# Cooperative Automation Research: CARMA Proof-of-Concept Transportation System Management and Operations Use Case 3—Traffic Signal Optimization with CDA at Signalized Intersections

PUBLICATION NO. FHWA-HRT-22-052

JANUARY 2022

U.S. Department of Transportation
**Federal Highway Administration**

Research, Development, and Technology
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# FOREWORD

CARMA℠ is an initiative led by the Federal Highway Administration (FHWA) to enable collaboration for research and development of cooperative driving automation (CDA). CDA enables communication between vehicles and roadside infrastructure devices to support coordinated movement, with the aim of improving the safety, traffic throughput, and energy efficiency of the transportation network.

In 2015 the Office of Operations Research and Development at FHWA developed a cooperative adaptive cruise control proof-of-concept prototype that was installed in five research vehicles. The CARMA Ecosystem further evolved through testing and integration. At the time of this writing, CARMA is advancing into automated driving systems (ADS) to support cooperative automation strategies for ADS-equipped vehicles. This project expands CARMA functionality to include transportation systems management and operations (TSMO) strategies on surface arterials with intersections. The intended audience for this report is CDA stakeholders such as system developers, analysts, researchers, and application developers.

This is the third in a series of four proof-of-concept reports exploring research and development for the basic TSMO use cases on arterials. This report focuses on the traffic signal optimization with CDA at signalized intersections use case.

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Recommended Citation: Federal Highway Administration, *FHWA Cooperative Automation Research: CARMA Proof-of-Concept Transportation System Management and Operations Use Case 3—Traffic Signal Optimization with CDA at Signalized Intersections* (Washington, DC: 2022) https://doi.org/10.21949/1521854.

# TECHNICAL REPORT DOCUMENTATION PAGE

| 1. Report No.<br>FHWA-HRT-22-052 | 2. Government Accession No. | 3. Recipient's Catalog No. |
|---|---|---|
| 4. Title and Subtitle<br>FHWA Cooperative Automation Research: CARMA Proof-of-Concept Transportation System Management and Operations Use Case 3—traffic signal optimization with CDA at signalized intersections | | 5. Report Date<br>January 2022<br>6. Performing Organization Code |
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| 9. Performing Organization Name and Address<br>Leidos, Inc.<br>11251 Roger Bacon Drive<br>Reston, VA 20190 | University of South Florida<br>4202 E. Fowler Ave.<br>Tampa, FL 33620 | 10. Work Unit No.(TRAIS)<br>11. Contract or Grant No.<br>DTFH6116D00030L (TO 19-360) |
| 12. Sponsoring Agency Name and Address<br>U.S. Department of Transportation<br>Federal Highway Administration<br>1200 New Jersey Avenue, SE<br>Washington, DC 20590 | | 13. Type of Report and Period Covered<br>Final Report; May 2021<br>14. Sponsoring Agency Code<br>HRSO |

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16. Abstract
Cooperative driving automation (CDA) aims to improve the safety, traffic throughput, and energy efficiency of the transportation network by allowing vehicles and infrastructure to work together to coordinate movement. The objective of this project is to advance the CARMA℠ ecosystem and its capabilities by enhancing CDA participants' interaction with road infrastructure, infrastructure performance, network efficiency, and the flow of traffic. The focus of this concept of operations is on transportation systems management and operations (TSMO) use case 3 (UC), which investigates traffic signal optimization (SO) with CDA at signalized intersections. The proposed approach for TSMO UC3 has three main components: SO (designed for roadside equipment (RSE) and CARMA Platform℠), critical time step estimation (designed for RSE), and trajectory smoothing for cooperative automated driving system-equipped vehicles (designed for CARMA Platform). The proposed control component will increase traffic throughput and reduce energy consumption of vehicles while ensuring safety at signalized intersections and optimizing the signal settings.

| 17. Key Words | 18. Distribution Statement |
|---|---|
| C–ADS-equipped vehicles; signalized intersection; cooperative driving automation (CDA); CARMA 3; trajectory smoothing; trajectory planning; trajectory control; signal optimization; critical time step estimation | No restrictions. This document is available to the public through the National Technical Information Service, Springfield, VA 22161. http://www.ntis.gov. |

| 19. Security Classif.(of this report) | 20. Security Classif.(of this page) | 21. No. of Pages | 22. Price |
|---|---|---|---|
| Unclassified | Unclassified | 65 | n/a |

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

| SI* (MODERN METRIC) CONVERSION FACTORS | | | | |
|---|---|---|---|---|
| **APPROXIMATE CONVERSIONS TO SI UNITS** | | | | |
| **Symbol** | **When You Know** | **Multiply By** | **To Find** | **Symbol** |
| | | **LENGTH** | | |
| in | inches | 25.4 | millimeters | mm |
| ft | feet | 0.305 | meters | m |
| yd | yards | 0.914 | meters | m |
| mi | miles | 1.61 | kilometers | km |
| | | **AREA** | | |
| $in^2$ | square inches | 645.2 | square millimeters | $mm^2$ |
| $ft^2$ | square feet | 0.093 | square meters | $m^2$ |
| $yd^2$ | square yard | 0.836 | square meters | $m^2$ |
| ac | acres | 0.405 | hectares | ha |
| $mi^2$ | square miles | 2.59 | square kilometers | $km^2$ |
| | | **VOLUME** | | |
| fl oz | fluid ounces | 29.57 | milliliters | mL |
| gal | gallons | 3.785 | liters | L |
| $ft^3$ | cubic feet | 0.028 | cubic meters | $m^3$ |
| $yd^3$ | cubic yards | 0.765 | cubic meters | $m^3$ |
| | | **NOTE**: volumes greater than 1,000 L shall be shown in $m^3$ | | |
| | | **MASS** | | |
| oz | ounces | 28.35 | grams | g |
| lb | pounds | 0.454 | kilograms | kg |
| T | short tons (2,000 lb) | 0.907 | megagrams (or "metric ton") | Mg (or "t") |
| | | **TEMPERATURE (exact degrees)** | | |
| °F | Fahrenheit | 5 (F-32)/9 or (F-32)/1.8 | Celsius | °C |
| | | **ILLUMINATION** | | |
| fc | foot-candles | 10.76 | lux | lx |
| fl | foot-Lamberts | 3.426 | candela/$m^2$ | cd/$m^2$ |
| | | **FORCE and PRESSURE or STRESS** | | |
| lbf | poundforce | 4.45 | newtons | N |
| lbf/$in^2$ | poundforce per square inch | 6.89 | kilopascals | kPa |
| **APPROXIMATE CONVERSIONS FROM SI UNITS** | | | | |
| **Symbol** | **When You Know** | **Multiply By** | **To Find** | **Symbol** |
| | | **LENGTH** | | |
| mm | millimeters | 0.039 | inches | in |
| m | meters | 3.28 | feet | ft |
| m | meters | 1.09 | yards | yd |
| km | kilometers | 0.621 | miles | mi |
| | | **AREA** | | |
| $mm^2$ | square millimeters | 0.0016 | square inches | $in^2$ |
| $m^2$ | square meters | 10.764 | square feet | $ft^2$ |
| $m^2$ | square meters | 1.195 | square yards | $yd^2$ |
| ha | hectares | 2.47 | acres | ac |
| $km^2$ | square kilometers | 0.386 | square miles | $mi^2$ |
| | | **VOLUME** | | |
| mL | milliliters | 0.034 | fluid ounces | fl oz |
| L | liters | 0.264 | gallons | gal |
| $m^3$ | cubic meters | 35.314 | cubic feet | $ft^3$ |
| $m^3$ | cubic meters | 1.307 | cubic yards | $yd^3$ |
| | | **MASS** | | |
| g | grams | 0.035 | ounces | oz |
| kg | kilograms | 2.202 | pounds | lb |
| Mg (or "t") | megagrams (or "metric ton") | 1.103 | short tons (2,000 lb) | T |
| | | **TEMPERATURE (exact degrees)** | | |
| °C | Celsius | 1.8C+32 | Fahrenheit | °F |
| | | **ILLUMINATION** | | |
| lx | lux | 0.0929 | foot-candles | fc |
| cd/$m^2$ | candela/m2 | 0.2919 | foot-Lamberts | fl |
| | | **FORCE and PRESSURE or STRESS** | | |
| N | newtons | 2.225 | poundforce | lbf |
| kPa | kilopascals | 0.145 | poundforce per square inch | lbf/$in^2$ |

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

## TABLE OF CONTENTS

# LIST OF FIGURES

## LIST OF TABLES

## LIST OF ACRONYMS

| | |
|---|---|
| ADS | automated driving system |
| CACC | cooperative adaptive cruise control |
| C–ADS | cooperative automated driving system |
| CDA | cooperative driving automation |
| ConOps | concept of operations |
| CTSE | critical time step estimation |
| C–V2X | cellular vehicle-to-everything |
| DDT | dynamic driving task |
| DSRC | dedicated short-range communication |
| DV | discharging vehicle |
| EET | earliest entering time |
| ET | entering time |
| EV | entering vehicle |
| FHWA | Federal Highway Administration |
| GHG | greenhouse gas |
| HRSO | Office of Safety and Operations Research and Development |
| Hz | hertz |
| I2V | infrastructure-to-vehicle |
| ID | identifier |
| IHP | Integrated Highway Prototype |
| IICS | isolated intersection traffic control |
| IOO | infrastructure owner and operator |
| MPC | model predictive control |
| OBU | onboard unit |
| PID | proportional-integral-derivative |
| RSE | roadside equipment |
| SO | signal optimization |
| SPaT | signal phase and timing |
| STOL | Saxton Transportation Operations Laboratory |
| TBD | to be decided |
| TS | trajectory smoothing |
| TSMO | transportation systems management and operations |
| UC | use case |
| V2I | vehicle-to-infrastructure |
| V2V | vehicle-to-vehicle |

# CHAPTER 1. SCOPE AND SUMMARY

## IDENTIFICATION

This document serves as a concept of operations (ConOps) for a transportation systems management and operations (TSMO) use case (UC) on arterials. The document is focused on traffic signal optimization with cooperative driving automation (CDA) at signalized intersections.

## DOCUMENT OVERVIEW

### Background

The Office of Safety and Operations Research and Development (HRSO) performs transportation operations research and development for the Federal Highway Administration (FHWA). Onsite research and development are conducted at the Saxton Transportation Operations Laboratory (STOL), located at the Turner-Fairbank Highway Research Center. HRSO conducts operations research and development based on the national transportation needs of the United States.

In 2015, HRSO designed, built, and installed a cooperative adaptive cruise control (CACC) proof-of-concept prototype system in a fleet of five research vehicles. The CACC system was built on the CARMA Platform℠ as an advancement of standard adaptive cruise control systems, utilizing vehicle-to-vehicle (V2V) dedicated short-range communications (DSRC) to automatically synchronize the longitudinal movements of many vehicles within a string. This proof-of-concept system was the first in the United States to demonstrate the capabilities of this technology with a five-vehicle CACC string.

A subsequent task order was created to develop a new reference platform, CARMA℠ 2, using the Robot Operating System™ to enable research capabilities to be easily shared and integrated into industry research vehicles. The project advanced the CACC functionality and developed a proof-of-concept platooning application that enabled leader-follower behavior and allowed vehicles to begin to negotiate with one another. The project also developed the Integrated Highway Prototype (IHP), which integrated speed harmonization, lane change/merge, and platooning into one trip. This research focused on developing understanding of negotiations between entities, and how these negotiations can be achieved efficiently to help improve traffic flow based on cooperative tactical maneuvers.

A task order underway at the time of this writing is producing the third iteration of CARMA. CARMA 3 is currently advancing into automated driving systems (ADS), first to the SAE International Level 3 (conditional driving automation) and then to full automation. The approach takes advantage of an open-source ADS platform, Autoware®, to enable ADS functionality to be used for cooperative automation strategies.

Along with those projects, CARMA Cloud℠, CARMA Messenger℠, and CARMA Streets℠ are also being developed. CARMA Cloud is the part of CDA where vehicles and other entities may communicate with infrastructure to increase the safety and efficiency of the transportation network. CARMA Messenger enables moving, but not automated, entities (e.g., first-responder vehicles, pedestrians, and buses) to communicate with CARMA-equipped vehicles and infrastructure to improve the performance of the network. CARMA Streets enables vehicles to communicate with the infrastructure at intersections and provides an interface to the traffic signal controller to optimize travel through an intersection. As open-source software, all CARMA components (i.e., platform, cloud, messenger, and streets) are being developed to benefit universities and other organizations conducting CDA research.

The various projects associated with this development are listed in table 1 for reference.

**Table 1. Projects associated with this development effort.**

| Task Order | Product | Title |
|---|---|---|
| STOL I T-13005 | CARMA | Development of a Platform Technology for Automated Vehicle Research |
| STOL II 0013 | CARMA2 | Development of Connected and Automated Vehicle Capabilities: Integrated Prototype I |
| STOL II 693JJ318F000225 | CARMA3 | Development of Cooperative Automation Capabilities: Integrated Prototype II |
| STOL II 693JJ319F000369 | CARMA IHP2 | Cooperative Automation Research: CARMA IHP II |

IHP: Integrated Highway Prototype; STOL: Saxton Transportation Operations Laboratory.

## Objective

This project, Cooperative Automation Research: CARMA Proof-of-Concept Transportation System Management and Operations Use Case Testing, will extend the research from prototype II by enhancing the CARMA Platform to enable further capabilities of CDA participants to interact with the road infrastructure. All TSMO UCs under this project consider CDA operations at at-grade intersections. The UC discussed in this document, TSMO UC 3, focuses on incorporating traffic signal optimization (SO) with cooperative automated driving system-(C-ADS) equipped vehicle trajectory optimization at signalized intersections. This project aims to tactically address three high-level objectives: reduce traffic congestion, improve energy efficiency, and increase infrastructure efficiency. This project investigates to what extent these objectives can be achieved for different CDA cooperation classes as given by the SAE J3216™ standard. External partners, such as universities and private companies, will support this project's product development, testing, and demonstrations.

### *Transportation System Management and Operations Arterial Use Cases*

- Use Case 1—Vehicle coordination and trajectory optimization: stop-controlled intersections.
- Use Case 2—Trajectory optimization: fixed-time and actuated signals.
- Use Case 3—Signal phase and timing (SPaT) plan and trajectory optimization: adaptive traffic signals.

- Use Case 4—Dynamic lane assignment integrated with SPaT plan and trajectory optimization: active traffic management.

**Audience**

The intended audience for this document includes:

- U.S. Department of Transportation and CDA stakeholders, such as program managers, assistant managers, research engineers, and transportation technology specialists.
- System developers who will create and support CDA algorithms based on the system concepts described in this document.
- Analysts, researchers, and CDA application developers.

**Document Structure**

The structure of this document is generally consistent with the outline of a system operational concept document described in "Annex A" of ISO/IEC/IEEE Standard 29148:2011.[(1)] A document conforming to this content structure is called a ConOps in U.S. transportation systems engineering practice, and that title is applied to this document. Some sections include more detailed content than in a standard ConOps, and, as a result, some section titles may have been modified. The structure of this document is as follows:

- Chapter 1 defines the scope of the ConOps.
- Chapter 2 describes the current situation and identifies the need for changes with respect to processes and systems to be affected by the ConOps.
- Chapter 3 describes the concept for the new TSMO UC3 system capabilities and their operations and presents detailed descriptions of operational concepts.
- Chapter 4 describes operational scenarios of TSMO UC3 at signalized intersections.
- Chapter 5 provides an analysis of the expected improvements, operational and research impacts, validation plans, disadvantages, and limitations.
- References provides a list of reference documents.

