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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.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1,000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2,000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2,000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	2.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003)

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LIST OF ABBREVIATIONS

BSM	basic safety message
CAV	connected and automated vehicle
CAVe	Connected and Automated Vehicle Education
CDA	cooperative driving automation
DOT	department of transportation
FHWA	Federal Highway Administration
LiDAR	light detection and ranging
MMITSS	Multimodal Intelligent Traffic Signal System
MOM	mobility operation message
MPM	mobility path message
NCV	nonconnected vehicle
POC	proof of concept
RPC	remote procedure call
SDSM	sensor data sharing message
SMART	Strengthening Mobility and Revolutionizing Transportation
SNMP	simple network management protocol
SPaT	signal phase and timing
SRM	signal request message
SSM	signal status message
TIM	traffic incident management
TRB	Transportation Research Board
TSMO	transportation systems management and operations
TSP	transit signal priority
UDP	user datagram protocol
USDOT	U.S. Department of Transportation
V2X Hub℠	Vehicle-to-Everything Hub℠
V2X	vehicle-to-everything
VOICES	Virtual Open Innovation Collaborative Environment for Safety
XML	extensible markup language

MESSAGE FROM THE DIRECTOR

Technology continues to change the transportation sector at a rapid pace. Every day, exciting developments are occurring in relation to transportation infrastructure and automated driving that have the potential to make driving safer, more efficient, and more cost effective.

This second installment of the *Cooperative Driving Automation (CDA) Annual Report* covers the work of the Federal Highway Administration (FHWA) in enabling communication among infrastructure, vehicles, and other road users through vehicle-to-everything (V2X) communication to support CDA implementation. This work will help shape the future of transportation.

CDA combines emerging technologies in advanced vehicle automation and interoperable connectivity with transportation system management and operations strategies to bring safe, efficient, and equitable autonomous driving to the Nation's roadways. CDA is aligned with the principles of the National Roadway Safety Strategy and the Safe System Approach.(1,2)

Much of the research involving CDA is new, making this work both exciting and challenging. CDA testing and development involves an array of vehicles, sensors, and infrastructure components and requires high-end hardware and ongoing updates to critical software. Building relationships with other researchers from industry and academia is also crucial.

Highlights of CDA work by FHWA in 2023 include the following:

- Adding the ability for connected and automated vehicles (CAVs) to communicate directly and indirectly with other connected vehicles and infrastructure via cellular V2X communication and cellular network communication in CARMA℠ tools.(3)
- Integrating CARMA Streets℠ and V2X Hub℠ into CDASim's open-source cosimulation environment.(4,5)
- Introducing new tools and updating CARMA Streets, CDASim, and the CAV Telematics tool, which are designed to improve highway operations, intersection safety and optimization, corridor management, and vulnerable road user safety.(4,5)
- Establishing a CDA roadmap, as outlined here, that illustrates the direction CDA research and development is expected to move in over the next decade.
- Engaging with stakeholders through three technical working groups and other events to ensure everyone is informed, involved, and working toward the same goals when it comes to the accelerated implementation of CDA technology.

FHWA is excited to share this report and demonstrate the progress made in 2023 in continuing the development of CDA. This report is centered around two key use cases that were completed in 2023 to advance CDA in a diverse set of applications and conditions. The report also discusses FHWA's collaboration with stakeholders to advance CDA technology.

Looking ahead to 2024, the U.S. Department of Transportation (USDOT) announced the $40 million Saving Lives With Connectivity: Accelerating V2X Deployment program.(6) This program will promote the deployment of V2X technology aimed at improving road safety, mobility, and efficiency. The goal of this program is to unlock the full lifesaving potential of secure V2X technologies, which can include multiple wireless technologies, such as mobile, in-vehicle, and roadside devices that can communicate and operate with each other.

FHWA looks forward to sharing more work on V2X and other CDA-related technologies in the coming years. For more information about the CARMA Program's work in addition to the CDA research, please explore the videos, research, and reports available on the CARMA Program web page.(7)

Sincerely,

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

CDA PROGRAM MISSION, VALUES, AND GOALS

FHWA's CDA Program leads the research, development, and standardization of CDA technologies to accelerate industry deployment. This research seeks to enable a cooperative, safe, efficient, and sustainable surface transportation system for all users. The CDA Program closely aligns with FHWA's strategic objectives of safety, organizational excellence, climate and sustainability, economic strength and global competitiveness, equity, and transformation.[8]

SAFETY

Safety is the top priority of USDOT and FHWA. Although the United States has made significant progress in preventing roadway deaths over the past 30 yr, nearly 43,000 traffic-related deaths occurred in 2022, according to the National Highway Traffic Safety Administration.[9] In accordance with USDOT's National Roadway Safety Strategy, FHWA is dedicated to the goal of zero deaths and serious injuries on the Nation's highways.[1]

Promising vehicle and infrastructure technologies, such as V2X, CDA, and automated driving systems, can potentially improve roadway safety significantly in the long term. CDA and V2X communication can help make the Nation's roads safer by enabling communication and cooperation among properly equipped vehicles, infrastructure, and other road users. V2X communication is used by connected vehicle and CDA applications to help improve vehicle perception performances, enhance situational awareness, avoid collisions, and improve mobility and energy performances. CDA, V2X, and related technologies help improve the flow of traffic; increase awareness of other vehicles and vulnerable road users, such as pedestrians; and reroute traffic to alternate routes in the event of a crash.

The CDA Program's testing of cooperative perception technology is an example of how CDA technology can make the Nation's roadways safer. This CDA feature is able to locate objects, such as other vehicles and pedestrians, that are obscured by a driver's line of sight; the feature then relays the data to CDA-equipped vehicles via V2X communications. This information has the potential to improve roadway safety by alerting drivers to objects in their path and can potentially also support path and trajectory planning for improved mobility and energy performance.

ORGANIZATIONAL EXCELLENCE

FHWA seeks to achieve organizational excellence by establishing policies, processes, and an inclusive and innovative culture to effectively serve communities and responsibly steward the public's resources. CDA technology helps achieve this objective by improving first responder mobility and safety. For example, in the event of a traffic crash, CDA technology improves first-responder mobility and safety by adjusting lane closures and helping reroute traffic so that first responders are not in harm's way due to the close proximity of other vehicles. Improvements in the flow of traffic will help improve efficiency by reducing traffic congestion and getting drivers to their destinations in a timely fashion. By identifying congested roads and traffic crashes, CDA will reroute vehicles to alternate paths and optimize traffic speed.

CLIMATE AND SUSTAINABILITY

FHWA seeks to ensure that transportation plays a central role in tackling the climate crisis. The CDA Program supports this objective by lessening travel time, which reduces fuel consumption and decreases harmful emissions released into the atmosphere.

ECONOMIC STRENGTH AND GLOBAL COMPETITIVENESS

FHWA invests in the transportation system to provide workers and businesses with reliable and efficient access to resources, markets, and jobs. CDA applications smooth traffic flow at signalized intersections, resulting in less wear and tear on the Nation's roadways and potentially reducing expenditures for repaving and other maintenance. Freeway truck platooning enhances the traffic system by decreasing average travel times. A more efficient traffic system helps to increase lane capacity, which ensures more access to the Nation's roadways.

EQUITY

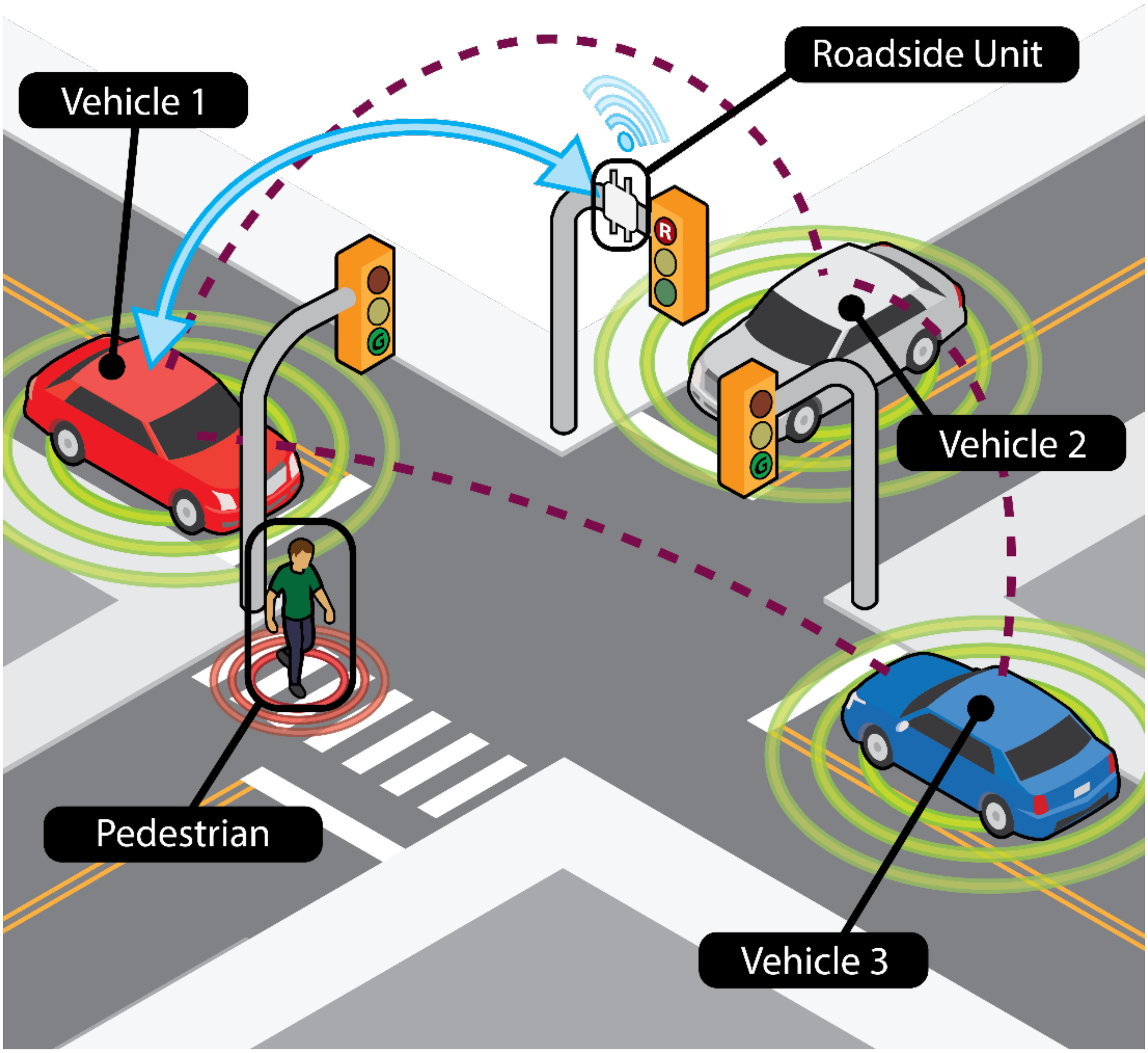
To reduce inequities across our transportation systems, FHWA promotes safe, affordable, accessible, and multimodal access to opportunities and services while reducing transportation-related disparities, adverse community impacts, and health effects. One way the CDA Program supports this objective is through the Connected and Automated Vehicle Education (CAVe) program.[10] The CAVe program provides community colleges, trade schools, universities, and other academic stakeholders with tools and resources to develop an intelligent transportation workforce. The CAVe program helps prepare the workforce for a rapidly changing automotive and transportation environment. By reducing the cost barriers of entry, the CAVe program improves equity by ensuring more stakeholders receive practical exposure to CAV technology. By creating and using open-source software and support programs for users and researchers, FHWA provides easy open-source access to its CDA research, promoting an equitable approach to adopting CDA technology.

TRANSFORMATION

FHWA will invest in purpose-driven research and innovation to meet today's challenges and modernize the Nation's future transportation system to best serve everyone in the decades to come. Transforming the Nation's roads and vehicles by incorporating CDA and its related technologies results in safer and more efficient travel. By providing open access to CDA technologies, related data, and analytical tools, the CDA Program ensures an equitable rollout of these wide-ranging and groundbreaking technologies.

ABOUT CDA AND RESEARCH AT TURNER-FAIRBANK HIGHWAY RESEARCH CENTER

CDA leverages machine-to-machine communication (vehicles, sensors, and hardware over cellular or wired networks) to facilitate cooperation among infrastructure, vehicles, and other road users. Figure 1 shows CDA-equipped vehicles communicating with each other and smart infrastructure to improve situational awareness of other vehicles and road users.



Source: FHWA.

Figure 1. Illustration. CDA-equipped vehicles communicating with one another and smart infrastructure.

CDA is an advanced vehicle automation and intelligent transportation system that builds on the capabilities of traditional advanced driver assistance systems. CDA enables vehicles to communicate and interact with other vehicles, infrastructure, and road users to enhance safety, traffic flow, and overall transportation efficiency.

SAE standard J3216™ defines CDA as having four classes of cooperation, Classes A–D, with increasing cooperation in each successive class, as follows:[(11)]

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

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

For more than a decade, FHWA's CDA Program, based at Turner-Fairbank Highway Research Center in McLean, VA, has helped promote CDA solutions to the transportation sector's biggest challenges, including traffic congestion, crashes, pollution, and energy consumption.[(8,12)]

CDA ANNUAL REPORT OVERVIEW

This report highlights the CDA Program's achievements and progress in 2023 and objectives for 2024 and beyond, as follows:

- The "CDA Program Roadmap" section outlines FHWA's objectives for implementing CDA over the next decade. The CDA roadmap begins with setting standards for SAE Level 1 and Level 2 advanced driver assistance systems by 2026 and ends with implementing SAE Level 3–5 advanced driver assistance systems by 2034.[13]
- The "CDA Program Research Tracks" section discusses CDA projects, research, and CARMA proof-of-concept use cases. This report focuses on use cases involving CDA Program research tracks for traffic, reliability, and freight. These use cases help to develop, verify, and improve CDA software, tools, and services.
- The "Stakeholder Engagement" section details how FHWA engaged with more stakeholders than ever in 2023 by increasing stakeholder outreach at conferences and events and codeveloping CDA improvements with stakeholders. Additionally, the section summarizes results of these efforts and plans for future engagement with stakeholders.
- The "Publications and Grants" section of this report highlights FHWA's support of CDA in 2023, including publications, videos, and the many Federal grants supporting CDA research and development. The report also highlights and discusses the goals and targets of the CDA Program in 2024.

CDA PROGRAM ROADMAP

CDA technology will help improve the efficiency and safety of vehicles and other road users across the transportation system. FHWA developed a CDA Program roadmap to enable a cooperative, safe, efficient, and sustainable surface transportation system for all users. This roadmap has short-, medium-, and long-term milestones that support the CDA Program's mission by leading research, development, and standardization, demonstrating the benefits of CDA technologies, and accelerating industry deployment.

The roadmap includes designing and developing use cases that are focused on meeting the CDA Program's goals of improving safety and mobility and reducing energy usage and emissions related to the Nation's transportation system. Additional portions of the roadmap focus on collaborating with industry on prototype design and testing; developing CDA tools and workforces; and engaging with stakeholders through technology transfer, workshops, and support services. The remaining sections in this chapter provide the plans for achieving the near-term goals of CDA deployment—as well as the short-, medium-, and long-term milestones.

METHODS USED TO ACHIEVE CDA ROADMAP GOALS

To meet the objectives of the CDA Program, the research team is working with industry representatives to develop real-world CDA pilots over the next decade. The CDA roadmap will use the following high-level steps to meet the program's goals:

- Engage with stakeholders: Identify and engage with stakeholders to find cases that are feasible for prototypes and pilots. This step will help the research team understand stakeholder requirements and expectations and support the program's equity goal by fostering collaboration across government, academia, and the private sector.

