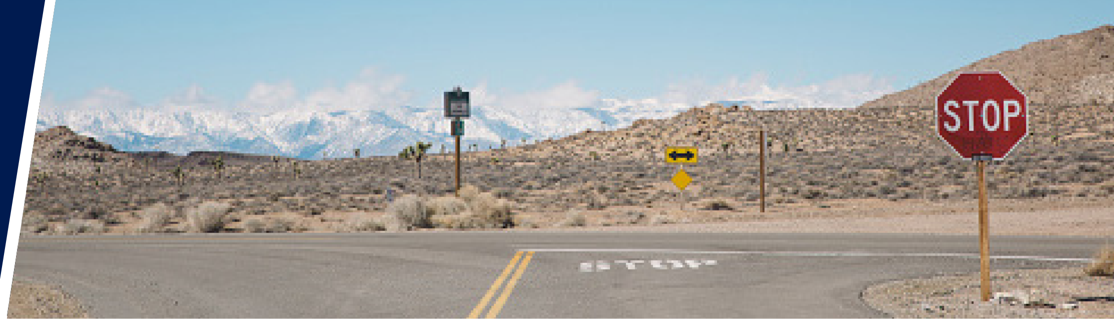
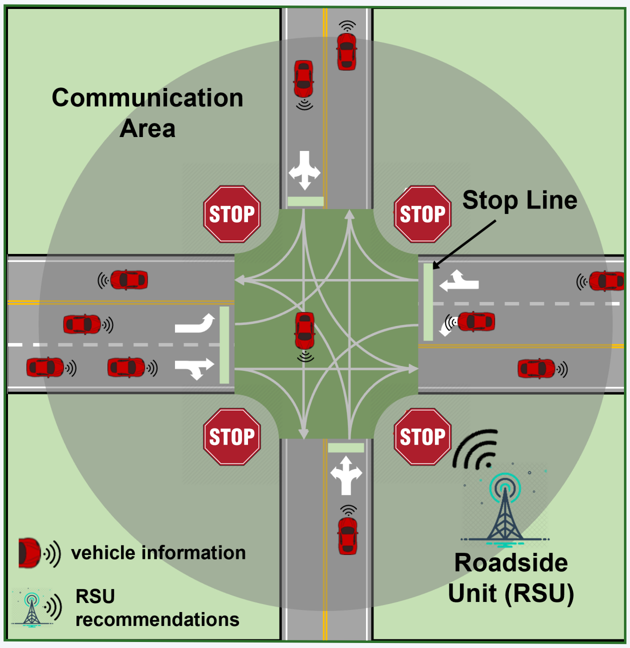
U.S. Department of Transportation
Federal Highway Administration

**Office of Safety and Operations
Research and Development**



Cooperative Driving Automation (CDA) at Stop-Controlled Intersections

Stop-controlled intersections help vehicles avoid potential crash risks and extremely high accelerations or decelerations. Currently, multiple vehicles cannot pass through a stop-controlled intersection at the same time. However, with available real-time vehicle information, vehicles can optimize their trajectories to be aware of other vehicles, plan accordingly to arrive and leave intersections at the best time from the stop line, and pass through the intersection simultaneously with other vehicles that do not have conflicting directions. Figure 1 shows a four-way, stop-controlled intersection and the technology the intersection uses. With the available real-time vehicle information, vehicles can also minimize delay and wait times, maximize safety, decrease energy consumption, and improve riding comfort.



Source: FHWA.

