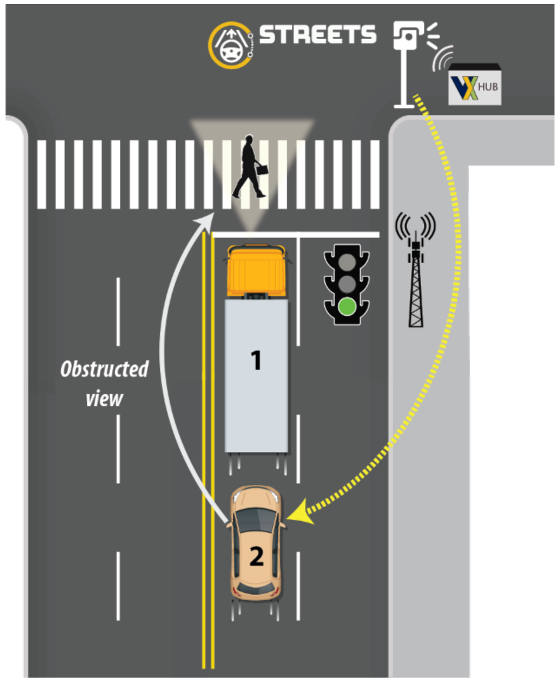
Industry Landscape

Five technical considerations have been identified as necessary for designing a CP system for CDA: enhanced object detection and perception, communication issues, cybersecurity issues, data fusion algorithms, and the effective application of information obtained through CP. At the time of the use case testing (2021 to early 2022):

- Extensive research had been conducted in the areas of object detection and perception, communication issues, and data fusion algorithms. Standardization efforts were trailing behind.
- Research into cybersecurity issues in a CDA CP environment and effective application of CP information were sparse.
- Only a few test pilots and deployments have occurred. Practical considerations for large-scale deployment had yet to be explored and investigated.

PoC System

The PoC CP system developed under the CARMA PoC project focused on developing the CP communication pipeline in the CARMA Ecosystem. The PoC CP system was demonstrated through a VRU use case that involved a roadside sensor for object detection and perception, CARMA Streets with V2X Hub for information processing and communication, and a stationary CARMA Platform vehicle (vehicle 2) with blocked line of sight (figure 9).(15,16,18)



Source: FHWA.

Figure 9. Illustration. CP sketch.

The PoC CP system was tested and proven to be reliable and efficient in:

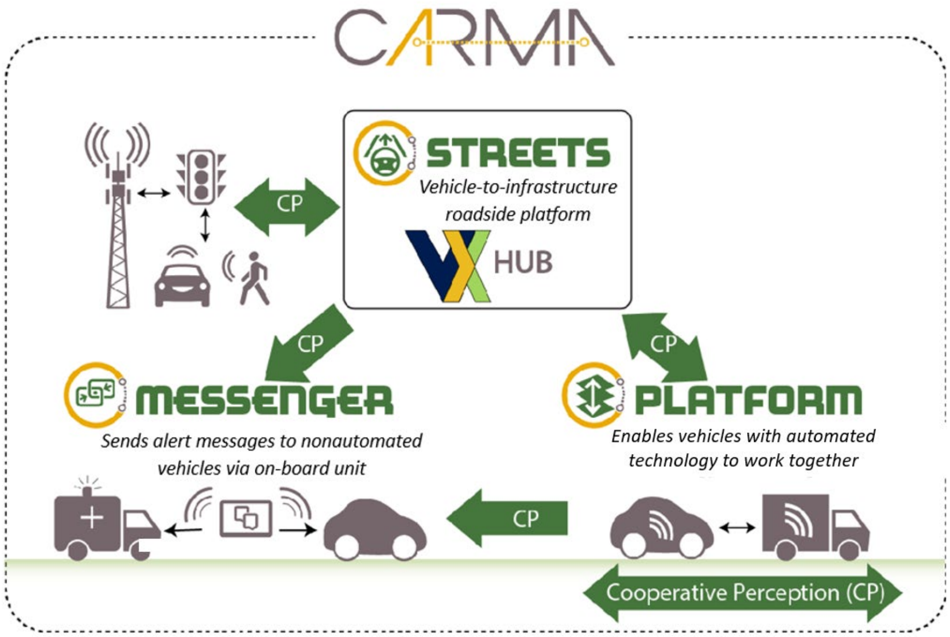
- Receiving information about the VRU from the infrastructure-based sensor. This step was achieved through software on both the infrastructure-based sensor and CARMA Streets with V2X Hub.(15,16)
- Creating and broadcasting CP messages via CARMA Streets with V2X Hub.(15,16)
- Receiving and adapting the information about the VRU from the CP message into an object that can be tracked by a CARMA Platform vehicle.(15)

The PoC system delivered the groundwork for future CP work by ensuring that pipelines for information transfer and manipulation exist and are quick in processing and transmitting the information.

Technical Specifications

Parts of CARMA Ecosystem Used

In the high-level concept of operations (ConOps), the research team identified CARMA Streets with V2X Hub, CARMA Platform, and CARMA Messenger℠ as the CARMA Ecosystem components relevant to the CP feature (figure 10).(15,16,17)



Source: FHWA.

Figure 10. Illustration. CP in the CARMA Ecosystem.[17]

Hardware and Software

On the infrastructure side:

- Smart infrastructure-based sensors (thermal camera) that can:
    - Detect, perceive, classify, and track pedestrians.
    - Publish object track data through an application programming interface.
- V2X Hub release 7.3 and above.[16]
- CARMA Streets with V2X Hub: V2X Hub pedestrian plug-in.[15]
- CARMA Streets with V2X Hub: V2X Hub dedicated short range communication (DSRC) message manager plug-in.[15,16]

On the vehicle side:

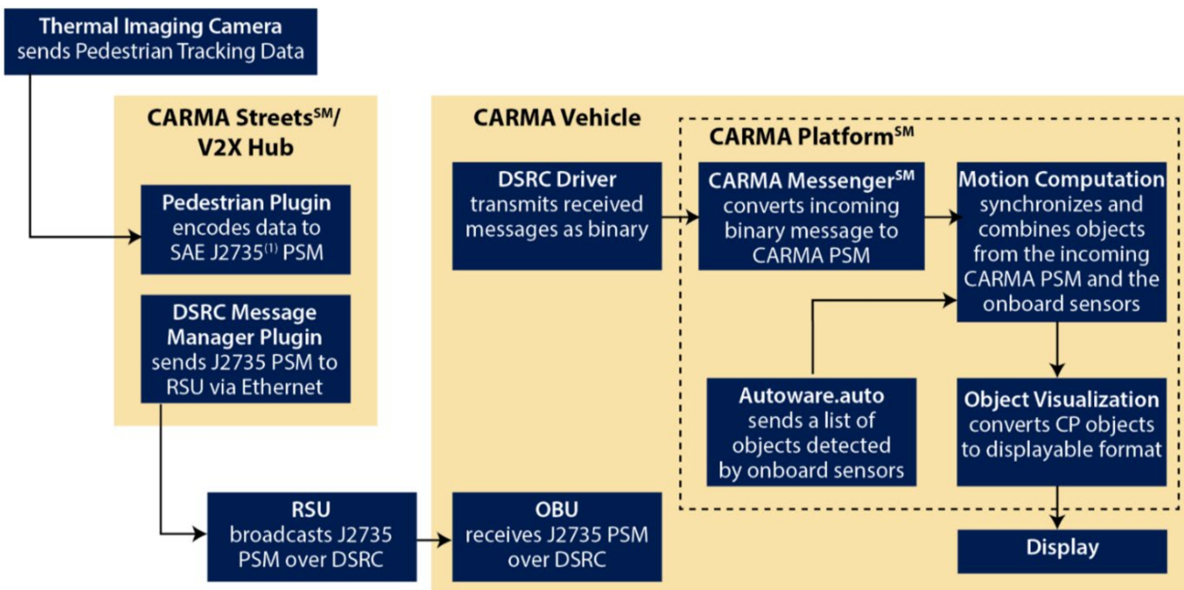
- CARMA Platform vehicle.[15]
- CARMA Platform: CARMA Messenger.[18]
- CARMA Platform: Motion computation.[18]
- CARMA Platform: Object visualization.[18]
- CARMA Platform release 4.1 and above.[18]

Standards:

- SAE Taxonomy and Definitions for Terms Related to CDA for On-Road Motor Vehicles: J3216_202107.(12)
- SAE Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles: J3016_202104.(13)
- SAE V2X Communications Message Set Dictionary: J2735_202211.(19)

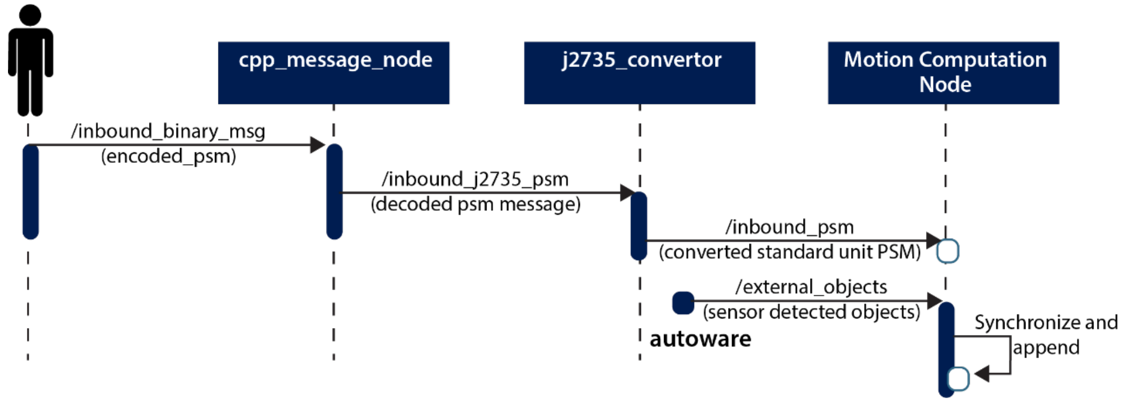
Architecture, Logic, Connectivity, and Communication

The CP architecture is depicted in figure 11.



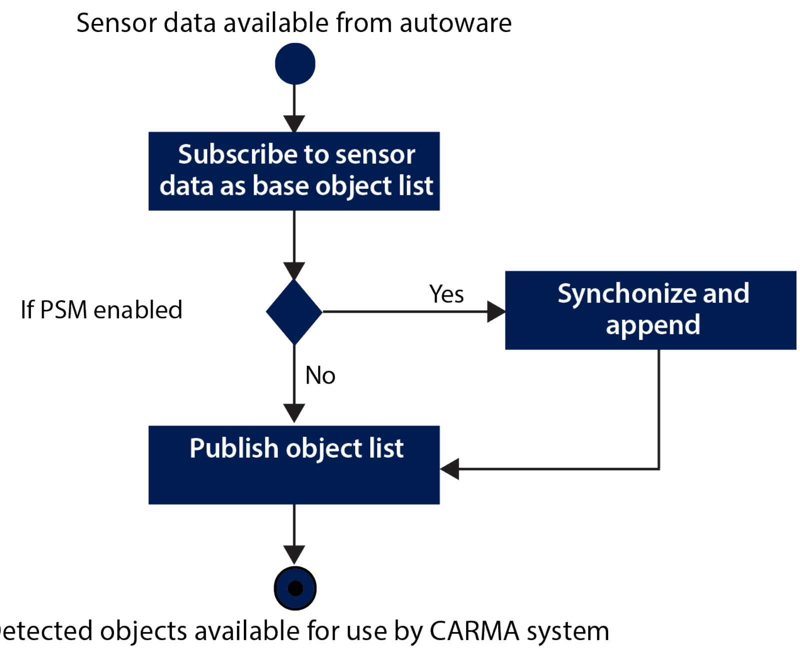
Source: FHWA.
DSRC = dedicated short-range communications; OBU = onboard unit; PSM = personal safety message.

A. Process for CP.



Source: FHWA.

B. Sequences for Robot Operating System (ROS™) messages and topics.[23]



Source: FHWA.

C. Motion computation processing and synchronization.

Figure 11. Diagrams. CP architecture.

Results

Testing Overview

Verification and validation testing focused on five key performance metrics: detection, accuracy, message latency, message frequency, and message drop rate. The following items describe the five key performance metrics:

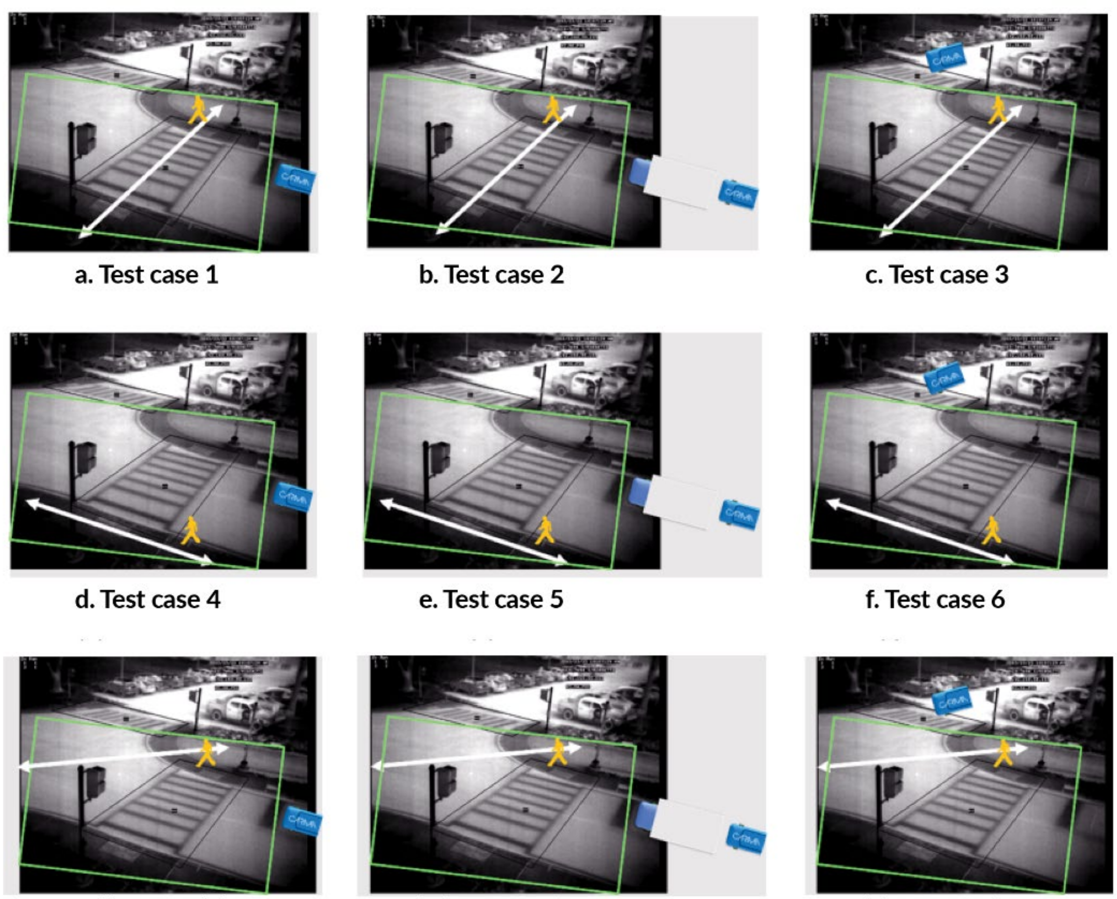
- Detection focuses on whether the CARMA vehicle can register a pedestrian out of its line of sight through the CARMA CP pipeline.

