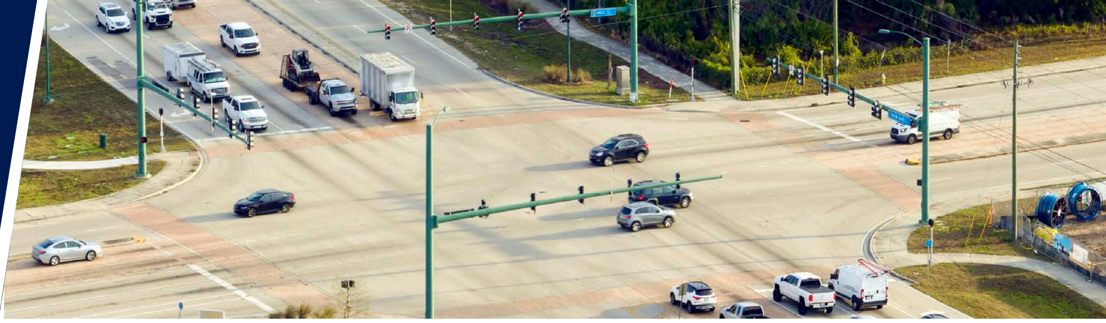
U.S. Department of Transportation
Federal Highway Administration

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



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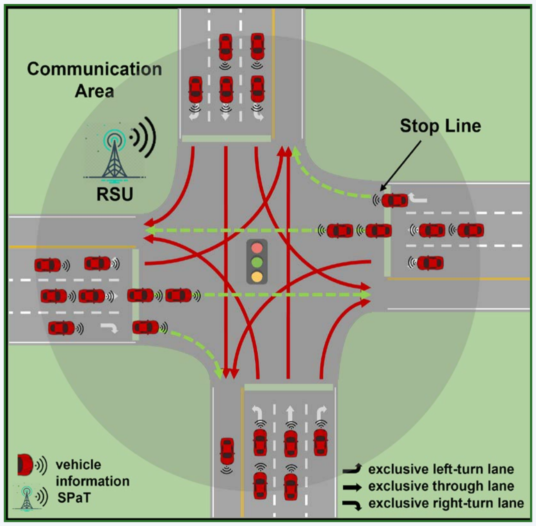
Optimizing Vehicle Trajectories at Fixed-Time Traffic Signal Intersections using Cooperative Driving Automation (CDA)

Automated vehicles communicating with smart traffic signals can travel through signalized intersections more safely and efficiently. The functionality developed in this project demonstrates CDA's potential to benefit automated vehicles by supporting them as they navigate signalized intersections with fixed-time settings. As shown in figure 1, vehicles approaching an intersection may share status and intent information (such as the vehicle's current location and speed, the intended future path, etc.) with a roadside unit (RSU) and receive signal phase and timing (SPaT) inputs from the traffic signals connected to the RSU once in range.(1,2) SpaT inputs communicate to the vehicle current phase and interval for the traffic light and how much time remains at that interval. The vehicle can then determine how best to proceed based on the intervals. Vehicles can automatically adjust and smooth their trajectory to minimize their stopping times by reducing their speed ahead of a yellow light change. They can also pass through an intersection during a green interval with a higher speed, within designated limits. This technology allows for smoother transitions through intersections, better flowing traffic patterns, fewer delays, less energy consumption, and less backward shock-wave propagation.(3)



Source: Federal Highway Administration (FHWA).

Figure 1. Graphic. Vehicles entering a signalized intersection.

BENEFITS TO TRANSPORTATION

Improve Energy Efficiency

With reduced stopping and delay and less stop-and-go traffic, **general fuel economy may improve by up to 30 percent.**(4)

Reduce Travel Delays

With stop-and-go traffic from signalized intersections reduced, road users could experience **50 percent less stop time during travel, and shorter commute times.** Less stop-and-go traffic would also contribute to smoother driving experiences.(4)

