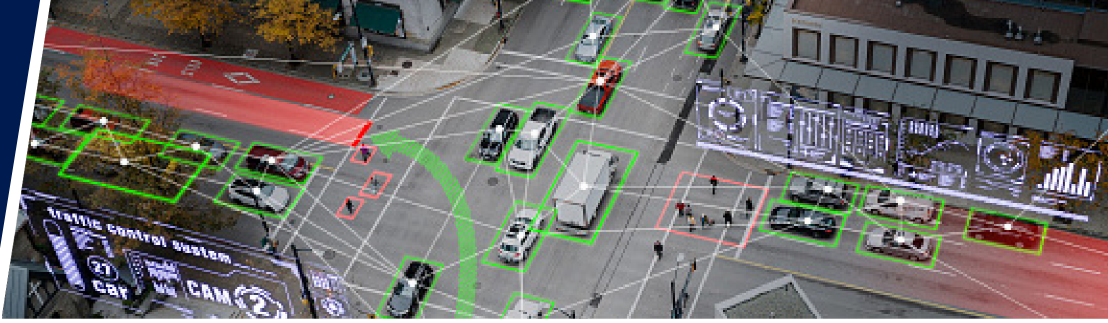
U.S. Department of Transportation
Federal Highway Administration

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



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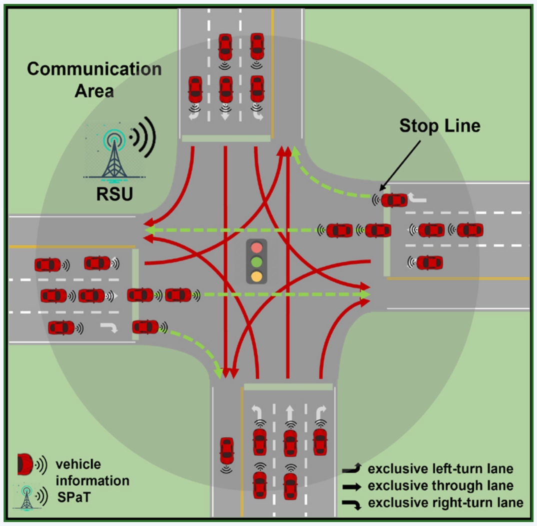
Adaptive Traffic Signal Control Optimization in a Cooperative Driving Automation (CDA) Environment

Automated vehicles can navigate signalized intersections with enhanced safety and efficiency by establishing communication with smart infrastructure. The functionality developed in this project demonstrates CDA's potential to benefit automated vehicles by supporting them as they navigate signalized intersections with adaptive settings.(1) 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).(2) RSUs use this information to continuously estimate the time each vehicle will enter the intersection box and optimize the signal timing plan. The signal timing plan optimization aims to efficiently serve the incoming traffic and minimize the overall travel delay at the intersection.



Source: Federal Highway Administration (FHWA).

Figure 1. Graphic. Vehicles entering a signalized intersection with adaptive settings.

Vehicles may also receive signal phase and timing (SPaT) inputs from the traffic signals connected to the RSU once in range.(3) SPaT inputs communicate to the vehicle current and future phases and intervals for the traffic light and how much time remains for those intervals. 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 action will allow for smoother transitions through intersections, better flowing traffic patterns, fewer delays, less energy consumption, and less backward shock-wave propagation.(1)

BENEFITS TO TRANSPORTATION[1]

Improve Energy Efficiency

The smoothed vehicle trajectories minimize, and possibly eliminate, speed fluctuations and stopping times, which, in turn, may **improve general fuel economy by up to 30 percent**. Less stop-and-go traffic would also contribute to smoother driving experiences.