- Accuracy is not only just message correctness; attention is also given to whether the CARMA CP pipeline amplifies upstream sensor error creating compounding and cascading failures.
- Latency testing ensures that the communications are fast enough to be impactful.
- Message frequency and message drop rate measure the reliability of CP message broadcasting.

Verification Testing

Test Description

Nine different scenarios were tested during verification testing, each of them designed to emulate real-life conditions (figure 12). In each scenario, the locations of vehicles and pedestrians were altered to prove the system's effectiveness regardless of context. Each test was run eight times to confirm the results.



a. Test case 1 b. Test case 2 c. Test case 3

d. Test case 4 e. Test case 5 f. Test case 6

g. Test case 7 h. Test case 8 i. Test case 9

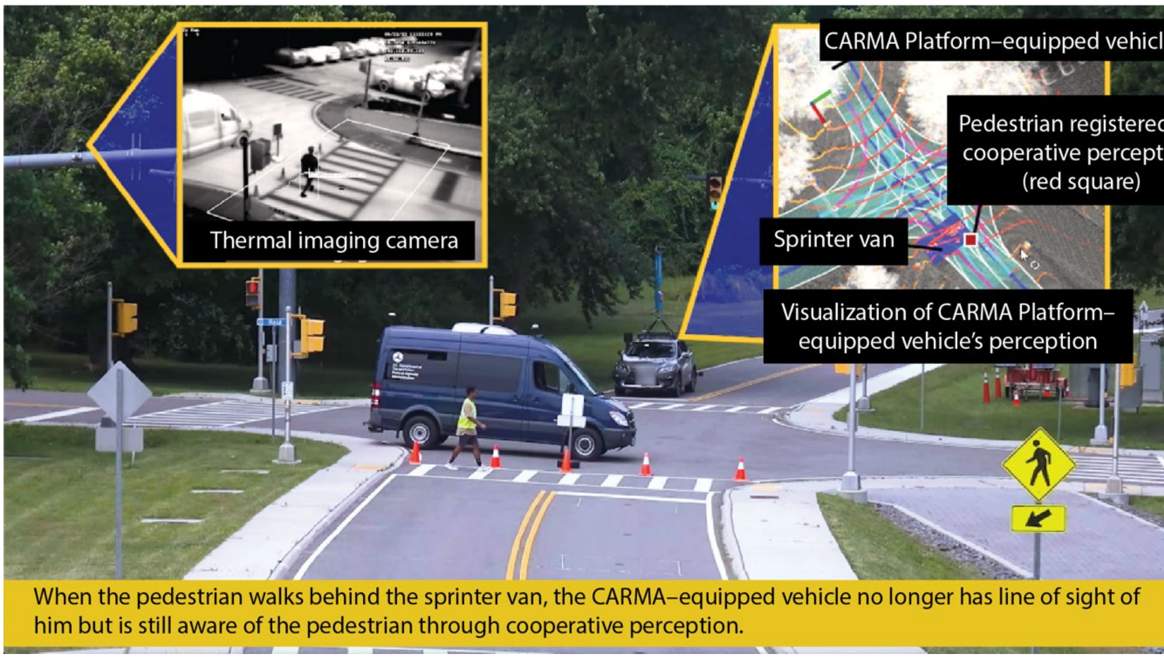
Source: FHWA.

Figure 12. Photo. Nine CP test cases.

Validation Testing

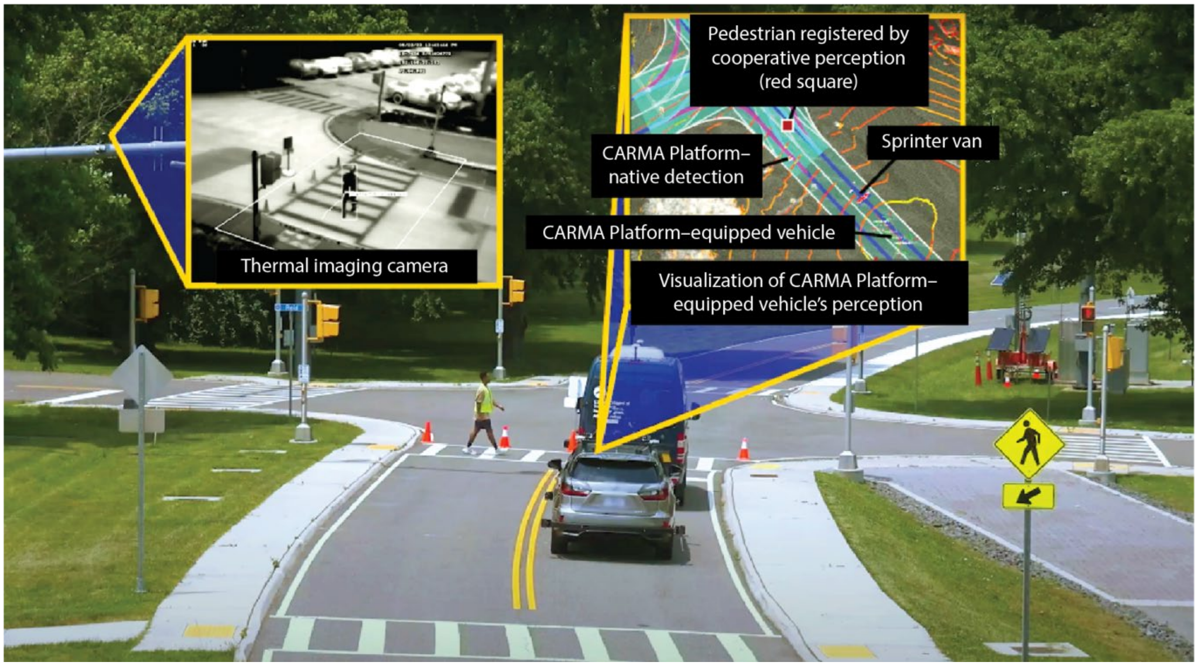
Test Description

Five additional scenarios were created for validation testing. The scenarios emulated on-road situations that presented the highest likelihood of collision and harm between a VRU and a vehicle. The scenarios are depicted in figure 13.



Source: FHWA.

A. CP scenario 1.



Source: FHWA.

B. CP scenario 2.

Figure 13. Photos. CP scenarios.

Test Results: Level of Performance and Advancement

Detection results provided the following findings:

- No missed detection of pedestrian by infrastructure-based sensor.
- No missed registration of pedestrian by CARMA Platform based on CP information received.(18)
- Occasional false-positive detection by the infrastructure-based sensor.

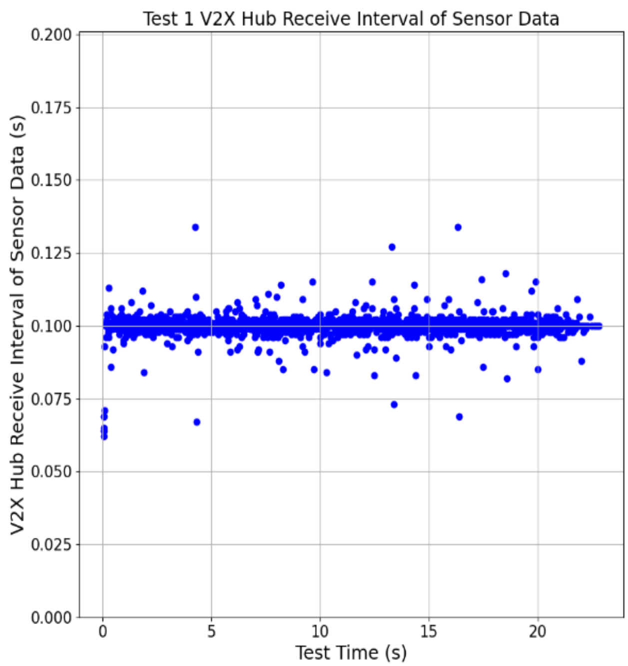
Accuracy results provided the following findings:

- All CP messages were verified to be accurate in reflecting information obtained from the infrastructure-based sensor.
- Locations of the same pedestrian registered through CP and through CARMA Platform vehicle's native LiDAR detection had noticeable discrepancy.(18) Through careful analysis, researchers determined the discrepancy was caused largely by inaccurate calibration of the infrastructure-based sensor in the deployment environment. In the best case among all verification testing results, the mean discrepancy was about 4.01 m.

Latency results found that all test runs (a total of 72) showed that end-to-end latency was within an acceptable range. "Acceptable range" refers to the time from when CARMA Streets with

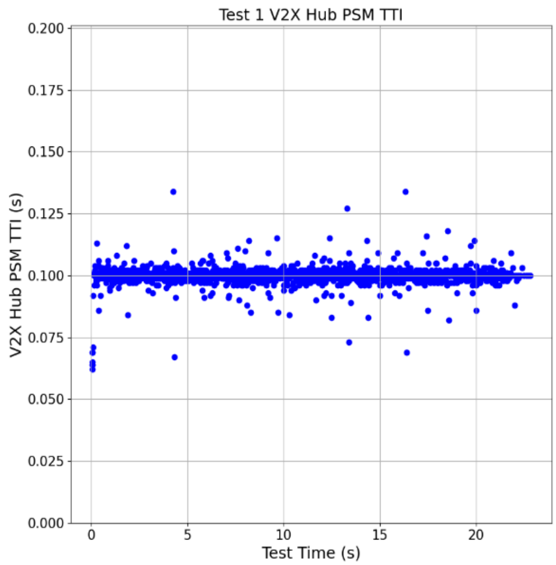
V2X Hub received data from the infrastructure-based sensor to when the onboard unit (OBU) equipped with CARMA Platform received the CP message packaged by CARMA Streets with V2X Hub.[15,16] That end-to-end latency was less than 6 ms for both the mean and the 75th percentile. Moreover, DSRC latency between the roadside unit (RSU) and OBU was less than 1 ms for both the mean and the 75th percentile.[14]

Message frequency results provided the following finding: All processes sufficiently followed the configured frequency of 10 Hz (figure 14).



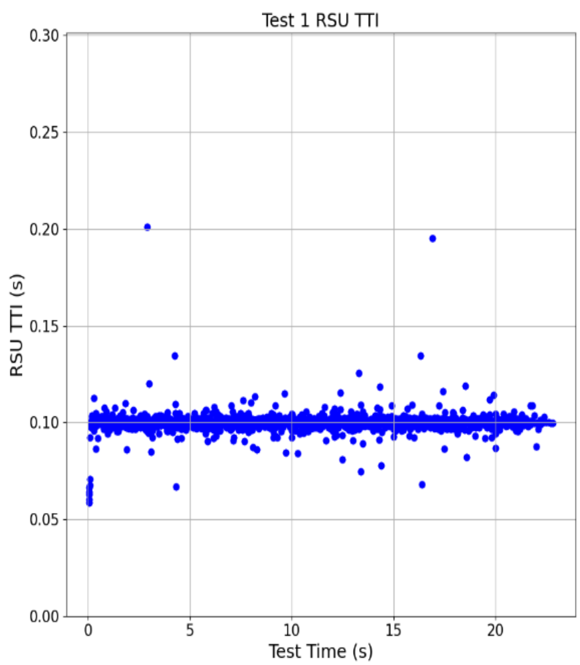
Source: FHWA.

A. Sensor data interval received at V2X Hub.[16]



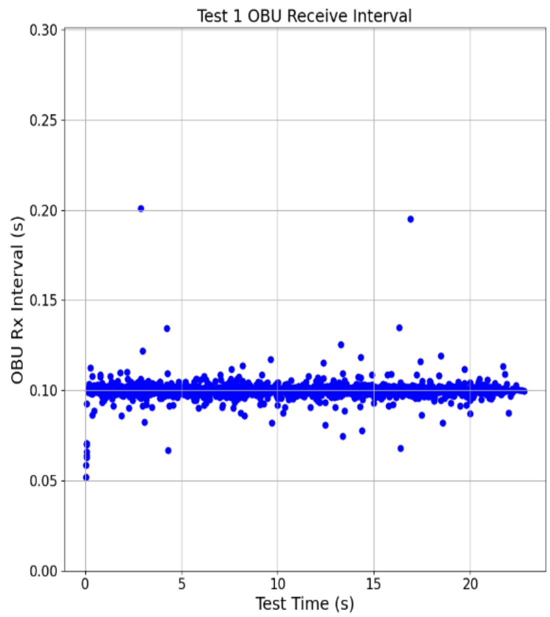
Source: FHWA.

B. V2X Hub PSM TTI.(16)



Source: FHWA.

C. RSU transmission time interval.



Source: FHWA.

D. OBU message packet receive interval.

Figure 14. Graphs. Message frequency.

The researchers were unable to quantify the message drop rate due to issues with data logging. The issues were fixed for validation testing.

Next Steps

Building upon the PoC CP system, STOL is currently (2022–23) working to expand the CARMA CP feature by developing a framework for both CARMA Streets and CARMA Platform that enables data fusion.(15,18) The ongoing work will also update the CP message format from the PSM used in the PoC system (following the SAE J2735_202211 standard)(19) to the sensor data sharing message defined in the new SAE J3224 standard.(24)

The development and testing of the PoC system also identified three areas for potential future field deployment as follows:

- The careful calibration of infrastructure-based sensors in the deployment environment was found to be especially determinative in system efficacy. Achieving more accurate detection and perception could prove to be a key component in CP technology's success.
- Standardized sensor outputs (i.e., de facto interface between sensors and RSUs, of object detection and perception—especially standardized uncertainty measures) would significantly accelerate CP technologies by enabling effective data fusion.
- Standardized sensor application programming interfaces would also significantly accelerate CP technologies by enabling relevant software to work with different sensors from various vendors (i.e., plug and play).

BASIC TRAVEL AND INTEGRATED HIGHWAY PROTOTYPE

Objective

The objective of basic travel is to give vehicles the capability to travel efficiently on roadways. Three applications enable that capability: platooning, cooperative merge, and speed harmonization. Integrated highway prototype (IHP) takes those capabilities a step further by integrating them and enabling them to operate in tandem. This work introduces such benefits as including collaborators in the development and testing process.

Description

Basic travel and IHP expand on previous functionality to include three key feature groups on freeways: cooperative lane follow (platooning and cooperative adaptive cruise control (CACC)), cooperative lane coordination (cooperative lane change, merge, and weave), and cooperative traffic management (speed and gap control, lane assignment, and queue management). Figure 15 provides an example of fully instrumented vehicles traveling in a platoon on a closed loop testing.

The concept of IHP involves a combination of applications to move vehicles more efficiently on roadways. IHP1 implemented those applications on a fleet of SAE Level 1 vehicles, while IHP2 focused on the use of the applications on SAE Level 2 and 3 vehicles.(25) An example involves an SAE Level 2 and 3 vehicle's coordination with other vehicles to smoothly enter a freeway (cooperative lane change), negotiation and obtaining of entry into a platoon (platooning), and response to infrastructure rules for reduced speed to smoothly pass a bottleneck (speed harmonization).(26)

Source: FHWA.

