Cooperative Automation Research: CARMA Proof-of-Concept Transportation System Management and Operations Use Case 2

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Turner-Fairbank Highway Research Center
6300 Georgetown Pike
McLean, VA 22101-2296

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 coordinate movement with the aim to improve 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, which 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 enable ADS functionality for cooperative automation strategies. This project expands CARMA functionality to include transportation systems management and operations strategies on surface arterials that have intersections. The intended audience for this report is CDA stakeholders such as system developers, analysts, researchers, and application developers.

Brian P. Cronin, P.E.
Director, Office of Safety and Operations
Research and Development

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7. Author(s)

Saeid Soleimaniamiri (ORCID: 0000-0002-0139-8319), Xiaopeng (Shaw) Li (ORCID: 0000-0002-5264-3775), Handong Yao (ORCID: 0000-0002-2778-084X), Amir Ghiasi (ORCID: 0000-0002-0986-9840), Govindarajan Vadakpat (ORCID: 0000-0001-9060-3216), Pavle Bujanovic (ORCID: 0000-0001-6589-3207), Taylor Lochrane (ORCID: 0000-0002-1933-6554), John Stark (ORCID: 0000-0002-1558-4630), Katie Blizzard (ORCID: 0000-0002-8718-7642), David Hale (ORCID: 0000-0001-5486-9367), Sujith Racha (ORCID: 0000-0002-5217-0779)

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Leidos, Inc.
11251 Roger Bacon Drive
Reston, VA 20190

University of South Florida
4202 E. Fowler Ave.
Tampa, FL 33620

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The Federal Government Task Managers were Govindarajan Vadakpat (ORCID: 0000-0001-9060-3216) and Taylor Lochrane (ORCID: 0000-0002-1933-6554).

16. Abstract

CARMA℠ is an initiative to enable collaboration for research and development of cooperative driving automation (CDA). The goal of CDA is to improve safety, traffic throughput, and energy efficiency of the transportation network by enabling vehicles and the infrastructure to communicate to coordinate movement. This project aims to advance the CARMA ecosystem to enable further capabilities for CDA participants to interact with the road infrastructure, to enhance infrastructure performance, to improve network efficiency, and to reduce traffic congestion through transportation systems management and operations strategies on arterials. This concept of operations has two components: including a critical time step estimation (designed for roadside equipment) and trajectory smoothing for cooperative automated driving system-equipped vehicles (designed for CARMA Platform℠) with the available vehicles' real-time information. The authors expect this approach to increase throughput and reduce energy consumption while ensuring safety at signalized intersections with a fixed-time/actuated signal setting.

17. Key Words

C–ADS-equipped vehicles; signalized intersection; cooperative driving automation; CDA; CARMA3; critical time step estimation; trajectory smoothing; trajectory planning; trajectory control

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

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

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LIST OF ACRONYMS

ACC	adaptive cruise control
ADS	automated driving system
C–ADS	cooperative automated driving system
CACC	cooperative adaptive cruise control
CAV	connected and automated vehicle
CDA	cooperative driving automation
ConOps	concept of operations
CTSE	critical time step estimation
C–V2X	cellular vehicle-to-everything
DAS	driving automation system
DDT	dynamic driving task
DSRC	dedicated short-range communication
DV	discharging vehicle
EAD	eco-approach and departure
EET	earliest entering time
ET	entering time
EV	entering vehicle
FHWA	Federal Highway Administration
HRDO	Office of Operations Research and Development
Hz	hertz
I2V	infrastructure-to-vehicle
ID	identifier
IOO	infrastructure owner and operator
LiDAR	light detection and ranging
MPC	model predictive control
OBU	onboard unit
PID	proportional-integral-derivative
RSE	roadside equipment
SPaT	signal phase and timing
STOL	Saxton Transportation Operations Laboratory
TCD	traffic control device
TS	trajectory smoothing
TSC	traffic signal controller
TSMO	transportation system management and operations
UC2	use case 2
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 on arterials. The document is focused on SAE Level 3+ automated driving systems (ADS) with and without connectivity and cooperation.

DOCUMENT OVERVIEW

Background

The Office of Operations Research and Development (HRDO) performs transportation operations research and development for the Federal Highway Administration (FHWA). On-site research and development is conducted at the Saxton Transportation Operations Laboratory (STOL) established at Turner-Fairbank Highway Research Center. HRDO conducts operations research and development based upon a national perspective of the transportation needs of the United States.

In 2015, HRDO 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 (ACC) systems by 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 designed to develop a new reference platform, CARMA2℠, using the Robot Operating System™ (ROS) 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 1, which integrated speed harmonization, lane change/merge, and platooning into one trip. This research focused on developing the understanding around negotiations between entities and how this can be done efficiently to help improve traffic flow based on cooperative tactical maneuvers.