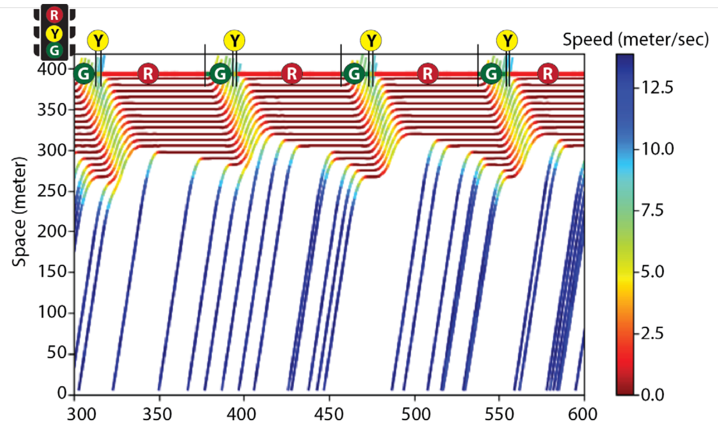
Maintain Safety

In 2021, 42,939 people were killed in motor vehicle traffic crashes on U.S. roadways. With intersections being potentially unpredictable, CDA technology could **reduce the chance of collision,** improving road safety for all users with enhanced awareness.(4)

EVALUATION OF THE CONCEPT

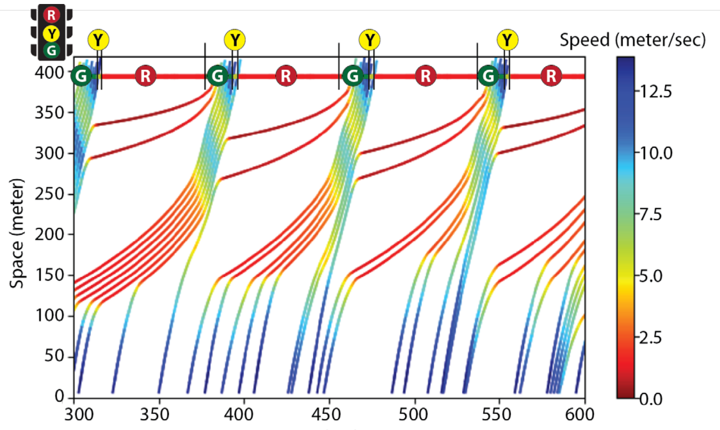
The research team first conducted simulation experiments to evaluate and fine-tune the developed algorithms for four cooperation classes as defined by SAE International® J3216™.(5) In scenarios where vehicles and infrastructure are equipped with CDA technology, the objective of the experiment is for the vehicle to achieve smoother trajectories and enter the intersection box at relatively higher speed. This approach results in a reduced departure headway between consecutive vehicles, thereby increasing throughput. The results show that the developed algorithms reduce average travel delay, fuel consumption, and stopping time at signalized intersections with fixed time traffic signals.

Figure 2 and figure 3 depict vehicle trajectories (space-time motion) for human-driven and CDA vehicles, respectively, in a selected lane and the optimal cycle length. 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 human-driven vehicles, which come to a complete stop and wait at the signal for a signal change before entering the intersection, vehicles equipped with automation Level 3 and using Class A(5) cooperation show a smoother flow by slowing down before reaching the intersection. These graphs demonstrate that the algorithms developed in this research project effectively eliminate stop-and-go traffic patterns and backward shock-wave propagations.(3) This feature ultimately enhances the travel experience and reduces traffic time for a vehicle navigating a signalized intersection.



Source: FHWA.

Figure 2. Graph. Trajectory of human-driven vehicles as they approach a traffic signal over time.



Source: FHWA.

Figure 3. Graph. Trajectory of cooperation Class A vehicles as they approach a traffic signal over time.(5)

After completing traffic simulation studies, the team carried out multiple rounds of proof-of-concept (PoC) testing using full-sized FHWA vehicles and infrastructure equipped with CDA on controlled test tracks. These tests assessed various operational aspects, including communication, safety, mobility, and the smoothness of vehicle trajectories. All testing took place at the Turner-Fairbank Highway Research Center. Tests evaluated system performance in critical scenarios, such as vehicle arrival at an intersection at the beginning or the end of a green light interval. After several initial testing rounds to verify the implemented algorithms, the Volpe National Transportation Systems Center led additional testing rounds to validate the algorithms and the findings, helping set a foundation for further research and development.