Improve Travel Delays

With the optimized signal timing plan and reduced stop-and-go traffic at signalized intersections, road users could experience **up to 65 percent less stop time during travel and shorter commute times.**

Maintain Safety

In 2021, more than 42,000 people were killed in motor vehicle traffic crashes on U.S. roadways. With intersections being potentially unpredictable, CDA technology could reduce the chances of collisions, **improving road safety for all users with enhanced awareness.**

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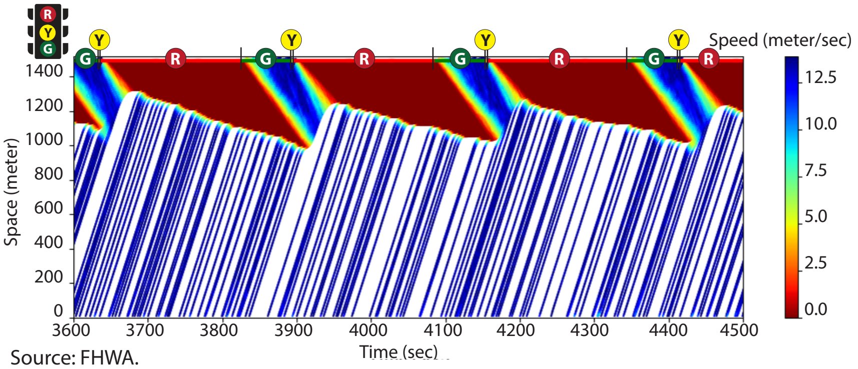
[1] From a report in progress: S. Soleimaniamiri, X. Li, H. Yao, A. Ghiasi, G. Vadakpat, P. Bujanovic, and T. Lochrane. *CARMA Proof-of-Concept TSMO Use Case 3 Algorithm*. Washington, DC: Federal Highway Administration.

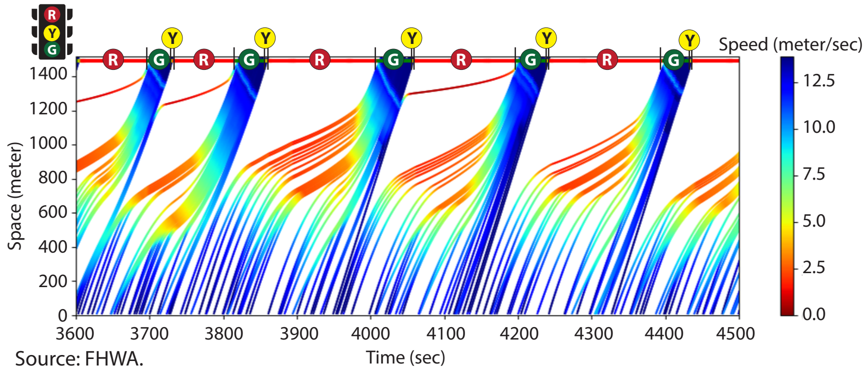
EVALUATION OF THE CONCEPT

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™.(4) In scenarios where vehicles and infrastructure are equipped with CDA technology, the objective of the experiment is to minimize travel delay at the intersection by optimizing the signal timing plan and to achieve smoother vehicle trajectories with relatively higher speed when the vehicle enters the intersection box. 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 adaptive traffic signals.



Source: FHWA.

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



Source: FHWA.

Figure 3. Graph. Trajectory of automation Level 3, cooperation Class D(4) vehicles as they approach an adaptive traffic signal over time.

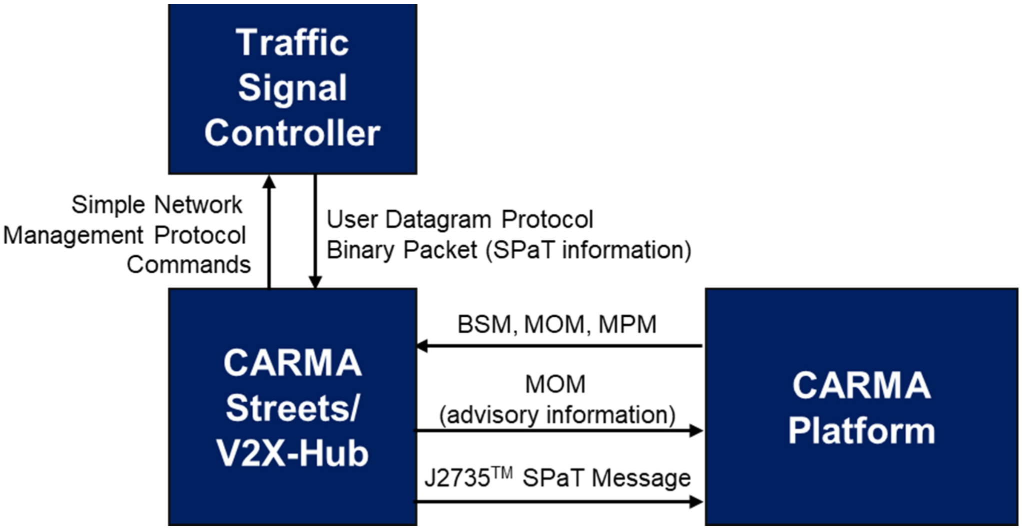
Figure 2 and figure 3 depict vehicle trajectories (space-time motion) for human-driven and CDA vehicles, respectively, in a selected lane. The optimal cycle length for the human-driven vehicle scenario was selected. The vertical axis represents space in meters, while the horizontal axis represents time 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 crucial observations. First, the optimized signal timing plan in the CDA vehicle scenario can efficiently allocate the intersection resources to the incoming traffic and eliminate the queue and backward shock-wave propagations at the intersection. Second, 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 D(4) 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. This feature ultimately enhances the travel experience and reduces traffic time for a vehicle navigating a signalized intersection.(4)