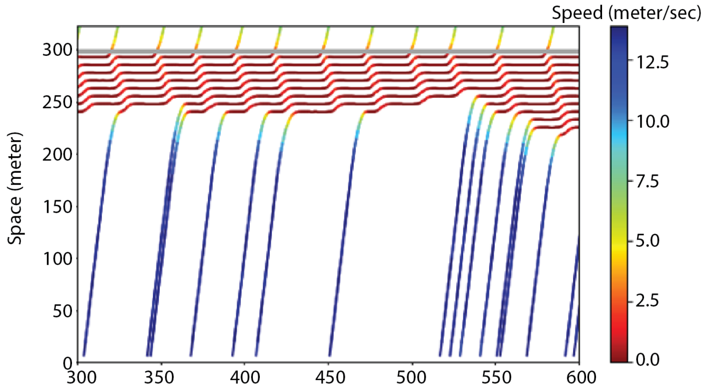
Figure 1. Graphic. Four-way, multilane, stop-controlled intersection.

BENEFITS TO TRANSPORTATION

This research project aims to demonstrate the benefits of CDA use at stop-controlled intersections.(1) This research provides an initial building block toward systems receiving digital vehicle messages that provide the real-time information and planned trajectory of the vehicle and sharing digital infrastructure messages that represent basic signage, rules of the road, or instructions for vehicles. In this research project, vehicles broadcast real-time information about the vehicles' operating states, communicate directly with infrastructure to coordinate movement through stop-controlled intersections, and receive advisory messages from the infrastructure that help the vehicles smooth their trajectory, thus improving traffic safety, throughput, and energy efficiency.

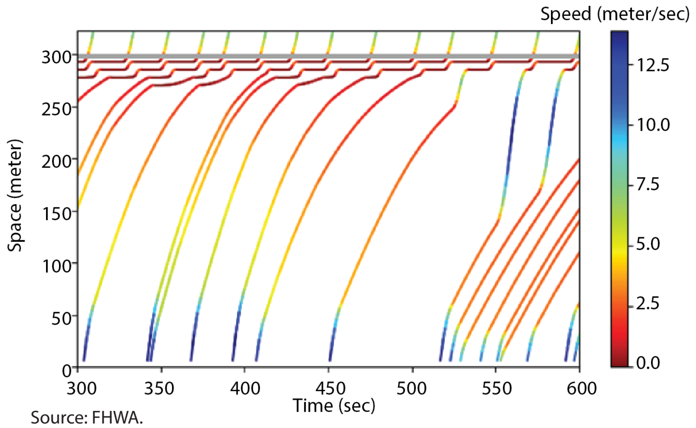
EVALUATION OF THE CONCEPT

The research team first conducted simulation experiments to evaluate and fine-tune the developed algorithms. The team conducted simulations at a typical four-way, stop-controlled intersection with two lanes on the eastbound and westbound approaches and a single lane on the northbound and southbound approaches. Simulation results show that the developed algorithms reduce average travel delay, fuel consumption, and stopping time at stop-controlled intersections.(1) The results demonstrate that with reduced stopping time and less stop-and-go traffic, general fuel economy will improve with CDA and will improve even more when vehicles can optimize departure sequence and utilize intersection resources to maximum capacity with CDA. This enhancement also leads to less average delay, highlighting the reduction in stop time during travel for the cases illustrated in figure 2 through figure 4. Table 1 displays the improvement in the level of service at stop-controlled intersections for different CDA cooperation class scenarios compared to the baseline human-driven vehicle (HV) scenario.



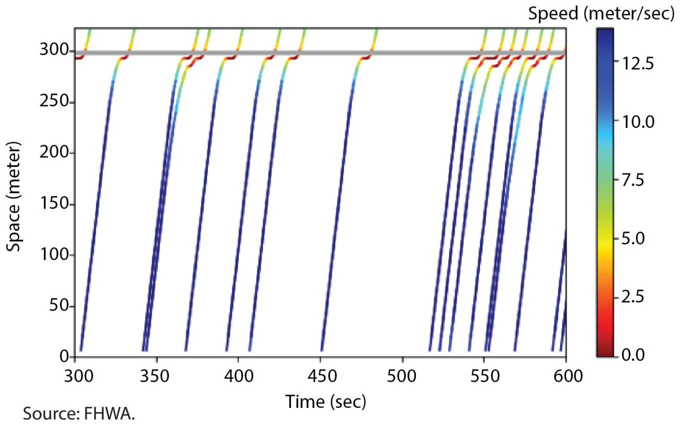
Source: FHWA.