CDA COOPERATION CLASSES

Defined in SAE J3216 Standard(5)

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

STANDARDS

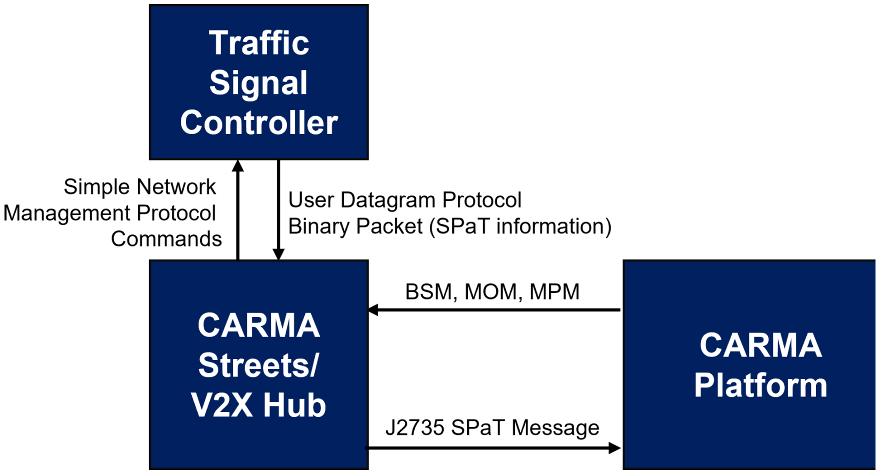
This technology meets the following standards established by SAE International:

- SAE J3216_202107: *Taxonomy and Definitions for Terms Related to CDA for On-Road Motor Vehicles.*(5)
- SAE J3016_202104™: *Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles.*(6)
- SAE J2735_202007™: *Vehicle-to-Everything Communications Message Set Dictionary.*(7)

USE CASE ARCHITECTURE

While the algorithms were developed and simulations were conducted for all different CDA cooperation classes defined in SAE International J3216, the implementation of this use case on the CARMA^{SM} ecosystem focuses solely on cooperation Class A.(5,8) The components of the CARMA ecosystem used in this cooperation class include CARMA Platform^{SM} and the Vehicle-to-Everything (V2X) Hub.(9,10) Figure 4 provides a look at how each aspect of the CARMA components works together. The V2X Hub broadcasts the SPaT messages, and CARMA Platform estimates the time the vehicle can enter and spend at the intersection.(2) In this architecture, vehicles may also share status information via the RSU using the basic safety message (BSM) and customized mobility operations messages (MOM) and mobility path messages (MPM).(1)

This shared data can potentially enhance the CARMA Platform's time to enter the intersection estimations by leveraging the information of other vehicles.(9) However, due to the CARMA Platform limitation at the field testing time, this feature could not be tested and consequently has not been fully implemented. The CARMA Platform then controls the vehicle trajectory accordingly to minimize the vehicle stopping time and optimize the vehicle's energy and fuel efficiency.



Source: FHWA.

Figure 4. Graphic. CARMA design and architecture for fixed-time traffic signals use case—cooperation Class A. (See references 2, 4, 8, 9, 10, and 11.)

RESULTS AND LESSONS LEARNED

The results of analyses from testing show that the PoC frameworks meet a set of key objective metrics that the research team considered to be related to message processing, communication rates, and algorithm logic. These metrics include, in particular, vehicle trajectory sequencing, estimation of the time the vehicles enter the intersection during different signal phases, and adherence to specified deceleration and acceleration boundaries. One aspect not considered in this test that could be considered in future testing is vehicle-to-vehicle communication. While the team identified some limitations through data collection and analysis, these limitations can be addressed as part of future CDA program efforts.

CONCLUSIONS

This test case proved the benefits of CDA application in signalized intersections with fixed-time settings and helped provide a better understanding of its advantages. Potential for future work remains high. In particular, the developed framework can be significantly improved by completing further research in the following scenarios:

Large-Scale Testing

Applying vehicle-to-vehicle communications in a fixed time traffic signal environment allows for higher scale deployments, which would result in increased confidence and reliability when quantifying individuals and systems.

Mixed-Traffic Environment

Extending this use case to test in a mixed-traffic environment, where only part of the traffic is equipped with CDA technology, would further research that will accelerate industry deployment.

More Dynamic Situations

Using more complex components (lane changes, multiple vehicles, vulnerable road users, presence of incidents) will help improve the technology.

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TO LEARN MORE AND FOLLOW UPDATES

CDA Program
https://www.fhwa-stol.org/

V2X GitHub
https://github.com/usdot-fhwa-OPS/V2X-Hub

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

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

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