# CHAPTER 2. CURRENT SITUATION AND OPPORTUNITIES FOR CHANGES

This chapter discusses the existing approaches toward congestion and energy consumption mitigation at signalized intersections. Also, this chapter examines the current application of CDA technologies that reduce traffic congestion at signalized intersections. Some of the advantages and disadvantages of the existing solutions are highlighted. Current CDA issues are spurring the development of new solutions to congestion and energy problems.

## BACKGROUND AND CURRENT SITUATION

Through the roadway network, various roadway facilities intersect to provide accessibility to commuters, causing conflicts of vehicles from various movement traffic streams. Inappropriate operations of a conflict area (e.g., signalized/unsignalized intersections and merging roadways) result in unstable traffic flow (i.e., stop-and-go traffic) that may exacerbate travel delay, energy consumption and emissions, driving discomfort, and safety risks. Fortunately, operations of conflict movements at a common conflict area may completely change with the advent of CDA technology. C–ADS-equipped vehicles have the needed communication and automation technologies that allow them to coordinate with each other and with infrastructure to maximize safety and network efficiency; C–ADS are part of a connected ecosystem that relies on V2V, vehicle-to-infrastructure (V2I), and infrastructure-to-vehicle (I2V) communications. V2V, V2I, and I2V all have a role in helping to improve the transportation network. For example, facilities at a common conflict area can be equipped with traffic sensors and communication networks (e.g., DSRC systems) to help support C–ADS-equipped vehicle coordination.

Such a connected ecosystem, combined with the current level of vehicle automation, provides an opportunity for incremental, traffic-flow improvements at a common conflict area that may produce widespread mobility, safety, and environmental benefits. With these emerging technologies, the passing sequence of C–ADS-equipped vehicles at an intersection can be further improved with proper coordination (e.g., allowing movements without conflict to take place simultaneously at an intersection instead of only allowing one vehicle to proceed at the intersection at a time) to increase traffic throughput.

Furthermore, C–ADS-equipped vehicles can be aware of downstream traffic and the conflict area's conditions and approximately determine the time that the vehicles can enter the conflict area. As a result, vehicle speeds can be smoothed/optimized so that stop-and-go traffic and backward shock-wave propagation are reduced/eliminated. Smoothed/optimized speeds would also create a reduction in energy consumption, harmful emissions, and crashes. At signalized intersections, such an improvement becomes even more significant since vehicles must come to one or multiple complete stops before passing the intersection at red-signal indications, creating unstable stop-and-go traffic.

Among the various CDA applications related to conflict areas, developing control strategies near signalized intersections has received increasing attention due to its ability to communicate with traffic signal controllers and receive real-time SPaT information. These control strategies usually have two aspects. First, the traffic signal-timing plan can be optimized to efficiently serve different traffic approaches, per their demands. Second, C–ADS-equipped vehicles can be controlled to simultaneously smooth their trajectories (i.e., the paths that vehicles follow in space as a function of time) to minimize fuel consumption, driving discomfort, and travel delay.

Several studies have been conducted on these two aspects. On the traffic signal side, several studies aim to optimize the signal-timing plan to improve traffic efficiency. (See references 2, 3, 4, 5, 6, and 7.) On the trajectory control side, a centralized control scheme and a decentralized control scheme are proposed to minimize speed/acceleration variations, reduce travel delay, and increase energy efficiency. (See references 8, 9, 10, 11, 12, and 13.) In the centralized control scheme, a single central controller makes decisions in a global manner for all vehicles. In the decentralized control scheme, each vehicle is treated as an autonomous agent that determines its own operations based on the information sensed or received from other vehicles and roadside equipment (RSE) to maximize its own performance. Additionally, another class of studies integrates traffic SO and vehicle trajectory optimization at signalized intersections simultaneously. (See references 14, 15, 16, and 17.) Despite these breakthroughs, due to the complex nature of trajectory optimization problems and the added complexity from signal timing, existing studies on joint optimization problems either optimize only a single vehicle trajectory without considering multivehicle interactions or use only numerical approaches (e.g., mathematical programming or computer simulation) that require substantial computational resources (even without guarantees of the solution optimality). Neither of these options is suitable for real-time applications. This issue may prevent applying these proposed methods to real-time applications and compromise their scalability to address network-level traffic control.

Only a few studies have conducted field experiments with real C–ADS-equipped vehicles, mostly focusing on controlling vehicle trajectories through an intersection. For instance, Wang et al. developed a connected eco-driving system and equipped it on a heavy-duty diesel truck using cellular-based wireless communications.[(18)] Field trials were conducted in the city of Carson, California, along two corridors with six connected signalized intersections that can communicate their SPaT information. Ma et al. tested and verified a set of newly developed algorithms on an innovative CDA platform and quantified the fuel-saving benefits of the eco-drive.[(19)] Furthermore, the project Integrated Prototype I developed the Glidepath Prototype System, which developed, demonstrated, and evaluated a partially automated vehicle system with an eco-approach and departure feature.[(20)] Omidvar et al. deployed an intelligent real-time isolated intersection traffic control (IICS) system at the Traffic Engineering and Research Laboratory, the Florida Department of Transportation's closed-course facility.[(21)] A mixed-traffic scenario consisting of one SAE International Level 4 autonomous vehicle, three V2I DSRC-equipped connected vehicles, and two regular human-driven vehicles was utilized to test the performance of the joint optimization of traffic signal and vehicle trajectories under low-traffic demand scenarios. While these real-world field experiments provided impactful insights into CDA operations at signalized intersections, the scenarios investigated in these experiments are limited. Most of these studies solely focused on the C–ADS-equipped vehicle trajectory optimization, except the IICS system, which considered the incorporation of traffic SO and C–ADS-equipped vehicle trajectory optimization. The IICS system, however, only investigated a single CDA operation at signalized intersections under the low-traffic demand scenario.

## OPPORTUNITIES FOR CHANGES

Although the existing studies bring advantageous insights into CDA operations at intersections, they face some challenges that can be further addressed. For instance, most of the existing studies applied either decentralized or centralized control. On the one hand, while the short communication range required by decentralized control suits real-time applications, the self-selective nature of this control approach prevents the system from achieving the maximum benefit of CDA operations. On the other hand, although these centralized control studies bring advantageous insights into CDA operations at signalized intersections, these control schemes put all computational burden on one or few centralized unit(s) that may substantially increase operational complexity and associated risks and liabilities in real-time applications. These operational complexities and associated risks and liabilities for traffic operators can be reduced by applying a cooperative control framework that focuses the infrastructure system only on key high-level scheduling decisions while leaving complex low-level trajectory control and collision avoidance to individual C–ADS-equipped vehicles in a decentralized manner. Such a cooperative control framework can also distribute the computational burden among different entities in an edging-computing structure, making the framework much more suitable for real-time applications.

Furthermore, all these existing studies have simple assumptions of cooperation behaviors (e.g., assume all vehicles accept and follow a prescriptive plan), while the cooperation capabilities of C–ADS-equipped vehicles might not always be the same. SAE International already standardized how cooperation between vehicles should be regarded. Similar to the levels of automation defined in SAE J3016™, the new standard, SAE J3216, defines classes of cooperation.(22) The classes address different capabilities of a C–ADS-equipped vehicle that would affect its ability to cooperate with other CDA participants (e.g., vehicles and infrastructure). Table 2 summarizes the cooperation classes. Table 3 shows the opportunities CDA technology provides by depicting examples of CDA features related to cooperative traffic signals at intersections based on different cooperation classes. Some of these examples are taken from the SAE J3216 standard. Therefore, the need for investigating the effects of different cooperation classes defined in SAE J3216 remains unaddressed.

**Table 2. Overview of SAE International cooperation classes and automation levels.**

| No Automation | | Partial Automation of DDT | | | Complete Automation of DDT | | |
|---|---|---|---|---|---|---|---|
| | | Level 0: No Driving Automation (human does all driving) | Level 1: Driver Assistance (longitudinal or lateral vehicle motion control) | Level 2: Partial Driving Automation (longitudinal and lateral vehicle motion control) | Level 3: Conditional Driving Automation | Level 4: High Driving Automation | Level 5: Full Driving Automation |
| **No Cooperative Automation** | | E.g., signage, TCD | Relies on driver to complete DDT and supervise feature performance in real time | | Relies on ADS to complete DDT under defined conditions (fallback condition performance varies between levels) | | |
| **SAE class A: Status Sharing** | **Here I am, and what I see** | E.g., brake lights, traffic signal | Potential for improved object and event detection[*] | | Potential for improved object and event detection[**] | | |
| **SAE class B: Intent Sharing** | **This is what I plan to do** | E.g., turn signal, merge | Potential for improved object and event prediction[*] | | Potential for improved object and event prediction[**] | | |
| **SAE class C: Agreement Seeking** | **Let's do this together** | E.g., hand signals, merge | N/A | | C–ADS designed to attain mutual goals through coordinated actions | | |
| **SAE class D: Prescriptive** | **I will do as directed** | E.g., hand signals, lane assignment by officials | N/A | | C–ADS designed to accept and adhere to a command | | |



[*] = improved object and event detection prediction through CDA class A and B status and intent sharing may not always be realized, given that level 1 and 2 driving automation features may be overridden by the driver at any time, and otherwise have limited sensing capabilities compared with level 3, 4, and 5 ADS-operated vehicles. [**] = class A and B communications are one of many inputs to an ADS's object and event detection and prediction capability, which may not be improved by the CDA message. ADS = automated driving system; C–ADS = cooperative automated driving system; DDT = dynamic driving task; N/A = not applicable.

**Table 3. Examples of cooperative signalized intersection features.**

| Feature | Class of CDA | CDA Device Transmission Mode and Directionality | Information Exchanged | Level of Functionality |
|---|---|---|---|---|
| Signal priority | A) Status sharing | One way: C–ADS-equipped vehicles → RSE | Vehicle location, speed, and priority status (e.g., emergency vehicles) | Enabling signal-timing changes based on the approaching vehicle. |
| Eco-approach and departure | A) Status sharing<br>B) Intent sharing | One way: RSE→ C–ADS-equipped vehicles | SPaT messages | Enabling C–ADS-equipped vehicles to plan their motions based on the future signal phase that would otherwise be unavailable. |
| Tandem approach and departure | C) Agreement seeking | Two way:<br>1) C–ADS-equipped vehicles → RSE<br>2) RSE → C–ADS-equipped vehicles<br>3) C–ADS-equipped vehicles → C–ADS-equipped vehicles | 1) SPaT messages<br>2) Velocity profile<br>3) Negotiations results | Enabling SPaT changes based on the approaching vehicle.<br><br>Enabling C–ADS-equipped vehicles to plan their motions and optimize their velocity based on the future (and possibly optimized) signal phases and the status of the other vehicle.<br><br>Supporting more efficient motion plans with increased reliability and look-ahead distance to reduce energy consumption and emissions. |

Note: In practice, one-way transmission will typically send the message to multiple CDA devices in the vicinity. C–ADS = cooperative automated driving system; CDA = cooperative driving automation; RSE = roadside equipment; SPaT = signal phase and timing.

To fill the existing research gaps, this ConOps proposes an edge-computing-based cooperative control framework for C–ADS-equipped vehicles at a signalized intersection in the TSMO context. This ConOps serves as part of the CARMA framework and distinguishes between the levels of vehicle automation and classes of vehicle cooperation.

## TRANSPORTATION SYSTEMS MANAGEMENT AND OPERATIONS STAKEHOLDERS

Stakeholders are entities whose actions influence travel in the transportation environment; these stakeholders may include transportation users engaged in travel on publicly accessible roadways, emergency responders, and infrastructure owners and operators (IOOs). This section identifies two types of TSMO stakeholders—transportation users and IOOs—and their corresponding needs.

### Transportation Users

A transportation user is a traffic participant on or adjacent to an active roadway for the purpose of traveling from one location to another. For TSMO, motorized vehicles—human driven or automated—are the main users of traffic systems at intersections. The general needs of transportation users include the following:

- Smooth, low-stress, and fast travel.
- Reliable travel times.
- Energy-efficient and safe trips.
- Accurate information to help transportation users make optimal decisions about driving tasks (decision support systems).

The following benefits will also be supported and enhanced by integrating CDA technology into TSMO from the transportation users' perspective:

- Smoother, faster, and lower stress travel—Controlling C–ADS-equipped vehicle trajectories at signalized intersections can increase the throughput of intersections as well as reduce the friction and energy consumption in traffic flow by improving vehicle-following stability.

- Greater operational efficiency and travel-time reliability—Controlling vehicle trajectories based on the optimized SPaT can substantially reduce travel delay and uncertainty in travel times by increasing departure speed, smoothing traffic, and enabling real-time prediction of travel times.

- Improved traffic safety—Reducing crashes is one of the most significant potential benefits of CDA technology. The National Highway Traffic Safety Administration estimates that the combined use of V2V and V2I communications has the potential to significantly reduce unimpaired driver crashes.(23) Furthermore, smoothed vehicle trajectories with proper trajectory control reduce the risks and severity of rear-end collisions.

- More productive travel experience—Overall travel experience can be improved through various CDA features, such as SO and trajectory smoothing (TS). Improvements include, but are not limited to, the elimination of stop-and-go movements, reduction in travel delay and energy consumption, and improvement of travel-time reliability.

Table 4 identifies four categories of transportation users and defines the characteristics and needs of each category.

**Table 4. Transportation user characteristics and needs.**

| Driver | Transportation User Categories | User Characteristics and Needs |
|---|---|---|
| Human driving | Regular human driver | Regular human drivers have neither connectivity nor automation capability and have uncertain driver behavior.<br>Needs alignment with general transportation user needs as defined. |
| Human driving | Connected human driver | Connected human drivers receive additional traveler information and can make better informed travel decisions.<br>Needs alignment with general transportation user needs as defined. |
| Automated driving | Nonconnected ADS-equipped vehicle | Nonconnected ADS-equipped vehicles operate independently, relying on local sensor information and automated control software and usually have conservative behavior to provide increased comfort and safety margin.<br>Needs include accurately sensing local traffic conditions and actuating control of vehicles to ensure safety and travel efficiency. |
| Automated driving | C–ADS-equipped vehicle | Compared with ADS-equipped vehicles, C–ADS-equipped vehicles partner with other CDA participants in the traffic stream to improve overall traffic performance.<br>Needs include availability of other vehicles to perform cooperative actions, improving overall system safety and efficiency while guaranteeing individual vehicle travel experiences. |

ADS = automated driving system; C–ADS = cooperative automated driving system; CDA = cooperative driving automation.

### Infrastructure Owners and Operators

IOOs are traffic participants who provide, operate, and maintain roadways and supporting infrastructure for transportation users. These traffic participants include public, public-private, or private-sector entities that operate in accordance with applicable laws at the Federal, State, and/or local level.

Broadly speaking, the goal of IOOs is safe and efficient traffic management, which consists of monitoring and managing traffic as well as the factors affecting traffic flow (i.e., incidents, weather, intersections, and the dissemination of routing information). The goals of IOOs may therefore include:

- Reducing recurring congestion.
- Improving transportation reliability and safety.
- Reducing travel time as well as fuel consumption and emission.
- Maintaining and increasing the use of alternative and emerging transportation modes (e.g., car-sharing options; connected and automated vehicles are considered a separate mode by travelers, according to a recent survey).(24)

TSMO can provide the following benefits for IOOs:

- Faster realization of efficiency goals—Early adoption of CDA at existing intersections allows the operator to improve congestion management to increase throughput, enhance safety, and improve driver experience. These benefits will increase as the fraction of C–ADS-equipped vehicles using the intersection, as compared with the total number of users, increases.

- Maximized resource utilization for more efficient solutions—Traditional approaches to managing congestion, such as capacity expansion, are increasingly becoming obsolete both due to funding constraints as well as inherent limitations of these approaches in alleviating transportation problems. CDA technologies can be considered as operational strategies that offer the potential for innovative solutions to the hard problems of congestion and travel-time variability at intersections that continue to plague facilities.