Figure 2. Graph. HV trajectory plots.



Source: FHWA.

Figure 3. Graph. Automation Level 3, cooperation Class A vehicle trajectory plots.(2)



Source: FHWA.

Figure 4. Graph. Automation Level 3, cooperation Class D vehicle trajectory plots.(2)

Table 1. Level of service at the stop-controlled intersection.(2)

Vehicle Type or Level 3 Automation Cooperation Class Scenarios											
Vehicle Type or Level 3 Automation Cooperation Class Scenarios(2)	**600**	**720**	**840**	**960**	**1,080**	**1,200**	**1,320**	**1,440**	**1,560**	**1,680**	**1,800**
CLASS A	A	B	C	E	F	F	F	F	F	F	F
CLASS B	A	A	A	A	A	A	A	C	D	E	F
CLASS C	A	A	A	A	A	A	A	A	B	C	D
CLASS D	A	A	A	A	A	A	A	A	B	B	C

A = free flow; B = reasonably free flow; C = stable flow, at or near free flow; D = approaching unstable flow; E = unstable flow, operating at capacity; F = forced or breakdown flow.

Figure 2 through figure 4 illustrate vehicle trajectories with space-time motion plots for a selected lane and simulation run. The vertical axis represents space in meters, while the horizontal axis represents time in seconds. In these graphs, each solid line corresponds to the trajectory of a single vehicle, and a change in the line's slope directly correlates to a change in the vehicle's speed. For example, as the slope of the line increases, the speed of the vehicle also increases and vice versa. These visuals highlight a crucial observation; unlike HV, which might have to stop at the stop bar multiple times before entering the intersection, vehicles equipped with Level 3 Class A CDA technology demonstrate a smoother flow by proactively slowing down.(2) Additionally, figure 4 underscores the significance of optimizing the departure sequence of vehicles with Level 3 Class D CDA technology.(2) This optimization maximizes intersection resources, leading to a substantial reduction in waiting times at stop-controlled intersections.

The research team then performed several levels of proof-of-concept (PoC) testing with real vehicles and infrastructure on closed test tracks. The defined acceptance criteria included various operational aspects such as communication, safety, mobility, and trajectory smoothness. The team installed algorithms on FHWA vehicles and infrastructure and independently tested those algorithms.(1) All testing took place at the Turner-Fairbank Highway Research Center and evaluated system performance in critical edge case scenarios, such as two vehicles with conflicting directions or two vehicles without conflicting directions. Validation testing was led by the U.S. Department of Transportation Volpe National Transportation Systems Center. Analyses of the verification and validation testing show that the PoC frameworks met most of the metrics and requirements identified in in the test plans.

USE CASE ARCHITECTURE

While the algorithms were developed and simulations were conducted for different CDA cooperation classes defined in SAE International® J3216™, the implementation of this use case on the CARMA℠ ecosystem focuses solely on automation Level 3, cooperation Class D.(3,4) The components of the CARMA ecosystem used in this cooperation class include CARMA Platform℠, CARMA Streets℠, and Vehicle-to-Everything (V2X) Hub. (See references 4, 5, 6, and 7.) Figure 5 shows how each aspect of CARMA infrastructure works together. CARMA Streets and the V2X Hub reside within the infrastructure and are jointly responsible for processing the information received from vehicles and scheduling those vehicles by calculating their stopping and entry times.(6,7) Stopping time refers to the time a vehicle takes to decelerate and come to a full stop, while entry time is the time a vehicle takes to cross into the intersection. CARMA Platform is situated within the vehicle and receives advisory messages from the infrastructure, controlling vehicle trajectories to minimize stopping time and optimize vehicle energy and fuel efficiency.(5)

Source: FHWA.