- Prioritize use cases: Include discussions on arterial, transition, and freeway use cases. This step will help identify and prioritize the different use cases that must be addressed to meet the program's safety goals by working to reduce crashes and protect vulnerable road users. To meet the program's mobility goals, use cases are designed and developed to improve and smooth traffic flow on highways and arterials, improve the reliability of transit travel times, and improve freight port operations.

- Create use case groups: Work with stakeholders to group these use cases to operate concurrently in different environments. This step will help prioritize the use cases and address them in a logical order to meet the program's goals for safety, mobility, equity, climate, and sustainability.

- Update architecture: Update architecture for use case groups. This step will help ensure the architecture is optimized for the use cases to operate concurrently in the real world and can handle the different scenarios. These efforts include applying CDA capabilities to better manage future electric vehicle charging demand to support the program's climate goal.

- Deploy pilots: Develop and demonstrate the benefits of CDA through real-world pilots based on the updated architecture, including improving freight port operations to support the program's mobility goal.

ROADMAP MILESTONES

Following are short-term milestones (2024–2026):

- Engage with stakeholders to identify prioritized use cases.
- Update standards to enable prioritized use cases for industry-led advanced driver assistance systems for SAE Level 1 and Level 2.[13]
- Update the reference architecture to enable the deployment of CDA using SAE Level 1 and Level 2 automation.[13]

Following are medium-term milestones (2027–2029):

- Develop a CDA pilot deployment leveraging SAE Level 1 and Level 2 advanced driver assistance systems.[13]
- Develop metrics for the evaluation of CDA use cases to validate benefits.
- Conduct human factors research to assess public acceptance of CDA pilots.

Following are long-term milestones (2030–2034):

- Update the use cases to operate at SAE Level 3, Level 4, and Level 5 and demonstrate within the pilot deployments.[13]
- Develop use cases for evaluation and validate additional benefits.
- Conduct workshops to provide necessary education for the real-world deployment of CDA by infrastructure owner-operators and original equipment manufacturers.

V2X technology enables networked, wireless communication between vehicles, infrastructure, and personal communication devices. V2X provides a foundation for CDA development because of its ability to create an interoperable environment. V2X is ready for implementation; however, as progress is made toward achieving the objective of real-world CDA pilots, some challenges with V2X technologies will be addressed as part of the short-term milestones.

One primary challenge is the efficient use of available communication technologies. Some CDA message sets and use cases may not require low-latency communication, and these messages will be transitioned to use cellular and other technologies. The research team will also be working with the FHWA spectrum team to ensure radio congestion mitigation and certify that the communication channels are not congested. Support for future compatibility with virtual roadside units may also be considered, as this support involves ensuring the V2X network is compatible with future virtual roadside units.

The CDA roadmap has identified the need for updating standards. One such update is addressing backward compatibility. Some challenges the roadmap may address include adding version identifiers to message sets to ensure that messages are compatible with each other, defining metrics to measure the benefits of CDA technologies, and developing effective transitioning between SAE J2735™ MAP messages and high-definition maps to enable CDA vehicles to leverage the benefits of existing V2X deployments.[14] Standardization of high-definition maps will also be important, as pilots may require mapping key city intersections across the United States.

The CDA roadmap also highlights technology transfer goals, which include remote and onsite support to ensure successful deployment of CDA through research or pilots. Another goal is to establish a singular virtual location to provide comprehensive information on CDA tools and research. This could help create an easy adoption package for CDA, thus accelerating future pilots. Finally, developing documentation on understanding data to show benefits of CDA will help create opportunities to expand CDA pilots and may lead to a large-scale CDA deployment.

CDA PROGRAM RESEARCH TRACKS

Introducing CDA concepts to the Nation's roadways affects several existing transportation systems management and operations (TSMO) strategies.(15) To anticipate the scope of these impacts and conduct relevant use case studies, the CDA Program developed research tracks that explore traffic, reliability, and freight operation scenarios.(16) The traffic research track focuses on scenarios for highway operations, intersection safety and optimization, corridor management, and vulnerable road user safety. The reliability research track develops use cases for road weather management, traffic incident management, and work zone management. The freight research track explores CDA applications for commercial vehicles and port operations.

All research tracks address components of the CDA roadmap—specifically the short-term milestones, such as demonstrating CDA applications—and the benefits and impacts of using cellular V2X, cellular, and multi-access edge computing. The research tracks also encourage stakeholder collaboration to accelerate CDA development, testing, and implementation.

Source: FHWA.

TRAFFIC RESEARCH TRACK

Through partnerships with the USDOT Intelligent Transportation Systems Joint Program Office and the National Highway Traffic Safety Administration, the traffic research track investigates solutions to recurring traffic congestion on the Nation's roadways. The traffic research track aims to demonstrate how CDA can improve road safety and traffic conditions in recurring traffic scenarios. The CDA research team has used several basic CDA algorithms in simulated road scenarios to improve road and traffic conditions. Eventually, these algorithms will be implemented and tested on test tracks.

Thus far, use cases for the traffic research track have focused on scenarios for highway operations, intersection safety and optimization, and vulnerable road user safety. The research team conducted the following use cases in 2022, with details provided in the *2022 CDA Annual Report:*[(17)]

- Stop-controlled intersection.
- Fixed-time traffic signals.
- Cooperative perception.
- Integrated highway prototype.

In 2023, the Adaptive Traffic Signal Optimization use case was conducted under the traffic research track.

Adaptive Traffic Signal Optimization Use Case

Background

The objective of this use case is to demonstrate the potential benefits of using CDA technologies at signalized intersections to optimize adaptive traffic signal control and the trajectories of vehicles equipped with cooperative automated driving systems while maintaining safety.

Cooperative automated driving system-equipped vehicles inside the communication area of the intersection broadcast real-time information to infrastructure. Real-time information includes the vehicles' operating states (e.g., location, speed, acceleration) and intents (e.g., direction, estimated entering times). The infrastructure uses this information to optimize the signal phase and timing (SPaT) in realtime to optimally serve the incoming traffic streams from various approaches. The infrastructure broadcasts the optimized SPaT and recommended estimated intersection entering times to the cooperative automated driving system-equipped vehicles at a given frequency. With this information, each equipped vehicle optimizes its own trajectory to enter the intersection box with a desired departure speed in a green-light interval with minimum or no stopping time.

Benefits for Transportation

This use case was designed to maximize intersection throughput and minimize overall travel delay at signalized intersections by optimizing the SPaT plan based on the incoming traffic information.[(18)] This use case also sought to smooth vehicle trajectories so that they could enter the intersection box at a green-light interval with a desired departure speed. This smoothing, in turn, increased the intersection's throughput by minimizing the amount of time vehicles occupied the intersection box. These smoothed vehicle trajectories can potentially minimize—or even possibly eliminate—speed fluctuations and stopping times. In turn, this trajectory smoothing can minimize energy consumption and improve riding comfort.

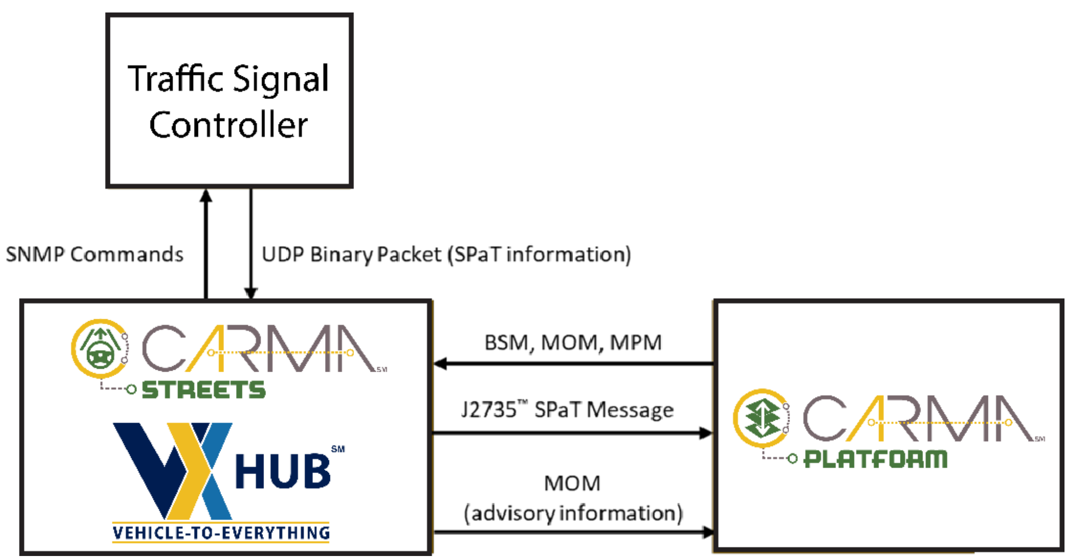
State of Practice

From an operations perspective, the proposed CDA framework demonstrates that traffic can be operated in significantly different ways at signalized intersections. The proposed CDA framework, leveraging V2X communication, facilitates direct communication with vehicles and enables the integration of traffic signal phase sequence control with the precise timing of vehicle arrivals at intersections. This integration aims to enhance vehicle mobility and fuel efficiency while optimizing traffic signals for improved responsiveness to traffic conditions.

With proper upgrades in intelligent transportation infrastructure systems (e.g., equipping with roadside equipment), C-ADS-equipped vehicles can accommodate the needs of such CDA use cases. Agencies are encouraged to initially evaluate these emerging systems within their local contexts to understand their applicability and potential benefits. The conventional process of transportation system performance monitoring and reporting can potentially be improved with the prevalence of cooperative automated driving system-equipped vehicles and advanced sensors. CDA technologies can enhance conventional strategies for TSMO that agencies are already familiar with.[15]

Architecture, Logic, and Connectivity and Communication

The components of the CARMA Ecosystem used in this cooperation class include CARMA Platform℠, CARMA Streets, and V2X Hub.[4,7,19] Figure 2 illustrates how each of the aspects of CARMA infrastructure works with the others.



Source: FHWA.
BSM = basic safety message; MOM = mobility operation message; MPM = mobility path message; SNMP = simple network management protocol; UDP = user datagram protocol.

Figure 2. Diagram. Adaptive traffic signal optimization use case high-level architecture.

In this architecture, vehicles are equipped with CARMA Platform and share status information via the roadside unit using three messages:

- Basic safety message (BSM): A message broadcast by a vehicle to provide its status (e.g., location, speed, acceleration).

- Mobility operation message (MOM): A prototype message broadcast by a vehicle that includes a string payload customized for a specific use case. In this use case, the MOM contains information regarding the vehicle profile and its characteristics (e.g., vehicle length, reaction time, estimated entering time into the intersection).

- Mobility path messages: A message broadcast by a vehicle at a low frequency that describes its currently planned 6-s trajectory in a geocentric frame.

CARMA Streets and V2X Hub reside within the infrastructure and are jointly responsible for processing the information received from vehicles, estimating the time vehicles can enter the intersection box, and optimizing the signal timing plan.(20,21) CARMA Streets is also responsible for communicating with the traffic signal controller to change the signal timing plan and broadcasting SPaT and advisory messages to vehicles.(20) CARMA Platform then controls the vehicle trajectory accordingly to minimize stopping time and optimize vehicle energy and fuel efficiency.(22,23)

Evaluation of the Concept

To evaluate and fine-tune the developed algorithms, the research team conducted simulation experiments in Eclipse® SUMO™, an open-source traffic simulator.(23)

Simulation Testing

For simulation experiments, the research team considered the following objective measures:

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

The research team conducted simulations for a typical four-way signalized intersection with three exclusive lanes on each approach. To examine the impact of fluctuating arrival traffic patterns on system performance, the team designed the traffic flow rate for each entry lane to vary from low to high and then back to low over a 2-h period. Researchers compared the performances of the proposed CDA frameworks to scenarios that employed fixed-time traffic signal settings optimized for average delay through adjustments to cycle length and green splits, both with and without CDA-equipped vehicles. The results demonstrate that the algorithms developed for this study effectively reduce average travel delay, fuel consumption, and stopping time at signalized intersections equipped with adaptive traffic signals in a CDA environment.

Verification and Validation Testing

After conducting traffic simulation studies, the research team performed several levels of proof-of-concept testing (i.e., integration, verification, validation) with full-size FHWA vehicles and infrastructure equipped with CDA on controlled test tracks. The intent of these test-revision cycles was to research and support the development of software that will be used to support the implementation of CDA. The test plan documents defined test acceptance criteria, which are used to determine 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, researchers collected and processed log files from CARMA Streets and CARMA Platform.[20,21]

The verification and validation tests took place at the west intersection at FHWA's Turner-Fairbank Highway Research Center. This intersection is a typical four-way, two-lane road (one lane each direction) signalized intersection. Figure 3 shows the National Electrical Manufacturers Association phase configurations for the four straight movements.[24]

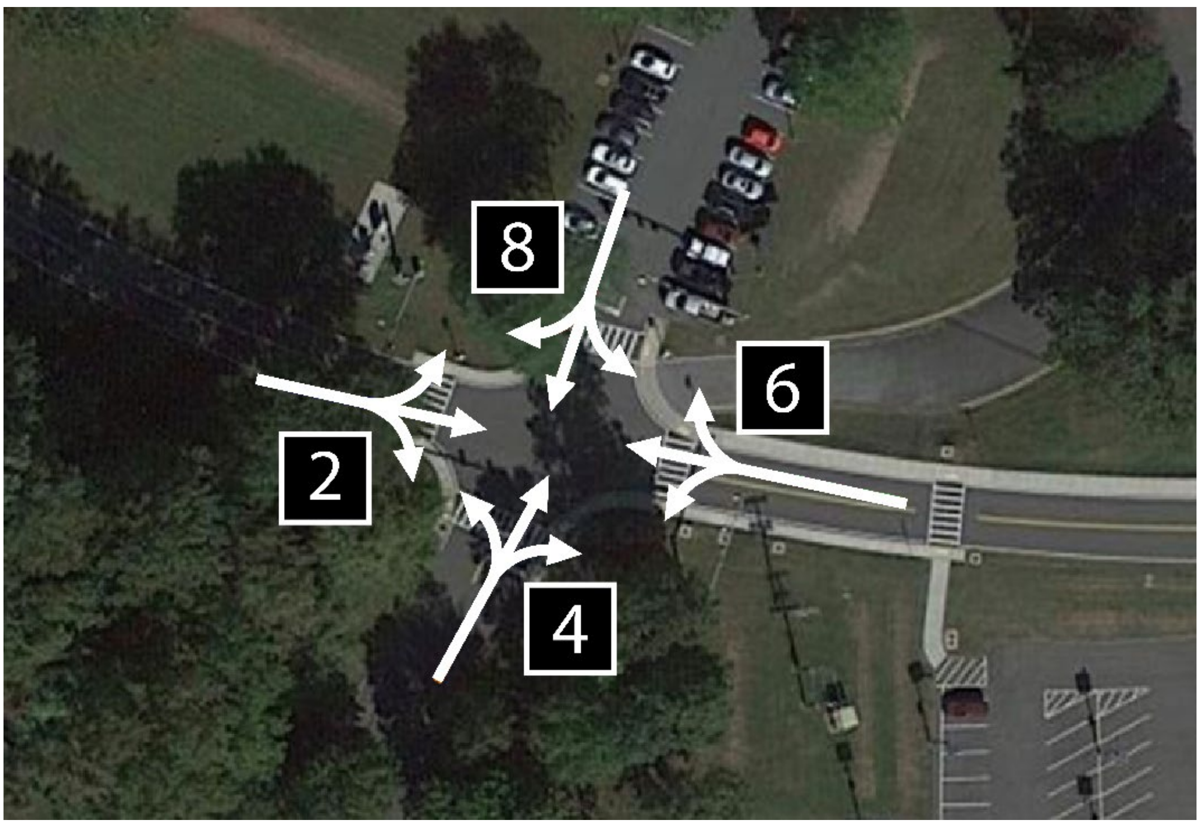


Figure 3. Photo. Verification testing at Turner-Fairbank Highway Research Center's west intersection.