- Gaining first-mover advantage—If operators that are currently primed to accommodate C–ADS-equipped vehicles on their facilities do not make the voluntary move to test and advance this technology, outside actors are likely to fill that role and dictate the direction of CDA technology development. This direction may or may not be in line with a specific agency's goals or organizational capacity.

- Organizational evolution to accommodate the future of mobility technology—Organizations that learn to respond to rapid technological change will be more likely to thrive in this era of rapid technological enhancement in the transportation field.

## JUSTIFICATION FOR AND NATURE OF CHANGES

The transportation industry is moving toward improving safety with ADS by enhancing various vehicle technologies (i.e., levels of automation and ubiquitous sensing using automated vehicle sensors). As more advanced sensing and computing capabilities are integrated with ADS, questions emerge around what changes need to be made to enable the deployment of CDA systems and what additional capabilities and possibilities can be expected. This section discusses the changes that need to be made.

### Organizational/Institutional Changes

The following organizational/institutional changes should be implemented to enable the deployment of CDA systems:

- Adopt a systems-engineering process approach—A systems-engineering process is important for developing operational scenarios to accommodate CDA applications on intersection facilities. A ConOps must be developed for the system (regional level) as well as for the corridor in question.

- Develop a performance management system—C–ADS-equipped vehicles should be aligned with agency performance standards and holistic data requirements so that transportation agencies can leverage data sources across the organization. A performance management system will collect and process relevant data to determine whether system goals and performance targets for all CDA applications and operational alternatives are being achieved.

- Develop a data collection and management system—This system will obtain all the relevant data in real time from the various vehicles, onboard sensors, wireless devices, RSE, roadway traffic sensors, weather systems, message boards, and other related systems. These data should be placed in, or be accessible from, a common data environment.

- Include rich, accurate data sources—Key data will come from a variety of sources and should include:

    - Real-time traffic data—Real-time traffic data include vehicle speed and location data collected and disseminated by vehicles as part of a connected system; they also include traditional detection sources (e.g., inductive loop detectors, overhead radar, and closed-circuit television cameras) that provide traffic data for the system.
    - Traffic signal plan data—Traffic signal plan data include the planned SPaT at signalized intersections from the signal.
    - Weather condition data—Infrastructure-based road weather information systems and third-party weather data feeds can supplement vehicle-acquired weather data.
    - Pavement condition data—In-pavement sensors can provide information on real-time pavement surface conditions (e.g., dry, wet, snowy, iced, and salted).
    - Crowdsourced data—Crowdsourced data platforms enable data collection from large installed user bases, supplementing data gathered from other sources.

    - Historical data—In addition to real-time data, historical data will be a key input to applications. Historical data can improve the accuracy of traffic analysis and the prediction of traffic conditions.

**Technical/Technological Changes**

The following technical/technological changes should be implemented to enable the deployment of CDA systems:

- Procure new hardware to support technology—Hardware enhancements include the following:
    - The infrastructures at intersections would need to be enhanced with the installation of DSRC (e.g., or another communication technology, such as cellular vehicle-to-everything (C–V2X)) and other hardware to support algorithms that enable CDA applications.
    - The vehicles that use the CDA system would need to be equipped with DSRC radios (e.g., onboard units (OBU) and vehicle-awareness devices), a camera, light detection and ranging, radar sensors, and the computational resources to implement the new control software.

- Develop/acquire new software—The application(s) should:
    - Make use of the frequently collected and rapidly disseminated multisource data drawn from connected travelers, vehicles, and infrastructure.
    - Include a vehicle-awareness application (e.g., an OBU that is installed either by the vehicle manufacturer or as an aftermarket integrated device), a personal wireless application (e.g., a smartphone or other handheld device), or another application capable of collecting, receiving, and disseminating needed CDA data.
    - Enable systems and algorithms that can generate traffic condition predictions, alternative scenarios, and solution evaluations in real time.
    - Contain microscopic and macroscopic traffic simulations.
    - Incorporate real-time and historical data.
    - Utilize traffic optimization models.
    - Encourage the constant evaluation, adjustment, and improvement of traffic optimization models, which requires an increase in computational capability as well as long-term storage of historical data.
    - Evolve and improve its algorithms and methods based on performance measurements.
    - Include DSRC (or another communication technology, such as C–V2X) and software elements that enable the developed CDA system to act upon the received information.

**Operational Policy Changes**

The operational policies of intersections are generally designed to accommodate traffic operations that meet the goals of operators. The key questions to ask to determine proper operational policies of intersections include:

- Who are the stakeholders and users of the CDA system?
- What are the elements and capabilities of the CDA system?
- Where are the affected CDA systems?
- When and where will activities be performed?
- Why are the strategies being used?
- How will the system be operated and maintained?
- How will the performance of the system be measured?

All stakeholders must have clear expectations and incentives to participate. Improved throughput and smoother travel experience are shared goals between IOOs and CDA applications. There also needs to be an agreement with users to set expectations, encourage investment, and measure performance.

**Facility Infrastructure Changes**

Facility infrastructure changes will depend upon the configuration and operations of the existing facility. Depending upon the type of facility and existing equipment, the following categories of facility infrastructure changes may be needed:

- I2V infrastructure (e.g., RSE) to transmit central information to all vehicles within the communication area; if unequipped vehicles are allowed, traditional dynamic message signs are used to convey public traveler information.
- Roadside sensors (e.g., video cameras, radars, or loop detectors) to detect or estimate real-time vehicle trajectories of unequipped vehicles upstream of intersections.
- Striping and pavement markings.
- Appropriate signage to convey relevant information to all drivers (for all types of users identified in table 4).

For early CDA deployment, infrastructure equipped with existing communication devices offers the opportunity to begin integrating CDA systems into traffic. Due to the enabled cooperation capabilities, even the presence of a small number of C–ADS-equipped vehicles can still significantly impact traffic operations at intersections and, therefore, improve system performance and the individual traveler's experience.

# CHAPTER 3. OPERATIONAL CONCEPT OF THE PROPOSED SYSTEM

This chapter details the operational concept of TSMO UC3. It describes how automated driving technology can be used in a cooperative manner beginning when CDA vehicles enter the communication area of signalized intersections with optimal signal settings to when they exit. This chapter also discusses the role of infrastructure in supporting and enabling automated driving technology to help manage the transportation system while addressing congestion, energy efficiency, and roadway safety during normal travel at arterials.

## TECHNOLOGICAL FRAMEWORK FOR TRANSPORTATION SYSTEMS MANAGEMENT AND OPERATIONS BASIC ARTERIAL TRAFFIC USE CASE

This section describes the algorithm framework of CDA applications for TSMO UC3. This framework focuses on a signalized intersection with an optimized signal setting formed by multilane approaches, as illustrated in figure 1. The proposed algorithm is developed for the fully connected and automated environment and works independently of the parameters associated with the intersection design (e.g., number of entry and exit lanes at each approach, free-flow speed of each approach, and lane width). Each lane of an entry approach at the intersection is assigned to only one movement group (i.e., through, left turn, and right turn). Therefore, the information regarding the current position and lane of a vehicle essentially determines the movement group of the vehicle. Also, no right turn is permitted at the red-signal indication (right-turn vehicles must wait for the traffic light to turn green before turning). Furthermore, the speed limit of each lane is determined based on its associated movement groups. All C–ADS-equipped vehicles will aim to pass the intersection box with a speed designed to maximize the throughput of the intersection.

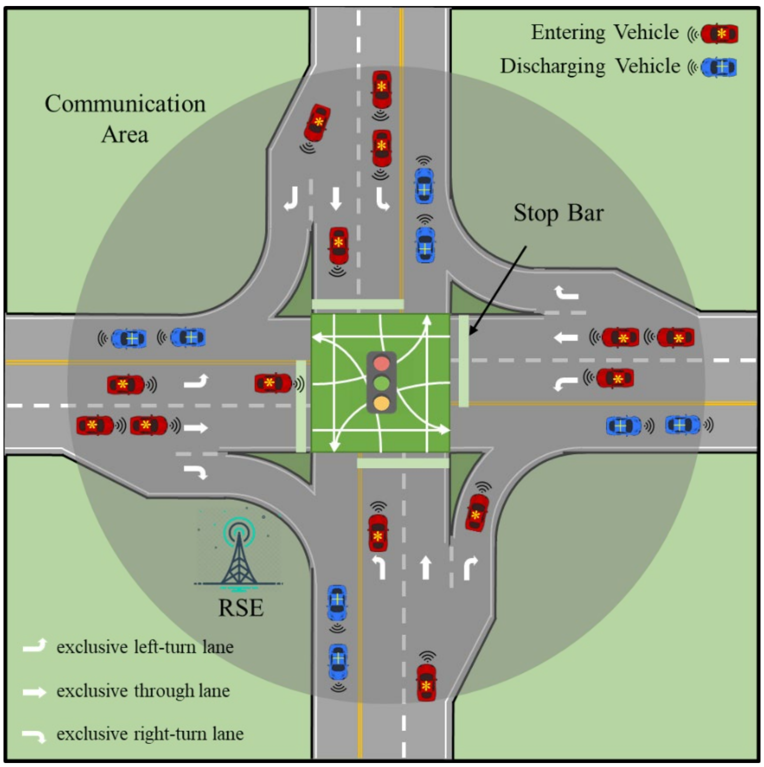
In this framework, all vehicles are assumed to be equipped with CDA technologies. The infrastructure at the intersection is assumed to be equipped with the necessary software and hardware that allow it to transmit information to, and receive information from, all vehicles. The communication area of the intersection is defined as the area around the intersection in which the infrastructure can communicate with vehicles. If needed, the communication area can be expanded by adding more RSE to relay the communications. Thus, all vehicles inside the communication area of the intersection can broadcast real-time information regarding their operational status (e.g., location, speed, acceleration, movement group, and vehicle type) and intents (e.g., entering time (ET) and speed to the intersection box) to infrastructure and surrounding vehicles (i.e., following and preceding vehicles). In addition, the infrastructure can assist the system by optimizing and transmitting the needed information (e.g., SPaT) to the vehicles. This section also discusses the performance of the proposed control mechanism for different CDA cooperation classes.

The TSMO UC3 first focuses on optimizing the SPaT plan at signalized intersections in real time based on the received real-time operational information from C–ADS-equipped vehicles. It then focuses on smoothing C–ADS-equipped vehicle trajectories with the available and optimized SPaT plan. The operational goal of this UC may be prioritized as follows:

- Safety: The primary goal of this algorithm is to maintain safety while traversing through a signalized intersection. The algorithm contains a set of stringent safety constraints that avoid potential crash risks and uncomfortably high accelerations and decelerations.

- Mobility: Within the feasible range allowed by the guaranteed safe and comfortable travel experience, the algorithm aims to maximize the throughput of signalized intersections by minimizing vehicles' ETs into the intersection box and maximizing their departure speeds.

- Energy efficiency: Within the feasible range allowed by the safety and mobility priorities, the algorithm seeks to smooth vehicle trajectories to minimize energy consumption as well as improve riding comfort.




Source: FHWA.

**Figure 1. Illustration. Four-way multilane signalized intersection.**

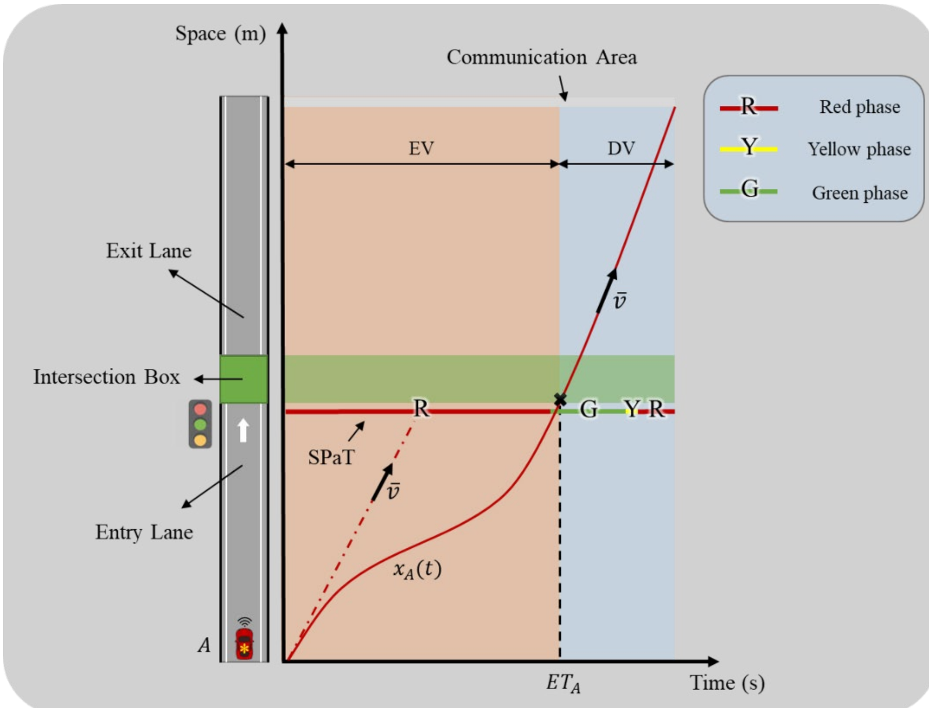
As illustrated by figure 1, at each time step in the control time horizon, two different states can be defined for vehicles inside the communication area:

- Entering vehicles (EV): Vehicles that are approaching the signalized intersection and have not yet entered the intersection box (shown as red vehicles with a star symbol in figure 1).

- Discharging vehicles (DV): Vehicles that have already entered or departed the intersection box (shown as blue vehicles with a plus symbol in figure 1).

A vehicle entering the communication area will initially join the EV set and begin transmitting information to RSE and other vehicles. The RSE will store this information and use it for optimizing the SPaT plan. The optimized SPaT plan will be shared with all C-ADS-equipped vehicles. During the SPaT plan optimization process, the RSE will estimate a desired ET for each C-ADS-equipped vehicle. Depending on the cooperation class of C–ADS-equipped vehicles, the RSE might also share the estimated desired ETs with vehicles. While the vehicle is traveling through its associated entry lane and approaching the intersection, it might decide a desired ET or receive it from the RSE. The vehicle will subsequently plan its trajectory to enter the intersection box at the desired ET at the speed limit or the highest speed allowed by safety constraints. Passing the intersection at the maximum possible speed improves the throughput of the intersection by reducing the time a vehicle occupies the intersection box. As soon as the vehicle enters the intersection box, it will be removed from the EV set and will be added to the DV list. Finally, the vehicle will be removed from the DV list as soon as it leaves the communication area. The vehicles are classified into these two different sets, as the algorithm might control different vehicle sets with different logic.

Figure 2 illustrates the state of transition of a vehicle. The focus of this algorithm is on an isolated intersection, which indicates that no bottleneck is considered at the end of the communication area. Also, DVs have already passed the intersection box and do not need to estimate any critical time step. Therefore, the proposed algorithm does not consider controlling DV trajectories, and DVs will simply follow their predefined car-following behavior. For controlling a corridor of intersections, DV trajectories might need to be controlled as well. In this case, depending on the communication ranges of the adjacent intersections, DVs of one intersection might simply be seen as EVs by another intersection. As a result, the proposed algorithm could handle a corridor of intersections.




Source: FHWA.
$ET_A$ = entering time of vehicle A.
$x_A(t)$ = trajectory of vehicle A.
$\bar{v}$ = maximum speed.