A task order currently underway at the time of this writing is producing the third iteration of CARMA℠. CARMA3℠ is currently advancing into automated driving systems (ADS) for the SAE Level 3 (conditional driving automation) automation and above. The approach takes advantage of an open-source ADS platform Autoware® to enable ADS functionality to be used for cooperative automation strategies.

In addition to CARMA3, CARMA Cloud℠, CARMA Messenger℠, and CARMA Streets℠ are also being developed. CARMA Cloud is the infrastructure piece of cooperative driving automation (CDA) in which vehicles and other entities may communicate to increase the safety and efficiency of the transportation network. CARMA Messenger is designed to allow non-automated, moving entities (e.g., first-responder vehicles, pedestrians, 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 traffic signal controllers, which optimizes travel through intersections. All CARMA components (i.e., Platform, Cloud, Messenger, and Streets) are open source and are being built with the goal of benefitting CDA research at universities and with other research groups. Table 1 lists various projects associated with this development effort.

Table 1. Projects associated with the CARMA 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 Integrated Highway Prototype II

STOL = Saxton Transportation Operations Laboratory.

Objective

This report, *Cooperative Automation Research: CARMA Proof-of-Concept Transportation System Management and Operations Use Case 2*, will extend the research from Prototype II by enhancing CARMA Platform to enable further capabilities of CDA participants to interact with the road infrastructure. All TSMO use cases under this project consider CDA operations at at-grade intersections. The particular use case discussed in this document, TSMO Use Case 2 (UC2), focuses on CDA optimization at fixed-time/actuated traffic signals. The aim of this project is to address three high-level objectives on a tactical level: (1) reduce traffic congestion, (2) improve energy efficiency, and (3) 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. This project is supported by a team of CARMA participants for development and testing.

Transportation System Management and Operations Arterial Use Cases

- Use Case 1—vehicle coordination and trajectory optimization: stop-controlled intersections.
- UC2—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, including program managers, assistant managers, research engineers, and transportation technologies specialists, and others.
- 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 concept of operations in U.S. transportation systems engineering practice, and that title is retained for this document. Some sections have been enhanced to accommodate more detailed content than what is described in the standard, and titles of some sections may have been edited to more specifically capture those enhancements.

- 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 UC2 system capabilities and their operations, and it presents detailed descriptions of operational concepts.
- Chapter 4 describes operational scenarios of TSMO UC2 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 taken toward congestion and energy consumption mitigation at signalized intersections. It examines the current application of CDA technologies that reduce traffic congestion at signalized intersections, and it highlights some of the advantages and disadvantages of the existing solutions. These insights are now motivating the development of the new CDA solutions to congestion and energy problems at signalized intersections.

BACKGROUND AND CURRENT SITUATION

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

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

Further, vehicles can be made aware of downstream traffic and conflict areas' conditions to determine the best approximate times to enter the conflict areas. This way, vehicle speeds can be smoothed/optimized such that stop-and-go traffic and backward shock wave propagation would be reduced or eliminated. Smoothed/optimized speeds would also reduce energy consumption, harmful emissions, and crashes. Particularly at signalized intersections, such improvements could become even more significant because vehicles must come to complete stops. They must wait before passing through intersections at red signal indications, which creates unstable stop-and-go traffic that delays vehicles.

Among various developing CDA applications related to conflict areas, control strategies near signalized intersections have received increasing attention because of their capability to communicate with traffic signal controllers (TSC) and receive real-time SPaT information. These control strategies usually have two aspects. First, the traffic signal timing plan can be efficiently optimized to serve different traffic approaches according to their demands. Second, accordingly, 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.

A number of 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, centralized control schemes[8,9,10] and decentralized control schemes[11,12,13] are proposed to minimize speed/acceleration variations, reduce travel delay, and increase energy efficiency. In the centralized control scheme, decisions are made in a global manner for all vehicles by a single central controller. 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.

From the real-world testing perspective, only a few researchers have conducted field experiments with real C–ADS-equipped vehicles, and they have focused mostly on only controlling vehicle trajectories through an intersection. For instance, Wang et al.[14] developed a connected eco-driving system and equipped it on a heavy-duty diesel truck using cellular-based wireless communications. Field trials were conducted in the City of Carson, CA, along two corridors with six connected signalized intersections that were capable of communicating their SPaT information. Ma et al.[15] tested and verified a set of newly developed algorithms on an innovative CDA platform and quantified the fuel saving benefits of the eco-drive. Furthermore, the Integrated Prototype I project developed the Glidepath Prototype System,[16] which developed, demonstrated, and evaluated a partially automated vehicle system with an eco-approach and departure feature.

OPPORTUNITIES FOR CHANGES

Although the existing studies bring advantageous insights into CDA operations at intersections, they face a number of challenges that can be further addressed. For instance, most of the existing studies applied either decentralized or centralized control. On the one hand, although the short communication range required by decentralized control suits real-time applications, the self-selectivity 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 of the 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 complexity 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 and thus makes it much more suitable for real-time applications.