A. Five platooning vehicles on a closed track.

Source: FHWA.

B. Basic travel and IHP testing team posed with four CARMA vehicles.

Figure 15. Photos. Basic travel and IHP testing.

Benefits for Transportation

The use of C-ADS on freeways has the potential to improve safety and mobility, reduce congestion, and increase infrastructure efficiency. The three applications relevant to this work are listed in table 2. The work helped develop a better understanding of the benefits that could be realized by applying CDA to the highway.

Table 2. Basic travel and IHP applications.

Application	Description	Benefit to Road Users	Benefit to Highway System
Platooning	A hierarchical control framework in which a group of vehicles exchange data to coordinate maneuvers and travel with short spacings. The platoon leader coordinates maneuvers of platoon members.	Reduces following distance while maintaining safety.	Increases capacity, efficiency, and throughput.
Cooperative merge	Enables intelligent decisionmaking for merge and mainline vehicles at a merge area.	Increases confidence of a merge location.	Minimizes disturbance to traffic flow.
Speed harmonization	Provides speed guidance for vehicles approaching a bottleneck.	Reduces travel time and delay.	Increases throughput, fuel efficiency, and energy efficiency.

Third-party collaborators developed the platooning and cooperative merge code, which was integrated into CARMA Platform.(18) The collaborators also installed the new code developed under this use case into their own CARMA vehicle and conducted joint testing with the research team.

The collaborations showed the capacity for others in the industry to use the functionality of the CARMA Ecosystem and contribute back to it for the benefit of others, thereby accelerating adoption of this technology.

State of Practice

Advances are being made in vehicle automation technology. The use of V2V and vehicle-to-infrastructure (V2I) communication technology alongside vehicle automation facilitates a growing set of applications that are valuable to the highway system. Three of the applications are platooning, cooperative merge, and speed harmonization, which were developed and demonstrated under this use case on a closed track.

The research team achieved an industry first: successfully deploying a five-car platoon using SAE Level 2+ vehicles.(13) The platoon consisted of four different vehicle types, each with a different drive-by-wire controller (one of the vehicles was developed by a third party). The work provided the following lessons about working and testing with outside collaborators, about using HD maps for freeway applications, and about processing data in real time:

- Localizations driven by HD maps work well at low speeds, but delays and image skews at higher speeds make the data less useful.
- Collaborators are valuable resources for expanding the use of C-ADS. Abstraction between different vehicle platforms is key for successfully operating cooperative applications in the future.
- Computing demands increase at higher vehicle speeds because the vehicle covers much more distance in each amount of time (minimizing delays in the processing pipeline is critical).
- While human drivers are still in the loop (below SAE Level 5), visual communications about the status of surrounding vehicles are necessary.[13]
- Cooperative applications that are not low latency—such as cellular—may benefit from communication paths other than the direct low-latency 5.9-GHz band.

Technical Specifications

Parts of CARMA Ecosystem Used

To enable CDA for freeway applications, several CARMA tools were used, including:

- CARMA Platform: Runs the platooning and cooperative merge plug-ins and provides control of the vehicle.[18]
- CARMA Streets (with V2X Hub): Serves as a roadside interface between the infrastructure and the vehicles.[15,16]
- CARMA Cloud℠: Runs the speed harmonization algorithm and provides speed guidance for vehicles based on traffic data (traffic data were simulated for this use case).[17]

Hardware and Software

To enable CDA for freeway applications, the following hardware and software was used:

- Fully instrumented vehicle (steering, brake, and throttle automation; global navigation satellite system receiver; LiDAR).
- Roadside infrastructure (or cellular as it becomes available).

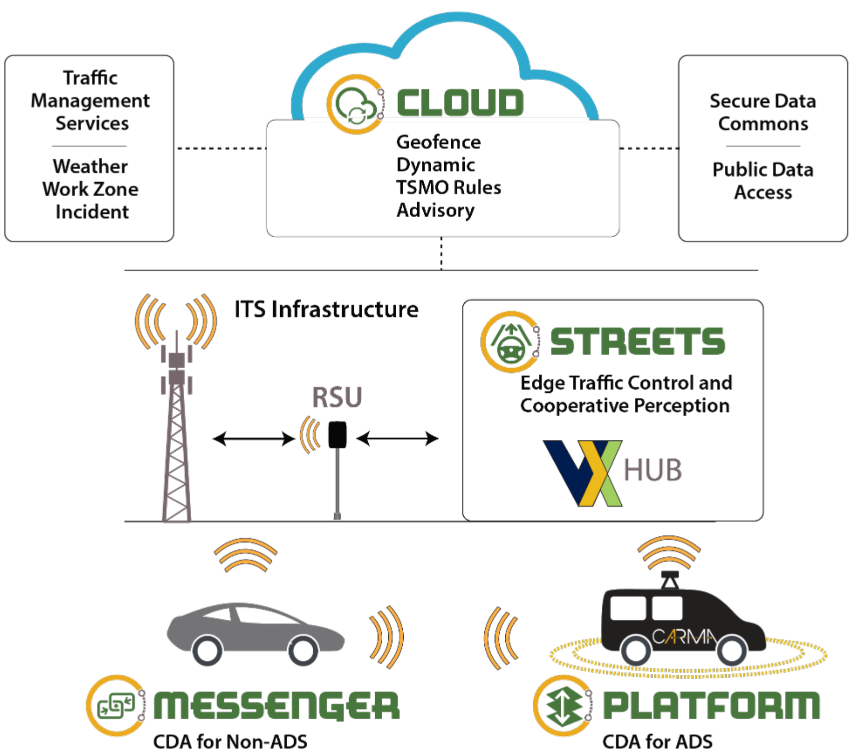
Standards

The following standards were used in this use case:

- SAE Taxonomy and Definitions for Terms Related to CDA for On-Road Motor Vehicles: J3216_202107.(12)
- SAE Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles: J3016_202104.(13)
- SAE V2X Communications Message Set Dictionary: J2735_202211.(19)

Architecture, Logic, Connectivity, and Communication

The components of the basic travel and IHP testing are depicted in figure 16.



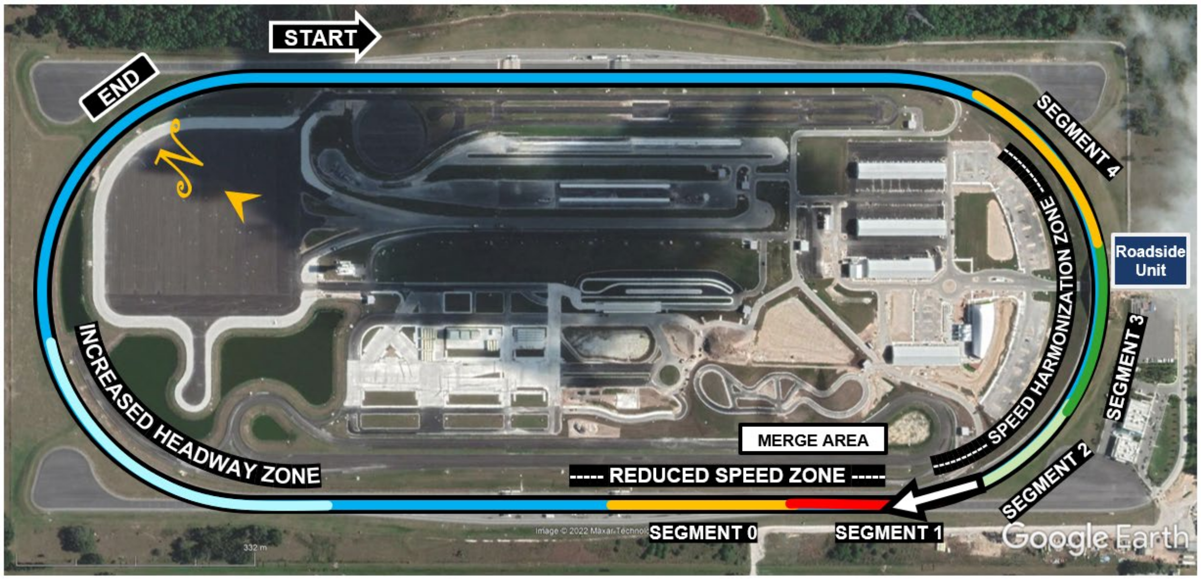
Source: FHWA.
TSMO = intelligent transportation system.

Figure 16. Illustration. CDA program products.(11,15,16,23)

Results

Testing Overview

Limited integration testing took place using the test facilities at TFHRC in McLean, VA. Integration testing and subsequent test phases took place at a facility in Auburndale, FL. The facility has a large oval track that is compatible with testing the freeway applications that IHP2 used (figure 17).



© 2022 Google® Earth™, modified by FHWA (see Acknowledgments section).

Figure 17. Map. Aerial view of the test track.(21)

The core testing involved three vehicles carrying out a single scenario that combined the three applications. The following steps were carried out to test the scenario:

1. Two mainline vehicles are stationed at the starting point along the oval track.
2. One merging vehicle is stationed at the on-ramp alongside the oval track.
3. The mainline vehicles start moving under automated control.
4. The mainline vehicles form a platoon.
5. The mainline vehicles slowdown in response to speed harmonization commands from the infrastructure.
6. As the mainline vehicles approach the on-ramp, the merging vehicle negotiates with the mainline platoon leader and calculates a trajectory to merge into the platoon.
7. The new platoon exits the speed harmonization zone and speeds up to its prior speed.
8. The platoon dissolves, starting from rear to front.
9. The vehicles are manually returned to their starting positions for another run.

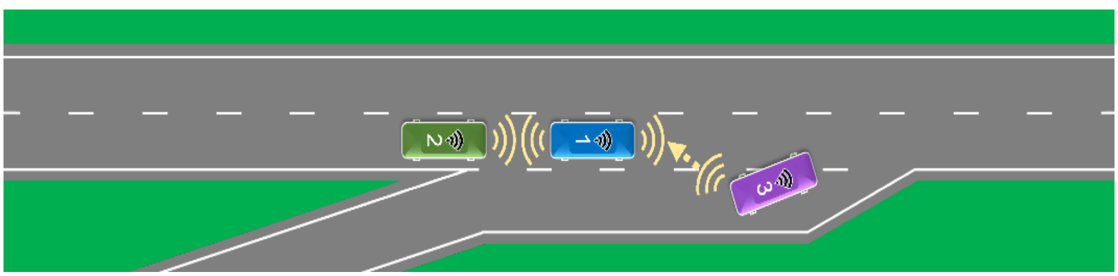
Verification Testing

Internal Testing Results and Detailed Conclusions

The research team performed verification testing to ensure the system and the various IHP2 plug-ins on CARMA Platform, CARMA Streets, and CARMA Cloud had been built correctly.(15,17,18) In this use case, the team tested the different actions in the IHP2 use case, including:

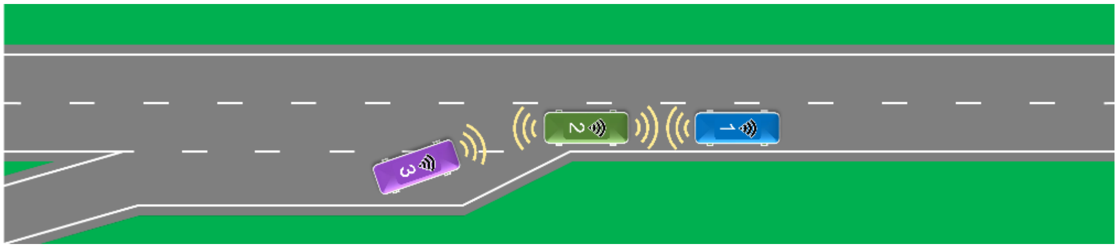
- Communication between CARMA Messenger, the platooning plug-in, CARMA Streets, and CARMA Cloud.(17)
- The vehicles' initial ability to form a platoon.
- Communication between vehicles in a platoon.
- A vehicle's speed reduction and acceleration in joining a platoon.
- A vehicle's ability to join an already-formed platoon, including from the same lane versus from different lanes and positioning in the front versus the back of the platoon.
- Platooning vehicles' ability to increase and reduce speed when entering and exiting a speed change zone.

The focus was on ensuring that the passenger vehicles were capable of safely entering and forming a platoon, reducing and increasing speed and headway while in a platoon, and communicating with CARMA Streets.(15) Several runs were performed, and the team iteratively fine-tuned various parameters in the platooning plug-ins. All actions the team considered during the prior integration testing stage were tested in a more comprehensive and complete-trip type of setting during verification testing. Some of the platoon scenarios are illustrated in figure 18.



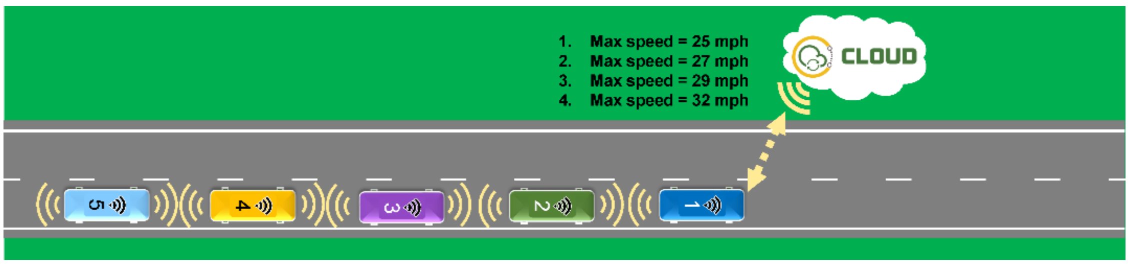
Source: FHWA.

A. Three-car platoon created from a front merge.



Source: FHWA.

B. Three-car platoon created from a rear merge.



Source: FHWA.
max = maximum.

C. Five-car platoon responding to speed guidance from infrastructure.

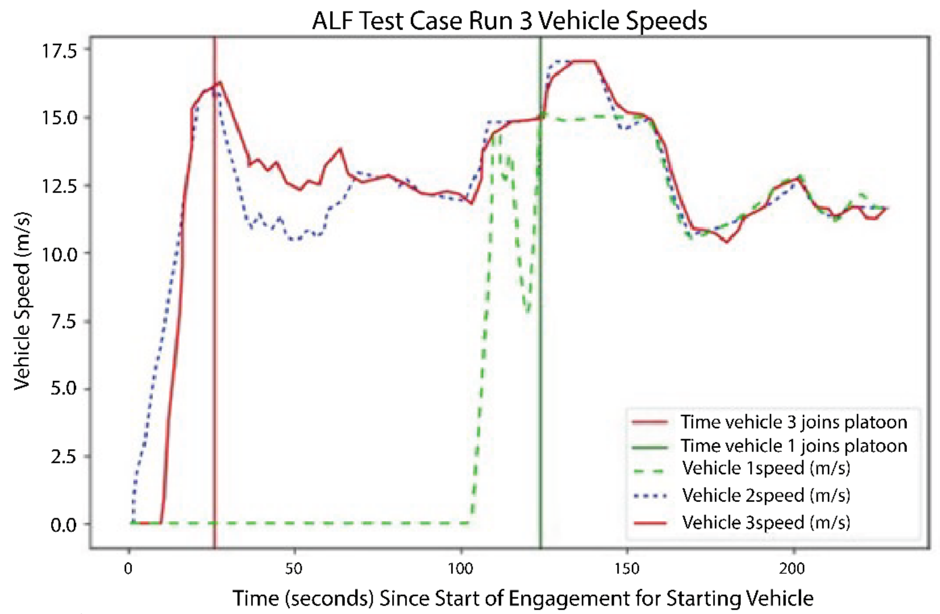
Figure 18. Illustrations. Platoon scenarios.