**Figure 2. Illustration. Vehicle state transition.**

The algorithm framework in this ConOps is designed to run on both vehicles and infrastructure (e.g., RSE). Therefore, RSE and all vehicles use a global clock (e.g., the Global Positioning System clock) to synchronize their movements. This way, vehicles can transmit their real-time information to and receive traffic signal information (e.g., current signal phase and optimized SPaT plan) and their desired operations from RSE more accurately. The proposed framework is a real-time application of CDA, and the algorithm will be run at each real-time time step.

The proposed cooperative framework has three main components: SO, critical time step estimation (CTSE), and TS. The SO component is designed to determine a proper departure sequence of vehicles and convert it to a SPaT plan with a centralized manner. The CTSE component is designed to estimate a desired ET for each vehicle, which is called either at each individual C–ADS-equipped vehicle in a decentralized manner (in cooperation classes A, B, and C) or at the RSE (in cooperation classes C and D) in a centralized manner. Then, the TS component is called at each C–ADS-equipped vehicle in a decentralized manner to control C–ADS-equipped vehicle trajectory based on the estimated ET. Such a cooperative-control framework can distribute the computational burden among different entities in an edge-computing structure, making the framework much more suitable for real-time applications.

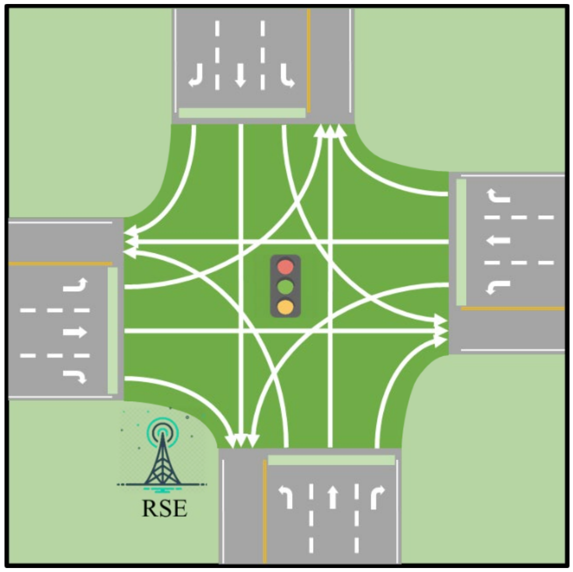
**Transportation System Management and Operations Use Case 3: Signal Phasing and timing Plan and Trajectory Optimization (Adaptive Traffic Signals)**

- UC3.1—SO: Determining a proper departure sequence of vehicles and converting it to a SPaT plan.
- UC3.2—CTSE: Estimating ETs to the intersection box for C–ADS-equipped vehicles based on the SPaT plan.
- UC3.3—TS: Smoothing C–ADS-equipped vehicle trajectories with the estimated ETs.

The components of the proposed cooperative framework are described in the following subsections.

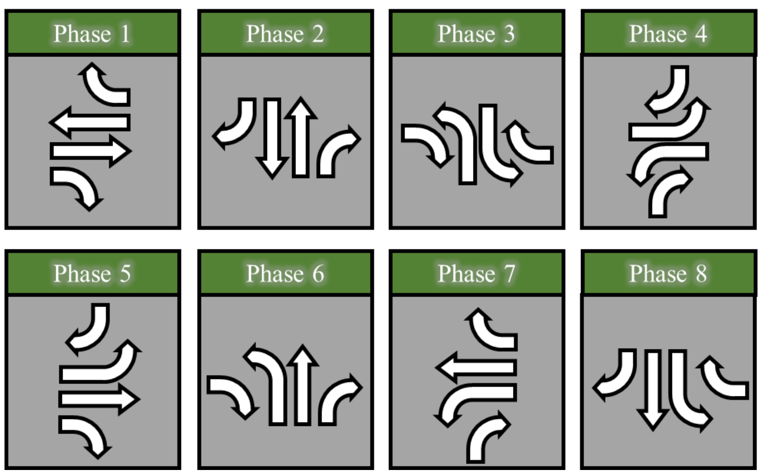
**Signal Optimization**

The SO component aims to properly allocate the intersection box to C-ADS-equipped vehicles from different traffic streams. This component is designed to run at the intersection RSE in a centralized manner. As oppose to the traditional fixed-time signal control systems (see figure 3C), this component does not fix the SPaT plan for the entire control horizon. Instead, this component will only keep the next $N^S$ green phases in the SPaT plan at each time point, as shown in figure 3d. With this, as soon as a green phase ends, this component will add a new green phase with a given duration along with its yellow and red phases to the SPaT plan, as shown in figure 3e. This way, this component can efficiently serve C-ADS-equipped vehicles from different traffic streams at the intersection box based on their real-time demand and characteristics. Further, this component does not restrict the SPaT plan to have a fixed number of phases and follow a given phase sequence. Instead, this component allows the SPaT plan at an intersection to contain any possible defined phase and follow any possible phase sequence. With this algorithm, the frequency of RSE calling this component (i.e., the frequency of adding a phase to the SPaT plan) has a direct relationship with existing phase durations, which can vary depending on a number of factors (e.g., maximum-allowed speed on each entry lane, traffic-flow rates, communication radius, etc.).



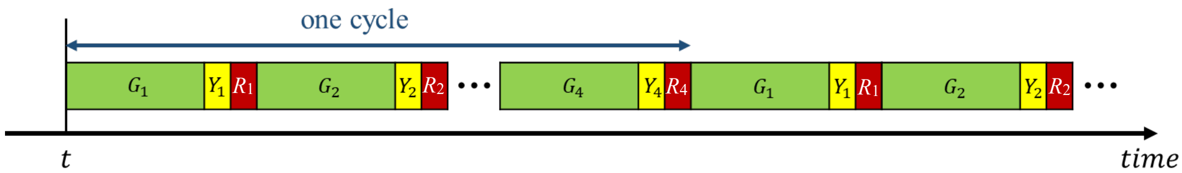

Source: FHWA.

A. A typical four-way signalized intersection.



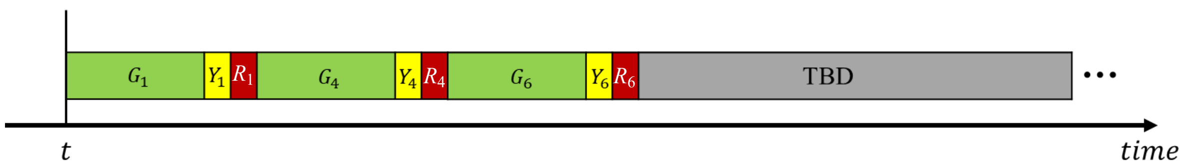

Source: FHWA.
Note: This figure is not intended to illustrate a typical eight-phase, dual-ring signal-timing plan. Instead, this figure shows all possible phases that can be included in a signal-timing plan.

B. All possible phases.



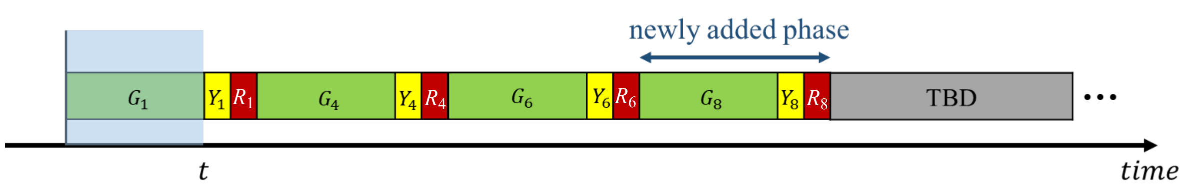

Source: FHWA.
*t* = current time point.
*G* = green portion of phase.
*Y* = yellow portion of phase.
*R* = red portion of phase.
Note: The index in each phase refers to the phase ID. The total of eight possible phases are considered for this example. This particular subfigure focuses on a fixed-time four-phase SPaT plan. Each cycle in this SPaT plan has four phases.

C. A traditional fixed-time four-phase SPaT plan.




Source: FHWA.
*t* = current time point.
*G* = green portion of phase.
*Y* = yellow portion of phase.
*R* = red portion of phase.
TBD = to be decided.
Note: The index in each phase refers to the phase ID. The total of eight possible phases are considered for this example. This particular subfigure focuses on an adaptive SPaT plan which can have any possible phase sequence and each phase can have any given duration.

D. Adaptive SPaT plan designed for this UC before the end of a green phase.




Source: FHWA.
*t* = current time point.
*G* = green portion of phase.
*Y* = yellow portion of phase.
*R* = red portion of phase.
TBD = to be decided.
Note: The index in each phase refers to the phase ID. The total of eight possible phases are considered for this example. This particular subfigure focuses on an adaptive SPaT plan which can have any possible phase sequence

and each phase can have any given duration. As soon as a green phase ends, the proposed signal optimization algorithm will add a new green phase with a given duration to the SPaT plan.

E. Adaptive SPaT plan designed for this UC after the end of a green phase.

**Figure 3. Illustration. Comparison between a traditional fixed-time four-phase and the developed adaptive SPaT plan structures.**

As soon as a green phase ends, the SO component will first estimate the earliest possible ET of each EV considering speed, acceleration, and safety constraints while ignoring vehicles from other entry lanes. This means that the RSE will regard those times that are not part of a fixed phase in the SPaT plan (TBD in figure 3D and figure 3E) as a green phase for all entry lanes. Then, based on the information received from those EVs that cannot enter the intersection box during an existing green phase in the optimized SPaT plan, the RSE will calculate the queue information from each entry lane (e.g., number of vehicles in the queue, queue dissipation time, and queue delay). Based on the stored queue information, the RSE will select a set of phase options that includes candidate phase IDs and their durations and can be added to the SPaT plan. For each phase ID, several options with different phase durations will be considered. (The phase duration for each option is calculated based on the queue dissipation time of an entry lane covered by the phase.) The RSE will also calculate how much delay will be served and added to the overall traffic if a given option is selected and fixed in the SPaT plan. The proposed algorithm in the SO component uses a defined objective function to select a proper option. The objective value in this UC is defined as a function of the served delay during the selected phase and the added delay to the traffic. As a result, the option with the highest served delay and least added delay will be selected. The defined objective function, however, can be modified depending on system operator preferences. As soon as an option is selected, the RSE will add it to the existing SPaT plan.

The proposed algorithm, however, is not the only available option for obtaining a proper departure sequence of vehicles at an intersection. An alternative solution to this problem is using machine-learning techniques to learn queueing patterns to predict a proper departure sequence of vehicles. The central RSE can be designed to follow one or more of these algorithms to obtain the vehicles' departure sequence so that the best possible traffic performance can be achieved. The decision regarding the applied algorithm depends on several factors, including the intersection design (e.g., the number of entry approaches and lanes), traffic demand, and available computational resources.

At each time point in the control time horizon, the RSE will also estimate an ET for each EV regardless of whether the SPaT plan needs to be modified or not. Then the RSE will share the existing SPaT plan with all vehicles. In cooperation classes C and D, the RSE will also instruct EVs with the estimated ETs. EVs will use the received SPaT plan and/or ETs from the RSE to smooth their trajectories.

### Critical Time Step Estimation

The CTSE component aims to estimate ETs of vehicles, with the available SPaT plan, to help vehicles smooth their trajectories. At each time step $t$, each EV needs to estimate and receive an ET based on the SPaT plan and the first available time step to enter the intersection box. The estimated ET of an EV will be always greater than its estimated earliest entering time (EET), which is the earliest time that it can arrive and enter the intersection box considering speed and acceleration constraints only while ignoring all other vehicles. This way the estimated ET of an EV will always be feasible for the vehicle to reach. Depending on the cooperation class of C-ADS-equipped vehicles, the estimation of ETs might be done by the vehicles themselves based on the received SPaT plan, or they might be instructed by the deployed RSE. The following subsections specify the algorithm framework of the CTSE component for each of the cooperation classes. It is assumed that all C–ADS-equipped vehicles inside the communication area are in the same cooperation class.

***Class A Cooperation***

In this cooperation class, C–ADS-equipped vehicles will only transmit their current status to each other, and no information regarding their intents will be available. Also, C–ADS-equipped vehicles have full authority to decide their own actions and do not have negotiation capabilities (table 2). Therefore, in this cooperation class, the CTSE component at RSE cannot instruct EVs by estimating their ETs, and RSE will just share the SPaT plan with vehicles and may just serve as an information-relay station to assist the information exchanges between vehicles.

Furthermore, since no information regarding vehicles' intents is available in this cooperation class, vehicles cannot be aware of the estimated ETs of their preceding vehicles. Thus, the estimation of ETs in this cooperation class might not be as accurate as possible, and vehicles may face red-signal indications due to this inaccurate estimation. Each vehicle will first determine the number of its preceding vehicles from the same entry lane. Then the vehicle will estimate the green time required for the determined number of vehicles to enter the intersection box with free-flow speed. As a result, each vehicle estimates the first possible ET with a simple search of green phases and durations.

***Class B Cooperation***

In this cooperation class, C–ADS-equipped vehicles will transmit their current status and intents to each other. Like class A, vehicles in this class do not have negotiation capabilities, so the CTSE component at RSE cannot instruct EVs by estimating their ETs. Since the intents of all C–ADS-equipped vehicles are available in this cooperation class, C–ADS-equipped vehicles can be aware of the estimated ETs of their preceding vehicles. Therefore, each C–ADS-equipped vehicle can simply check whether it can enter the intersection box at the same green phase as its preceding vehicle. Alternatively, each C–ADS-equipped vehicle must wait for the next green phase.

***Classes C and D Cooperation***

In these cooperation classes, C–ADS-equipped vehicles have negotiation capabilities. Therefore, each vehicle will receive a desired ET from RSE. While all vehicles in cooperation class D are forced to accept RSE's instructions, vehicles in cooperation class C have the ability to reject the received instructions from RSE. In this case, they will follow the procedure described for class B C–ADS-equipped vehicles to estimate their ETs. ET estimation with the described procedure for class B C–ADS-equipped vehicles will be almost the same as the one RSE estimated. Therefore, the difference between the traffic performances of classes B, C, and D is expected to be negligible.

Furthermore, the estimated and received ET serves as the input of the TS component. With the available ET, each individual vehicle can smooth its own trajectory and enjoy a more comfortable trip with the procedure described in the following subsection.

### Trajectory Smoothing

The TS component will run in the corresponding C–ADS-equipped vehicles, and, thus, the scheme of this component is decentralized/distributed. This component seeks to smooth vehicle trajectories with the received information from other vehicles or RSE and mitigate the backward shockwave propagations and the stop-and-go traffic patterns at signalized intersections. This component is intended to increase traffic throughput and improve energy efficiency. The TS component contains two main functions: trajectory planning and trajectory control.

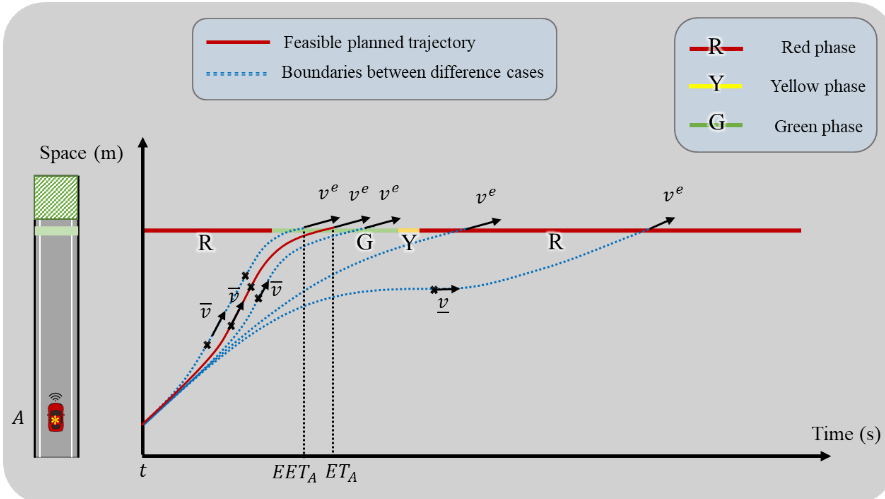
#### *Trajectory Planning*

This function will first plan a smooth trajectory profile for vehicles from entry lanes based on the received vehicles' status (e.g., current location, speed, acceleration, lane, and maximum acceleration/deceleration rate), intent (e.g., target ET and speed), traffic signal information (e.g., SPaT plan), and the estimated/received ET. A desired speed for the next time step will then be determined based on the obtained smooth trajectory.