The verification testing for the adaptive traffic signal optimization use case involved scenarios across three groups, differentiated by the number of CARMA Platform-equipped vehicles (one, two, and three vehicles) and their initial conditions.[25] All testing targeted evaluating system performance at critical edge case scenarios, such as when multiple vehicles simultaneously approach the intersection and compete to receive the earliest green interval. The research team modified traffic signal configuration, vehicle placement, and maximum vehicle speed for each test case to evaluate and test the proposed framework and algorithms for the use case. The team then evaluated the use case's effectiveness by measuring the capability of the configurations to positively impact performance, using 33 performance metrics that addressed communication, safety, mobility, and trajectory smoothness, calculated after data collection and processing. Then, researchers collected and processed log files from CARMA Streets and CARMA Platform to analyze these test results.(20,21)

After several initial testing rounds to verify the implemented algorithms, the USDOT Volpe National Transportation Systems Center led additional testing rounds to validate the algorithms and findings. These testing rounds help to set a foundation for further research and development.

Test Results and Level of Performance and Advancement

The analysis of test results indicates the proof-of-concept (POC) framework met a key set of objective metrics related to traffic management:

- Message processing.
- Communication rates.
- Algorithm logic.

Specifically, the proof-of-concept framework demonstrated effectiveness in the following:

- Prioritizing vehicles for optimal signal timing.
- Smoothing vehicle trajectories.
- Estimating vehicle entry times at intersections during various signal phases.
- Adhering to set acceleration and deceleration limits.

Vehicle-to-vehicle communication was not considered in this testing and will need to be considered in future research. While the research team identified some limitations through data collection and analysis, these limitations can be addressed as part of future CDA Program efforts.

The significance of this use case is the potential to revolutionize urban traffic management and contribute to the development of smart cities. The findings suggest a promising pathway toward more sustainable urban environments, as efficient traffic flow directly contributes to reduced greenhouse gas emissions and energy usage. In the context of growing urban populations and the increasing importance of sustainable development, these advancements in traffic signal optimization and vehicle cooperation represent an important step toward creating more livable, efficient, and environmentally friendly urban spaces.

Next Steps

The benefits of the adaptive traffic signal optimization use case are best evaluated in simulation, where a variety of traffic and roadway conditions can be generated. With the development of the CDA anything-in-the-loop cosimulation tool, CARMA Streets and CARMA Platform will both be integrated into the anything-in-the-loop environment. (See references 20, 21, 22, and 26.) Additional simulation studies and analysis may potentially shed more light on the benefits of the adaptive traffic signal optimization use case.

Possible extensions and enhancements to the current POC system include the following:

- Extension to a corridor, with multiple CARMA Streets coordinating with each other.[21]
- Extension to accommodate vulnerable road users.
- Extension to a mixed traffic environment, where only a portion of traffic is equipped with automated driving and connectivity systems.
- Extension to accommodate vehicle-to-vehicle communication.
- Advancement of trajectory control algorithms to accommodate road features, such as curves and slopes and adapting to diverse weather conditions and varying traffic densities.

Actual system development and testing have revealed that variations in roadway geometry and conditions—as well as uncertainties in actuation, handling, and other behaviors of cooperative automated driving system-equipped vehicles—should be better accounted for in the design of the system. Potential use cases for 2024 under the traffic research track include the following:

- Cooperative perception with sensor data sharing message (SDSM).
- Transit signal priority.

RELIABILITY RESEARCH TRACK

Through partnerships with the Intelligent Transportation Systems Joint Program Office and the Federal Transit Authority, the reliability research track examines CDA applications for nonrecurring traffic congestion. The CDA Program conducted the following use cases in 2022:

- Work zone management for light vehicles.[27]
- Move-over-law adherence for traffic incident management.[28]
- Road weather management with a closed lane.[29]

Through the CDA proof-of-concept project, the reliability research track focuses on scenarios for road weather management, traffic incident management (TIM), and work zone management. The road weather management scenario accounts for inclement weather that may affect the flow of traffic. As a vehicle approaches a zone of hazardous weather, the vehicle will adjust its speed and prepare for other necessary adaptions. In the TIM scenario, vehicles detect a stationary emergency vehicle with flashing lights, move over to the adjacent lane, and adjust their speeds accordingly. The work zone management scenario investigates a one-lane, two-way traffic control implemented at a work zone. Ultimately, this research aims to reduce traffic congestion under these scenarios. More details about these 2022 use cases are provided in the *2022 CDA Annual Report*.[17]

The CDA Program planned, designed, and started two use cases in 2023 under the reliability research track that are expected to be completed in 2024:

- Traffic incident management/transit signal priority (TIM/TSP).
- Vulnerable road user detection at traffic signal intersection.

The next section discusses the progress of the TIM/TSP use case.

TIM/TSP Use Case

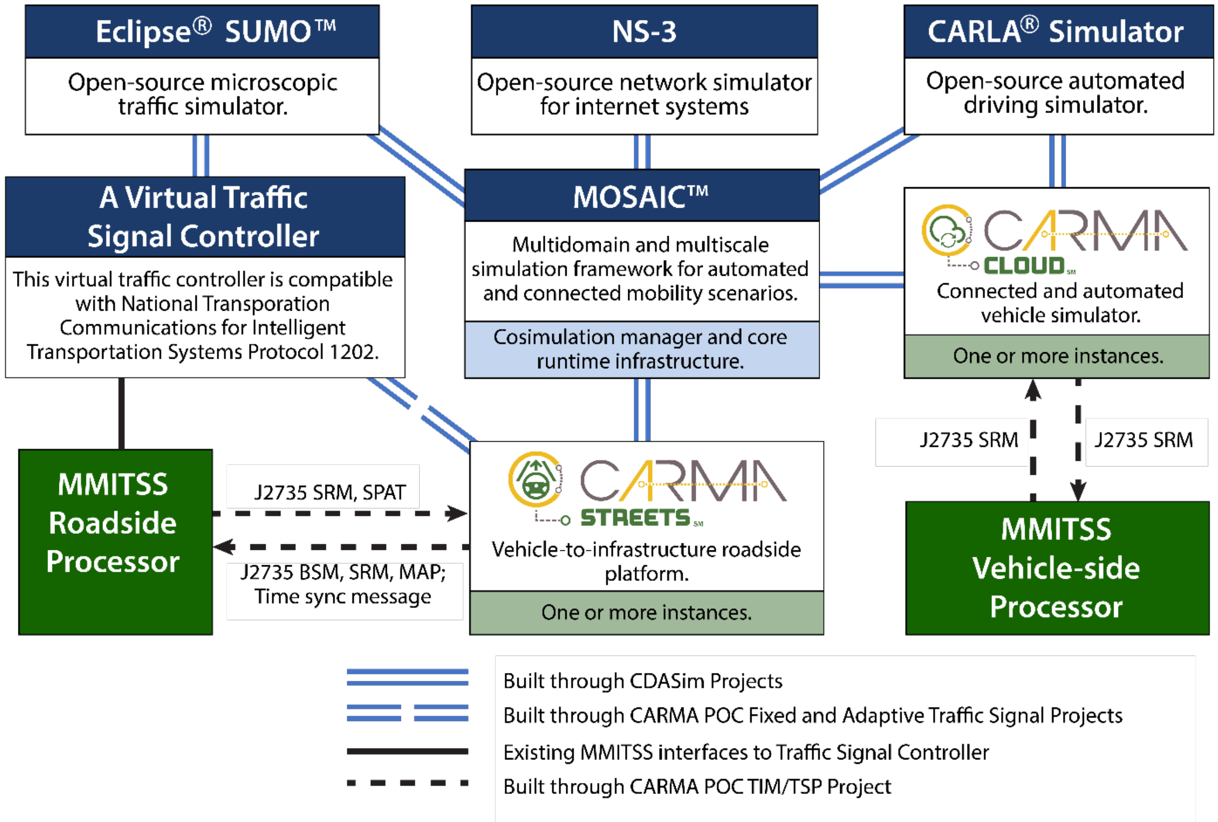
Background and Objective

The TIM/TSP use case is based on the logic and algorithms of the Multimodal Intelligent Traffic Signal System (MMITSS).[30] Using vehicle information received from vehicle-to-infrastructure communications, MMITSS algorithms optimize traffic signal phasing and timing to minimize overall traffic delays at a signalized intersection. Such optimization algorithms reside on the infrastructure side. MMITSS signal preemption and signal priority algorithms try to minimize a weighted sum of delays at a single intersection that consists of delays to priority-eligible vehicles, delays to known actuation calls, and delays caused by shifted cycle offset.

A major benefit of the MMITSS over existing TIM/TSP practices is that MMITSS algorithms can account for multiple and hierarchical preemption/priority requests in minimizing overall traffic delays. Additionally, the MMITSS algorithms take into consideration equipped freight vehicles that may be trapped in dilemma zones due to a preemption request. Simulation and field pilot studies have shown that MMITSS is effective in reducing traffic delays, especially for equipped priority vehicles.[30] MMITSS is a connected vehicle application, where equipped vehicles share their status (e.g., where they are) and intent (e.g., their intended turning movements) with the infrastructure (i.e., CDA Class B with level-zero vehicle automation). Integrating MMITSS into the CARMA ecosystem may potentially allow the MMITSS to work with higher levels of vehicle automation (as defined in SAE J3216).[11]

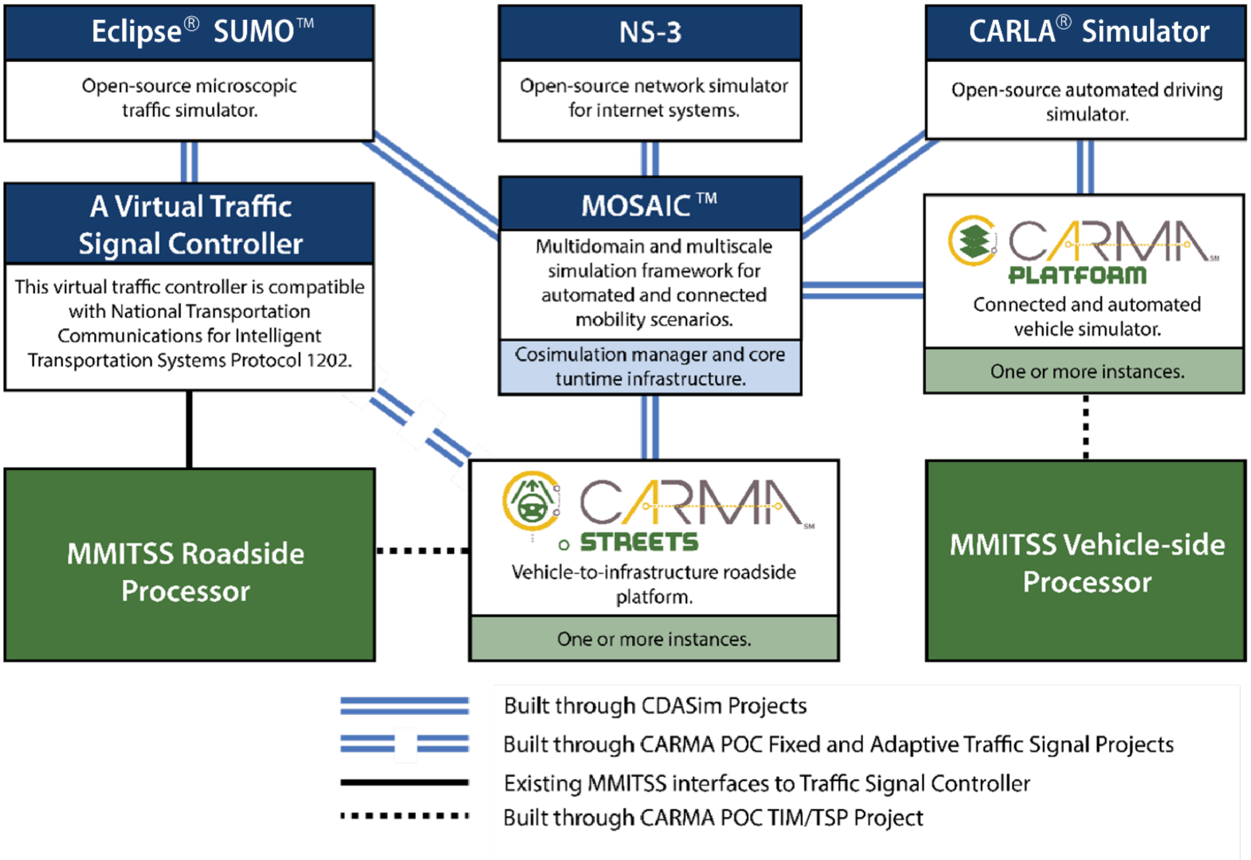
Scope

The goal of this project is to show preliminary benefits from CDA for the transit management and TIM use cases. To achieve the project goal, the MMITSS system is being integrated into the CDASim environment, together with a virtual traffic signal controller (see figure 4).[26,30] The MMITSS Roadside Processor is being integrated into the CDASim environment through CARMA Streets.[20,26,30] The MMITSS Vehicle-Side Processor is being integrated into the CDASim environment through CARMA Platform.[22,26,30] The integrations are denoted by single dashed lines in figure 5.



Source: FHWA.

Figure 4. Illustration. Key message flows for TSMO CDA TIM and TM use cases.



Source: FHWA.

Figure 5. Illustration. CDASim Platform for transit management and TIM use cases.

Milestone 1 of the project focused on the development of the integration between MMITSS and CARMA software.[1,30] The research team developed SAE J2735 messaging interfaces between MMITSS and CARMA components.[14] Additionally, the team completed initial design work on time-synchronization approaches between the MMITSS Roadside Processor and CDASim.[26,30] As part of the software development effort, the team performed unit testing and initial component-level integration testing. Some efforts went to initial scenario development and a new CARMA Platform feature (dwell at bus stops) to support simulation scenario needs.[22] However, additional component-level integration testing and full system-level integration testing are still needed before scenario runs can be performed to verify software functionalities and analyze CDA benefits.

The remainder of the project scope, starting from milestone 1, includes the following:

- Implementing the time synchronization mechanism between the MMITSS Roadside Processor and CDASim.[26,30]
- Performing additional component-level integration testing.

- Conducting full system-level integration testing.
- Finalizing simulation scenarios, scenario runs, and relevant data analysis to verify software functionalities (verification testing).
- Conducting scenario runs and relevant data analysis to demonstrate preliminary benefits of CDA.

By integrating MMITSS into the CDASim environment through CARMA Streets and CARMA Platform, TIM/TSP scenarios can now be simulated in CDASim—potentially with higher-level vehicle automation—to study preliminary benefits for CDA. [20, 22, 26, 30]) The MMITSS system includes additional arterial traffic signal applications, such as intelligent traffic signal systems, freight signal priority, and mobile accessible pedestrian signal systems.[30] The integration work completed in milestone 1 can potentially enable the simulation of these applications in CDASim in the future.[26]

By developing CARMA Streets functionalities, the CARMA POC project is the first step toward a vision of coordinated corridor management. Multiple CARMA Streets instances communicate with each other to manage multiple intersections.[20] For example, the algorithms and systems developed in the CDA TSMO TSP/TIM use case can be enhanced in the future to account for coordinated signal timing and queuing situations at different segments along the corridor. This potential enhancement allows for more mobility and safety improvements for the entire corridor system.

Details of Work Completed

The research team developed initial scenarios that could be used to demonstrate software features and functionalities and CDA benefits. The scenarios involved a single corridor with three intersections, one of which (the center intersection) was equipped with CARMA Streets and/or the MMITSS Roadside Processor.[20,30] The priority-eligible vehicles involved in the scenarios were bus and emergency vehicles.