Validation Testing

Results and conclusions of validation testing are in process.

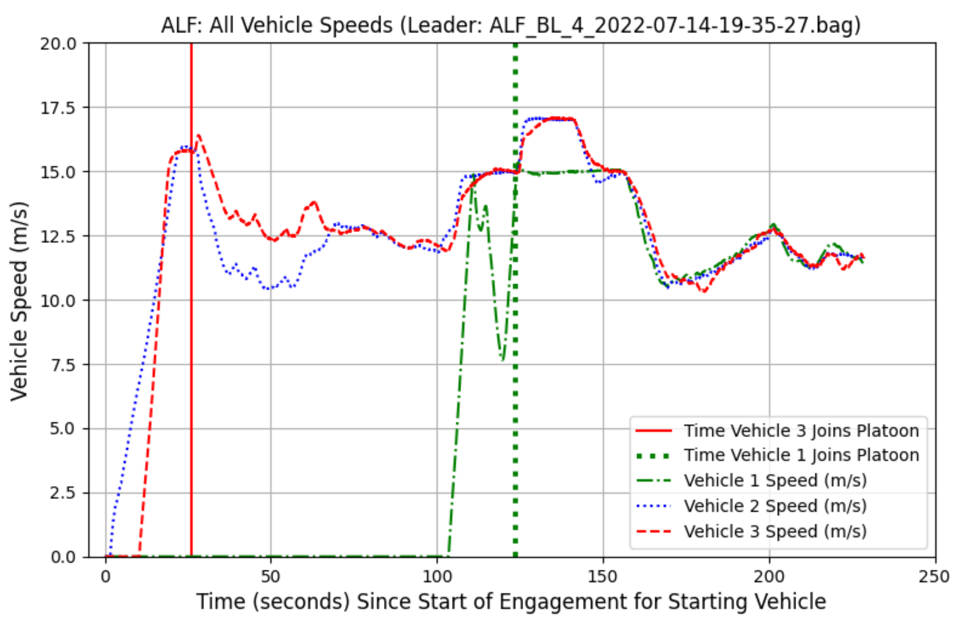
Test Results and Level of Performance and Advancement

The validation testing showed that the vehicles could execute the applications on a closed test track. The plots in figure 19 show a subset of data for the front-join, rear-join, and speed harmonization operations.



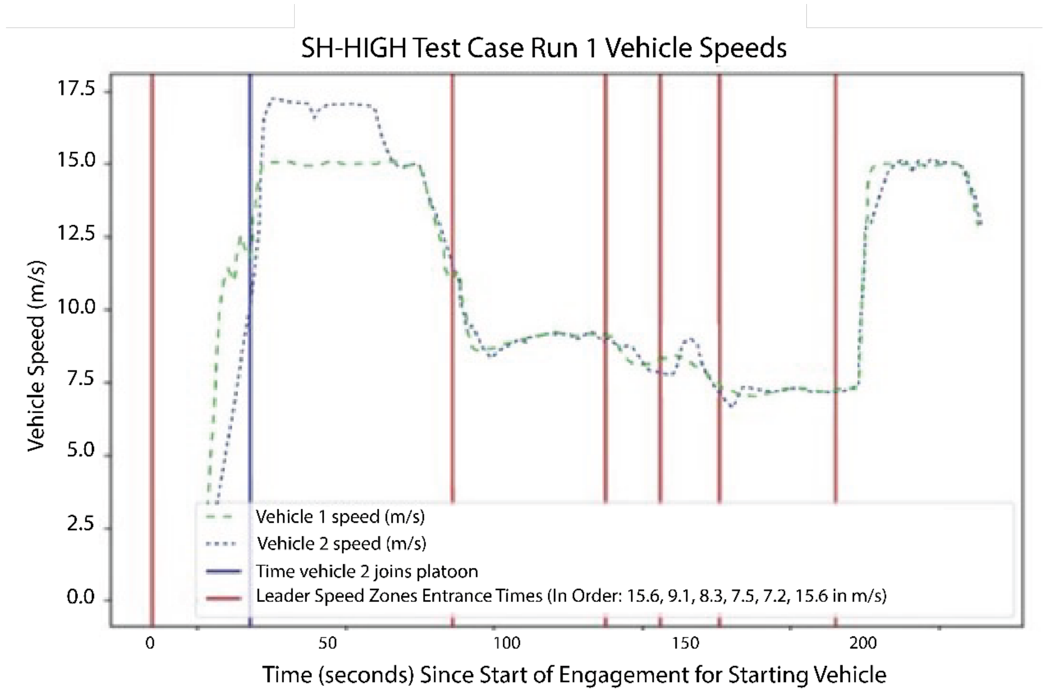
Source: FHWA.
ALF = adjacent lane front.

A. Results of adjacent lane front runs.



Source: FHWA.
ALR = adjacent lane rear.

B. Results of adjacent lane rear runs.



Source: FHWA.
SH = speed harmonization.

C. Results of speed harmonization (high).

Figure 19. Graphs. Results of adjacent lane join and speed harmonization.

The PoC was completed on a closed test track. Several steps should be completed before the full concept can be realized on a live freeway, according to the ConOps. The most challenging step involves achieving high market penetration through wide-scale industry adoption, which will lead to the full benefits of these cooperative applications.

Next Steps

The IHP2 concept showed benefits in the following areas:

- Three freeway applications (i.e., platooning, cooperative merge, and speed harmonization) can work in tandem on multiple SAE Level 3 vehicles.(13)
- A platoon of five SAE Level 3 vehicles can operate through reduced speed and increased headway zones.(13)
- Vehicles of different low-level-control manufacturers can operate together.
- CARMA is portable and can be successfully deployed by different development teams.

The work can be extended in the following areas to investigate potential effects and benefits of the concept:

- Simulation: The simulation capability in STOL has been improving with the development of CARMA everything-in-the-loop (XiL).(18) This simulation environment combines an open-source traffic simulator and car learning to act (CARLA®) to provide the ability to evaluate vehicle dynamics and traffic performance.(27) Vehicle communication simulation is incorporated to simulate the wireless channel characteristics the vehicles and infrastructure will experience. Features of CARMA are integrated, which enables the direct testing of new code. Continuing the testing of IHP2 in the CARMA XiL simulation environment would enable further refinement of IHP2 features in a wider range of scenarios.(18)

- Increased number of vehicles: A five-vehicle test of the IHP2 applications was conducted by using a vehicle from a stakeholder. Although the test is an accomplishment for PoC, a deployment in the real world would see far more vehicles. Now that the concept has been demonstrated with stakeholder vehicles, further testing may be done with an expanded set of collaborators on a closed test track.

- Cut-in merge: Because of limited resources (time, track geometry, vehicle controls, etc.), this PoC focused on joining the platoon from the front and the rear. In short, platoon front join and rear join can cover most instances of platoon joining. In a longer platoon, it may not be feasible to efficiently position a joining vehicle in the front or the rear. Therefore, midjoin is a feature that would be valuable to implement. Further testing may study the opening of a gap into which a joining vehicle could enter in the middle of a platoon.

- Cellular communication: The IHP2 PoC relied on direct low-latency V2X (in this case, DSRC) for the communication path that provided guidance on reduced speed and increased headway.(14) Since this information is communicated to the vehicles well before the vehicles enter the segment of roadway where the information applies, the messages do not depend on low-latency communication to be effective. Rather, a higher-latency communication path (e.g., a cellular network) would satisfy the delivery of those messages. STOL has work ongoing to enable delivery infrastructure messages over cellular. Further work may explore the use of cellular to deliver reduced-speed and increased-headway guidances.

- Public road testing: The PoC testing was conducted on a closed test track, which provided an isolated environment in which the applications could be tested and improved. Future testing may involve operating the vehicles on a public roadway, which would demonstrate the concept in a real-world environment. Prior to such an event, several pieces of the concept would have to be improved. First, the vehicle controls would have to enable the vehicles to reliably remain in their own lanes at highway speeds. Second, the gap regulation would have to let the platoon maintain formation at a reasonably low headway. Finally, sensing capabilities need to be integrated into the platform to enable object detection and avoidance functions.

WORK ZONE MANAGEMENT–LIGHT VEHICLES

Objective

Work zone management (WZM) uses solutions and strategies to minimize traffic delays and increase safety for all road users, including workers, drivers, and pedestrians. This use case looks at CDA applications to WZM with respect to light vehicles. Through the application of CDA technologies, C-ADS-equipped vehicles will be able to navigate work zones safely and efficiently.

Description

Work zones pose challenges for human drivers and ADSs because they sometimes drastically change lane geometries, disrupt lane markings, and obscure other vehicles or pedestrians. Because many AVs use previously created HD maps of their driving environments, work zones cause sudden disruptions to the AV's perception systems. CDA can reduce such risk by communicating work zone geometries and restrictions to ADSs ahead of time for more accurate decisionmaking.

To show such communication, the research team demonstrated a signalized work zone navigation application using CARMA. This use case had C-ADS-equipped vehicles (using CARMA Platform as pictured in figure 20) approach a single-lane bidirectional work zone with a fixed timing light to control lane access.[18] The work zone geometry was communicated to the CARMA vehicles via traffic control messages (TCMs) created in CARMA Cloud.[17] The controls also included signal identifiers so that the CARMA Platform vehicle could identify SPaT messages being broadcast by the signal controller via V2X Hub and an RSU.[18] The signal identifiers enabled CARMA vehicles to appropriately reroute through the work zone and appropriately respond to the traffic signal.[18]

Source: FHWA.

Figure 20. Photo. CARMA-equipped vehicle used for a demonstration.

Benefits for Transportation

When a signalized work zone results in significant changes to lane geometries, lane markings, and the general road environment in which the work zone is located, both the vehicles and the work zone operators face increased safety risks. In such situations, C-ADS vehicles, which may be equipped with outdated HD maps, face a challenge when navigating through that work zone. But the challenge can be mitigated through traffic control requests (TCRs) and TCMs, which enable C-ADS vehicles to receive enough environment information for dynamically updating their internal maps to match the current work zone road environment and adjusted traffic laws, such as a reduced speed limit. Through the use of infrastructure-to-vehicle communication, SPaT messages can be broadcast to C-ADS vehicles to inform the vehicles of the traffic signal status of an upcoming signalized work zone, thereby ensuring that vehicles proceed only when permitted by the signal status.

By providing approaching C-ADS vehicles with detailed road geometry information and traffic signal status pertaining to an upcoming work zone, this use case demonstrated its primary goal of improving the safety of active work zones by ensuring that C-ADS vehicles can properly navigate a work zone's environment.

State of Practice

To realize in a real work zone the benefits demonstrated by this use case, intelligent transportation infrastructure systems must be deployed at the site to enable the kinds of broadcasting messages that are needed by C-ADS vehicles. Depending on the communication coverage of existing RSUs in the region of the work zone, it may be necessary to set up additional RSUs at determined distances outside the work zone entrances and exits to provide approaching C-ADS vehicles with work-zone-related messages in advance of the work zone environment.

Technical Specifications

The following parts of CARMA Ecosystem were used in this use case:

- CARMA Platform.(18)
- CARMA Cloud.(17)
- V2X Hub.(16)

The following hardware and software were used in this use case:

- CARMA Platform vehicle.(15)
- CARMA Cloud server.(17)
- V2X Hub-capable computer and RSU.(16)
- Signal controller.
- Signal head.

The following messages were used in this use case:

- TCM.
- TCR.
- SPaT.

The architecture reference for cooperative and intelligent transportation (ARC-IT) service package MC06 used to plan, define, and integrate intelligent transportation systems in this use case is WZM.(28)

Results

Testing Overview

The research team successfully demonstrated and tested the use case at TFHRC, with validation testing conducted by FHWA. Development of this use case highlighted the challenges of communicating road geometries in a standard way between separate systems. Work zone data have to be capable of integrating into existing ADS HD maps if they are to be used by those systems' planning and perception systems. That integration means having a standard coordinate frame conversion process and an understanding and assurance of data accuracy.

Figure 21 provides an overview of the red light and green light test cases the research team ran in a CARMA-equipped vehicle as part of both verification testing and validation testing at TFHRC.

Verification Testing

Verification testing took place at TFHRC on a two-way, two-lane road, with a blocked-off lane to match the mock work zone used in the test (figure 21). The updated road environment was communicated to approaching vehicles via TCM to describe:

- The work zone lane with a tapered geometry to enable merging into the adjacent lane.
- A reversed adjacent lane to enable vehicles to travel against its typical travel direction as part of the reconfigured work zone road geometry.
- A speed advisory indicating a reduced speed limit in the lane adjacent to the work zone.

Additionally, the signal status for approaching vehicles was communicated via SpaT messages. The team created and tested several test cases to ensure that vehicles properly navigated the work zone in both red light and green light scenarios.

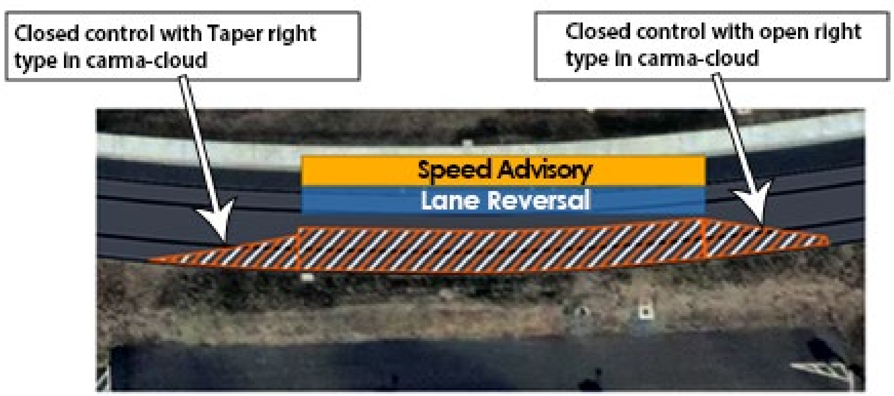


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Figure 21. Photo. WZM verification testing setup.[21]

Validation Testing

Validation testing took place at TFHRC. An independent evaluator in developed and executed the validation test plan.

Test Results and Level of Performance and Advancement

To evaluate the system's performance, the team collected data and calculated several performance metrics. The evaluation showed that most of the performance metrics were passed in all test runs, and the metrics that were not reliably passed still resulted in acceptable performance. In general, the issues encountered during testing were due to vehicle control issues, including deceleration rates above the system's maximum threshold. During red light test cases, the team found that a vehicle stopped with its rear axle positioned over a traffic signal stop bar rather than with the front bumper positioned over the stop bar.

Next Steps

Proposed next steps for this use case involve collaborating with industry stakeholders to determine effective practices pertaining to the messaging of work-zone-related information and the behavior of C-ADS vehicles in these situations. Future research could focus on the risks of running CDA trajectory optimization algorithms used for standard signalized intersections with signalized work zones.