The smooth trajectories are constructed with a polynomial equation, using the entry and exit boundaries. This function constructs a smooth trajectory for each vehicle individually without considering safety constraints. The safety constraints, however, are considered in a safety feature after the smoothed trajectory is planned; the safety feature will guarantee a safe and comfortable travel experience since safety is the primary objective of this algorithm. Since all C–ADS-equipped vehicles with different cooperation classes receive the SPaT plan from RSE and can estimate their own ETs, the proposed trajectory planning function will follow the same procedure for all CDA cooperation classes. The only difference between different cooperation classes is the accuracy of the decided trajectory and the violation of the safety constraints.

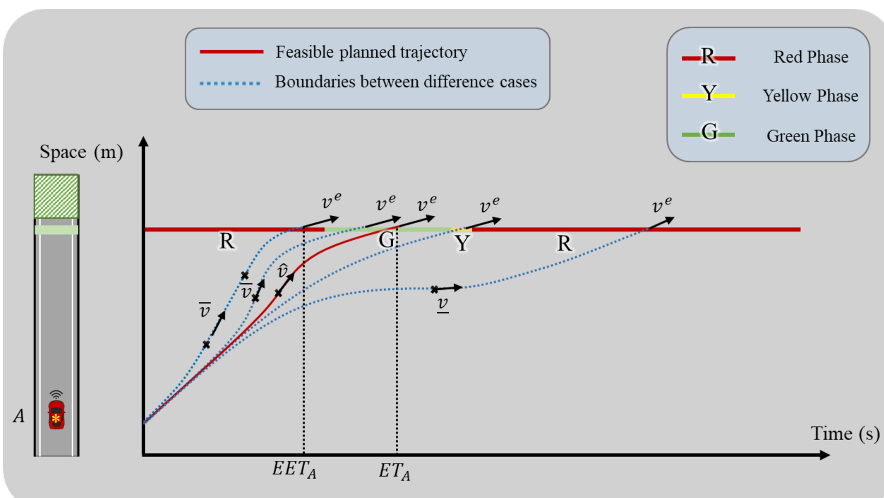
Regardless of the C–ADS-equipped vehicles' cooperation class, each vehicle from an entry lane aims to smooth its own trajectory to enter the intersection box at the estimated/received ET. The planned vehicle trajectory follows a third-, fourth-, or fifth-degree polynomial equation, depending on the available information at the entry and exit boundaries (e.g., current and target locations, speeds, and accelerations). The required variables for constructing trajectories with polynomial equations are the current and entering times, locations, and speeds, which enables the construction of third-order polynomial trajectories. The other variables, such as current and predicted entering accelerations and jerks, are optional, which enables the construction of higher order polynomial trajectories. As the order of the polynomial equation increases, the planned trajectory becomes differentiable at a higher order and smoother. For example, a second-order polynomial trajectory has continuous speed but jumping acceleration at transition points, but a third-order polynomial trajectory would have both continuous speed and acceleration everywhere. Accurately following a smoother planned trajectory in the trajectory control function is easier for C–ADS-equipped vehicles.

While the safety constraints are not considered in this function, the planned smoothed trajectories are guaranteed to be feasible in terms of speed and acceleration constraints. As shown in figure 4, depending on the estimated EET, the estimated/received ET, and the vehicle's current location and speed, the constructed smooth trajectory might fall in one of the illustrated four cases to ensure the speed and acceleration feasibility.



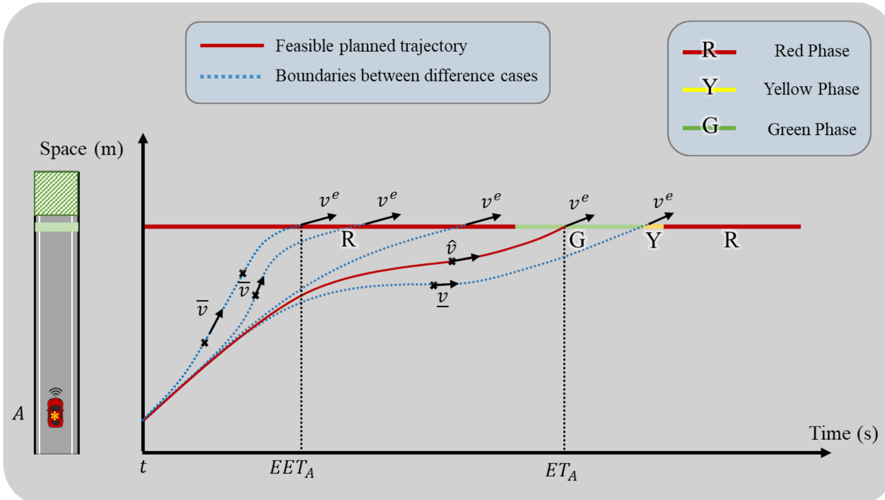

Source: FHWA.
$t$ = current time step.
$EET_A$ = earliest entering time of vehicle A.
$ET_A$ = entering time of vehicle A.
$\overline{v}$ = maximum speed.
$\underline{v}$ = minimum speed.
$v^e$ = the entering speed.

A. Case 1: Acceleration, cruising with maximum speed, deceleration.



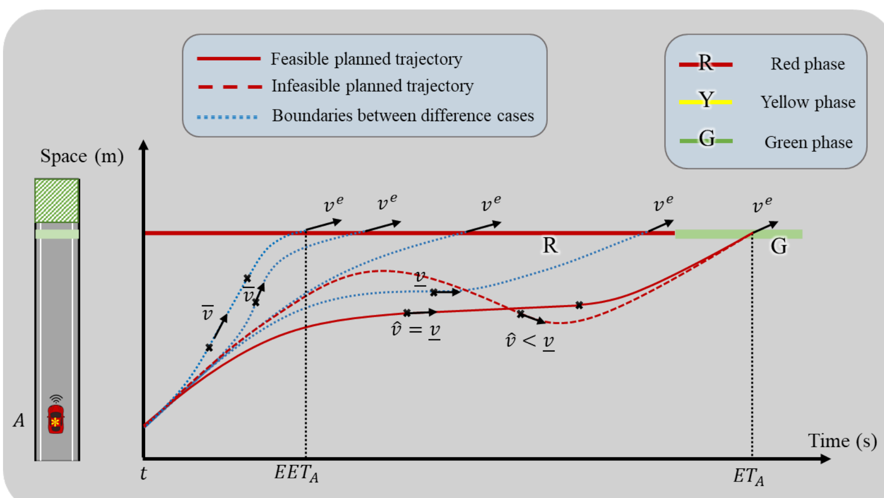

Source: FHWA.
$t$ = current time step.
$EET_A$ = earliest entering time of vehicle A.
$ET_A$ = entering time of vehicle A.
$\overline{v}$ = maximum speed.
$\underline{v}$ = minimum speed.
$\hat{v}$ = the joint speed between the acceleration and deceleration pieces.
$v^e$ = the entering speed.

B. Case 2: Deceleration, deceleration.




Source: FHWA.
$t$ = current time step.
$EET_A$ = earliest entering time of vehicle A.
$ET_A$ = entering time of vehicle A.
$\bar{v}$ = maximum speed.
$\underline{v}$ = minimum speed.
$\hat{v}$ = the joint speed between the acceleration and deceleration pieces.
$v^e$ = the entering speed.

C. Case 3: Deceleration, acceleration.



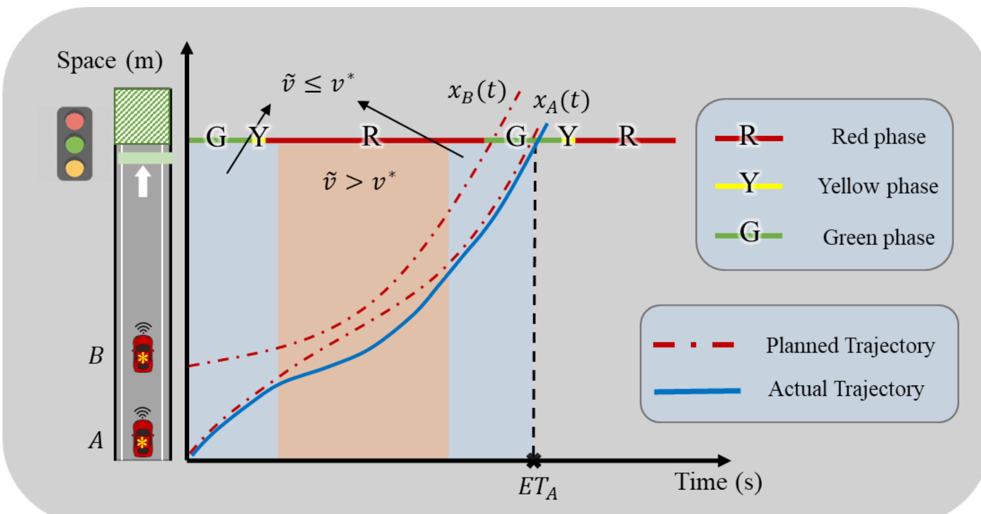

Source: FHWA.
$t$ = current time step.
$EET_A$ = earliest entering time of vehicle A.
$ET_A$ = entering time of vehicle A.
$\bar{v}$ = maximum speed.
$\underline{v}$ = minimum speed.
$\hat{v}$ = the joint speed between the acceleration and deceleration pieces.
$v^e$ = the entering speed.

D. Case 4: Deceleration, cruising, acceleration.

**Figure 4. Illustration. Different cases of planned trajectory.**

***Safety Feature***

Although the proposed trajectory planning feature smooths vehicle motions and improves fuel/energy consumption, it does not guarantee that the planned trajectory is safe. Therefore, a safety feature is needed to ensure the avoidance of collisions. The safety feature in this study is considered for each vehicle by determining the maximum safe speed that the vehicle can have at each time step (denoted by $v^*$). This maximum speed guarantees a minimum safe-time headway between the subject vehicle and its preceding vehicle (similar to what occurs in car-following models). $v^*$ is a function of the subject vehicle's current location, speed, minimum spacing, and communication delay (i.e., the time needed for sensors and the computer to process data added to the actuator time) and its preceding vehicle's current location, speed, and acceleration. This way, if the speed obtained from a vehicle's planned trajectory, denoted by $\tilde{v}$, is greater than the determined maximum safe speed, the vehicle will follow the maximum safe speed. Otherwise, the vehicle will follow the speed obtained from the planned trajectory. An example is presented in figure 5.




Source: FHWA.
$ET_A$ = entering time of vehicle A.
$x_A(t)$ / $x_B(t)$ = space-time trajectory of vehicle A/B.
$v^*$ = the maximum safe speed.
$\tilde{v}$ = the speed obtained from the planned trajectory.

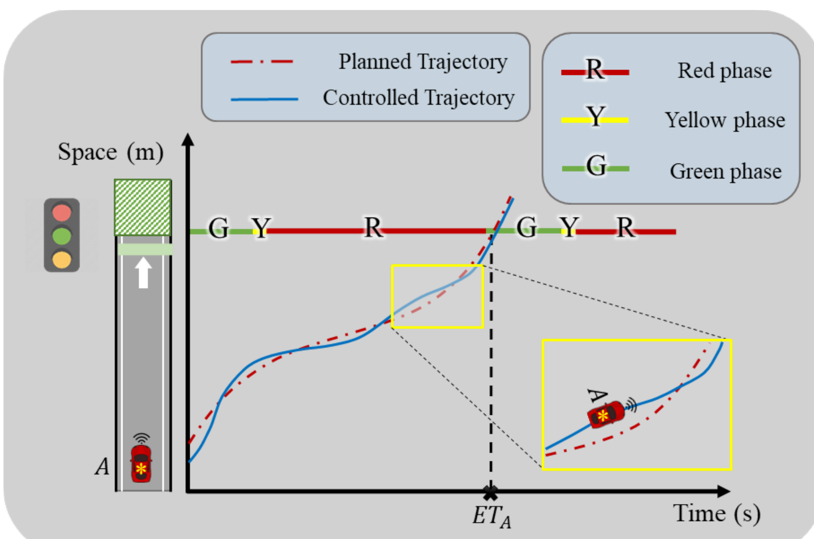
**Figure 5. Illustration. Safety feature.**

Also, for all the cooperation classes, a safety constraint is considered when the light turns yellow. Regardless of a vehicle's cooperation class, when the light turns yellow, the vehicle will first test a planned trajectory to come to a stop within its safe deceleration. If the trajectory is feasible, the vehicle will slow down to a full stop at the intersection, per the planned trajectory. Otherwise, if the vehicle is too close to the intersection and the test trajectory is infeasible, the vehicle will treat the yellow-signal indication the same as the green-signal indication and will aim to pass the intersection before the light turns red.

With the planned trajectory and maximum safe speed established, the advisory speed profile of each vehicle can be determined. Each vehicle then seeks to follow the determined advisory speed with the trajectory control function.

***Trajectory Control***

This function minimizes the control error of a vehicle following its planned-trajectory profile. Each vehicle may need to frequently (e.g., every 20 m) adjust its direct drive-by-wire control variables (e.g., throttle and brake levels and steering wheel angle) to ensure the actual vehicle trajectory can closely follow the planned trajectory, which will be implemented by the model predictive control (MPC) or the proportional-integral-derivative (PID) controller, depending on the capabilities of the experimenting C–ADS-equipped vehicles. As illustrated in figure 6, the actual controlled trajectory of a vehicle likely slightly deviates from the planned trajectory. An objective measure of the error will be proposed in the MPC (e.g., the weighted mean square errors of location and speed). In the PID control, each control variable is a simple linear function of the discrepancies of the status (e.g., location and speed) between the actual and the planned trajectories. Field experiments need to be conducted to calibrate the weights of the linear function to minimize the objective error measure for typical runs. Then the calibrated weights will be applied in the actual control. In the MPC, a mapping from the control variables (e.g., throttle level) and the vehicle infrastructure status (e.g., velocity, road grade and condition) to the vehicle's kinematic response (e.g., acceleration) needs to be constructed with offline field tests. Then, in the real-time control, a series of control variables within the following control window will be optimized to minimize the expected objective error measure while the offline mapping is called to predict the controlled trajectory in this optimization. Standard packages may be applied in the real-time control. The control error can only be quantified after the field experiments with the specific C–ADS-equipped vehicles. Different sensing, computing, and vehicle mechanics may result in different control errors.




Source: FHWA.
$ET_A$ = entering time of vehicle A.

**Figure 6. Illustration. Trajectory control function.**

## INFRASTRUCTURE CONFIGURATION AND NEEDS

This section describes technological and institutional infrastructure for CDA and explains the role of the IOO in developing the strategies for addressing congestion problems at signalized intersections with CDA.