The research team developed the following software features as part of milestone 1:

- Messaging interface between MMITSS Roadside Processor and CARMA Streets: New software functionalities in CARMA Streets and V2X Hub process and broadcast signal request messages (SRMs) received from vehicles for consumption by the MMITSS Roadside Processor and process and broadcast signal status messages (SSMs) received from the MMITSS Roadside Processor for consumption by CDA-equipped vehicles.[20,21,30] New functionalities developed in the MMITSS Roadside Processor publish and receive messages through a message broker, such as Apache® Kafka® broker (used by CARMA Streets).[20,30,31]
- Messaging interface between MMITSS Vehicle-Side Processor and CARMA Platform: A Robot Operating System 2 node, MMITSS message transceiver, was developed as the messaging interface between the MMITSS Vehicle-Side Processor and CARMA

Platform.(22,30,32) This transceiver handles the transmission of J2375 MAP, signal request, and SSMs between CARMA Platform and the MMITSS Vehicle-Side Processor.(14,22,30)

- Time synchronization between MMITSS and CDASim: Initial design of the time synchronization mechanism is underway. The current design leverages the time synchronization mechanism between CARMA Streets and CDASim, developed as part of the CDASim projects.(20,26) A time sync message will be published from CDASim to CARMA Streets, which will then publish the message to MMITSS Roadside Processor.(20,26.30)

- CARMA Platform able to dwell at bus stops: A new strategic plug-in, Stop and Dwell, has been developed for CARMA Platform to allow the software to recognize a bus stop from a map of lanelets ("atomic, interconnected drivable road segments which may carry additional data to describe the static environment") and stop for a random dwell time.(33,22)

Figure 4 showed the message flows supported by the interfaces. The research team completed initial component-level integration testing for the relevant SAE J2735 messaging interfaces between MMITSS and CARMA software.(3,14,30) The initial component-level integration testing involved a limited number of test cases and focused on basic functionalities (e.g., sending, receiving, encoding, decoding messages). Additional component-level integration testing is still needed before full system integration can be performed.

Vulnerable Road User Detection at Traffic Signal Intersection Use Case

Background and Objective

Cooperative perception can potentially support CDA technology to improve the safety and mobility of transportation systems.(33) Based on CDA technology, different entities (e.g., vehicles and infrastructure) are equipped with sensors (e.g., light detection and ranging (LiDAR), radar, cameras) to detect different objects to provide more information for each entity. Each entity's sensors may have blind spots and limited detection ranges due to the sensors' capabilities and the nearby environment. Using V2X communication, cooperative perception can potentially enable the exchange of key safety and mobility information among different entities within the communication coverage.

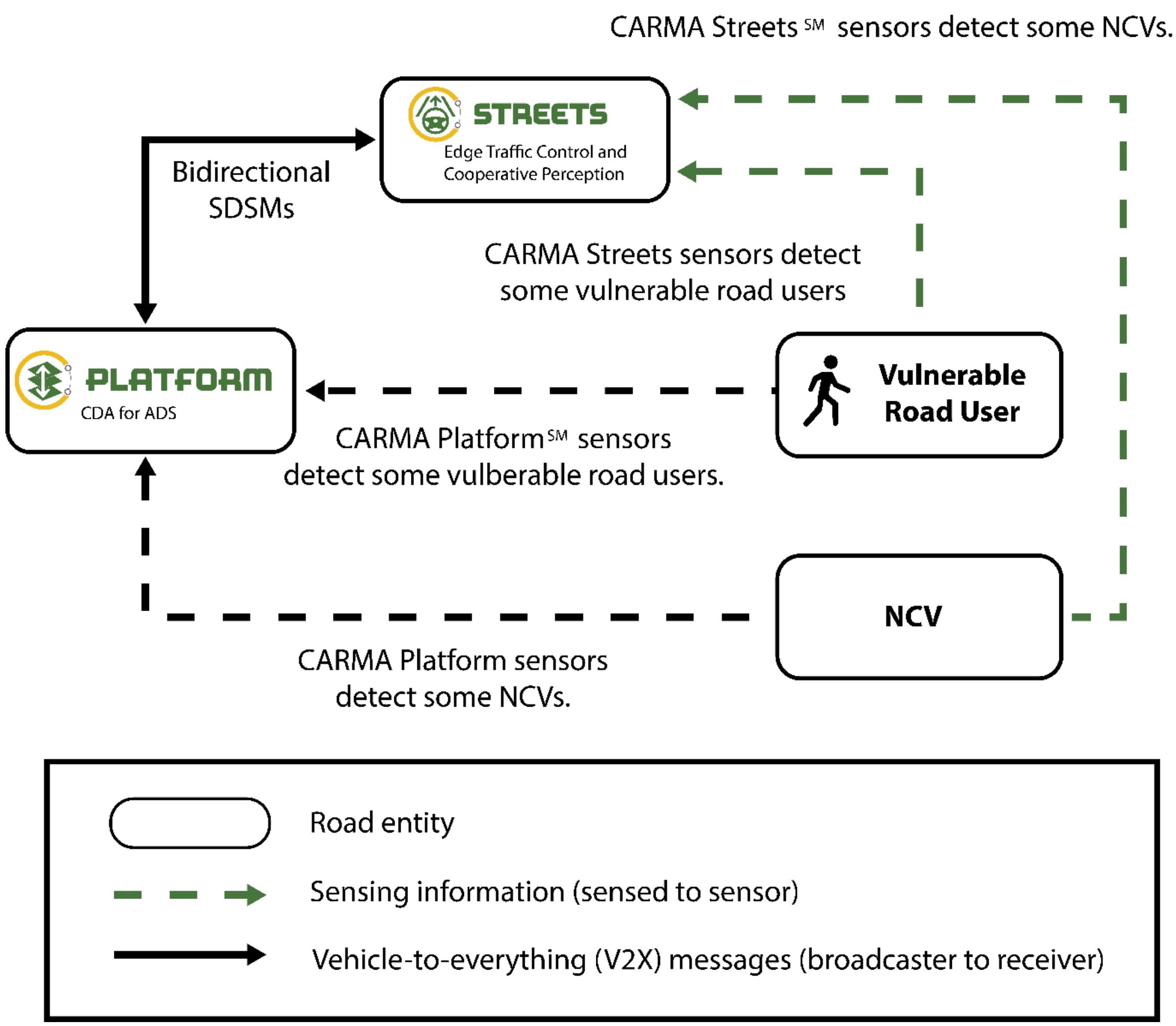
The Office of Safety and Operations Research and Development initialized the cooperative perception research under CARMA POC development and testing. The CARMA POC project developed and tested the cooperative perception feature at one of the signalized intersections at Turner-Fairbank Highway Research Center. The cooperative perception research conducted under the current project is a follow-up to the CARMA POC project. The objective is to demonstrate that vulnerable road user state information collected by infrastructure sensors can be effectively combined and shared with nearby connected road users—such as vehicles equipped with cooperative automated driving systems—to establish a state of cooperative perception.

Scope

This use case focuses on developing data fusion and communication capabilities for signalized intersection infrastructure and vehicles equipped with cooperative automated driving systems. This cooperative perception state aims to enhance the safety of all road users within the vicinity, particularly by minimizing the risk of vehicle collisions with vulnerable road users, such as pedestrians and bicyclists.

Architecture and Design

Infrastructure and vehicles equipped with cooperative automated driving systems detect all entities within a signalized intersection through transmission and receipt of SDSMs. Detectable entities include vulnerable road users, nonconnected vehicles (NCVs), and vehicles equipped with cooperative automated driving systems (figure 6).

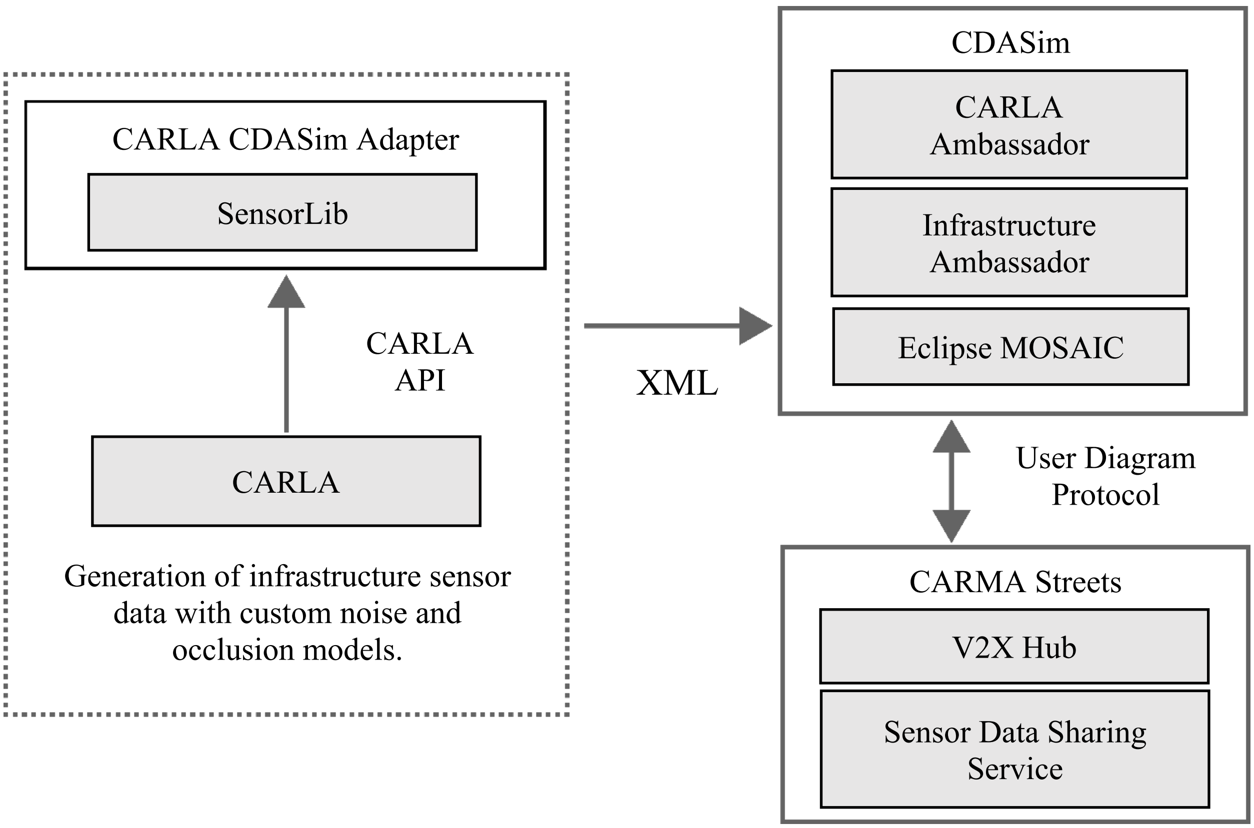


Source: FHWA.

Figure 6. Diagram. Object detection and involved entities at traffic signal intersections.

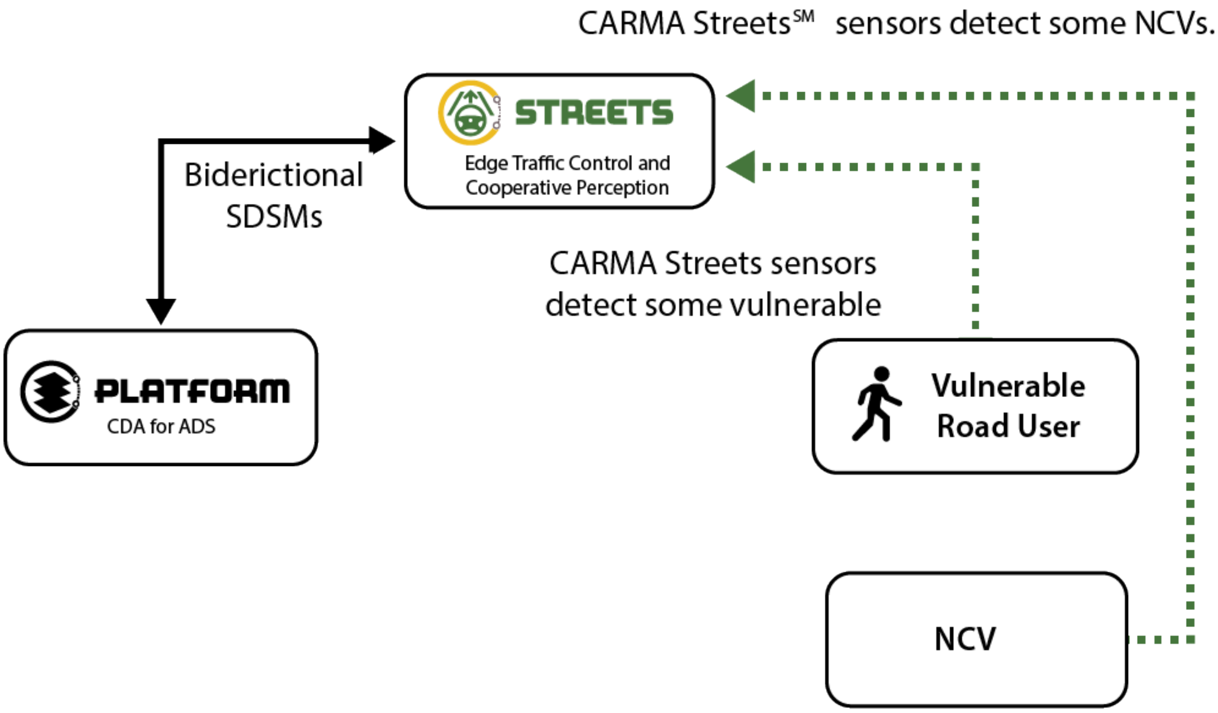
Infrastructure Detection Data Flow

The infrastructure detection data flow is shown in figure 7, and corresponding road entities are highlighted in figure 8. CDASim is now integrated with CARLA to provide CARMA Streets with simulated detections.(20,26,35) To better simulate real-world data, the research team developed a wrapper library for the CARLA application programming interface called SensorLib, which will be used to apply configurable noise and line-of-sight occlusion models to the sensor detection data from CARLA.(34,35) The CARLA-CDASim adapter uses this library to simulate infrastructure sensor data and forward it to CDASim.(26) CARMA Streets converts incoming sensor-detected data from CDASim into a SDSM for broadcast to other connected actors within a signalized intersection.(20,26)



Source: FHWA.
RPC = remote procedure call; XML = extensible markup language.

Figure 7. Diagram. Infrastructure detection data flow.