BSM = basic safety message; MOM = mobility operations message; MPM = mobility path message; Json = JavaScript Object Notation.

Figure 5. Graphic. CARMA design and architecture for stop-controlled intersections use case—automation Level 3, cooperation Class D. (See references 3, 5, 6, 7, and 8.)

CDA COOPERATION CLASSES

Defined in SAE J3216 Standard(3)

- Class A: Status Sharing
- Class B: Intent Sharing
- Class C: Agreement Seeking
- Class D: Prescriptive

STANDARDS

This technology meets the following standards established by SAE International:

- SAE J3216_202107: *Taxonomy and Definitions for Terms Related to CDA for On-Road Motor Vehicles.*(3)
- SAE J3016_202104™: *Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles.*(2)
- SAE J2735_202007™: *Vehicle-to-Everything Communications Message Set Dictionary.*(9)

CONCLUSION

This test case proved the benefits of CDA application in stop-controlled intersections. While the research team identified some limitations through data collection and analysis, the results raised no safety concerns and the potential for future work remains high. In particular, the developed framework can be improved in the following three ways:

▶ Extend this test case to a mixed-traffic environment, where only part of traffic is equipped with CDA technology.

▶ Continue to apply vehicle-to-vehicle communications to enable higher scale deployments and further examine the benefits demonstrated in simulation experiments.

▶ Add consideration of vulnerable road users to the system to increase reliability and accuracy.

REFERENCES

1. Soleimaniamiri, S., X. S. Li, H. Yao, A. Ghiasi, G. Vadakpat, P. Bujanovic, T. Lochrane, J. Stark, S. Racha, and D. Hale. 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.* Report No. FHWA-HRT-22-052. Washington, DC: Federal Highway Administration.
2. SAE International. 2018. *Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles*. J3016_201806. Warrendale, PA: SAE International. https://www.sae.org/standards/content/j3016_201806, last accessed May 30, 2023.
3. SAE International. 2020. *Taxonomy and Definitions for Terms Related to Cooperative Driving Automation for On-Road Motor Vehicles.* SAE J3216_202005. Warrendale, PA: SAE International. https://www.sae.org/standards/content/j3216_202005/, last accessed October 19, 2020.
4. USDOT. n.d. "CARMA" (web page). https://its.dot.gov/cda/, last accessed May 30, 2023.
5. FHWA. n.d. "carma platform" (software and configuration files in GitHub repository). https://github.com/usdot-fhwa-stol/carma-platform, last accessed April 12, 2023.
6. FHWA. 2023. "carma streets" (software and configuration files in GitHub repository). https://github.com/usdot-fhwa-stol/carma-streets, last accessed April 12, 2023.
7. FHWA. 2023. "V2X-Hub" (software and configuration files in GitHub repository). https://github.com/usdot-fhwa-OPS/V2X-Hub, last accessed April 13, 2023.
8. JavaScript Object Notation. n.d. "Introducing JSON" (web page). https://www.json.org/json-en.html, last accessed October 4, 2023.
9. SAE International. 2023. V2X Communications Message Set Dictionary. J2735_202007. Warrendale, PA: SAE International. https://www.sae.org/standards/content/j2735_202007/, last accessed November 27, 2023.

TO LEARN MORE AND FOLLOW UPDATES

CARMA Streets

https://github.com/usdot-/fhwa-stol/carma-streets

CARMA Platform

https://github.com/usdot-fhwa-stol/carma-platform

U.S. Department of Transportation
Federal Highway Administration

For more information, please contact the CDA Program at CDA@dot.gov

FHWA-HRT-24-030
HRSO-40/12-23(200)E
Recommended citation: Federal Highway Administration. *Cooperative Driving Automation (CDA) at Stop-Controlled Intersections* (Washington, DC: 2023)
https://doi.org/10.21949/1521470