One key feature of CDA operations is the dynamic vehicle-infrastructure interactions, particularly the exchange of real-time vehicular and roadway information that an ADS-equipped vehicle can understand and share. This project considers RSE that supplements a traffic controller to enable C–ADS functionalities proposed in this UC. RSE can communicate to C–ADS-equipped vehicles, irrespective of the particular communication technologies on both the vehicles and infrastructure, using the appropriate protocols. C–ADS-equipped vehicles can also share their status and what they sense about the surrounding dynamic traffic environment for better static and dynamic world models. The two-way information exchange is the foundation of CDA and includes both cooperative perception and cooperative vehicle control. CDA participants, vehicles, and infrastructure may use this information to improve situational awareness and expand their operational design domain. The algorithm for this particular UC does not require a cloud-based service because the focus of the algorithm is on an isolated intersection. However, the algorithm can certainly be extended to use a cloud-based service, especially when an entire corridor of intersections is under investigation.

With this background and perspective, the set of user needs relevant to the operator-traveler interactions is limited. While travelers are the primary beneficiaries, they can also be the information providers. Traffic operators, working on behalf of the infrastructure, are the primary service and information providers. They receive information from C–ADS-equipped vehicles, process and analyze them with all other available information and send the resulting pertinent information back to C–ADS-equipped vehicles. A list of needs for both road users and IOOs is shown in table 5. In this table, road users are C–ADS-equipped vehicles, so one-way or two-way information exchange can occur between road users and IOOs.

**Table 5. Infrastructure needs for road users and responsibilities of road users (i.e., cooperative driving automation vehicles) and infrastructure owners and operators.**

| Road Users (C–ADS-equipped vehicles) | IOOs |
|---|---|
| Get maps for navigating to their destination, including turns. | Monitor traffic conditions. |
| Get information on traffic conditions ahead. | Monitor environmental conditions. |
| Get information on weather conditions. | Receive traffic condition information from travelers. |
| Get information on accessible lanes. | Control access to lanes. |
| Get information on current local speed limits. | Control speed limits. |
| Get information on the SPaT plan. | Inform travelers of their estimated ET. |
| Get information on the estimated ET. | Inform travelers of the SPaT plan. |
| Estimate the ET to the intersection box. | Inform travelers of traffic conditions. |
| Inform IOOs of observed traffic conditions. | Inform travelers of weather conditions. |
| Inform IOOs of observed weather conditions. | Inform travelers of accessible lanes. |
| Inform IOOs of their planned trajectories. | Inform travelers of current local speed limits. |
| Inform IOOs of their status, intents, and what they see. | Inform travelers of any special rules that are currently being enforced. |
| Control trajectory. | — |

—No information available; C–ADS = cooperative automated driving system; ET = entering time; IOO = infrastructure owner and operator; SPaT = signal phase and timing.

Furthermore, based on the proposed control algorithm, the intersection controller will send a set of planning rules to and will receive some perception and vehicle operational information from C–ADS-equipped vehicles, as shown in table 6.

**Table 6. Exchanges between roadside equipment and vehicles.**

| RSE-to-vehicle | Vehicle-to-RSE |
|---|---|
| **Planning rules** | **Cooperative perception** |
| • Speed rules.<br>• Mapping rules.<br>• SPaT plan.<br>• Estimated ETs.<br>• Other vehicles' information. | • Vehicle current status, intent, etc.<br>• Local world information sensed by each C–ADS-equipped vehicle. |

C–ADS = cooperative automated driving system; ET = entering time; RSE = roadside equipment; SPaT = signal phase and timing.

## SUMMARY OF TRANSPORTATION SYSTEMS MANAGEMENT AND OPERATIONS NEEDS AND REQUIREMENTS

To summarize the discussion on key features of TSMO UC3 and guide the future development of requirements of the TSMO UC3 system, this section describes the operational needs and functional requirements for both C–ADS-equipped vehicles and infrastructures. These needs and requirements are specified for different CDA cooperation classes and different components of the proposed control algorithm. A central computer (e.g., CARMA Streets) might be needed to connect a set of RSEs deployed around the intersection box to store information and transfer them from one RSE to another and essentially from and to all C–ADS-equipped vehicles. In these operational needs and functional requirements:

- Static infrastructure data may include a map, speed limits, and lane restrictions.
- C–ADS-equipped vehicle's status and intent data may include a vehicle identifier (ID) (e.g., license plate or a temporary anonymous ID), vehicle type, location, speed, braking status, heading, priority position, ET to the intersection box, and departing time from the intersection box. This data set may vary across different cooperation classes.
- RSE advisory data may include the desired ET for each C–ADS-equipped vehicle, and RSE signal data include the SPaT plan. The central computer and RSEs in all cooperation classes are needed since C–ADS-equipped vehicles need to receive the SPaT plan. However, the central computer and RSEs might not be used for transferring information from one C–ADS-equipped vehicle to another if the V2V communication range is sufficient in the control area.

Table 7 provides a list of operational needs.

**Table 7. Operational needs for vehicles and infrastructure in transportation systems management and operations use case 3.**

| C–ADS-Equipped Vehicle System | ID Number | Operational Need | Cooperation Classes |
|---|---|---|---|
| CTSE | TSMO UC3-N01 | Need for static infrastructure data (e.g., map, speed limits, and lane restrictions). | A and above. |
| CTSE | TSMO UC3-N02 | Need for signal data (e.g., planned SPaT) and advisory data (e.g., desired ET to the intersection box) from the central RSE. | A and above. |
| CTSE | TSMO UC3-N03 | Need to process the status and intent data from other C–ADS-equipped vehicles and/or RSE advisory data to estimate vehicles' ET to the intersection box. | A, B, and C. |
| TS | TSMO UC3-N04 | Need to plan and follow the future trajectory and speed profile from the current location and speed to the target location, the speed at the target time. | A and above. |
| TS | TSMO UC3-N05 | Need for the status and intent data from the preceding C–ADS-equipped vehicles on the same lane for a car-following/collision-avoidance mechanism. | A and above. |
| Central computer (SO) | TSMO UC3-N06 | Need to store static infrastructure data (e.g., map, speed limits, and lane restrictions). | A and above. |
| Central computer (SO) | TSMO UC3-N07 | Need for C–ADS-equipped vehicle status and intent information data received from all RSE. | A and above. |

| C–ADS-Equipped Vehicle System | ID Number | Operational Need | Cooperation Classes |
|---|---|---|---|
| Central computer (SO) | TSMO UC3-N08 | Need for the capability to process relevant data to estimate vehicles' ET to the intersection box and determine the SPaT plan. | A and above. |
| RSE | TSMO UC3-N09 | Need to receive the status and intent data from C–ADS-equipped vehicles in the communication area (covered by DSRC or C–V2X devices). | A and above. |
| RSE | TSMO UC3-N10 | Need for relay data received from other RSE sent from the central computer. | A and above. |
| RSE | TSMO UC3-N11 | Need for vehicle-specific advisory data and the planned SPaT sent from the central computer. | A and above. |

C–ADS = cooperative automated driving system; C–V2X = cellular vehicle-to-everything; CTSE = critical time step estimation; DSRC = dedicated short-range communication; ET = entering time; RSE = roadside equipment; SO = signal optimization; SPaT = signal phase and timing; TS = trajectory smoothing; TSMO = transportation systems management and operations; UC = use case.

Table 8 illustrates the functional requirements of the C–ADS-equipped vehicles, RSE, and the central computer. These requirements are also specified for different cooperation classes.

**Table 8. Functional requirements for vehicles and infrastructure in transportation systems management and operations use case 3.**

| Functional Requirement Identifier | Functional Requirement | Cooperation Class |
|---|---|---|
| TSMO UC3-R01 | A C–ADS-equipped vehicle with at least cooperation class A has an onboard computer with storage and computing functions. | A and above. |
| TSMO UC3-R02 | A C–ADS-equipped vehicle with at least cooperation class A has a drive-by-wire control system, a navigation system, and corresponding algorithms (e.g., PID or MPC) to follow a given space-time trajectory. | A and above. |
| TSMO UC3-R03 | A C–ADS-equipped vehicle with at least cooperation class A broadcasts its location, speed, heading, and brake status. The communication frequency is approximately 10 Hz or more. | A and above (status data only for class A). |
| TSMO UC3-R04 | A C–ADS-equipped vehicle with at least cooperation class A receives, decodes, processes, analyzes, and uses locations, speeds, and headings from other preceding C–ADS-equipped vehicles with at least cooperation class A on the same lane. The communication frequency is approximately 10 Hz or more. If the range of V2V communications is smaller than the worst-case communication distance, RSE is | A and above. |

| Functional Requirement Identifier | Functional Requirement | Cooperation Class |
|---|---|---|
| | installed along each road segment to relay the data. | |
| TSMO UC3-R05 | A C–ADS-equipped vehicle with at least cooperation class A avoids crashes with other vehicles (vehicles with or without cooperation class capabilities) before, during, and after completion of the intersection control. Valid car-following and collision-avoidance components are installed in each C–ADS-equipped vehicle. These safety components are built upon in-vehicle sensors and may be enhanced with status and intent information shared by the surrounding vehicles. If communications are used to assist the safety component, the communication frequency is approximately 10 Hz or more. | A and above. |
| TSMO UC3-R06 | The central computer has storage and computational functions. | A and above. |
| TSMO UC3-R07 | The central computer relays vehicle intent and status information between RSE within certain geofenced areas in real time through DSRC or C–V2X communications. The connection between the central computer and the RSE is through cables. | A and above. |
| TSMO UC3-R08 | The central computer processes and analyzes C– ADS-equipped vehicle status and intent data received from each RSE to compute the vehicle-specific advisory data. | A and above. |
| TSMO UC3-R09 | The central computer sends vehicle-specific advisory data and the determined SPaT plan to the corresponding RSE in real time. The connection between the central computer and the RSE has minimum latency. | A and above. |
| TSMO UC3-R10 | RSE receives status and intent data from C– ADS-equipped vehicles with at least cooperation class A within the communication range. The communication frequency is approximately 10 Hz or more. | A and above. |

| Functional Requirement Identifier | Functional Requirement | Cooperation Class |
|---|---|---|
| TSMO UC3-R11 | RSE broadcasts the status and intent data among C–ADS-equipped vehicles through DSRC or C– V2X communications within the communication range. The communication frequency is approximately 10 Hz or more. | A and above (optional for when the CDA communication range is not enough and needs relay with the RSE). |
| TSMO UC3-R12 | RSE sends vehicle-specific advisory data and the determined SPaT plan through DSRC or C–V2X communications within its communication range. The communication frequency is approximately 10 Hz or more. | A and above. |

C–ADS = cooperative automated driving system; C–V2X = cellular vehicle-to-everything; CDA = cooperative driving automation; DSRC = dedicated short-range communication; Hz = hertz; MPC = model predictive control; PID = proportional-integral-derivative; RSE = roadside equipment; SPaT = signal phase and timing; TSMO = transportation systems management and operations; UC = use case; V2V = vehicle-to-vehicle.

Finally, the functional requirements described in table 8 for each of the operational needs illustrated in table 7 are presented in table 9.

**Table 9. Needs-to-requirements traceability matrix for transportation systems management and operations use case 3.**

| C–ADS-Equipped Vehicle System | Operational Need Identifier | Operational Need | Functional Requirement Identifier | Functional Requirement |
|---|---|---|---|---|
| CTSE | TSMO UC3-N01 | Need for static infrastructure data (e.g., map, speed limits, and lane restrictions). | TSMO UC3-R01 | A C–ADS-equipped vehicle with at least cooperation class A has an onboard computer with storage and computing functions. |
| CTSE | TSMO UC3-N02 | Need for signal data (e.g., planned SPaT) and advisory data (e.g., desired ET to the intersection box) from the central RSE. | TSMO UC3-R12 | RSE sends vehicle-specific advisory data and the determined SPaT plan through DSRC or C–V2X communications within its communication range. The communication frequency is approximately 10 Hz or more. |

| C–ADS-Equipped Vehicle System | Operational Need Identifier | Operational Need | Functional Requirement Identifier | Functional Requirement |
|---|---|---|---|---|
| CTSE | TSMO UC3-N03 | Need to process the status and intent data from other C–ADS-equipped vehicles and/or RSE advisory data to estimate vehicles' ET to the intersection box. | TSMO UC3-R01 | A C–ADS-equipped vehicle with at least cooperation class A has an onboard computer with storage and computing functions. |
| CTSE | TSMO UC3-N03 | Need to process the status and intent data from other C–ADS-equipped vehicles and/or RSE advisory data to estimate vehicles' ET to the intersection box. | TSMO UC3-R03 | A C–ADS-equipped vehicle with at least cooperation class A broadcasts its location, speed, heading, and brake status. The communication frequency is approximately 10 Hz or more. |
| CTSE | TSMO UC3-N03 | Need to process the status and intent data from other C–ADS-equipped vehicles and/or RSE advisory data to estimate vehicles' ET to the intersection box. | TSMO UC3-R04 | A C–ADS-equipped vehicle with at least cooperation class A receives, decodes, processes, analyzes, and uses locations, speeds, and headings from other preceding C–ADS-equipped vehicles with at least cooperation class A on the same lane. The communication frequency is approximately 10 Hz or more. If the range of V2V communications is smaller than the worst-case communication distance, RSE is installed along each |

| C–ADS-Equipped Vehicle System | Operational Need Identifier | Operational Need | Functional Requirement Identifier | Functional Requirement |
|---|---|---|---|---|
| | | | | road segment to relay the data. |
| CTSE | TSMO UC3-N03 | Need to process the status and intent data from other C–ADS-equipped vehicles and/or RSE advisory data to estimate vehicles' ET to the intersection box. | TSMO UC3-R11 | RSE broadcasts the status and intent data among C–ADS-equipped vehicles through DSRC or C–V2X communications within the communication range. The communication frequency is approximately 10 Hz or more. |
| TS | TSMO UC3-N04 | Need to plan and follow the future trajectory and speed profile from the current location and speed to the target location and speed at the target time. | TSMO UC3-R01 | A C–ADS-equipped vehicle with at least cooperation class A has an onboard computer with storage and computing functions. |
| TS | TSMO UC3-N04 | Need to plan and follow the future trajectory and speed profile from the current location and speed to the target location and speed at the target time. | TSMO UC3-R02 | A C–ADS-equipped vehicle with at least cooperation class A has a drive-by-wire control system, a navigation system, and corresponding algorithms (e.g., PID or MPC) to follow a given space-time trajectory. |
| TS | TSMO UC3-N05 | Need for the status and intent data from the preceding C–ADS-equipped vehicles on the same lane for a car-following/collision -avoidance mechanism. | TSMO UC3-R01 | A C–ADS-equipped vehicle with at least cooperation class A has an onboard computer with storage and computing functions. |
| TS | TSMO UC3-N05 | Need for the status and intent data from the preceding C–ADS-equipped vehicles on the same | TSMO UC3-R02 | A C–ADS-equipped vehicle with at least cooperation class A |

| C–ADS-Equipped Vehicle System | Operational Need Identifier | Operational Need | Functional Requirement Identifier | Functional Requirement |
|---|---|---|---|---|
| | | lane for a car-following/collision-avoidance mechanism. | | has a drive-by-wire control system, a navigation system, and corresponding algorithms (e.g., PID or MPC) to follow a given space-time trajectory. |
| TS | TSMO UC3-N05 | Need for the status and intent data from the preceding C–ADS-equipped vehicles on the same lane for a car-following/collision-avoidance mechanism. | TSMO UC3-R05 | A C–ADS-equipped vehicle with at least cooperation class A provides for the capability to avoid crashes with other vehicles (vehicles with or without cooperation class capabilities) prior to, during, and after completion of the intersection control. Valid car-following and collision-avoidance components are installed within each C–ADS-equipped vehicle. These safety components can be built upon in-vehicle sensors and may be enhanced with status and intent information shared by the surrounding vehicles. If communications are used to assist the safety component, the communication frequency is approximately 10 Hz or more. |