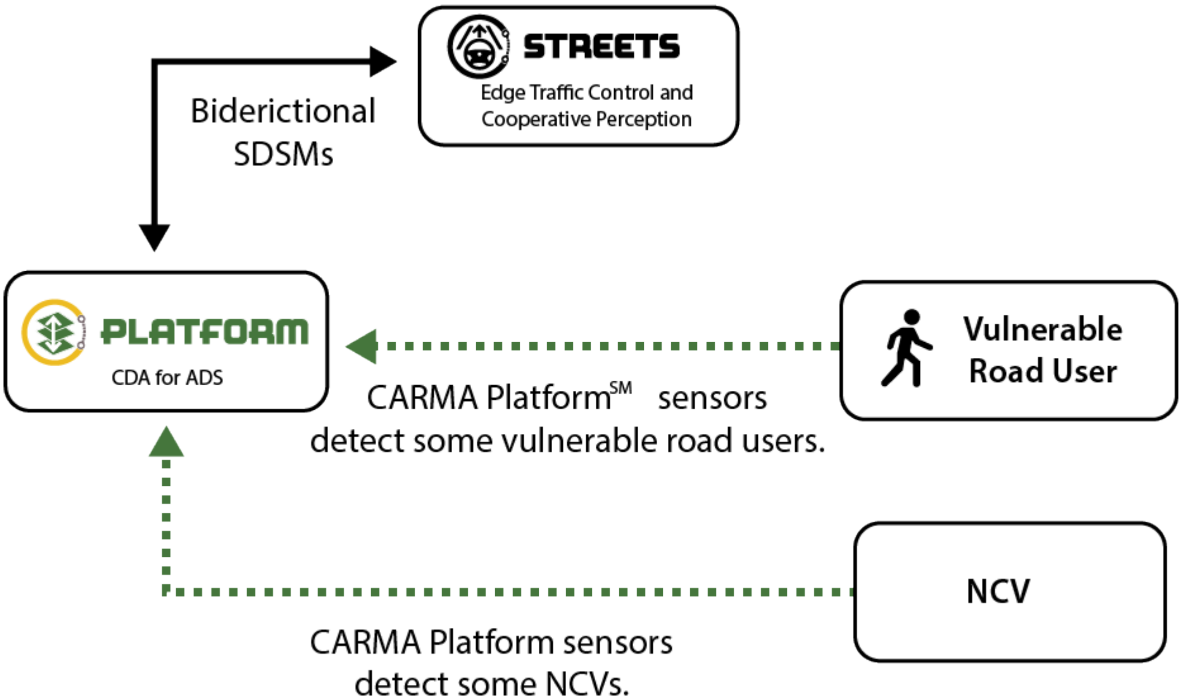


Source: FHWA.

Figure 8. Diagram. Involved entities in infrastructure object detection at traffic signal intersections.

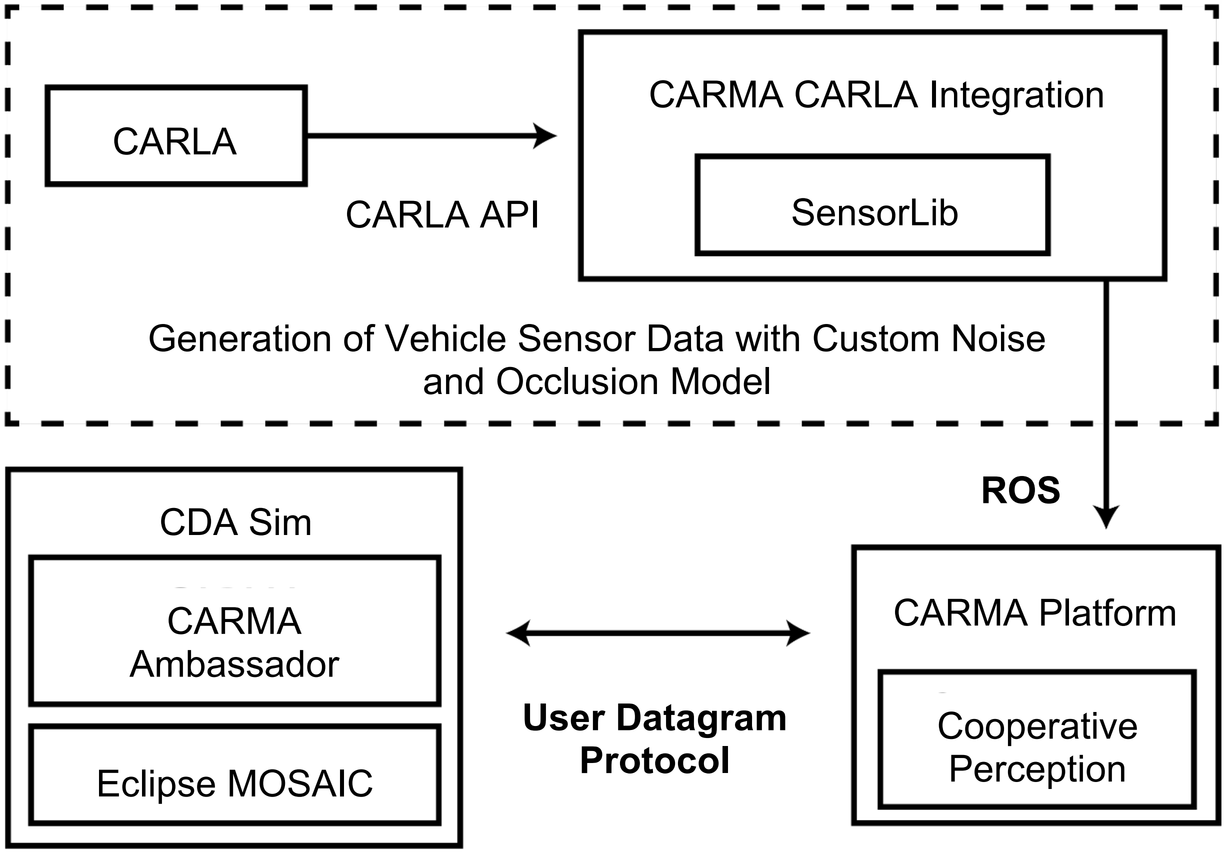
CARMA Platform Detection Data Flow

Figure 9 illustrates CARMA Platform's detection flow, and figure 10 highlights corresponding road entities involved.[22] Similar to the infrastructure side, CARMA Platform also retrieves sensor detections modified by SensorLib—with the help of the CARMA CARLA integration tool—to emulate the real-world vehicles' onboard sensors.[22,36] CARMA-equipped vehicles detect obstacles within their line of sight and then yield, but vulnerable road users outside the perception zone pose a collision risk.[22] SDSMs from the infrastructure, orchestrated by CDASim, provide additional detections of occluded vulnerable road users to CARMA-equipped vehicles.[22,26] Finally, CARMA Platform uses its cooperative perception stack to fuse and manage detection data from multiple sources to plan trajectories to avoid a potential collision.[22]



Source: FHWA.

Figure 9. Diagram. Involved entities in CARMA Platform's object detection at traffic signal intersections.

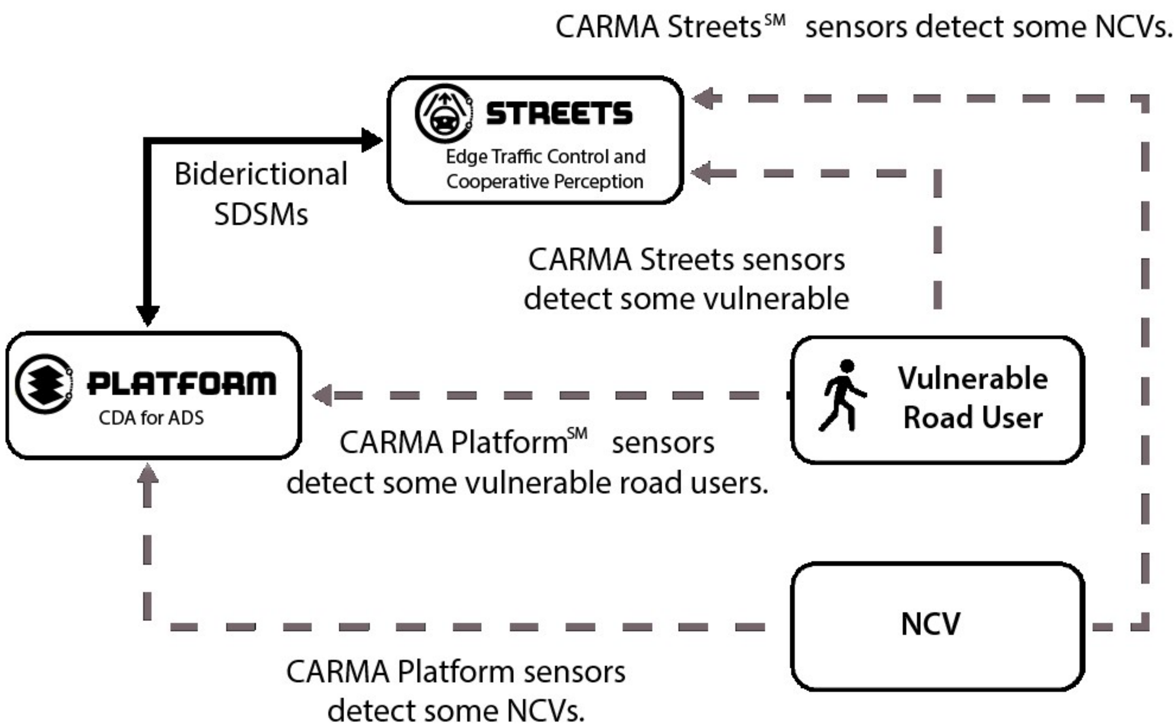


Source: FHWA.

Figure 10. Diagram. CARMA Platform detection data flow.

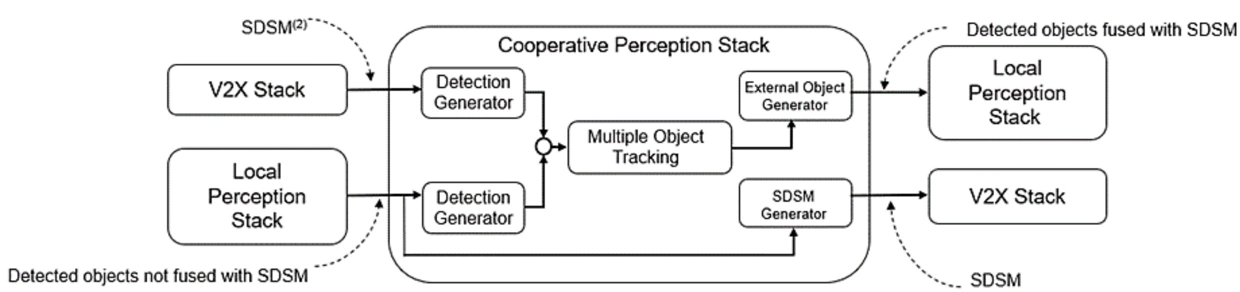
Cooperative Perception Stack

The cooperative perception stack shown in figure 11 comprises a main object fusion algorithm and message type conversions, each tailored to varying system requirements. Corresponding road entities are highlighted in figure 12. The object fusion algorithm is designed for multiple object tracking functions as a deployable library suitable for use in both vehicles and infrastructure. In this use case, the cooperative perception stack is integrated into CARMA Platform.(22)



Source: FHWA.

Figure 11. Diagram. Involved entities in cooperative perception at traffic signal intersections.



Source: FHWA.

Figure 12. Diagram. Cooperative perception data flow in CARMA Platform.

Status of Use Case

The research team completed development work and full system integration testing for the vulnerable road user use case. The use case is now transitioning into the verification testing phase.

Four test scenarios are proposed for execution within the CARMA ecosystem to validate the feasibility of the proposed cooperative perception concept and evaluate the impacts of this developed use case, as follows:(7)

- Scenario 1.1: Conflict, without cooperative perception, blocked line of sight, left turn:
  - Visibility obstructed: Bus and heavy vehicle obstructions are present within the intersection.
  - Imminent collision risk: The subject vehicle cannot detect the vulnerable road user because its line of sight is blocked. This situation presents an increased risk of collision between the vulnerable road user and subject vehicle.
- Scenario 1.2: Conflict, without cooperative perception, blocked line of sight, through movement:
  - Visibility obstructed: Bus and heavy vehicle obstructions are present within the intersection.
  - Imminent collision risk: The subject vehicle cannot detect the vulnerable road user because its line of sight is blocked. This situation presents an increased risk of collision between the vulnerable road user and subject vehicle.
- Scenario 2.1: Conflict, with cooperative perception, blocked line of sight, left turn:
  - Visibility obstructed: Bus and heavy vehicle obstructions are present within the intersection.
  - Reduced collision risk: A signalized intersection equipped with an infrastructure sensor detects the vulnerable road user and shares its object status information to connected road users via SDSMs. Through cooperative perception, the subject vehicle detects the vulnerable road users and proactively slows down to prevent a potential collision.
- Scenario 2.2: Conflict, with cooperative perception, blocked line of sight, through movement:
  - Visibility obstructed: Bus and heavy vehicle obstructions are present within the intersection.

- Reduced collision risk: A signalized intersection equipped with an infrastructure sensor detects the vulnerable road user and shares its object status information to connected road users via SDSMs. Through cooperative perception, the subject vehicle detects the vulnerable road user and proactively slows down to prevent a potential collision.

Next Steps

The project team will conduct the verification test of the vulnerable road user use case. The performance and benefits of the developed use case will subsequently be assessed and analyzed, with findings documented in the final report. A potential use case under the traffic research track in 2024 is Traffic Incident Management—Emergency Vehicle Preemption.

FREIGHT RESEARCH TRACK

The CDA freight research track is a joint effort among FHWA, the Federal Motor Carrier Safety Administration, the U.S. Maritime Administration, and the Intelligent Transportation Systems Joint Program Office. Through the CDA proof-of-concept project, the freight research track explores the use of CDA applications in commercial vehicles and port operations. CDA usage for freight operations has the potential to increase system efficiencies and safety while decreasing emissions. The freight research track's objective is to accelerate the adoption of CDA technologies in freight vehicles and demonstrate the potential for automated truck movement in ports and warehouses. A use case under freight research track in 2022 is Port Drayage. Details about this use case can be found in the *2022 CDA Annual Report*.[17]

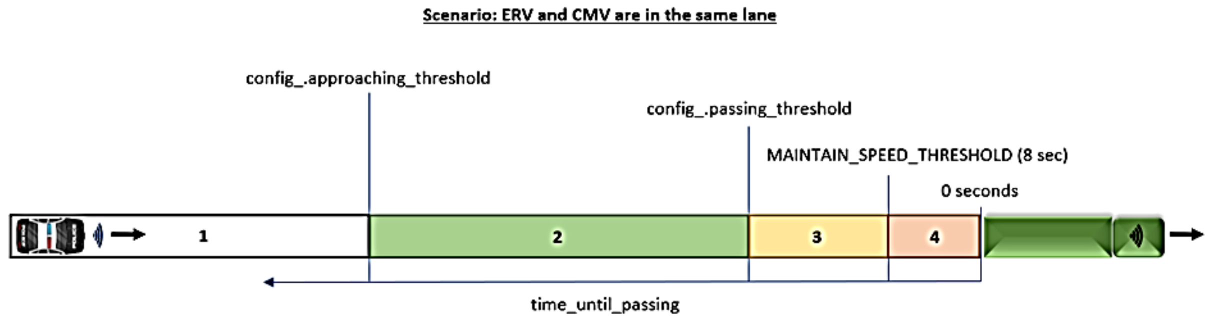
The next section discusses the Freight Emergency Response use case under the freight research track in 2023.

Freight Emergency Response Use Case

Background and Objective

The objective of this use case is to optimize the operation of automated commercial motor vehicles to improve interaction with emergency response vehicles. The project demonstrates CDA technology applications based on SAE J3216 to improve commercial motor vehicle awareness of and response to emergency response vehicles through vehicle-to-vehicle (and/or vehicle-to-infrastructure) communications, based on SAE J2735.[11,14] This effort results in technologies that can further be developed for adoption by State departments of transportation (DOTs) and the industry for emergency response, especially by commercial motor vehicles. The results can also inform future effective practices and operational standards.

This use case addresses a situation in which an emergency response vehicle on a freeway approaches an automated commercial motor vehicle from the rear. As shown in figure 13, if both vehicles are in the same lane, the commercial motor vehicle changes lanes out of the approaching emergency response vehicle's current lane and reduces its speed to an advisory speed limit. If the commercial motor vehicle is unable to alter its trajectory to change lanes out of the approaching emergency response vehicle's current trajectory, the commercial motor vehicle communicates this information back to the emergency response vehicle, which, in turn, alters its trajectory instead to avoid the commercial motor vehicle. The vehicle-to-vehicle scenario is shown in figure 14-A, and the vehicle-to-infrastructure scenario is shown in figure 14-B.