TRAFFIC INCIDENT MANAGEMENT: MOVE OVER

Objective

The goal of the FHWA Traffic Incident Management (TIM) program is to continuously improve the safety of incident responders and road users, the reliability of travel, and the efficiency of incident and emergency response through the institutionalization of TIM programs. FHWA TIM focuses on five tracks:

- National leadership and TIM organization.
- Data and performance management.
- R&D for technology, tools, and practice innovation.
- Training, education, and outreach.
- Policies, procedures, and laws.

The objective of the test described next is to verify and validate that emergency response vehicles (ERVs) can successfully broadcast TCMs for alerting C-ADS vehicles about safe navigation of the location in question and keep first responders out of harm's way.

Description

This use case focused on enabling lane closures adjacent to ERVs to ensure that vehicles on the roadway comply with move-over traffic laws regarding ERVs. The information required by the CDA vehicle to perform move-over maneuvers was unavailable through message sets included in existing standards. Message sets such as TIMs, roadside safety messages, and MAP messages were considered. Hence, the mobility message sets were developed. Those message sets, based on the situational requirements, may serve multiple purposes pertaining to the requests, responses, operations, and paths of CDA vehicles. In this scenario, the ERV (CARMA Messenger)(29) broadcast a mobility request message containing the GPS point, desired speed reduction, and desired safety margins of the ERV. The CDA vehicle (CARMA Platform)(18) interpreted the information so it could avoid the lane adjacent to the ERV and perform a slowdown maneuver when passing the incident.

Benefits for Transportation

First responders face increased safety risks when arriving at the scene of an incident. First responders may be positioned near active traffic lanes, and road users traveling nearby may be confused by what is otherwise the proper traffic pattern for safe navigation around the incident. Enabling connected ERVs to broadcast traveler information messages describing alternative paths for C-ADS vehicles to navigate a traffic incident location can decrease the likelihood of injury to incident-involved participants and first responders.

State of Practice

To enable an ERV to communicate alternative travel paths to approaching C-ADS vehicles, the ERV must be equipped with a communication-enabling system. During testing, it was confirmed that an ERV could have only a limited V2V range based on the state of its communication hardware or the environment it is positioned within. To mitigate communication range limitations and to ensure that approaching vehicles receive messages from the ERV early enough to consider the messages in their planning, researchers may find it beneficial to consider cellular communications between ERVs and C-ADS vehicles.

Technical Specifications

The following parts of CARMA Ecosystem were used in this use case:

- CARMA Platform.[18]
- CARMA Messenger.[29]

The following hardware and software were used in this use case:

- SAE Level 3 AV running CARMA Platform.[12,18]
- Connected but not AV running CARMA Messenger.[29]
- V2X communication using DSRC was used; however, due to the radio-agnostic nature of the software, the same tests may be repeated using cellular vehicle-to-everything (C-V2X) radios that follow the RSU 4.1 specification.[14]

The following standards were used in this use case:

- SAE Taxonomy and Definitions for Terms Related to CDA for On-Road Motor Vehicles: J3216_202107.[12]

- SAE Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles: J3016_202104.[13]

The following architecture, logic, connectivity, and communication framework was used in this use case:

- This UC follows ARC-IT Service Package VS04: V2V Special Vehicle Alert.[(30)]
- Internal messages used: mobility request, as defined in the CARMA Platform data dictionary.

Results

Testing Overview

The research team successfully demonstrated and tested the use case in Summit Point, WV, during May–June 2021. For verification and validation testing, the ERV broadcast messages that resulted in the approaching C-ADS vehicles' changing lanes to provide additional space between themselves and the incident location. The ERV's broadcast messages included instructions to set an advisory (reduced) speed limit for a segment of the lanes located near the incident location.

Verification Testing

Verification testing took place primarily on a straight section of a one-way two-lane road (figure 22). Figure 23 shows the test setup for the use case. In the figure, "CM" refers to the CARMA Messenger vehicle, which was used in place of a connected ERV.[(31)] Verification testing included 18 evaluation runs using CARMA-equipped vehicles.

Source: FHWA.

Figure 22. Photo. CARMA vehicles on a roadway.

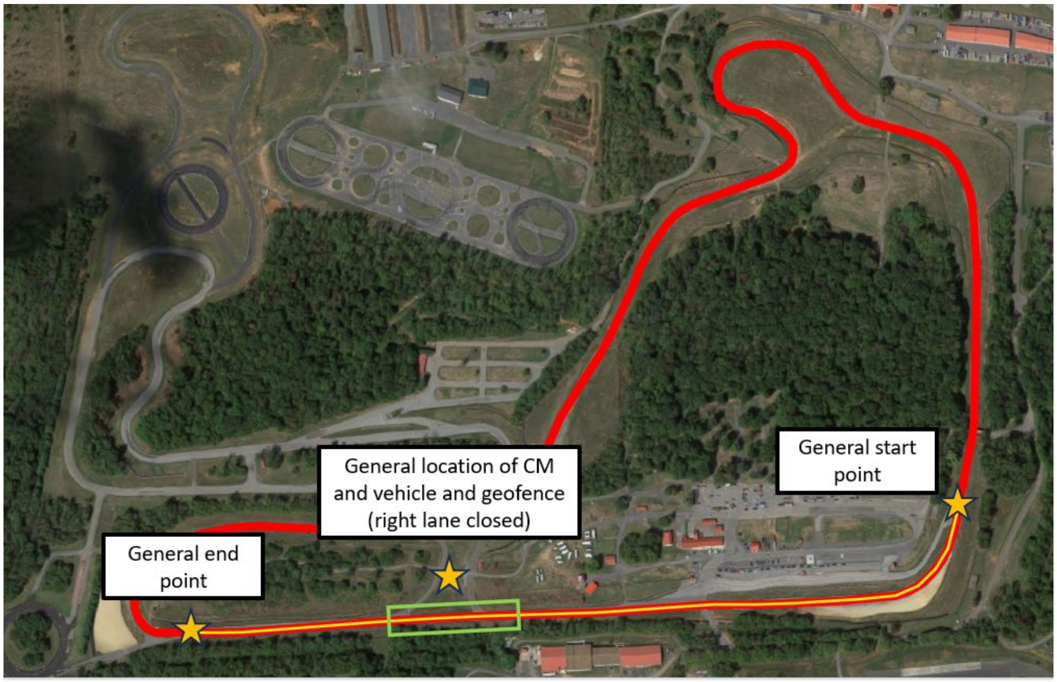

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Figure 23. Map. TIM test setup in Summit Point, WV.(21)

Validation Testing

An independent evaluator developed and executed the validation test plan.

Test Results and Level of Performance and Advancement

Development of this use case highlighted the differences in data accessible between AVs and ERVs. Modern ADSs often have access to HD mapping data, which are proprietary to OEMs. Access to such information may not be feasible for first responders, necessitating development of approaches not relying on this data from ERVs for initial deployments. This was the approach the team took in CARMA's use case implementation. The solution required manual user entry of desired safety margins in the ERV, but the safety of those choices is an open, human-factors question. Further research could consider either a full end-to-end use case, of which this is the last piece, or security questions of authentication for ERVs.

Next Steps

Next steps involve collaboration with industry stakeholders to determine effective practices pertaining to the messaging of traffic-incident-related information and the behavior of C-ADS vehicles in such situations. Another approach is to identify and suggest updates to existing standards to add support for the TIM use case.

ROAD WEATHER MANAGEMENT: CLOSE LANE

Objective

FHWA's Road Weather Management (RWM) program seeks to develop and promote effective tools for observing and predicting the impacts of weather on the roads and for alleviating those weather impacts.

The program's objectives are to:

- Develop a national open observing system that promotes data sharing that supports weather observing and forecasting and transportation operations.
- Develop resources and training methods to assist State and local stakeholders in deployment of weather management tools.
- Advance the state of the practice by developing proactive solutions and disseminating information on adverse weather.
- Foster a collaborative, comprehensive, and dedicated surface transportation weather research program.

The objective of this test was to examine the efficacy of using CARMA Cloud for communication with CDA vehicles enacting lane changes to avoid a simulated flood zone on a roadway.[17]

Description

This use case focused on enabling lane closures around known road-flooding locations. The TCM systems (CARMA Cloud) broadcast a TCM to CDA vehicles (CARMA Platform) to inform them of a flooded area and the need to change lanes to avoid that location.[17,29] CDA vehicles (CARMA Platform) used the information to plan new paths of travel and avoid the lane closure and thus the flooded area. Figure 24 shows a CARMA vehicle during verification testing.

Source: FHWA.

Figure 24. Photos. CARMA vehicles in icy road conditions.

Benefits for Transportation

Vehicles and their passengers face increased risks in adverse weather because of low visibility and roadway surface changes such as flooding. The situations pose similar risks to human drivers and AVs, although the extent varies based on the sensor suite in use. Road operators can use TCMs to publish weather information affecting travel to CDA-equipped vehicles that use TCR messages to request local route information. The publication of weather information can help mitigate the effects of flooding conditions by providing early alerts, suggesting alternative travel paths, and better equipping agencies' response and recovery efforts. The information may be distributed through short-range communication or cellular networks.

State of Practice

To realize the benefits demonstrated by this use case in a real RWM scenario, intelligent transportation infrastructure systems must be deployed at the site to enable the broadcasting of messages that C-ADS vehicles need.

Technical Specifications

The following parts of CARMA Ecosystem were used in this use case:

- CARMA Platform.[29]
- CARMA Cloud.[17]
- V2X Hub.[16]

The following hardware and software were used in this use case:

- CARMA Platform.[17]
- RSU.
- V2X Hub–capable personal computer, RSU, and cellular.[16]
- Server running CARMA Cloud.[17]

The following standards were used in this use case:

- SAE Taxonomy and Definitions for Terms Related to CDA for On-Road Motor Vehicles: J3216_202107.[12]
- SAE Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles: J3016_202104.[13]

The following architecture, logic, connectivity, and communication framework was used in this use case:

- This use case follows ARC-IT Service Package VS07: Road Weather Motorist Alert and Warning.[32]
- Internal messages used: TCM and TCR, as defined in the CARMA Cloud data dictionary.[17]

Results

Testing Overview

The research team successfully demonstrated and tested this use case in Summit Point, WV. For verification and validation testing, an RSU with a connection to CARMA Cloud broadcast TCMs to approaching vehicles to communicate an upcoming closed-lane section caused by inclement weather.[17] When received by a C-ADS vehicle, the TCM updated the vehicle's future path for changing lanes and avoiding the weather-related closed-lane section.

Verification Testing

The verification testing took place primarily on a straight section of a one-way, two-lane road. Figure 25 shows the general test setup for the use case.

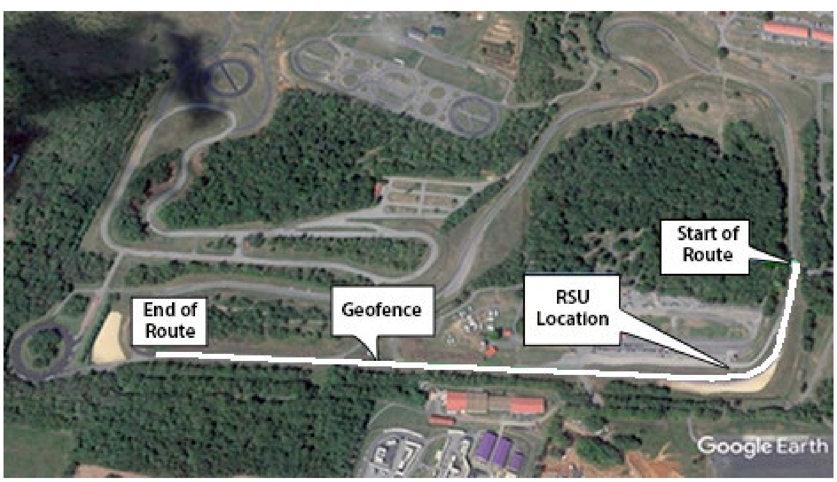
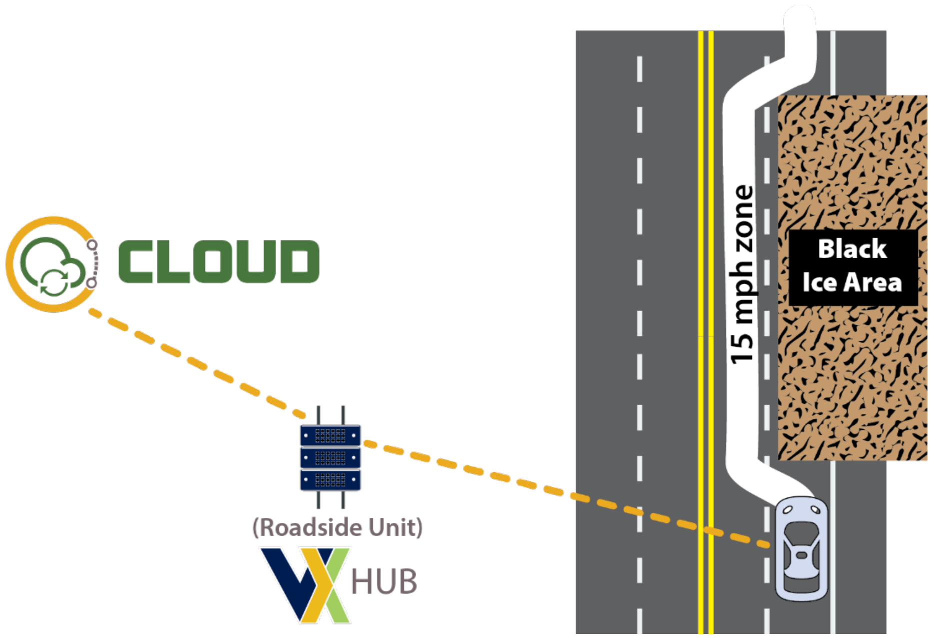


Figure 25. Photo. RWM verification testing set up in Summit Point, WV.[21]

Validation Testing

An independent evaluator developed and executed the validation test plan. Figure 26 details the simulation scenario with 15-mph safety zone placed around the black ice area.



Source: FHWA.

Figure 26. Graphic. RWM simulation scenario.

Test Results and Level of Performance and Advancement

To evaluate the system's performance, the team collected data and calculated several performance metrics. The evaluation showed that most of the performance metrics were passed in all test runs, and the metrics that were not reliably passed still resulted in minimum viable performance. In general, the issues encountered during testing were due to vehicle control issues, including the vehicle's performance of deceleration and acceleration rates that were slower than those stated in the desired performance metrics.

Next Steps

Development of this use case highlighted the challenges of ensuring spatial alignment from the available data generated by the different systems. It is necessary to ensure that all data sources accurately describe the relevant coordinate frames and that the receiving entity can make proper interpretations from this data. Having an approach to handle discrepancies between satellite-based maps and HD maps from the ADS may ensure proper spatial alignment. Future work could focus on developing more robust techniques for addressing spatial alignment issues or improving cybersecurity in CARMA Cloud and CARMA Platform connections.[17,18] And future work could explore using cellular communications to provide approaching vehicles with more advanced notice of an upcoming geofence.

PORT DRAYAGE

Objective

Port drayage is defined as "the short-haul transport of freight from an ocean port to a destination."(33) The objective of this use case is to examine the effectiveness of CDA technology for port drayage operations involving commercial motor vehicles (CMVs) that interact with a container terminal's infrastructure to perform container loading and unloading, inspection, and passage through port and staging area gates. Figure 27 shows the CDA-equipped trucks used in this use case. The objective is to further the implementation of technology in U.S. ports to accelerate adoption of the technologies available and to highlight the benefits CDA can bring to U.S. ports.