| C–ADS-Equipped Vehicle System | Operational Need Identifier | Operational Need | Functional Requirement Identifier | Functional Requirement |
|---|---|---|---|---|
| Central computer (SO) | TSMO UC3-N06 | Need to store static infrastructure data (e.g., map, speed limits, and lane restrictions). | TSMO UC3-R06 | The central computer has storage and computational functions. |
| Central computer (SO) | TSMO UC3-N07 | Need for C–ADS-equipped vehicle status and information data received from all RSE. | TSMO UC3-R07 | The central computer relays vehicle intent and status information between RSE within certain geofenced areas in real time through DSRC or C–V2X communications. The connection between the central computer and the RSE has minimum latency. |
| Central computer (SO) | TSMO UC3-N08 | Need for the capability to process relevant data to estimate vehicles' ET to the intersection box and determine the SPaT plan. | TSMO UC3-R06 | The central computer has storage and computational functions. |
| Central computer (SO) | TSMO UC3-N08 | Need for the capability to process relevant data to estimate vehicles' ET to the intersection box and determine the SPaT plan. | TSMO UC3-R08 | The central computer processes and analyzes C–ADS-equipped vehicle status and intent information data received from each RSE to compute the vehicle-specific advisory data and determine the SPaT plan. |
| RSE | TSMO UC3-N09 | Need for the status and intent data from C–ADS-equipped vehicles in the communication area (covered by DSRC or C–V2X devices). | TSMO UC3-R03 | A C–ADS-equipped vehicle with at least cooperation class A broadcasts its location, speed, heading, and brake status. The communication frequency is |

| C–ADS-Equipped Vehicle System | Operational Need Identifier | Operational Need | Functional Requirement Identifier | Functional Requirement |
|---|---|---|---|---|
| | | | | approximately 10 Hz or more. |
| RSE | TSMO UC3-N09 | Need for the status and intent data from C–ADS-equipped vehicles in the communication area (covered by DSRC or C–V2X devices). | TSMO UC3-R10 | RSE receives status and intent data from C–ADS-equipped vehicles with at least cooperation class A within the communication range. The communication frequency is approximately 10 Hz or more. |
| RSE | TSMO UC3-N10 | Need for relay data received from other RSE sent from the central computer. | TSMO UC3-R07 | The central computer relays vehicle intent and status information between RSE within certain geofenced areas in real time through DSRC or C–V2X communications. The connection between the central computer and the RSE has minimum latency. |
| RSE | TSMO UC3-N11 | Need for vehicle-specific advisory data sent from the central computer. | TSMO UC3-R09 | The central computer sends vehicle-specific advisory data to the corresponding RSE in real time. The connection between the central computer and the RSE has minimum latency. |

ADS = automated driving system; C–ADS = cooperative automated driving system; C–V2X = cellular vehicle-to-everything; CTSE = critical time step estimation; ET = entering time; Hz = hertz;
MPC = model predictive control; PID = proportional-integral-derivative; RSE = roadside equipment; SO = signal optimization; SPaT = signal phase and timing; TS = trajectory smoothing; TSMO = transportation systems management and operations; UC = use case.

## PERFORMANCE METRICS AND TARGETS

The effectiveness of TSMO UCs must be evaluated by measuring their capability in positively impacting performance. The performance metrics in this ConOps are presented from two perspectives: vehicle behavior and traffic flow.

### Performance Metrics for Vehicle Behavior

Key performance metrics for monitoring and evaluating vehicle operations during the execution of this situation should include:

- Separation distance: Longitudinal distances between the vehicles in the test. This performance metric is used to determine the frequency of minimum safe-distance violations.
- Travel speeds driven: Speeds driven by each vehicle during the tests that are used for evaluating the driving smoothness within the control area.
- Acceleration profile: Accelerations of each vehicle at different time steps during the tests that are used for approximating fuel and energy consumption.
- Speed control error: Differences between the advised speed and the actual speed driven by each vehicle during the tests. This performance metric is used to investigate how accurately each vehicle follows its planned trajectory.
- CTSE error: Differences between the estimated critical time steps and the actual ones during the test. This performance metric is used to investigate how accurately the CTSE component can estimate the critical time steps and how accurately vehicles can follow them.
- Data exchanges during communication/negotiation: Captures all data exchanges from V2V, V2I, and I2V to determine whether the communication and/or maneuver negotiations took place as designed. The data exchanges are to include the following data types:

    - Frequency of packet loss.
    - Total duration of the negotiation process.
    - Frequency of negotiation success/failure.
    - Number of attempts before a plan is accepted by all affected neighbors.
    - Message latency, the time between the message's origination in vehicle A and being read by infrastructure and vice versa. The latency time includes the length of time for the message to be composed and sent from vehicle A's computer to vehicle A's OBU; queue on vehicle A's OBU; be transmitted from vehicle A to infrastructure, queue on RSE; be transmitted from RSE to the infrastructure's computer; and be decomposed and read by infrastructure.

### Performance Metrics for Traffic Performance

This subsection identifies the performance measures on traffic performance to be used to evaluate the impact of TSMO UCs impact on traffic flow at intersections. Five main categories of impacts are identified and summarized in table 10[25]:

- Safety.
- Throughput.
- Flow stability.
- Flow breakdown and reliability.
- Sustainability.

***Safety***

Safety is a key factor in evaluating the impacts of CDA technologies. As the majority of crashes are due to human errors, automated vehicles have the potential to significantly decrease the number of crashes, specifically at high market penetration levels.(26) One way to quantify safety improvements is by calculating proxy safety metrics (e.g., time to collisions).

***Throughput***

CDA technologies are expected to increase the flow throughput of transportation facilities by increasing flow densities. However, such impacts are dependent on the cooperation level of those technologies. Throughput can be quantified by measuring the number of vehicles passing through the intersection/h and the variability of speeds within a facility segment.

***Stability***

There are several stability indexes developed in the literature that can be used. For example, string stability is stability with respect to spacing between vehicles within a platoon. If disturbances in vehicle spacing do not grow as they propagate along the platoon, the platoon is called string stable.

***Flow Breakdown and Reliability***

Flow breakdown is a traffic phenomenon in which throughput/capacity drops due to a perturbation (e.g., accident or sudden braking). CDA technologies are expected to improve traffic-flow reliability by providing smoother, safer, and more responsive vehicle operations. The UC can use multiple measures to quantify CDA impacts on flow breakdown and reliability, such as the occurrence and severity of shock waves.

***Sustainability***

The environmental impacts of CDA are uncertain. On the one hand, smoother operations associated with CDA can lead to lower greenhouse gas (GHG) emissions and energy consumption. On the other hand, impacts of CDA on travel demand are uncertain and could result in higher overall travel volume, increasing emissions and energy consumption. The tradeoff between the higher efficiency of flows and higher demand requires further research.

Calculating emissions and energy consumption is usually an offline process that uses data previously obtained by simulation or observed data.(27) Several methods are available in the literature for that purpose at different data aggregation levels. For the proposed UC, emissions and fuel consumption can be calculated using the speed profiles of vehicles (trajectories) at high temporal resolution obtained by the simulation platform. The proposed performance metrics include carbon dioxide, nitrogen oxide, particulate matter emissions, and the amount of energy (volume) consumed.

**Table 10. Summary of performance measures for transportation systems management and operations use cases evaluation.**

| Category | Impact | Performance Measure |
|---|---|---|
| Safety | Reduction in the number of crashes. | Number of crashes. |
| Safety | Improvement in the safety outcome of crashes. | Severity of crashes. |
| Throughput | Increase in traffic-flow volumes. | Number of vehicles passing through the intersection/hour. |
| Throughput | Smoothness of traffic flow. | Variability of speeds within traffic stream. |
| Flow stability | Improved local stability. | Local flow-stability index. |
| Flow stability | Improved string stability. | Mixed flow-string-stability index. |
| Flow breakdown and reliability | Occurrence of traffic shock waves. | Number of significant shock waves formed. |
| Flow breakdown and reliability | Severity of shock waves. | Propagation speed of formed shock waves relative to wave front. |
| Flow breakdown and reliability | Severity of shock waves. | Duration of shock wave-induced queues. |
| Sustainability | Impact on GHG emissions. | Level of carbon dioxide, nitrogen oxide, and particulate matter equivalent emissions. |
| Sustainability | Reduction in energy consumption. | Amount of energy consumed. |

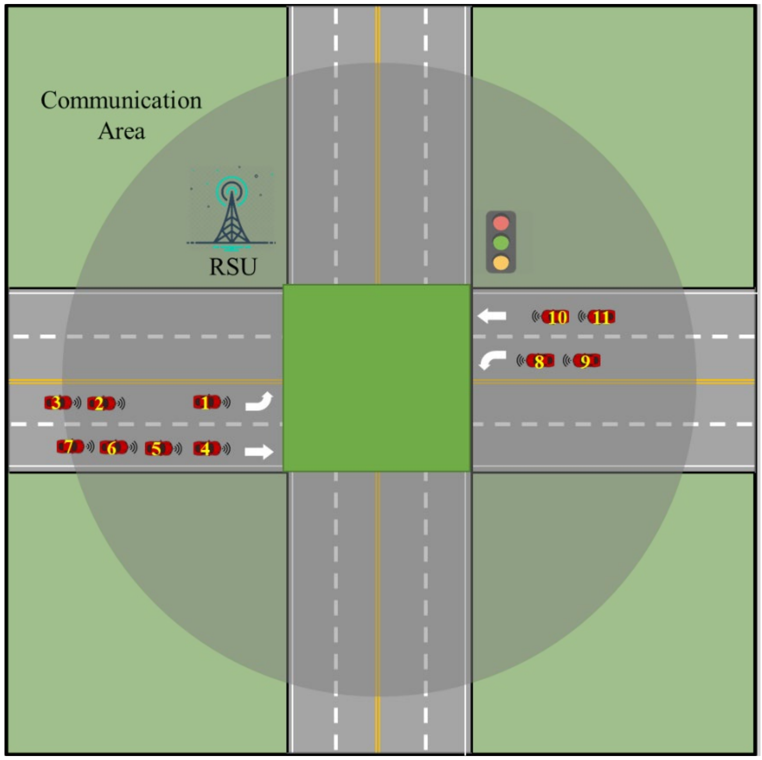
GHG = greenhouse gases.

# CHAPTER 4. OPERATIONAL SCENARIOS

This chapter identifies key TSMO UC3's operational scenarios to enhance TSMO at signalized intersections with the incorporation of SO, CTSE, and TS. This chapter also illustrates how these scenarios impact the early deployment of CDA on traffic operations. Two operational scenarios in which a set of vehicles enter the communication area of an isolated four-way signalized intersection with the optimal signal settings, engage in the CDA features described in the previous chapter, and move through the intersection are described in this chapter. These scenarios are described for the existing human-driven vehicles and C–ADS-equipped vehicles with different cooperation classes. These scenarios are designed to cover all key features of the proposed control framework and to illustrate their potential benefits.

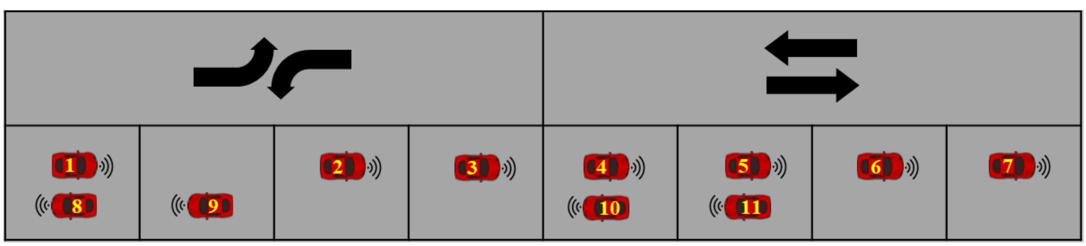
The proposed control method improves the traffic performance at the intersection from two aspects. First, optimizing the SPaT plan increases the possibility of having more vehicles passing the intersection box on average during a time interval, which increases the throughput and decreases the average travel delay. Second, smoothing vehicle trajectories not only decreases the fuel consumption but also increases the throughput as vehicles try to pass the intersection box at the maximum allowed speed without having to stop. In this section, two simple examples are presented to illustrate these two benefits. These examples are specified for only one batch of vehicles from two approaches for illustration purposes. Thus, the benefits of the proposed control algorithm are expected to increase as the number of considered approaches, directions, and vehicles increases.

The first illustrative example focuses on how optimizing the signal setting can increase the throughput and decrease the average travel delay at intersections. As shown in figure 7A, an isolated four-way two-lane intersection is considered for this example. The focus of this example is on only two phases of left turn and through for eastbound and westbound vehicles. The goal is to compare the throughput at the intersection box for two cases of fixed and optimized signal settings. As shown in figure 7B, a given fixed signal timing might require all through vehicles to wait for all left-turn vehicles to pass based on the given arrival pattern, which might introduce an unnecessary delay to through vehicles. However, by optimizing the signal setting, such an unnecessary delay can be eliminated. As shown in figure 7C, by introducing a new phase between left-turn and through phases, the throughput at the intersection increases. This example indicates how optimizing the signal setting can eliminate unnecessary delays. As the number of vehicles and approaches increases, the opportunity for eliminating unnecessary delays is expected to increase.



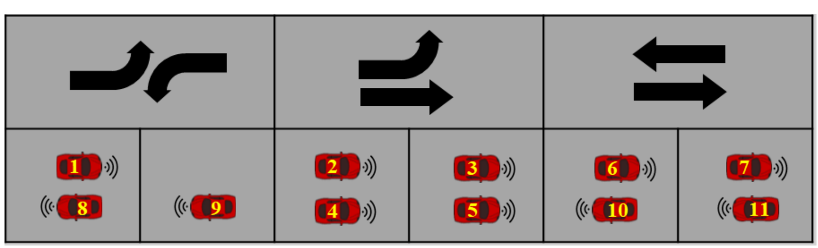

Source: FHWA.

A. Four-way two-lane signalized intersection.




Source: FHWA.

B. Fixed signal setting and the corresponding departure sequence.




Source: FHWA.

C. Optimal signal setting and the corresponding departure sequence.

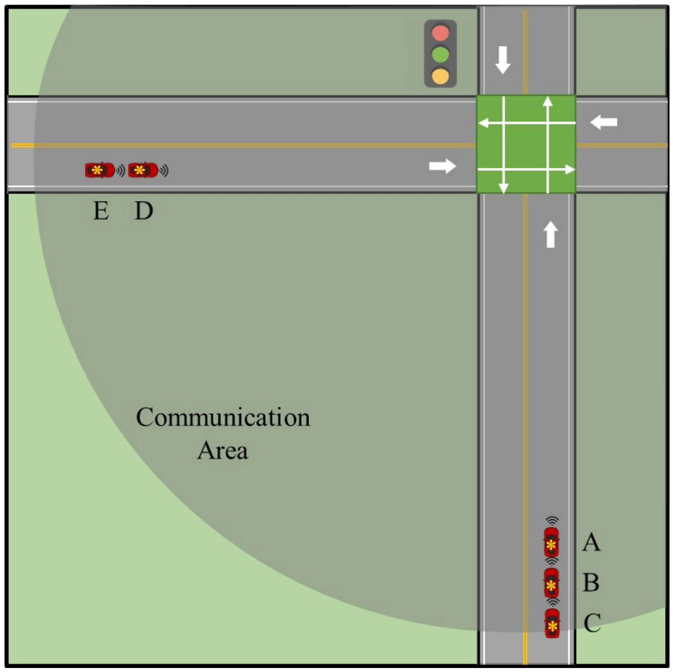
**Figure 7. Illustration. Cooperative driving automation operational scenario 1.**

The second illustrative example shows how smoothing vehicle trajectories and the available SPaT plan in a CDA environment can improve traffic performance at intersections. As specified by the SO component, the RSE adds a new phase to the SPaT plan as soon as a green phase ends regardless of the vehicles' cooperation classes. Therefore, the determined SPaT plan for scenarios with different cooperation classes will be the same. Also, regardless of the vehicle's cooperation class, the determined SPaT plan is shared among all vehicles. The only difference between different cooperation classes is the accuracy of the ET estimation in the CTSE component. Therefore, the difference between the traffic performances of different cooperation classes is expected to be negligible. This example is applied to two cases: existing human-driven vehicles and C–ADS-equipped vehicles.