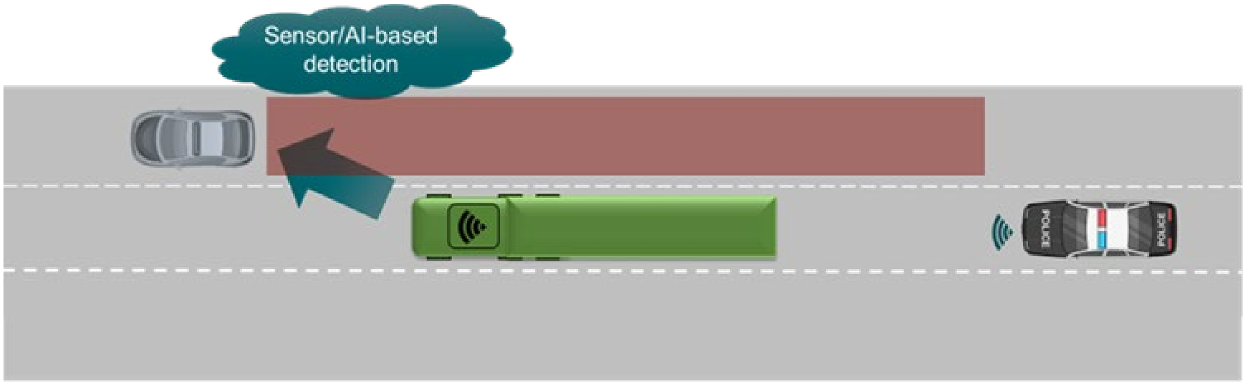
Based on the estimated "time_until_passing" (time in seconds until the ERV will reach the CMV's rear bumper) and the configured thresholds, the following CMV behavior is expected when CARMA Platform is engaged and an approaching ERV is detected:

CMV and ERV in the same lane:

1. **time_until_passing >= approaching_threshold**: Approaching ERV is ignored.
2. **approaching_threshold >= time_until_passing >= passing_threshold**: The CMV will attempt to change lanes at the speed limit.
    a. **NOTE**: If the CMV successfully changes lanes with this time window, the CMV will behave according to the 'ERV and reduce its speed after this lane change is completed.
3. **passing_threshold >= time_until_passing >= MAINTAIN_SPEED_THRESHOLD**: The CMV will remain in its lane and target a reduced speed.
    a. **NOTE**: CMV will begin broadcasting EmergencyVehicleResponse warning messages (to notify the ERV that the CMV is unable to change lanes out of the ERV's path) when it enters this time window.

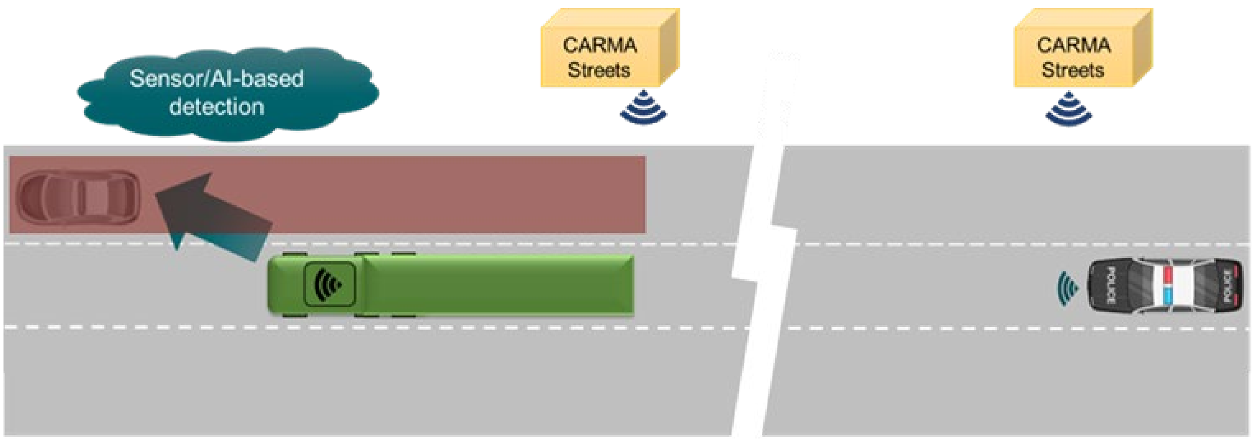
Source: FHWA.

Figure 13. Illustration. Time-based thresholds and associated behavior of a commercial motor vehicle in response to an emergency response vehicle approaching from the rear in the same lane.



Source: FHWA.

A. Vehicle-to-vehicle scenario.



Source: FHWA.

B. Vehicle-to-infrastructure scenario.

Figure 14. Illustrations. Freight emergency response use case scenarios.

For the commercial motor vehicle to detect the emergency response vehicle, the commercial motor vehicle receives and processes BSMs, which are initially broadcast by the emergency response vehicle, with information about the siren and light status added to part 2 of the message. The emergency response vehicle broadcasts these BSMs over cellular V2X at 10 Hz; the BSMs include the emergency response vehicle's current speed and location, emergency light and siren status, and future route waypoints. If the emergency response vehicle is within the line of sight of the commercial motor vehicle, direct vehicle-to-vehicle communication between the emergency response vehicle and commercial motor vehicle occurs. When vehicle-to-vehicle communication between the emergency response vehicle and commercial motor vehicle is not possible, indirect communication is achieved through vehicle-to-infrastructure and infrastructure-to-vehicle means.

Benefits for Transportation

During testing, this use case presented the following benefits for transportation:

- Increased commercial motor vehicle awareness of the presence of emergency response vehicles on freeways.
- Improved safety of interactions between emergency response vehicles and commercial motor vehicles.
- Reduced potential crashes associated with interactions between emergency response vehicles and commercial motor vehicles and other traffic participants.

State of Practice

Emergency and service vehicles often need higher priority on the road to arrive swiftly when responding to an emergency or a service call. When stopped in an emergency response area (either on the road or on the side of the road) tending to an incident, emergency and service responders are vulnerable to traffic and are at a higher safety risk. All States require vehicles on the road to yield right-of-way to approaching emergency response vehicles using flashing lights or sirens. To provide safety clearance to emergency response vehicles and personnel in an emergency response area, all States have passed move-over laws. These laws require vehicles to move over and/or slow down when approaching an emergency response area.[(37)]

CAVs should be subject to the same rules in these scenarios. Terry et al. (2018) examined emergency response scenarios for automated driving system-equipped vehicles. Law enforcement stakeholders identified how "to know if automated driving system-equipped vehicles have sensed or detected the presence of emergency response vehicles during an incident response or when conducting a traffic stop" as a high-priority need.[(38)]

In a survey of a diverse group of stakeholders, the following three concerns were identified as the most pressing regarding CAV interactions with emergency response vehicles (Transportation Safety Advancement Group 2020): [(39)]

- CAV ability to detect and safely respond to emergency scene traffic control.
- CAV ability to detect and appropriately respond to response vehicles with lights and sirens.
- CAV response to emergency response vehicles with lights on the side of the road (i.e., compliance with move-over laws).

These concerns are underscored by the 11 incidents since 2018 in which vehicles engaged in Tesla® Autopilot crashed into emergency response vehicles.[(40)] According to a Tesla Vehicle Safety Report, more than 9 billion miles have been driven by Tesla vehicles with Autopilot engaged. The report adds that, as of the fourth quarter of 2023, Tesla vehicles drove approximately 5.5 million miles with Autopilot engaged for every one accident involving them.

Additionally, 1 million miles are driven by Tesla vehicles without Autopilot engaged per one accident involving them—whereas approximately 500,000 miles are driven, on average, by all other vehicles in the United States before an accident occurs.(40)

Results

For verification testing, the research team conducted vehicle-to-vehicle and vehicle-to-infrastructure tests along the westbound straightaway at a test facility in Auburndale, Florida. This straightaway includes three one-way lanes with dashed lane markings. The research team set the automated commercial motor vehicle to a speed limit of 35 mph and the manually driven emergency response vehicle to a speed limit of 55 mph to perform the tests.

With regard to cellular V2X communication between the commercial motor vehicle and the emergency response vehicle, the research team conducted vehicle-to-vehicle test scenarios with no attenuators on the commercial motor vehicle's antennas and 10-decibel attenuators on the emergency response vehicle. With this configuration, communication between the commercial motor vehicle and the emergency response vehicle was reliable at distances of up to at least 1,200 ft.

Verification testing consisted of 12 testing scenarios. The first eight tests involved vehicle--to--vehicle messages, where communication and interaction of only the emergency response vehicle and commercial motor vehicle were tested. These tests were more extensive when testing various behaviors of the commercial motor vehicle and emergency response vehicle. The first five test cases examined the commercial motor vehicle's logic for detecting the emergency response vehicle's presence and deciding the required avoidance maneuver accordingly. For most of these test cases, the emergency response vehicle would not change its behavior because the commercial motor vehicle would move out of the way. In other test cases, the commercial motor vehicle could not change lanes, and the emergency response vehicle would have to change lanes to pass the commercial motor vehicle. The last three test cases for vehicle-to-vehicle communication examined both the passing threshold and the speed maintenance threshold with regard to the time until passing for the commercial motor vehicle and emergency response vehicle (figure 14).

The final four tests were vehicle-to-infrastructure tests. The research team lowered the communication range on the commercial motor vehicle and emergency response vehicle, such that the vehicles could not directly communicate at the beginning of the test case. The roadside units were stationed along the test track to receive messages from the emergency response vehicle and rebroadcast them to the commercial motor vehicle. The first two vehicle-to-infrastructure test cases checked the message communication between vehicle-to-infrastructure and infrastructure-to-vehicle. The last two of the vehicle-to-infrastructure scenarios were similar to testing two vehicle-to-vehicle test cases in behavior, but the major difference was that messages were being received through infrastructure.

Next Steps

The research team is working with the Federal Motor Carrier Safety Administration to identify use cases for future freight research.

RESEARCH TOOLS

USDOT provides research tools focused on infrastructure, vehicles, and simulation that offer advantages to transportation systems and their users. These tools help optimize traffic flow and management, enhance accessibility for road users, collect valuable data, and educate students at community colleges and trade schools. The tools help State and local agencies advance their knowledge and skills to accelerate adoption and deployment of V2X and CDA technologies.

CARMA RESEARCH TOOLS FOR INFRASTRUCTURE

Open-source CARMA research tools include CARMA Cloud℠, CARMA Streets, V2X Hub, CAV Telematics Tool, CAVe-in-a-box, CAVe-Lite, and the USDOT MAP creation tool. (See references 4, 14, 20, 21, 42, 43, and 44.)

CARMA Cloud(42)

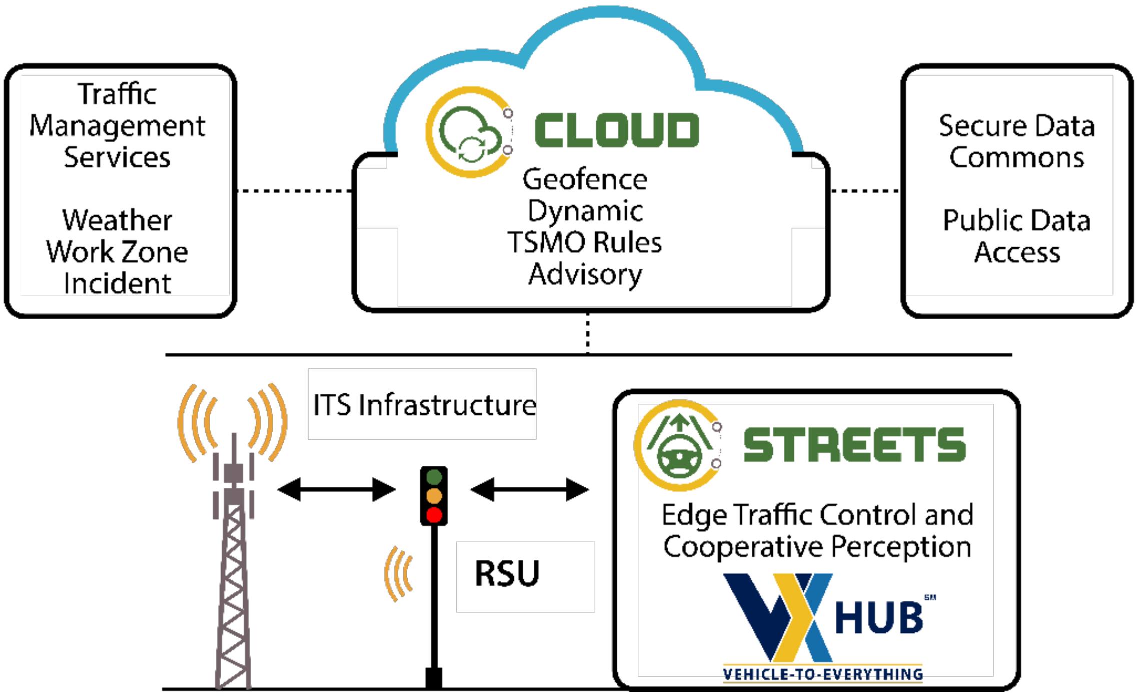
The CARMA Cloud software package represents traffic management services that contribute to safer and more efficient transportation systems. These services may include geofencing, work zone data exchanges, incident management, TSMO rules advisories, and operational and predictive traffic analyses. CARMA Cloud is cloud-based but may represent operational systems that are cloud-based or noncloud-based. A web interface provides a visual representation of road elements and associated data, including speed limits and lane closures.(4)

CARMA Streets(20)

The CARMA Streets software package is used to represent smart and connected infrastructure elements within the connected surface transportation ecosystem.(20) CARMA Streets allows automated and connected vehicles to share information with other vehicles and infrastructure to enable cooperation and improve transportation operations and safety. CARMA Streets allows for the testing of various TSMO use cases that will aid in the advancement of CDA technology.

V2X Hub(21)

V2X Hub is an open-source software and hardware configuration designed to facilitate real-time communication and data exchange between the physical and virtual elements of transportation infrastructure.(21) V2X Hub enables vehicles to establish communication with other vehicles, roadside infrastructure, pedestrians, bicyclists, and the cloud regarding vehicle surroundings, potential hazards, and other road conditions. This tool ensures safer integration of CAVs into the transportation system. Figure 15 illustrates CARMA products.



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

Figure 15. Illustration. CARMA products.

CAV Telematics Tool[4]

The CAV Telematics tool is an open-source data collection system to facilitate sharing and analysis of information related to CAVs.[4] With the ability to track and analyze data in near realtime, the tool enables quick data analysis to ensure systems are functioning as intended. This tool ensures real-time situational awareness of CARMA system performance during testing.

CAVe-in-a-Box[4]

CAVe-in-a-Box provides a hands-on learning experience to facilitate benchmarking connected vehicle equipment and to support onboarding new intelligent transportation system technicians.[4] The infrastructure and mobile kits in CAVe-in-a-Box include transportation radios, networking equipment, traffic control devices, and software necessary to train, deploy, and test scaled intelligent transportation systems in classrooms. The infrastructure kit of CAVe-in-a-Box is shown in figure 16.

Source: FHWA.

Figure 16. Photo. CAVe-in-a-Box.[19]

CAVe-Lite[4]

CAVe-Lite is a condensed version of CAVe-in-a-Box. CAVe-Lite further enhances access to education materials for students and researchers to test and validate connected vehicle messages.[20] This small, portable CAV testing kit focuses on application development. It allows fast and cost-effective setup, as the platform was developed on a Raspberry Pi™ computer.[45]

USDOT MAP Creation Tool[4,14,44]

The open-source MAP creation tool provided by USDOT simplifies the development of SAE J2735 MAP messages.[4,14] As seen in figure 17, this core-connected vehicle message details the layout, geometry, and usage rules of intersections and road segments. FHWA's Saxton Transportation Operations Laboratory aims to make this tool open source, enhancing flexibility for users.[4] The laboratory will also add support for the forthcoming Road Geometry Attributes message currently being defined by SAE J2945/A™.[46] The MAP creation tool provides a user-friendly graphical user interface for drawing road geometry on arterial imagery and visually inspecting existing MAP messages for accuracy.