After conducting traffic simulation studies, the team performed several levels of proof-of-concept (PoC) testing with full-sized FHWA vehicles and infrastructure equipped with CDA on controlled test tracks. The testing included three groups of scenarios with different numbers of FHWA vehicles and initialization conditions. Traffic signal configuration, vehicle placement, and maximum vehicle speed were modified for each test case to evaluate and test the proposed framework and algorithms. The research team designed tests to assess various operational aspects, including communication, safety, mobility, and the smoothness of vehicle trajectories. All testing took place at the Turner-Fairbank Highway Research Center and evaluated the system performance for critical edge case scenarios, such as multiple vehicles simultaneously approaching an intersection and competing to receive a green light interval. After several initial testing rounds to verify the implemented algorithms, the U.S. Department of Transportation Volpe National Transportation Center led additional testing rounds to validate the algorithms and the findings, helping set a foundation for further research and development.

USE CASE ARCHITECTURE

While the algorithms were developed and simulations were conducted for all different CDA cooperation classes defined in SAE International J3216,(4) the implementation of this use case on the CARMA$^{SM(5)}$ ecosystem focuses solely on cooperation Class D.(4) The components of the CARMA ecosystem used in this cooperation class include CARMA Platform^{SM},(6) CARMA Streets^{SM},(7) and the Vehicle-to-Everything (V2X) Hub.(8) Figure 4 provides a look at how each aspect of CARMA infrastructure works together. In this architecture, vehicles are equipped with CARMA Platform and share status information via the RSU(1) using the basic safety message (BSM) and customized mobility operations messages (MOM) and mobility path messages (MPM). CARMA Streets and the V2X Hub reside within the infrastructure and are jointly responsible for processing the information received from vehicles. These systems estimate the time vehicles can enter the intersection box and optimize the signal timing plan. CARMA Streets also communicates with the traffic signal controller to manipulate the signal timing plan and broadcasts SPaT and advisory messages to vehicles.(3) CARMA Platform then controls the vehicle trajectory accordingly to minimize stopping time and optimize vehicle energy and fuel efficiency.



Source: FHWA.

Figure 4. Graphic. CARMA design and architecture for adaptive traffic signal optimization use case for automation Level 3, cooperation Class D. (See references 3, 4, 5, 6, 7, 8, 9, and 10).

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 prioritization when optimizing the signal timing plan, 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.

STANDARDS

This technology meets the following standards as set by SAE International:

- SAE J3216_202107: *Taxonomy and Definitions for Terms Related to CDA for On-Road Motor Vehicles*.(4)
- SAE J3016_202104™: *Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles*.(11)
- SAE J2735_202007™: *Vehicle-to-Everything Communications Message Set Dictionary*.(10)

CONCLUSIONS

This test case proved the benefits of CDA application in signalized intersections with adaptive 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 areas:

Large-Scale Testing

Applying vehicle-to-vehicle communications in an adaptive traffic signal environment allows for higher scale deployments, which would result in increased confidence and reliability when quantifying individual 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 Situation

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

V2X HUB

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

CARMA PLATFORM

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

CARMA STREETS

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

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

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