Source: FHWA.

Figure 27. Photos. CARMA-equipped port drayage vehicles.

Description

The goal was to demonstrate the use of CDA for port drayage as part of the port drayage development and testing initiative. The use case demonstrated the application of connectivity and automation for CMVs transporting containers between staging areas and port areas. During each trip, various actions were performed, such as:

- Loading and unloading a shipping container onto and from a chassis attached to the CDA-enabled CMV.
- Stopping at an inspection point whereby vehicles that pass inspection continue onward with their routes, and vehicles that fail inspection navigate to a holding area for further inspection.
- Traversing gate passage and emulating a short-haul drayage before returning to the starting location.
- Looping around into an unloading and loading area.

Benefits for Transportation

Effective communication between automated CMVs and the infrastructure is key for facilitating intricate logistics operations at U.S. ports. For drivers and operators, such communication plays a role in directing the timing and location of CMV movements. Incorporating CDA technology into CMVs used for container drayage to and from container terminals can help minimize terminal congestion, mitigate environmental impact, aid drayage drivers, and enhance safety, productivity, and revenue. In turn, the incorporation of CDA technology can reduce CMVs' queuing times at terminal gates and congestion on approach roads that are caused by CMVs' waiting to enter terminals. Less congestion can reduce both CMV turn times and emissions from idling CMVs and can improve container terminals' throughput capabilities.

State of Practice

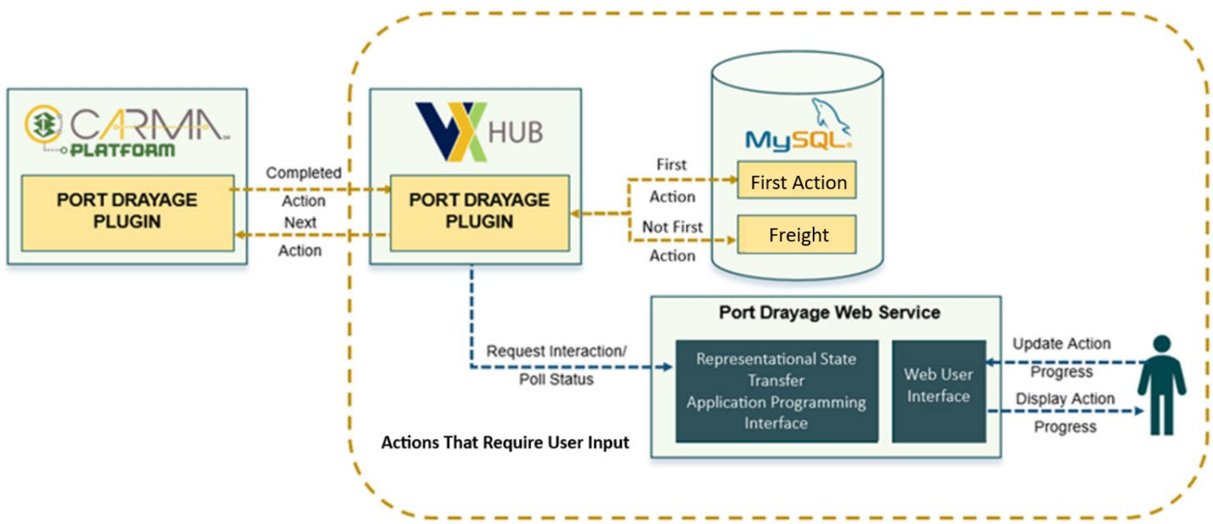
Drayage often accounts for a high percentage of overall transportation costs and a large proportion of CMV arrivals at container terminals. The U.S. Maritime Administration studies and develops ITS technology solutions through the CARMA Program. In phase 1 of this review inefficiencies in drayage turn times were addressed.[(34)] Many solutions identified in that study aimed at lowering the barrier between port terminals and the drayage trucking industry through improved transparency and visibility of cargo data. The short-haul drayage automation concept attempts to tackle the main challenges at many of today's ports. Those challenges include recurring congestion at entry and exit points because of bottlenecks and consolidations of international marine terminals, nonrecurring congestion due to accidents and vehicle breakdowns, and shortages of qualified drivers. This concept was attempted in a project in Germany.[(35)] The project involved testing an SAE Level 3 truck with a driver present in the vehicle on the road but who was free to do other tasks.[(12)] At the port gate, the driver could leave the vehicle, and the vehicle could operate in a fully automated mode for traversing the yard and loading and unloading. The concept proved successful because it contributed to increasing the throughput of container terminals as well as reducing downtimes at ports.

Technical Specifications

Parts of CARMA Ecosystem Used

To enable CDA for heavy trucks, CARMA Platform, CARMA Messenger, and V2X Hub (a component of CARMA Streets) were used.(17) Figure 28 shows the system architecture and how the three components interact. The infrastructure component of the port drayage use case has three major actors, all of which fall under CARMA Streets: V2X Hub, database, and port drayage web service.(15) Details of the functions of each component are as follows:

- The port drayage plug-in, which resides within V2X Hub, receives and transmits MOMs from the CDA-enabled CMV and facilitating communication with loading equipment operators or inspection personnel to complete port drayage operations.
- The database's main function is to store vehicle instructions and actions (e.g., loading and loading location) to be communicated later one by one with the CDA-enabled CMV through V2X Hub depending on the past action.(16)
- The port drayage web service provides an interface that enables user input. The interface is needed by inspection personnel (e.g., to indicate that loading is complete) or loading equipment operators (e.g., to indicate that loading or unloading is complete).

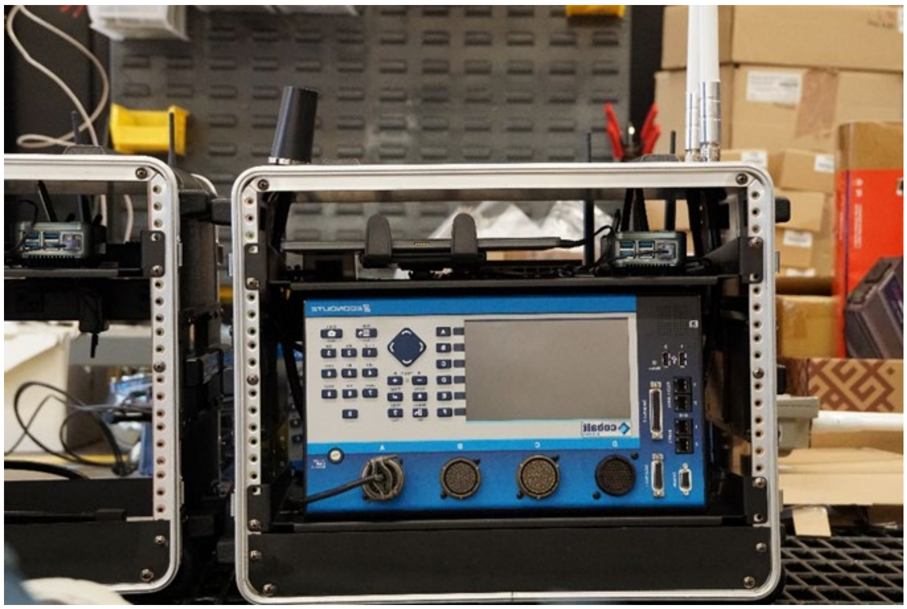


Source: FHWA.

Figure 28. Diagram. Components of the port drayage use case.

The following hardware and software were used in this use case:

- CAV education (CAVe)-in-a-box is a scaled-down representation of a CAV system (a vehicle and its environment). This technology is shown in figure 29.
- V2X Hub.[16] Custom MOMs were used by the research team to enable communication between the V2X Hub and loading equipment operators and inspection personnel in this use.



Source: FHWA.

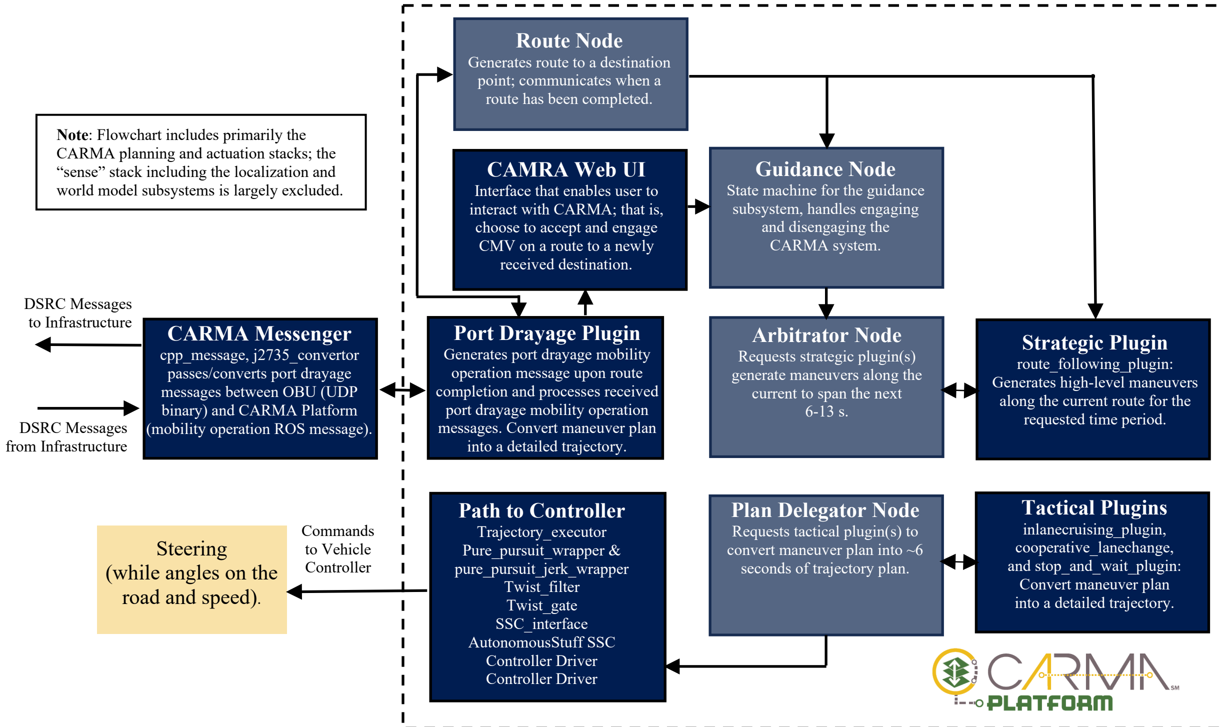
Figure 29. Photo. CAVe-in-a-box.

The following standards were used in this use case:

- SAE Taxonomy and Definitions for Terms Related to CDA for On-Road Motor Vehicles: J3216_202107.[12]
- SAE Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles: J3016_202104.[13]
- SAE V2X Communications Message Set Dictionary: J2735_202211.[19]

Architecture, Logic, Connectivity, and Communication

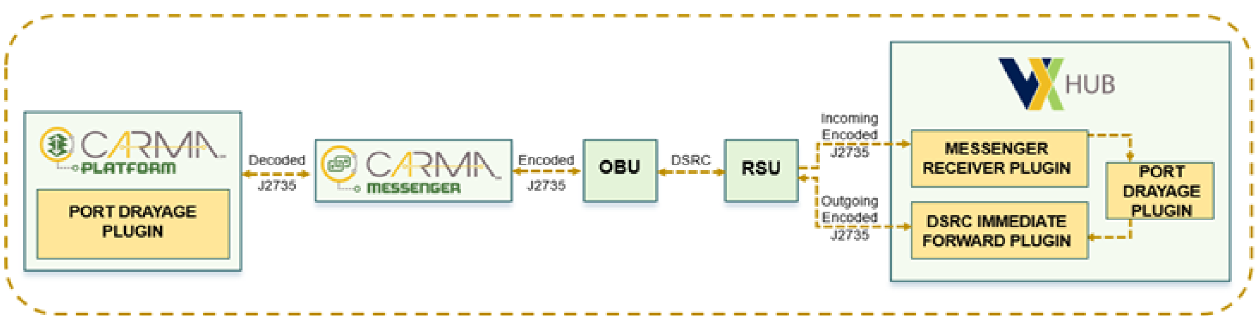
Like V2X Hub, a port drayage plug-in was developed and added to the CARMA Platform to enable automated operation of the CMV and execute the various actions outlined earlier.[18] The plug-in composes MOMs broadcast from the CDA-enabled CMV to the V2X Hub.[16] Finally, the plug-in processes MOMs the CDA-enabled CMV receives from V2X Hub.[16] Figure 30 shows the CARMA Platform architecture with the interactions between the various plug-ins.



Source: FHWA.
UDP = User Datagram Protocol; UI = user interface.

Figure 30. Diagram. Port drayage architecture.[22]

The MOM is often used for prototyping messages. For actions requiring user input, connection between the port drayage plug-in and the port drayage web service through request and response communication is established. To query actions from the database for each action sequentially, the port drayage plug-in sends information on actions performed and receives information on actions to be performed. Figure 31 shows the port drayage architecture.



Source: FHWA.
DSRC = dedicated short-range communication; OBU = onboard unit; RSU = roadside unit.

Figure 31. Diagram. CARMA Platform architecture.

Results

Test Results and Level of Performance and Advancement

To evaluate the system's performance, the research team collected data and calculated several performance metrics. The evaluation showed that the CDA-enabled truck was able to pass most of the performance metrics in all test runs. A few metrics relevant to the truck's stopping, acceleration, and deceleration behaviors showed that additional work is needed for the use case to be fully ready. Testing and demonstration of the use case showed no safety concerns that could prevent further development or consideration of other freight-related use cases.

Next Steps

While a few limitations were identified through data collection and analysis, the research team raised no safety concerns, and high potential for future work remains intact. Various applications could be developed and tested for port drayage and short haul, including enhanced port demonstration (the next stage of this use case) and signal preemption. As first next steps, the team will demonstrate this use case in a more complex environment on a miniature port at 1/10 scale. Following that work, the team will explore demonstration of the use case on the premises of an actual port.

FHWA's CDA Program Activities

Because there are so many potential collaborators, stakeholders, and usage applications of CDA, FHWA operates with a wide range of focus when planning projects and goals. Figure 32 shows the program's five activity categories: research, metrics, software, technology, and engagement. Equally important is the need to prioritize reaching a diverse network of collaborators and contributors across all areas of the CDA community. This section presents published research papers from 2022 and summarize other technologies FHWA is developing that were not directly involved in the use cases seen earlier in the report. This section also lays out the release schedule of the software that supports virtually all CDA projects as well as grants FHWA has funded and certain high-level metrics on our testing from the year. Finally, the section summarizes engagement activities from 2022 and introduces the universities involved with our academic work that are critical to current and ongoing CDA research.

Source: FHWA.

Figure 32. Graphic. CDA program activity categories; Exploratory Advanced Research Program.