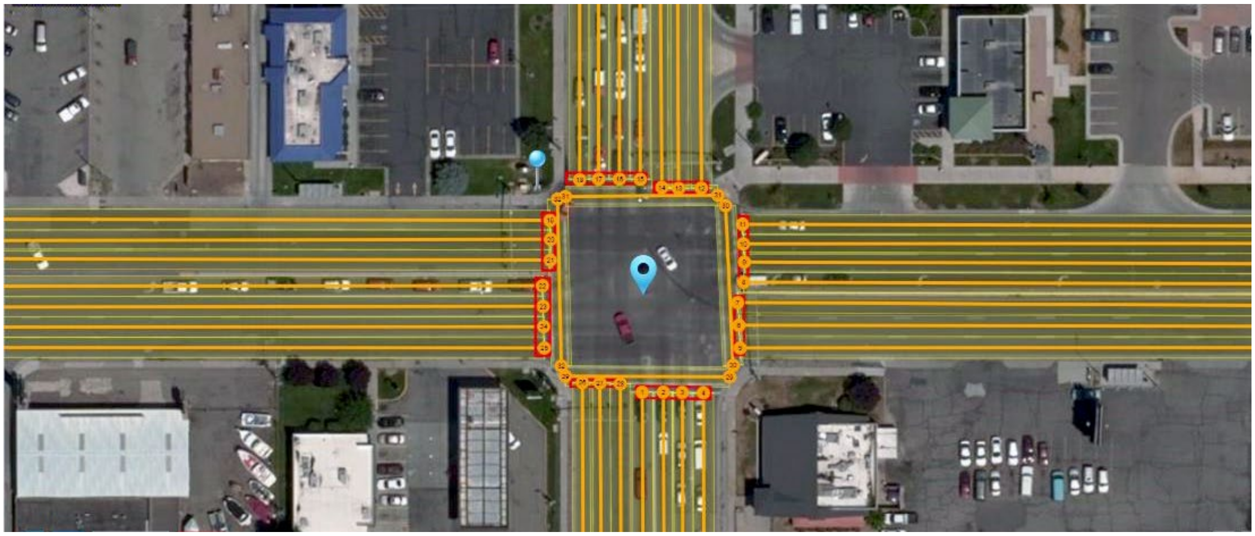


Figure 17. Map. Intersection definition in the USDOT MAP tool.[44,19]

CARMA RESEARCH TOOLS FOR VEHICLES

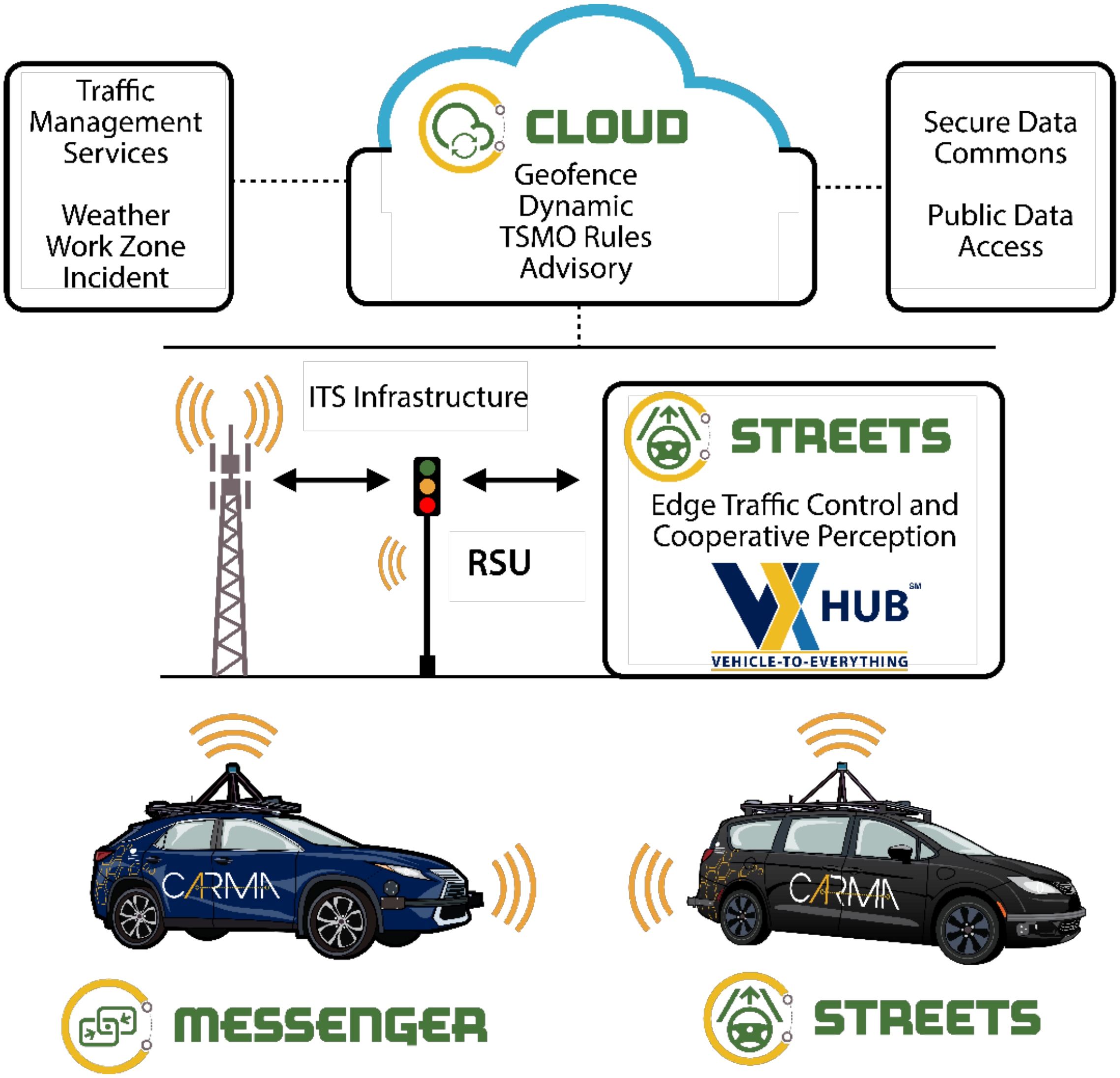
Road users are people who use and travel the roads, including pedestrians, bicyclists, and vehicle operators. A suite of CARMA research tools provided by USDOT enable road users to navigate and interact with roads more safely and efficiently. The suite includes CARMA Platform, CARMA Messenger, and CARMA 1Tenth, which aid in conducting research and testing of CDA technology.[3,46] CARMA Platform and CARMA 1Tenth are open-source software platforms that allow public access, enabling users to customize the software to meet their requirements.

CARMA Platform[23]

CARMA Platform facilitates the development and testing of CDA features in vehicles equipped with automated driving systems.[22] This software is designed to allow automated vehicles to interact seamlessly with other vehicles, infrastructure, and other road users. The primary objective of CARMA Platform is to establish a conceptual foundation for interoperable connectivity across different vehicle makes and models, laying the groundwork for safe introduction of these technologies on our Nation's roads. CARMA Platform also provides tools for the cooperative research functionalities of automated driving systems.

CARMA Messenger[4]

CARMA Messenger enables nonautomated vehicles to communicate with other transportation system users and engage in CDA interactions.[4] CARMA Messenger leverages infrastructure to share data with other users, broadening access to the technology and its benefits. CARMA Messenger supports research involving first responders and encourages transit participation in CDA. This tool encourages nonautomated vehicles to actively participate in the CDA network. Figure 18 shows how vehicles communicate with CARMA products.[4]



Source: FHWA.

Figure 18. Illustration. Vehicles use CARMA products to communicate with other vehicles and infrastructure.

CARMA 1Tenth(47)

CARMA 1Tenth is an integrated software and hardware solution that uses CARMA Platform on smaller, simplified versions of full-scale vehicles known as 1Tenth vehicles (figure 19).(47) CARMA 1Tenth is still under development. On completion, these vehicles will use a modified version of CARMA Platform, enabling researchers to conduct CDA research with a larger number of vehicles than full-scale connected automated driving systems allow. This feature will maintain the hands-on and demonstration-friendly nature of nonsimulated vehicles. 1Tenth vehicles will provide a safer environment for the initial development and testing by offering more control over the experimental conditions. This control will create a more equitable and affordable platform for researchers who do not have access to full-size, CDA-enabled vehicles.

Source: FHWA.

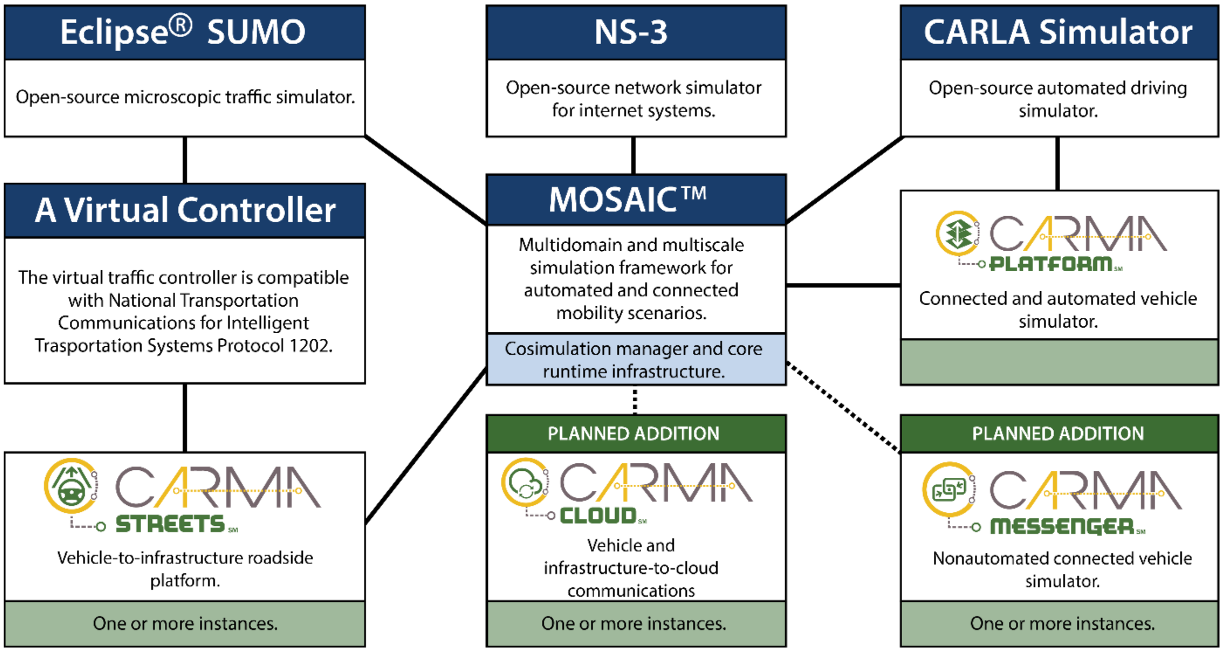
Figure 19. Photo. CARMA 1Tenth vehicle.[4]

SIMULATION TOOLS TO ADVANCE CDA RESEARCH

Simulations help users understand and explore various models of transportation systems and technology. The CDA simulation environment leverages multiple simulation frameworks—including the CDASim anything-in-the-loop cosimulation tool, CARLA Simulator, and Eclipse SUMO—to expand the capacity of CDA.[5,23,35] CDASim specifically supports CARLA Simulator and SUMO environments, both of which are open-source tools available to the public.

CDASim[5]

The CARMA suite of tools has historically been developed and tested on physical systems. With CDASim, CARMA capabilities have now been pulled into a single simulation environment with other traffic tools to help accelerate CDA development and testing before physical testing.[5] As illustrated in figure 20, CDASim allows simultaneous simulation of vehicles, traffic control devices, traffic management centers, and radio communications simulators. CDASim uses Eclipse® MOSAIC™ as its central execution manager but is designed to be flexible enough that modules can be replaced or removed based on the user's individual needs and preferences.[5,46] For instance, a university with its own automated driving system model can replace the CARMA Platform module while leveraging all the other modules integrated into CDASim.



Source: FHWA.

Figure 20. Diagram. CDASim cosimulation tool components.(5)

Virtual Open Innovation Collaborative Environment for Safety (VOICES)(48)

VOICES is a tool that enables virtual testing among multiple geographically distributed participating entities in an intellectual-property-protected environment. VOICES identifies conflicts among heterogeneous road user models and algorithms to resolve them earlier in the development process. VOICES enables researchers from different communities to crowdsource modeling capabilities they may lack in-house to answer different research questions.

HOW TO GET INVOLVED

The research tools discussed in this section are available on GitHub, a platform for collaborating, gaining experience with CDA, and customizing software for specific needs.(49) A section for frequently asked questions on GitHub offers solutions to commonly known issues. For technical support, contact the CARMA Support Services Help Desk at CARMASupport@dot.gov. Additionally, the USDOT FHWA STOL repository is a great resource, containing a collection of software and configuration files.(50)

STAKEHOLDER ENGAGEMENT

Involving stakeholders in research and development is a key part of the CDA Program. A main goal of the CDA Program is to encourage collaborative research and the adoption of CDA. More than 95 stakeholders are currently involved in the CDA Program's research and development efforts.

CONFERENCES AND EVENTS

The CDA Program's stakeholders consist of academic institutions, industry adopters, and State and local agencies. These stakeholders use the CDA Program's research and open-source tools in their own CDA projects. In 2023, FHWA engaged more than 320 stakeholders through conferences, workshops, events, and the CDA Support Services help desk.

Highlights of stakeholder engagement activities include the following:

- The CDA Program launched three technical working groups in each area of CDA research: infrastructure, road user, and simulation. The working groups are a place for interested stakeholders to discuss CDA applications for their area of choice:
    - The Simulation Technical Working Group was attended by 35 researchers from 30 universities. Discussions focused on simulation tools the researchers used and applications for CDA and cosimulation. Researchers from the University of Pittsburgh gave a presentation describing how the university integrated PTV Vissim®, a simulation tool, with CARLA, a simulator used in CDASim.(5,35,51) Such integrations expand the number of simulators that can work with CDASim, increasing its applicability. The working group also provided feedback on potential features to add to CDASim and other tools, such as the addition of typical traffic scenarios into the simulators.
    - The Road User Technical Working Group was attended by more than 45 stakeholders and discussed 8 CDA use cases and research areas. The discussions focused on ways to develop an architecture separating assisted driving systems from CDA systems while still allowing both types of systems to interface. The goal of creating this architecture is to increase CDA system accessibility and reduce limitations.
    - The Infrastructure Technical Working Group was attended by more than 50 stakeholders with 2 members sharing current infrastructure-related projects. The group discussed six open-source tools and their use cases. The topics discussed included latency metrics, the detection of multiple objects for cooperative perception, and the use of SDSMs.
- FHWA presented the CDA roadmap at several conferences, including the Intelligent Transportation Society of America (ITS America) meeting and the ITE Annual Meeting and Exhibition, to encourage stakeholder feedback on roadmap development and CDA Program direction.(52,53) See the "CDA Program Roadmap" section for more details.

- FHWA showcased how stakeholders are using the CDA Program's open-source tools in their own work at the Florida Automated Vehicle Summit.(54) FHWA also presented the CAV Telematics tool.(44) This open-source, real-time visualization tool enables researchers to quickly view and analyze data and respond to and adjust testing parameters spontaneously.