As shown in figure 8A, vehicles A, B, C, D, and E enter the communication area and are approaching the intersection box. The focus of this operational scenario is on this set of vehicles, especially on vehicle C. As shown in figure 8B, if vehicles are not equipped with a CDA system, they are not aware of the planned SPaT and will proceed in accordance with the predefined car-following model. However, if all vehicles are equipped with a CDA system that has cooperation class A or higher, they will receive the planned SPaT and other vehicles' status and intents. These vehicles are able to predict their own ETs, as shown in figure 8C, and plan their smooth trajectories.

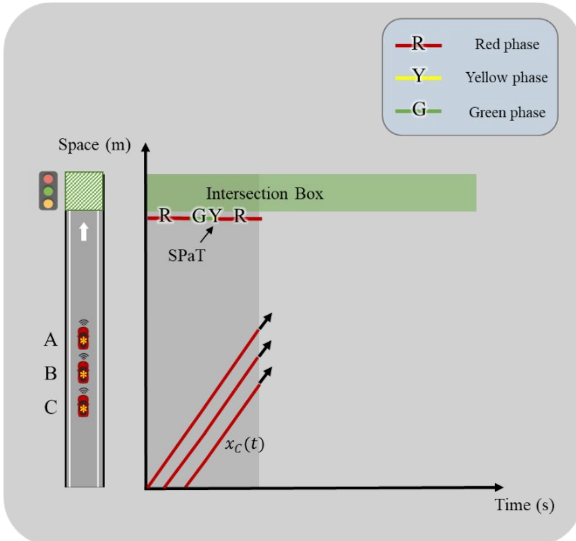
Furthermore, figure 8D and figure 8E show the investigated scenarios after the first green phase for vehicles A, B, and C. As shown in figure 8D, when all vehicles are conventional human driven, vehicles A, B, and C must stop at the red phase and wait for the light to turn green. After the light turns green for these vehicles, they will accelerate to pass the intersection box. The time it takes for vehicles A and B to accelerate from zero speed will not allow vehicle C to enter the intersection box at the green phase. Therefore, vehicle C must stop at the red phase again and wait for the next green phase. However, as shown in figure 8E, since vehicles are aware of the SPaT plan, they control their trajectories so that they can pass the intersection at the green phase at the maximum speed. Therefore, vehicle C can also pass the intersection at the first green phase and does not need to wait for the next cycle.

Overall, these operational scenarios illustrate the effectiveness of the proposed control framework at signalized intersections. These operational scenarios show that the combination of V2V and vehicle-to-RSE cooperation not only enhances the overall traffic system performance but also improves the experience of individual vehicle travel.



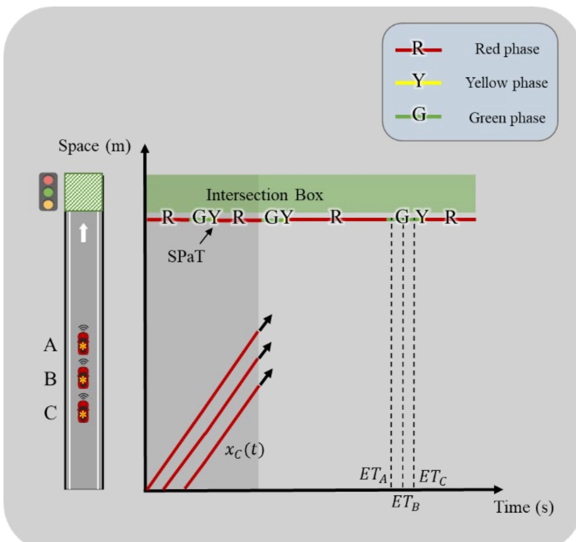

Source: FHWA.

A. Four-way single-lane signalized intersection.



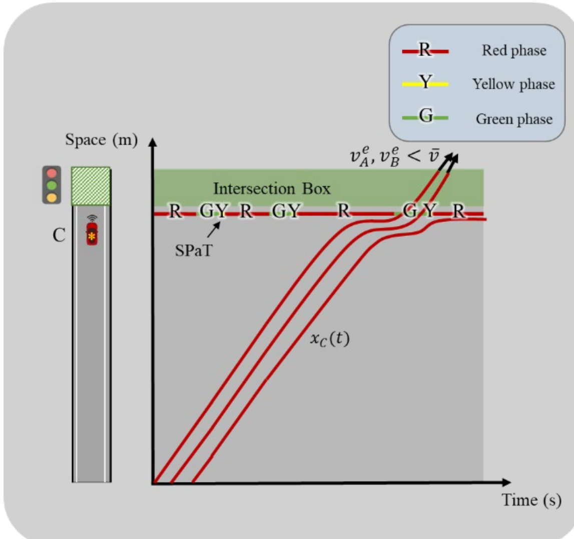

Source: FHWA.
$x_C(t)$ = trajectory of vehicle C.
SPaT = signal phase and timing.

B. Existing human-driven vehicles—Before green.



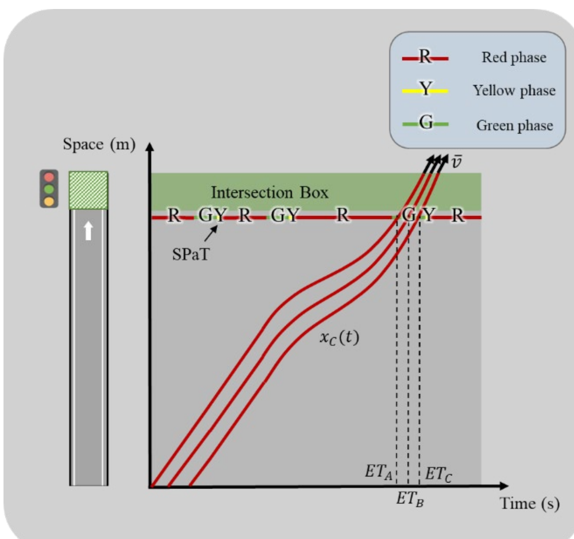

Source: FHWA.
$ET_A$ / $ET_B$ / $ET_C$ = entering time of vehicle A/B/C.
$x_C(t)$ = trajectory of vehicle C.
SPaT = signal phase and timing.

C. Cooperative automated driving system-equipped vehicles—Before green.




Source: FHWA.
$x_C(t)$ = trajectory of vehicle C.
$\bar{v}$ = maximum speed.
$v_A^e$ / $v_B^e$ = entering speed of vehicle A/B.
SPaT = signal phase and timing.

D. Existing human-driven vehicles—After green.




Source: FHWA.
$ET_A$ / $ET_B$ / $ET_C$ = entering time of vehicle A/B/C.
$x_C(t)$ = trajectory of vehicle C.
$\bar{v}$ = maximum speed.
SPaT = signal phase and timing.

E. Cooperative automated driving system-equipped vehicles—After green.

**Figure 8. Illustration. Cooperative driving automation operational scenario 2.**

# CHAPTER 5. ANALYSIS OF THE PROPOSED SYSTEM

This chapter provides an analysis of the advantages and disadvantages as well as the limitations of TSMO UC3 at signalized intersections with the integration of traffic SO and C–ADS-equipped vehicle TS. A high-level system validation plan is also discussed.

## SUMMARY OF POTENTIAL BENEFITS AND OPPORTUNITIES

CDA technologies enable mobile applications that are not achievable with individual ADS-operated vehicles by sharing information that can be used to increase the safety, efficiency, and reliability of the transportation system. Such benefits may accelerate the deployment of driving automation in on-road motor vehicles. CDA aims to improve the safety and flow of traffic and facilitate road operations by supporting the movement of multiple vehicles in proximity to one another. These benefits are accomplished, for example, by sharing information that can be used to directly or indirectly influence dynamic driving tasks by one or more nearby road users. Vehicles and infrastructure elements engaged in cooperative automation may share information, such as status (e.g., vehicle position, speed) and intent (e.g., estimated ET, SPaT plan) information, or seek agreement on a plan. Cooperation among multiple participants and perspectives in traffic, especially at conflict areas (e.g., intersections, merging roadways), can improve safety, mobility, situational awareness, and operations.

For TSMO UC3, a cooperative-control framework is proposed to efficiently control C–ADS-equipped vehicles at signalized intersections with an optimal signal setting. The proposed framework is illustrated for different cooperation classes defined in SAE J3216 and contains three main components: SO, CTSE, and TS. First, the SO component runs at a centralized RSE server to optimize SPaT with real-time information from all C–ADS-equipped vehicles. Second, the CTSE component aims to estimate an ET to the intersection box for each individual vehicle with the available SPaT plan, which, depending on its cooperation class, will be called by either the RSE or the vehicle itself. Finally, the TS component aims to smooth vehicle trajectories with the estimated ET, which is called by each vehicle in a decentralized manner. This cooperative-control framework focuses the infrastructure system only on key high-level scheduling decisions while leaving complex low-level trajectory control and collision avoidance to individual C–ADS-equipped vehicles in a decentralized manner. Thus, this framework greatly reduces operational complexity and associated risks and liabilities for traffic operators. Also, the cooperative-control framework distributes the computational burden among different entities in an edging-computing structure, making it much more suitable for real-time applications. Furthermore, as the operational scenarios in chapter 4 illustrated, the combination of cooperation between vehicles and the RSE can enhance the overall traffic system performance (because of the collaboration of the SO, the CTSE, and TS components) and improve individual vehicle travel experiences (as a result of the TS component). The proposed control framework is expected to reduce the stop-and-go traffic pattern and the backward shock-wave propagations, increase the throughput, decrease travel delay, and maintain safety for each individual vehicle at signalized intersections with an optimal signal setting.

## SYSTEM VALIDATION PLAN

This section describes system validation methods that will be used to validate the developed algorithms and software systems for TSMO UC3. The purpose of the validation testing is to ensure that the developed TSMO UC3 system can meet all the operational needs listed in table 7.

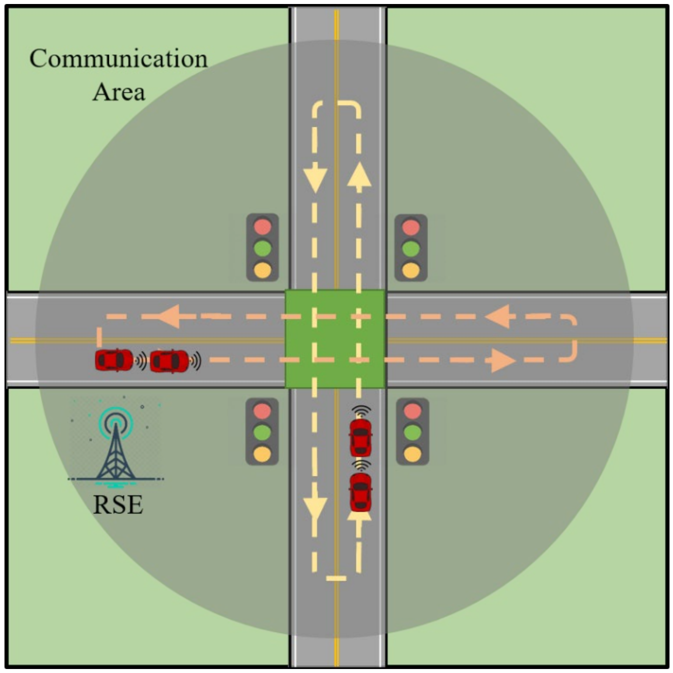
### Simulation Testing

Simulations can be designed to test the developed algorithm for TSMO UC3, using the performance metrics identified in chapter 3 of this report in terms of vehicle behavior and traffic system performance. Different types of simulations can be used and combined for testing purposes.

Traffic simulators offer the possibility to scale up the evaluation to an intersection corridor/network level (as compared to the limited number of vehicles and length of the roadway for ADS simulators). Through traffic simulators, one can study CDA impacts on transportation system performance, as measured by traffic performance metrics such as safety, efficacy, stability, and sustainability. The traffic simulators can evaluate different scenarios, such as various traffic demand, SPaT plan, and intersection geometry. Usually, the CDA-controlled algorithms will be simplified for calibrated/validated CDA behavioral models and algorithms that are implementable for large-scale testing.

### Field Testing

To ensure that the developed algorithm can be reliably and easily implemented into the CARMA Platform, a set of proof-of-concept tests will be conducted on a closed test track. These tests can be demonstrated onsite at a signalized intersection anywhere in the United States. Depending on participation by partners, multiple CARMA vehicles loaded with necessary feature groups can be instructed to run loops on the test track to represent continuous driving, as shown in figure 9. The operational scenarios discussed in chapter 4 of this report can be tested. The purpose of testing is to verify the software, collect vehicle behavior performance measures, and validate software requirements. Data collected from the test track can be used not only to calculate vehicle behavior performance metrics but also to calibrate traffic simulation CDA behavior models, which can improve evaluations of CDA's traffic impacts in simulation.




Source: FHWA.

**Figure 9. Illustration. Experimental plan for signalized intersection control.**

## SUMMARY OF IMPACTS

The proposed control strategy for TSMO UC3 will have a significant impact on the research and operations of future transportation systems management. From a research perspective, TSMO UC3 offers a unique approach to efficiently manage transportation systems at signalized intersections and reduce any type of disutility, such as excessive delay and emissions. The benefits of TSMO UC3 can only be realized when cooperative control can be enabled by effective algorithms, like those for SO, CTSE, and TS. The need for controlling each individual C–ADS-equipped vehicle calls for highly scalable algorithms and possibly a mixture of distributed and centralized approaches to manage all C–ADS-equipped vehicles in the transportation system.

From an operations perspective, the proposed control strategy for TSMO UC3 presents significant changes to how TSMO is conducted at signalized intersections. Intelligent transportation system infrastructure systems must be upgraded to accommodate the CDA system's needs, such as RSE services and supporting information technologies. Agencies also need to evaluate and build capabilities for operating such emerging systems. The conventional process of transportation system performance monitoring and reporting will be revolutionized with the prevalence of C–ADS-equipped vehicles and advanced sensors. Conventional strategies for TSMO that agencies are already familiar with can be significantly enhanced by CDA technologies.

## DISADVANTAGES AND LIMITATIONS

Although the proposed control strategy for TSMO UC3 provides advantageous insights to CDA operations at signalized intersections, the framework might suffer from some limitations that need to be further investigated. Some of these disadvantages and limitations include:

- The proposed SO and CTSE components require a centralized unit.
- The cooperation level of C–ADS-equipped vehicles greatly influences the performance of the traffic.
- The proposed algorithm focuses on completely automated traffic, and the full benefits of the proposed control algorithm might not be achieved in a mixed-traffic environment.
- The proposed control algorithm cannot accommodate pedestrians or bicyclists. The right-turn vehicles, for example, do not yield to pedestrians or bicyclists in the proposed control algorithm.
- The maximum benefits of the cooperation cannot be achieved due to the lack of cooperation among signalized intersections in a corridor.

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Recommended Citation: Federal Highway Administration,
*FHWA Cooperative Automation Research: CARMA Proof-of-Concept Transportation System Management and Operations Use Case 3—Traffic Signal Optimization with CDA at Signalized Intersections* (Washington, DC: 2022) https://doi.org/10.21949/1521854.

HRSO-10/01-22(WEB)E