The Exploratory Advanced Research Program enables CDA researchers at STOL to focus on long-term, high-risk, breakthrough research with high-potential payoff for improvements to transportation systems.(36) During 2022, several projects—related to CDA and that helped inform CDA activities—conducted research for the program as follows:

- Cooperative Perception and Control for Traffic System Operations.(37)
- Implementation of Artificial Intelligence to Improve Winter Maintenance.(38)
- Utilizing Mobile Ad Hoc Networks To Enhance Road Safety.(39)
- Harnessing Mobile Ad Hoc Networks To Improve Vulnerable Road User Safety.(40)
- MIMIC—Multidisciplinary Initiative on Methods To Integrate and Create Realistic Artificial Data.(41)

With the potential for transformational improvements to plan, build, renew, and operate safe, congestion-free, and environmentally sound transportation systems, the EAR Program explores the development of artificial intelligence (AI) and machine learning in surface transportation.

CDA DESIGN AND ARCHITECTURE PROJECT

The CDA Design and Architecture project explores ways to enhance the modularity, flexibility, and scalability of CDA technologies (CARMA Ecosystem),(22) including interfaces between different CARMA Ecosystem products and other, potential, CDA entities. The project's goals are to develop a CDA domain that can be achieved within the next 5–7 years, to gain an understanding of what a realistic CDA-enabled arterial and/or freeway might look like in the near future, and to demonstrate multiple use cases for mixed traffic. Efforts will focus on improving the CARMA Ecosystem architecture to ensure it aligns with national ITS ARC-IT and standards, thereby enabling it to interface with ITS technologies and other CDA entities. In addition to architecture improvements, the project will analyze spectrum requirements for the deployment of CDA applications developed under the CDA program so far.

CARMA XIL[17]

To better understand CDA behaviors and impacts, FHWA has been building open-source simulation tools to develop and test new CDA architectures and algorithms in simulation before any real-world testing. That practice can accelerate development and testing while bringing down costs. CDA sits at the intersection of multiple industries and the technology requires complex interactions between vehicles and infrastructure; therefore, the simulation tools must be modular and accommodate different types of models. This project developed CDASim, an open-source, multisimulation integration tool that facilitates research in developing, testing, and, eventually, deploying CDA applications.[17] The concept of this framework includes and integrates various items in transportation systems into the software-in-the-loop simulation.

The CDASim framework contains six main components:

- A vehicle-driving simulator (i.e., CARLA) that simulates sensors and vehicle dynamics.[27]
- A traffic simulator that simulates the behaviors of different types of non-CDA vehicles.
- A communication simulator that simulates V2X communication.
- A CDA vehicle control system (i.e., CARMA Platform)[17]
- An infrastructure-based system to enable cooperation between vehicles and infrastructure (i.e., CARMA Streets).[15]
- A National Transportation Communications for ITS Protocol–compatible virtual traffic signal controller.

CDASim supports users in configuring different scenarios to develop and evaluate various CDA applications.[17] For example, some scenarios may not be viable and safe for conducting field testing in the real world (e.g., in extreme weather conditions). CDASim could support different agencies and organizations in conducting CDA research without physical devices (e.g., vehicles).[17] That kind of research can reduce the resources needed to perform quality research while also generating data for use in training AI-based algorithms for sensing, signal operations, traffic message channel operations, and transportation management decision support.

VIRTUAL OPEN INNOVATION COLLABORATIVE ENVIRONMENT FOR SAFETY

The U.S. Department of Transportation's (USDOT's) prototype Virtual Open Innovation Collaborative Environment for Safety (VOICES) platform.[42] VOICES was built to enable transportation innovators to conduct collaborative testing of safety solutions in a synthetic test environment before deployment on the Nation's highways.

Initially developed by FHWA, the focus of VOICES is to facilitate collaborative research and testing of CDA among all stakeholders. CDA uses V2I communication to improve AV and transportation system-level outcomes, including increased road network throughput, reduced travel time, and improved fuel efficiency. The VOICES test platform enables data sharing and distributed collaboration, testing between physical and simulated hardware components, and testing with human interaction.

NEXT-GENERATION ENERGY TECHNOLOGIES FOR CONNECTED AND AUTOMATED ON-ROAD VEHICLES PROGRAM

A large portion of future vehicle energy efficiency improvements, driven by Federal fuel economy standards, were expected to be achieved through a mix of well-established technologies. A new opportunity enables FHWA to leverage advances in CAV technologies that the Advanced Research Projects Agency–Energy (ARPA-E) is using to demonstrate the energy efficiency of individual vehicles through this program. The use of onboard sensing and external connectivity such as V2V, V2I, and V2X, NEXT-Generation Energy Technologies for Connected and Automated On-Road Vehicles (NEXTCAR) projects enabled a vehicle to "know" with some certainty its future operating environment.[43] That knowledge enabled better coordination of vehicle-level and power-train-level actions, including acceleration, deceleration, grade climbing, efficient engine operation, efficient transmission operation, and regenerative braking and battery state-of-charge management in the cases of hybrid electric vehicles and electric vehicles.

ARPA-E's NEXTCAR program considers the energy aspect of CDA.[43] NEXTCAR coordinates vehicle dynamic controls and power train operation to optimize vehicle efficiency in real-world driving scenarios. The NEXTCAR program particularly highlights the use of such applications in vehicles that are not yet fully automated (National Highway Traffic Safety Administration and SAE Levels 0–3) or that are incapable of operating without human intervention in certain situations.[13,43]

TRAFFIC OPTIMIZATION FOR SIGNALIZED CORRIDORS

Traffic Optimization for Signalized Corridors (TOSCo) uses wireless communication between RSUs and connected vehicles (CVs) to enhance efficiency, reduce fuel consumption, and lower emissions when vehicles move through signalized intersections along urban corridors. By collecting and analyzing data and messages, the application calculates the optimal vehicle speed for approaching the next traffic signal—either to maintain a green light or decelerate smoothly—with a focus on reducing environmental impact. The data are then communicated to the vehicle's longitudinal control system to enable partial automation. During phase 2 of the project, the proposed system developed in phase 1 was implemented and verified under controlled conditions—and before the system was deployed on State Highway 105 in Conroe, TX. The purpose of this phase was to estimate the potential benefits of the system and to refine its design.

ADVANCED VEHICLE TECHNOLOGY COMPETITIONS SERIES ECOCAR ELECTRIC VEHICLE CHALLENGE

This competition challenges teams of university students across North America to design, build, and optimize energy-efficient vehicles using advanced technologies, such as CDA. Fifteen North American universities are participating in the EcoCAR electric vehicle challenge, which is the latest challenge in the Advanced Vehicle Technology Competitions series.(44) The challenge involves designing a cutting-edge battery electric vehicle that incorporates automation and V2X connectivity to deliver energy-efficient, customer-friendly features while addressing the decarbonization requirements of the automotive sector. The EcoCAR electric vehicle challenge showcases the fuel energy efficiency capabilities of CDA technology and cultivates a new generation of professionals with expertise in this field.(44)

FWHA Videos

FHWA developed the following eight CDA-focused videos in 2022:

- CARMA Core(45)

  https://www.youtube.com/watch?v=7xBo2C-SNIc

- CDA Road Weather Management(46)

  https://www.youtube.com/watch?v=PnPR5XDfutg

- CDA Workzone Scenario(47)

  https://www.youtube.com/watch?v=tZf2xE8tt10

- CAVERS Video(48)

  https://www.youtube.com/watch?v=fQ3B_KucEH8

- VOICES SIT-1 Video(5)

  https://www.youtube.com/watch?v=hoShDlT6iFk

- CAVe Lite Video(49)

  https://www.youtube.com/watch?v=t2qyqzunsRI

- CDA Freeway Applications(50)

  https://www.youtube.com/watch?v=ye_j86YgVSc

- Traffic Optimization for Signalized Corridors Video(51)

  https://www.youtube.com/watch?v=E31qTLF6e0o

FHWA Publications

FHWA developed 13 reports, 2 articles for *Public Roads* magazine, and 3 fact sheets. Additionally, many social media posts and materials were created for outreach that may not have been published but were made available to stakeholders.

Reports

The following reports on CDA were developed by FHWA in 2022:

- Final Project Report for Traffic Optimization for Signalized Corridors (TOSCo) Phase 2:[52] This report summarizes the potential mobility and environmental benefits associated with deploying the TOSCo system on the FM 1960 corridors in Houston, TX:

  https://rosap.ntl.bts.gov/view/dot/65659.

- *Modeling and Benefit Estimation Final Report for TOSCo Phase 2 for State Highway 105 Corridor*:[53]

  https://rosap.ntl.bts.gov/view/dot/66287.

- Modeling and Benefit Estimation Final Report for TOSCo Phase 2 for the FM 1960 Corridor:[54]

  https://rosap.ntl.bts.gov/view/dot/65980.

- Infrastructure and Architecture Final Report for TOSCo Phase 2:[55]

  https://rosap.ntl.bts.gov/view/dot/66288.

- Functional Safety Concept and Hazard Analysis Final Report for TOSCo Phase 2:[26]

  https://rosap.ntl.bts.gov/view/dot/64925.

- *ConOps for CARMA IHP2*:[56]

CDA aims to improve the safety and flow of traffic and facilitate road operations by supporting the movement of multiple vehicles in proximity to one another. That improvement outcome is accomplished by sharing information for influencing dynamic driving tasks directly or indirectly by one or more nearby road users. Vehicles and infrastructure elements engaged in CDA may share information such as state (e.g., vehicle position and signal phase) or intent (e.g., planned vehicle trajectory or signal timing), or the vehicles and infrastructure elements may seek agreement on a plan (e.g., coordinated merge). Cooperation between multiple participants in traffic can improve safety, mobility, situational awareness, and operations. For IHP2, three key feature groups were cooperative lane follow (platooning and CACC), cooperative lane coordination (cooperative lane change, merge, and weave), and cooperative traffic management (speed and gap control, lane assignment, and queue management). The combination of those feature groups to form IHP2 provides benefits for both individual travelers and the overall traffic system.

- *Strategic and Tactical Decisionmaking for CV Platooning With Organized Behaviors on Multilane Highways*:(57)

  Driving automation and V2V communication provide opportunities to deploy C-ADS for transportation system goals such as sustainability, safety, and efficiency. Among various C-ADS applications, vehicle platooning has great potential to achieve the aforementioned system management goals by establishing trajectory-aware V2V cooperative strategies among C-ADS vehicles. Previously, the concept of CACC—that is, single-lane decentralized ad hoc operations of multiple vehicles that follow each other closely—has been studied by researchers extensively. This study builds upon the existing research and proposes a comprehensive multilane platooning algorithm with organized behavior via a hierarchical framework.

- *CP for Estimated and Predicting Microscopic Traffic States to Manage Connected and Automated Traffic*:(58)

  Real-time, traffic state estimation and prediction are important to traffic management systems because they enable up-to-the-minute adjustments to improve the flow of traffic. New opportunities are enabled by the emerging sensing and automation technologies for managing connected and automated traffic—particularly with regard to controlling the trajectories of AVs. Traffic information from CAVs and roadside detectors can be fused and has great potential for providing the detailed microscopic traffic states (i.e., vehicle speeds and positions) of all vehicles.

- *CARMA Use Case PoC for Traffic Signal Optimization with CDA at Signalized Intersections*:(25)

  The objective of this use case is to advance the CARMA Ecosystem and its capabilities by enhancing CDA participants' interactions with road infrastructure, infrastructure performance, network efficiency, and the flow of traffic. The focus of this ConOps is on TSMO use case 3, which investigates traffic signal optimization with CDA at signalized intersections.

- *ConOps for CP in CARMA*:(59)

  The objective of this use case extends the research from the development of CDA capabilities related to Integrated Highway Protype II (IHP2) by enhancing the CARMA Ecosystem to enable CP capabilities. This ConOps focuses on the high-level system framework of the CP feature in the CARMA Ecosystem, its requirements, and potential effects on transportation systems.

- *CARMA Use Case PoC for Transit Management*:(60)

  This use case extends the research from IHP2 by using CARMA Streets, CARMA Platform, and CARMA Cloud to provide CDA participants with capabilities to interact with road infrastructure, including traffic signal controllers.(14) The use case in this ConOps focuses on active traffic management that incorporates signal optimization, signal coordination, and transit vehicle management.

- *CARMA PoC for CP*:(22)

  CARMA CP is a feature of the CARMA Ecosystem that enables entities to share locally perceived data. CP is expected to improve the perception performances of AVs and CARMA Streets.(31) The enhanced situational awareness is expected to lead to more effective CDA safety and mobility applications.

Articles

The following articles on CDA were developed by FHWA in 2022:

- "CDA Research Program's Development, Testing, and Evaluation":(61)

  This article provides an overview, background, and the most recent updates on FHWA's CDA Research Program.

- "CDA Infrastructure Ensuring Safety for VRUs"**:**(62)

  The goals of this literature review are to assess the potential impact of ADS-equipped vehicles and CDA technology on VRU safety and to determine the potential role of infrastructure in facilitating safe interactions.

Fact Sheets

The following fact sheets were developed by FHWA in 2022:

- *Fact Sheet for Automated Vehicles Working Together*:(63)

  This fact sheet illustrates how all the pieces of the CARMA Ecosystem—a technology-enabling initiative under the FHWA CDA program—work together to advance CDA R&D.

- *Fact Sheet for V2X Hub: Open-Source CV Software*:[64]

  This fact sheet gives background information on the V2X Hub project and functionalities that are integrated into the system.[16]

- *Reducing Traffic Congestion Through CDA*:[65]

  Traffic congestion is an ongoing transportation challenge for transportation researchers and leaders because roadways are becoming more populated and will eventually be unable to efficiently support the increased demand. This article highlights how FHWA is using CDA as a solution to traffic congestion.

ACTIVE GRANTS

The following grants actively supported CDA research in 2022: ADS Demonstration Grants.[66]

The USDOT provided nearly $60 million in Federal funding for the following projects to test the safe integration of ADS on the Nation's roadways:

- Texas A&M Engineering Experiment Station.
  - Project name: AVA: Automated Vehicles for All.[67]
  - Technology: SAE Level 4 vehicle, CARMA 2, and V2X Communication.
  - This project will develop and test ADS for rural roads without HD maps and with no or low-quality road signs or markings.
- University of Iowa.
  - Project name: ADS for Rural America.[68]
  - Technology: SAE Level 3+ automation, V2I, and onboard telemetry processors (i.e., V2V).
  - This project will connect rural transportation-challenged populations by using a mobility-friendly ADS built on a commercially available platform.
- Virginia Polytechnic Institute and State University.
  - Project name: Safely Operating ADS in Challenging Dynamic Scenarios: An Optimized Automated Driving Corridor Demonstration.[69]
  - Technology: SAE Level 4 ADS and adaptive ADS.
  - This project will define, develop, and demonstrate key dynamic scenarios and their potential solutions for safe interactions of ADS-equipped vehicles in a northern Virginia corridor optimized for vehicle automation.
- Virginia Polytechnic Institute and State University.
  - Project name: Trucking Fleet ConOps for Managing Mixed Fleets.[70]
  - Technology: Advanced prediction and camera-based self-driving.
  - This project will develop and demonstrate a fleet ConOps to provide the trucking industry with clear information on how to safely implement—and benefit from—ADS-equipped trucks.