- FHWA discussed several projects under the CDA Program at the Transportation Research Board's (TRB's) Automated Road Transportation Symposium in July 2023.(55) These topics included discussing the integration of CDASim with other elements of the CDA and CARMA ecosystem, such as CARMA Platform and CARMA Streets. (See references 4, 20, 22, and 26.) Additionally, the team discussed adaptive traffic signal optimization and trajectory smoothing at signalized intersections. The V2X Hub team also presented use cases in which the platform played a significant role.(55)

In 2023, the CDA Program answered more than 320 requests through the CDA Support Services help desk. The help desk provides technical assistance to academic institutions, industry adopters, and State and local agencies that are working to integrate CDA technology into their own work. Additionally, the help desk assisted around 32 stakeholders in acquiring equipment through the CAVe-in-a-Box equipment loan program and resolving technical issues.

The CDA Program debuted the CAV Telematics Tool at the Florida Automated Vehicle Summit in September 2023.(43,57) The CDA Program created this tool, which is designed to allow researchers to visualize data in realtime, in partnership with the Intelligent Transportation Systems Joint Program Office. Additionally, the CDA Program has been holding CAVe-in-a-Box workshops at various conferences throughout the country to train attendees on intelligent transportation systems. Workshop attendees learn about the design of these systems and how to assemble their own CAVe-in-a-Box. In 2024, the CDA Program will continue to focus on stakeholder outreach through conferences, workshops, technical working groups, and other outreach activities.

SAXTON TRANSPORTATION OPERATIONS LABORATORY TOURS

In 2023, the CDA Program hosted several tours of the Saxton Transportation Operations Laboratory. These tours are important for the continued development of CDA technology, as they not only highlight the work being done by the CDA Program but also produce stakeholder feedback that helps FHWA move from in-house CDA development to the development of real-world tools.

Following are highlights from the 2023 tours:

- Transportation Secretary Pete Buttigieg visited the Saxton Transportation Operations Laboratory to explore and gain insight into the CDA Program (figure 21 and figure 22).

- The Federal Motor Carrier Safety Administration visited the laboratory in September to discuss CARMA architecture and truck hardware in detail.

- A delegation from South Korea visited the laboratory in September to learn about FHWA's work with cellular V2X.

Source: FHWA.

Figure 21. Photo. Transportation Secretary Pete Buttigieg reviews the CAVe-in-a-Box and a CARMA 1Tenth model while touring the Saxton Transportation Operations Laboratory.

Source: FHWA.

Figure 22. Photo. Transportation Secretary Buttigieg tours the Saxton Transportation Operations Laboratory garage.

CODEVELOPMENT WITH STAKEHOLDERS

FHWA and a variety of stakeholders collaborated to integrate CDA Program tools into tools used by the stakeholders. Intel®; Nissan®; and the University of California, Riverside were among the stakeholders involved in integrating the CDA Program tools into their own CAV technologies.

Following are highlights of the collaborations:

- Intel worked on integrating V2X Hub into its smart roadside unit and added additional camera-based sensor support to V2X Hub. Intel used the traffic incident management plug-in in V2X Hub to transmit pedestrian location information from its smart roadside unit. Intel will use a different SAE J2735 message to broadcast wrong-way vehicle information from its smart roadside unit using V2X Hub.(14,21)

- Nissan has used the VOICES tool to obtain research data to support Assured Green Period standardization.(48,57)

- The University of California, Riverside is using CDASim to conduct research.(27) The university is also working with the CDA Program to increase the tool's functionality.

- Ohio State University is in the process of updating CARMA Messenger to work with the Autoware® Foundation to receive and decode cellular V2X messages.(4,58)

PUBLICATIONS AND GRANTS

In 2023, FHWA published four research articles, three technical reports, eight technical use case summaries, five fact sheets, and five videos focused on CDA. In 2024, FHWA plans to release five videos specifically centered around CDA.

CDA-RELATED PUBLICATIONS

In 2023, FHWA's technical reporting on CDA came in several forms, including research articles, technical reports, fact sheets, and videos.

Research Articles

FHWA published the following CDA-related research articles in 2023:

- "Extensible Co-Simulation Framework for Supporting Cooperative Driving Automation Research."(59)
- "Strategic and Tactical Decision-Making for Cooperative Vehicle Platooning with Organized Behavior on Multi-Lane Highways."(60)
- "Cooperative Automation Research: CARMA Proof-of-Concept TSMO Use Case Testing: Traffic Incident Management Concept of Operations."(61)
- "FHWA Cooperative Automation Research: CARMA Proof-of-Concept TSMO Use Case Testing: CARMA Cooperative Perception Low-Level Concept of Operations."(62)

Technical Reports

FHWA published the following technical reports on CDA in 2022:

- *FHWA Cooperative Automation Research: CARMA Proof-of-Concept Transportation System Management and Operations Use Case 3–Traffic Signal Optimization with CDA at Signalized Intersections*.(63)
- *VOICES Cooperative Driving Automation (CDA) Proof-of-Concept Systems Integration Test 1*.(64)

Technical Use Case Summaries

FHWA developed the following CDA-related technical use case summaries in 2023:

- *Advanced Traffic Signal Control Optimization in a Cooperative Driving Automation (CDA) Environment*.(26)
- *Perception Sharing for Cooperative Driving Automation (CDA)*.(65)

- *Optimizing Vehicle Trajectories at Fixed-Time Traffic Signal Intersections using Cooperative Driving Automation (CDA)*.(66)
- *Integrated Highway Prototype Using Cooperative Driving Automation (CDA)*.(67)
- *Cooperative Driving Automation (CDA) Applications for Port Drayage*.(68)
- *Cooperative Automation Driving System (C-ADS) With Road Weather Management (RWM) With a Lane Closure*.(30)
- *Cooperative Driving Automation (CDA) at Stop-Controlled Intersections*.(69)
- Move Over Law for Traffic Incident Management Using Cooperative Driving Automation (CDA).(29)

Fact Sheets

FHWA developed the following CDA-related fact sheets in 2023:

- *Cooperative Perception and Control for Traffic System Operations*.(70)
- *Saxton Transportation Operations Laboratory Research Tools To Enhance Connected Automated Vehicle (CAV) Capabilities*.(4)
- *Saxton Transportation Operations Laboratory Cooperative Driving Automation (CDA) Tools To Improve Road User Safety*.(19)
- *Saxton Transportation Operations Laboratory Simulation Tools To Advance Cooperative Driving Automation (CDA) Research.*(5)
- *Transforming Transportation Systems Through Research and New Technologies*.(71)

Videos

FHWA published the following CDA-focused videos in 2023:

- Cooperative Perception Scenario 1—Pedestrian Crossing.(72)
- Cooperative Perception Scenario 2—Pedestrian Crossing.(73)
- CDA Collaborative Pilot Test 1.(74)
- CAV Telematics Tool Overview.(75)
- CAV Telematics Tool Tutorial.(76)

Active Grants

Grants that actively supported CDA research in 2023 came from multiple USDOT and FHWA supported programs.

Automated Driving System Demonstration Grants

USDOT provided nearly $60 million in Federal funding to the following projects to test the safe integration of automated driving systems on the Nation's roadways:

- Texas A&M Engineering Experiment Station:
  - Project name: AVA: Automated Vehicles for All.(77)
  - Technology: SAE Level 4 vehicle, CARMA 2, and V2X communication.(4,13)
  - Project objective: Develop and test automated driving systems for rural roads without high-definition maps and with no- or low-quality road signs and markings.
- Virginia Tech:
  - Project name: Trucking Fleet Concept of Operations for Managing Mixed Fleets.(78)
  - Technology: Advanced prediction and camera-based self-driving.
  - Project objective: Develop and demonstrate a fleet concept of operations to provide the trucking industry with clear information on how to safely implement and benefit from automated driving system-equipped trucks.
- Ohio DOT:
  - Project Name: D.A.T.A. in Ohio: Deploying Automated Technology Anywhere.(79)
  - Technology: SAE Level 3 passenger vehicles,
  - Project objective: Take a multipronged demonstration approach focused on rural environments, cooperative automation, and robust data collection to enable the development of effective and informed automated driving system policies.
- Pennsylvania DOT:
  - Project name: Safe Integration of Automated Vehicles into Work Zones.(80)
  - Technology: Connectivity between automated vehicles and traffic control devices, construction workers, and construction vehicles by using a single device with dedicated short-range communication and cellular V2X radio; innovative coating for pavement markings; traffic control devices; and high-definition work zone mapping using radar, LiDAR, and cameras.

  - Project objective: Explore the safe integration of automated driving systems into work zones by examining connectivity, visibility, and high-definition mapping technologies.

- City of Detroit, MI:

  - Project name: Michigan Mobility Collaborative—Automated Driving System Demonstration.[81]

  - Technology: SAE Level 3 automated driving system.

  - Project objective: 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.[82]

  - Technology: Radar; LiDAR; detectors; cameras; vehicle-to-vehicle, vehicle-to-infrastructure, and V2X (e.g., SPaT) messages; MAP messages; BSMs; and pedestrian or personal safety messages.[14]

  - Project objective: Demonstrate SAE Level 3 and Level 4 vehicles using shared on-demand wheelchair-accessible vehicles that are equipped with automated driving systems.

Strengthening Mobility and Revolutionizing Transportation (SMART) Grants Program

The SMART Grants Program began in 2022 and will continue through 2026. In total, the grant program provides $100 million in annual funding to support public sector agency projects focused on improving transportation efficiency and safety.

The following CDA-related projects were supported by grants in 2023:

- Arizona Commerce Authority:

  - Project name: DRIVE Arizona: Digitizing Roadways With Innovative V2X Ecosystems for a Safe, Inclusive Arizona.[83]

  - Technology: V2X ecosystems

  - Project objective: Demonstrate back of queue warning, work zone warning, and transit signal priority by digitizing Phoenix's Interstate 17 and Interstate 10 corridors.

- City of Greeley, CO:

  - Project name: Connected Greeley—Emergency Vehicle Preemption (CG-EVP) Pilot.[84]

- Technology: Cooperative perception.
- Project objective: Provide emergency vehicle preemption, snowplow priority, and a vulnerable road user detection and warning system at intersections in Greeley, Colorado.

- Delaware DOT:
  - Project name: Future-Ready Delaware: Technology Enhancements for Safe, Resilient Intersections.[85]
  - Technology: V2X.
  - Project objective: Deploy cloud-based V2X technology and optimized signal timing along statewide roadways.
- Gwinnett County Board of Commissioners:
  - Project name: Singleton Road Corridor Technology Improvements.[86]
  - Technology: Cooperative perception.
  - Project objective: Prototype safety technologies along the Singleton Road corridor in Gwinnett County, GA, including passive pedestrian detection and transit signal priority.
- Bannock Transportation Planning Organization:
  - Project name: Innovative Transportation Solutions Project.[87]
  - Technology: Cooperative perception.
  - Project objective: Install smart, sensor-based traffic signals and monitoring across the Yellowstone Corridor in Idaho.
- Road Commission for Oakland County, MI:
  - Project name: Leading in Sustainable Safety With Vehicle-to-Everything Technology.[88]
  - Technology: Cellular V2X.
  - Project objective: Create a framework for deploying cellular V2X in a sustainable manner.

- Utah DOT:
    - Project name: Enabling Trust and Deployment Through Verified Connected Intersections.[89]
    - Technology: V2X.
    - Project objective: Prototype a connected intersection corridor and develop a plan for nationwide V2X systems deployment.
- Central Puget Sound Regional Transit Authority:
    - Project name: Rainier Valley Safe: Technology Investments To Improve Community Safety.[90]
    - Technology: Cooperative perception.
    - Project objective: Leverage smart sensing infrastructure and upgraded traffic signals to address safety at at-grade crossings and multimodal efficiency at signalized intersections in Rainier Valley, WA.

Advanced Transportation Technology and Innovation Program

The Advanced Transportation Technology and Innovation program provides $60 million in grants through FHWA to deploy, install, and operate advanced transportation technologies to improve safety, mobility, efficiency, system performance, intermodal connectivity, and infrastructure return on investment. The Advanced Transportation Technology and Innovation program began in 2022 and will run through 2026.

The following CDA-related grants were awarded through the program for 2023:

- Mohave County, AZ:
    - Project name: Vehicle-to-Infrastructure Enabled Rural Highway Traffic Control Signs.[91]
    - Technology: Vehicle-to-infrastructure systems.
    - Project objective: Deploy 50 vehicle-to-infrastructure traffic control sign systems throughout rural areas of Mohave County targeted to high-speed highway segments and intersection approaches to improve safety. The project area includes opportunity zones and disadvantaged communities.
- University of Michigan:

- Project name: Advanced Transportation Technology and Innovation (ATTAIN) Program "ATTAIN AACE 2.0: The Ann Arbor Connected Environment Reimagined."(92)
- Technology: Cellular V2X.
- Project objective: Prepare infrastructure for vehicle manufacturing collaborators to test and deploy new technologies under the Ann Arbor Connected Environment 2.0 project, which will use cellular V2X technology.

- Utah DOT:
  - Project name: Utah Connected Communities.(93)
  - Technology: V2X.
  - Project objective: Expand connected vehicle technology and capabilities, including V2X, throughout Utah. The project area includes disadvantaged communities in rural and urban parts of Utah.

Summary and Next Steps

FHWA made significant progress developing CDA technology in 2023. One of the biggest steps in 2023 was FHWA facilitating the increased usage of V2X technology, such as FHWA assisting in V2X deployment by providing V2X equipment loans to an increased amount of stakeholders. FHWA also helped stakeholders understand how V2X technology can make their operations safer.

In 2023, city and State DOTs and infrastructure owners and operators typically installed the loaned V2X equipment at one or two intersections and on public fleet vehicles. Prior to 2023, FHWA primarily directed loaned V2X equipment to universities for research.

An important milestone FHWA achieved in 2023 was adding full support in CARMA tools for cellular V2X communication and cellular network communication.(94) This technology enables CAVs to communicate with other connected vehicles and infrastructure directly and indirectly. Compared to digital short-range communication, cellular V2X has the potential to expand the range of communication between connected cars and infrastructure. FHWA will continue to work with stakeholders to identify spectrum and connectivity needs ahead of full implementation of this technology into the CARMA toolset.

FHWA's research this year focused on studying how CDA can improve highway operations, intersection safety and optimization, corridor management, and vulnerable road user safety. To support these efforts, FHWA introduced new tools and updates to CARMA Streets, CDASim, and the CAV Telematics tool. In 2023, FHWA interacted with more stakeholders by holding three technical working groups. These collaborations helped improve CDA technology and promoted further use of CDA.

FHWA also published its 10-yr CDA roadmap, which lays out the path of CDA research and development over the next decade. This roadmap has three target goals: short-term, medium-term, and long-term. The roadmap's long-term goals include the deployment of SAE Level 3, Level 4, and Level 5 CDA automated driving system applications by 2034.

In 2024, the research team will focus on the following priorities to continue development of CDA technologies from a research concentration toward real-word use:

- Continue stakeholder outreach through CDA prototype and pilot planning.
- Support standards development for the deployment of CDA through updated architecture based on stakeholder input.
- Continue spectrum research and testing to include additional cybersecurity testing and interference testing with the adjacent Unlicensed National Information Infrastructure 6-GHz band using cellular V2X radios, as well as testing communication within licensed cellular bands to promote mobile network operator interoperability to support future CDA use cases.

- Enhance the CDASim Tool to include simulated cellular V2X communication, CARMA Messenger, and CARMA Cloud integration.[42]
- Increase stakeholder engagement with the CAV Interoperability Test tool community to enable collaborative testing.
- Support radio supplier interoperability through participation in collaborative events, including the OmniAir® Plugfest @ MCity in Ann Arbor, MI.[95]
- Develop vulnerable road user use case functionalities that leverage CDASim by using sensor data from infrastructure and vehicles encoded and broadcast using SDSMs to facilitate cooperative perception.
- Support the deployment of V2X technology aimed at improving road safety, mobility, and efficiency.

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