- Ohio Department of Transportation.
  - Project Name: D.A.T.A. in Ohio: Deploying Automated Technology Anywhere.(71)
  - Technology: ADS Level 3 Passenger Vehicles, ADS Level 3, and Trucks with Platooning Autonomous ParaLift™.(71)
  - This project will take a multipronged demonstration approach focused on rural environments, cooperative automation, and robust data collection to enable the development of effective and informed ADS policies.
- Pennsylvania Department of Transportation.
  - Project name: Safe Integration of AV in Work Zones.(72)
  - Technology: Connectivity between AV and traffic control devices, construction workers, and construction vehicles by using a single device with DSRC and C-V2X radio;(14) innovative coating for pavement markings; traffic control devices; and HD work zone mapping using radar, LiDAR, and cameras.
  - This project will explore the safe integration of ADS into work zones by examining connectivity, visibility, and HD mapping technologies.
- City of Detroit, MI.
  - Project name: Michigan Mobility Collaborative.(73)
  - Technology: Level 3 ADS.
  - This project will implement the CARMA 3 software platform for demonstration testing focused on mobility, safety, and endurance.
- Contra Costa Transportation Authority.
  - Project name: Automated Driving System Demonstration Program.(74)
  - Technology: Radar; LiDAR; detectors; cameras; V2V, V2I, and V2X (e.g., SpaT) messages; MAP; basic safety messages; and pedestrian or PSMs.
  - This project will demonstrate SAE Level 3 and Level 4 vehicles using shared on-demand wheelchair-accessible ADS-equipped vehicles.

TESTING HOURS

More than 200 test runs were conducted with approximately 4,500 hours of testing support.

DATA COLLECTION

Approximately 17 terabytes of CAV data helped in evaluation of performance metrics to enhance highway safety and mobility operations.

TESTING MILES

The team logged roughly 23,000 miles of testing using six CDA-enabled vehicles (four light vehicles and two semitrucks).

Source: FHWA.

A. CARMA vehicle demonstration with pedestrian dummy.

Source: FHWA.

B. CARMA vehicle demonstration.

Figure 33. Photos. CARMA vehicle demonstration.

CDA COMMUNICATION MESSAGE SETS

Currently, most of the CDA technologies rely on message sets governed under SAE J2735, SAE J2945, and SAE J3224.(18,24,75) SAE J2735 specifies messages and its data frames and data elements for use by applications that use V2X communication systems.(18) SAE J3224 is for V2X sensor sharing for cooperative and automated driving.(24) SAE J2945 has nine subsections, listed in table 3, that center on the messages involved in V2X applications.(75)

Table 3. SAE J2945 subsections.

SAE J2945 Standard Code[75]	Standard Name
/1	V2V safety
/2	V2V DSRC[14]
/3	Road weather
/4	V2I road safety
/5	Security for CVs
/6	CACC and platooning
/7	Positioning enhancements for V2X
/8	CP system
/9	VRUs

Continued development in the field of CDA necessitates a new message set. The STOL team has been developing new message sets to address missing information in existing standard messages. For example:

- TCR, which is a request sent periodically by a vehicle for updates about the driving environment along the vehicle's current path of travel. The updates are sent from the vehicle to the infrastructure (CARMA Cloud).[17]

- TCM, which is a message sent in response to a TCR describing traffic controls for vehicles to follow such as a lane closure due to roadwork, advisory speeds, or platoon headway. The messages are sent from infrastructure to vehicles in response to TCR messages.

TCRs and TCMs enable applications such as speed harmonization, RWM work zone navigation (signals), work zone navigation, and freight work zone navigation.

SOFTWARE RELEASES IN 2022

FHWA released a series of new software versions throughout the year as new features got tested. FHWA also released new lines of code. Table 4 shows the full list of software releases in 2022. This section provides a comprehensive list of those updates and additions. A summary of each release for the CARMA Platform can be found on the CARMA Platform GitHub.[76] A summary of each V2X Hub release can be found on the V2X Hub GitHub.[10]

Table 4. FHWA open-source software releases for 2022.

Software	Feb.	Apr.	May	June	July	Aug.	Sept.	Oct.
carma-cloud(17)	—	—	—	—	carma-system 4.2.0	—	—	—
carma-messenger(29)	carma-system 3.11.0	—	—	—	carma-system 4.2.0	—	—	—
carma-platform(18)	carma-system 3.11.0	—	carma-system 4.0.3		carma-system 4.2.0	—	—	—
carma-streets(15)	carma-system 3.11.0	—	—	—	carma-system 4.2.0	—	—	—
Carma-simulation	—	—	—	—	—	—	carma-simulation 1.0.0	carma-simulation 1.0.0
Carma-carla-integration(27)	—	—	—	—	—	—	carma-simulation 1.0.0	—
autoware.ai(77)	carma-system 3.11.0	—	—	—	—	—	—	—
autoware.auto	carma-system 3.11.0	—	—	—	—	—	—	—
avt_vimba_camera(78)	carma-system 3.11.0	—	—	—	—	—	—	—
carma-base	carma-system 3.11.0	—	—	—	carma-system 4.2.0	—	—	—
carma-cohda-drsc-driver(7)	carma-system 3.11.0	—	—	—	carma-system 4.2.0	—	—	—
carma-config	carma-system 3.11.0	—	—	—	carma-system 4.2.0	—	—	—
carma-delphi-esr-driver	carma-system 3.11.0	—	—	—	carma-system 4.2.0	—	—	—
carma-delphi-srr2-driver	carma-system 3.11.0	—	—	—	carma-system 4.2.0	—	—	—
carma-garmin-lidar lite-v3-driver-wrapper	carma-system 3.11.0	—	—	—	carma-system 4.2.0	—	—	—
carma-lightbar-driver	carma-system 3.11.0	—	—	—	carma-system 4.2.0	—	—	—

Software	Feb.	Apr.	May	June	July	Aug.	Sept.	Oct.
carma-msgs	carma-system 3.11.0	—	—	—	carma-system 4.2.0	—	—	—
carma-novatel-oem7-driver-wrapper	carma-system 3.11.0	—	—	—	carma-system 4.2.0	—	—	—
carma-ssc-interface-wrapper	carma-system 3.11.0	—	—	—	carma-system 4.2.0	—	—	—
carma-utils	carma-system 3.11.0	—	—	—	—	carma-system 4.2.0	—	—
carma-vehicle-model-framework	carma-system 3.11.0	—	—	—	carma-system 4.2.0	—	—	—
carma-velodyne-lidar-driver	carma-system 3.11.0	—	—	—	carma-system 4.2.0	—	—	—
carma-web-ui	carma-system 3.11.0	—	—	—	carma-system 4.2.0	—	—	—
novatel_gps_driver	carma-system 3.11.0	—	—	—	carma-system 4.2.0	—	—	—
ros1_bridge	carma-system 3.11.0	—	—	—	carma-system 4.2.0	—	—	—
tim-bc	—	TIM-BC Tool Version 2.0.0	—	—	—	—	—	—
v2x-hub	V2xhub-7.1	—	V2xhub-7.2, 7.2.1, 7.2.2, 7.2.3	V2xhub-7.3.0	—	V2xhub-7.3.1	—	—

—No data.

ENGAGEMENT ACTIVITIES

In 2022, FHWA engaged in more than 120 outreach activities with stakeholders. The activities took the forms of virtual and in-person meetings, conferences, and emails through the CDA Support Services help desk. These engagement activities played parts in promoting CDA technologies and demonstrating to stakeholders the work being done by FHWA. The CDA support services help desk assisted industry adopters and collaborators who are trying to deploy CDA technologies for their own research.

Source: FHWA.

Figure 34. Photos. FHWA STOL staff at engagement activities.

FHWA has engaged with stakeholders across the transportation industry—including academia, technical industry, and Government—that will be key as CDA technologies become more readily available for deployment.

Source: FHWA.

Source: FHWA.

Source: FHWA.

Figure 35. Photos. FHWA STOL staff presenting technology at conferences.

Work With Academic Community

FHWA has engaged with academic stakeholders throughout the United States to research and test CDA technologies. The stakeholders help FHWA innovate using CDA technologies, and they provide students with hands-on CDA experience, thus preparing students to enter the transportation workforce. Some of the academic collaborators were key in testing and developing CDA features such as TSMO and IHP.

The relationships between FHWA and universities are some of the most beneficial in this program. FHWA benefits from the reputational weight of being associated with these well-respected academic institutions as well as access to the collective brainpower and shared energy that come from both professors in this space and their students. The following section lists the universities FHWA works with to advance CDA research:

- American University in Dubai.
- Arizona State University.
- Auburn University.
- California State University, Long Beach.
- Capitol Technology University.
- Carnegie Mellon University.
- Chattahoochee Technical College.
- City College of New York.
- Clemson University.
- Florida A&M University.
- Florida Atlantic University.
- Florida Institute of Technology.
- Florida International University.
- Florida Polytechnic University.
- Florida State University.
- Gonzaga University.
- Illinois State University.
- Iowa State University.
- Johns Hopkins University.
- Kansas State University.
- Kennesaw State University.
- Morgan State University.
- New Jersey Institute of Technology.
- North Carolina State University.
- Ohio State University.

- Pennsylvania State University.
- Purdue University.
- Stanford University.
- State University of New York at Buffalo.
- Texas A&M University.
- University of Alabama.
- University of Arizona.
- University of British Columbia.
- University of California, Berkeley, Partners for Advanced Transportation Technology.
- University of California, Los Angeles.
- University of California, Riverside.
- University of Central Florida.
- University of Cincinnati.
- University of Delaware.
- University of Florida.
- University of Hawai‘i at Mānoa.
- University of Illinois Urbana-Champaign.
- University of Iowa.
- University of Massachusetts Amherst.
- University of Massachusetts Lowell.
- University of Memphis.
- University of Michigan.
- University of Minnesota.
- University of Missouri.
- University of Nebraska–Lincoln.
- University of Nevada, Reno.
- University of New Hampshire.
- University of North Carolina.
- University of North Florida.
- University of Pennsylvania.
- University of South Florida.
- University of Southern California.
- University of Tennessee at Chattanooga.
- University of Utah.
- University of Virginia.
- University of Washington.
- University of Waterloo.
- University of Wisconsin–Madison.
- Virginia Commonwealth University.
- Virginia Polytechnic Institute and State University.
- Western Kentucky University.
- Western Michigan University.

Source: FHWA.

Figure 36. Photos. FHWA completes testing in various university locations.

Source: FHWA.

Figure 37. Photo. OBU during testing at TFHRC.

Source: FHWA.

Figure 38. Photo. VOICES platform at TFHRC.

Source: FHWA.

Figure 39. Photo. FHWA STOL staff with CARMA vehicles at testing site.

CLOSING AND WHAT IS NEXT FOR CDA

FHWA had a successful year of testing and exploring new technologies and applications for CDA that will facilitate a safe, cooperative, efficient, sustainable, and equitable transportation system for all users. The future of FHWA's success depends on solid planning, collaboration between stakeholders, and the integration of key technologies across infrastructure as well as vehicles. To facilitate the transition of technologies from research to the real world, the team is focusing on the following priorities for 2023:

- Release an independent, evaluation report on each of the use case verification and validation tests described in this report.
- Transition CARMA tools to fully support C-V2X connectivity and understanding of CDA performance with C-V2X and identify additional spectrum and connectivity needs to ultimately realize successful deployment.
- Publish the 10-year FHWA CDA roadmap to facilitate a cooperative, safe, efficient, and sustainable surface transportation system for all users. A comprehensive roadmap with collaborative participation and adoption will advance initiatives recommended for successful CDA implementation. FHWA will also conduct outreach and stakeholder engagement to obtain additional input on the roadmap and refine the decision criteria for moving to an on-road industry-developed pilot in the future.
- Demonstrate the capability of CDA technologies to reduce fatalities and serious injuries within the transportation system. A key challenge is to explore new ways of showing to what extent safe and effective CDA-enabling technologies can be—without the benefit of having the technologies deployed in the real world to scale. Testing completed on test tracks uses controlled situations to explore safely and efficiently.
- Demonstrate the capability of CDA technologies to improve system efficiency and the road user experience. In addition to mitigating risk for all users of the Nation's transportation systems CDA can help reduce traffic, establish smoother routes, offer more travel options, and increase access to transit options. Testing completed on test tracks uses controlled situations to explore safely and efficiently.
- Show the capability of CDA technologies to make contributions toward climate improvement and sustainability. As the volume of users increases on aging infrastructure, CDA presents opportunities to reduce traffic, reinvigorate public transportation and mass transit, and achieve environmental sustainability through less fuel consumption and more support for green energy initiatives. Testing completed on test tracks uses controlled situations to explore safely and efficiently.
- Enhance equity through development and support of open-source CDA research tools that lower barriers to entry and promote workforce development. Creating open-source tools will empower a new generation of researchers from industry and academia to test

fresh ideas that can further CDA's objectives for application across transportation systems. In addition to opening new doors for application and, potentially, creating new jobs, CDA presents opportunities for access to transportation systems that expand and promote workforce development in any community.

- Advance development of CDA standards to ensure interoperability as CDA moves through the R&D lifecycle toward development.

One of the challenges of CDA research is measuring or evaluating the crash that never happened.

—Sudhakar Nallamothu, FHWA

Key to the success of CDA will be establishing a multimodal program to develop and conduct research together. CDA going forward will have to support open-source research capabilities for workforce development, to expedite deployment, and to achieve successful milestones and decision points that demonstrate the value of CDA. Going forward, the transition from research tools to field-tested industry products and capabilities will be a focus. Finally, foundational to the future of CDA will be infrastructure owner–operator and private-sector stakeholder engagement (e.g., technical working groups), data sharing, research results, benefits to feed standards development, and CDA design and architecture framework.

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COLLABORATION IS THE KEY TO SUCCESS

For the successful transition of CDA technologies from research to real-world application, collaboration between a broad network of vendors, developers, manufacturers, users, policymakers, and industry groups is recommended. Our team will support open-source research capabilities for workforce development that expedites technology deployment to achieve successful milestones and decision points that demonstrate the value of CDA.

The Technical Review Panel applied its expertise in CDA, AV, computer science, and AI to critically revise and issue feedback on the products presented. We thank the Technical Review Panel for its dedication to the development and completion of this report.

ACKNOWLEDGMENTS

Figure 1 was modified by FHWA to make it text readable and compliant with Section 508 of the Rehabilitation Act of 1973. The original image is the copyright property of SAE International and can be accessed at https://www.sae.org/news/2019/01/sae-updates-j3016-automated-driving-graphic.(13)

Figure 7 was modified by FHWA to show the verification testing route for signalized intersections with fixed-time settings. The original maps are the copyright property of Google® Earth™ and can be accessed from https://www.google.com/earth.(21)

Figure 17 was modified by FHWA to show the test track used to test basic travel and integrated highway protype testing. The original maps are the copyright property of Google® Earth™ and can be accessed from https://www.google.com/earth.(21)

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Figure 23 was modified by FHWA to show the TIM test setup in Summit Point, WV. The original maps are the copyright property of Google® Earth™ and can be accessed from https://www.google.com/earth.(21)

Figure 25 was modified by FHWA to show the RMW verification testing setup. The original maps are the copyright property of Google® Earth™ and can be accessed from https://www.google.com/earth.(21)

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Recommended citation: Federal Highway Administration, *2022 CDA Annual Report* (Washington, DC: 2024)
https://doi.org/10.21949/1521761

HRSO-40/04-24(WEB)E