Further, 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 be different. SAE already standardized how cooperation between vehicles is regarded. Similar to the levels of automation defined in SAE J3016™, the new standard, SAE J3216™,[17] defines classes of cooperation. 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 CDA cooperation classes, and table 3 shows the opportunities provided by CDA technology by depicting examples of CDA features relating to cooperative traffic signal control at intersections, considering different cooperation classes. A number of these examples are taken from the SAE J3216 standard. With this, 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 Levels 1 and 2 driving automation features may be overridden by the driver at any time and otherwise have limited sensing capabilities compared with Levels 3, 4, and 5 ADS-operated vehicles. ** = class A and B communications are one of many inputs to an ADS's object and even detection and prediction capability, which may not be improved by the CDA message. ADS = automated driving system; C–ADS = cooperative automated driving system; CDA = cooperative driving automation; DAS = driving automation system; DDT = dynamic driving task; N/A = not applicable; TCD = traffic control device.

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/ 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: 1) C–ADS-equipped vehicles → RSE 2) RSE → C–ADS-equipped vehicles 3) C–ADS-equipped vehicles → C–ADS-equipped vehicles	1) SPaT messages 2) Velocity profile 3) Negotiations results	Enabling SPaT changes based on the approaching vehicle 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 Supporting more efficient motion plans with increased reliability and look-ahead distance to reduce energy consumption and emissions

Note: In practice, one-way transmission typically sends 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 and people whose actions influence travel in the transportation environment; these 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 user's 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 received SPaT information and current signal timing plan parameters 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.(18) Further, 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 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 they have uncertain driver behavior. Needs align with general user needs.
Human Driving	Connected human driver	Connected human drivers receive additional traveler information and can make better informed travel decisions. Needs align with general user needs.
Automated Driving	Non-connected ADS-equipped vehicle	Non-connected 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. 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 vehicle, C–ADS-equipped vehicles partner with other CDA participants in the traffic stream to improve overall traffic performance. 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 the mobility needs of transportation users by providing, operating, and maintaining roadways and supporting infrastructure. 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.

The general goal of IOOs is safe and efficient traffic management. This includes monitoring and managing traffic and the factors affecting traffic flow, including incidents, weather, intersections, the dissemination of routing information, and other actions that improve traffic flow efficiency. The goals of IOOs may, therefore, include:

- Reducing recurring congestion.
- Improving transportation reliability and safety.
- Reducing travel times, fuel consumption, and emissions.
- Maintaining and increasing the use of alternative and emerging transportation modes (e.g., car-sharing options; connected and automated vehicles are considered as a separate mode by travelers, according to a recent survey[(19)]).

The following benefits will be supported and enhanced by TSMO from IOOs' perspectives:

- Faster realization of efficiency goals—early adoption of CDA at existing intersections allows the operator to gain access to greater congestion management abilities 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 because of 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 who are currently primed to accommodate C–ADS-equipped vehicles on their facilities fail to 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 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 nature of 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—systems-engineering process is key 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 measurement 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 of the relevant data in real time from the various vehicles, onboard sensors, wireless devices, RSEs, 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; it also includes traditional detection sources (e.g., inductive loop detectors, overhead radar, closed-circuit television cameras) that provide traffic data for the system.

    - Traffic signal plan data—traffic signal plan data include the current status of the signal reflected in SPaT and the current signal timing plan parameters at signalized intersections.

    - 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, which can supplement 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 system would need to be equipped with DSRC radios (onboard units [OBU] and vehicle awareness devices), camera, light detection and ranging, radar sensors, and the computational resources to implement the new control software.
- Develop/acquire new software—the application 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, which 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 key 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 (this requires an increase in computational capability as well as long-term storage of historical data).
    - Evolve and improve its algorithms and methods on the basis of 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 system?
- What are the elements and capabilities of the system?
- Where are the affected 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 investments, 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 non-equipped 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 (both equipped and unequipped).

For early CDA deployment, infrastructure equipped with existing communication devices offer the opportunity to begin integrating CDA systems into traffic. Because of 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 UC2. It describes how automated driving technology can be used in a cooperative manner from when CDA vehicles enter the communication area of signalized intersections with a fixed-time/actuated signal setting to when they exit. The chapter also discusses the roles of infrastructure in supporting and enabling automated driving technology to help manage the transportation system in ways that address congestion and improve energy efficiency and safety during normal travel at arterials.

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

This section describes the tentative algorithm framework of CDA applications for TSMO UC2. In this framework, the focus is on a signalized intersection with a fixed-time/actuated signal setting, formed by multilane approaches, as illustrated by figure 1. The proposed algorithm is developed for the full 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, lane width) and the SPaT plan. 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 become green before turning). Further, the speed limit of each lane is determined based on its associated movement group. All C–ADS-equipped vehicles will aim to pass the intersection box with a speed designed to maximize the throughput of the intersection. Further, no lane-changing process is allowed in the communication area of the intersection.

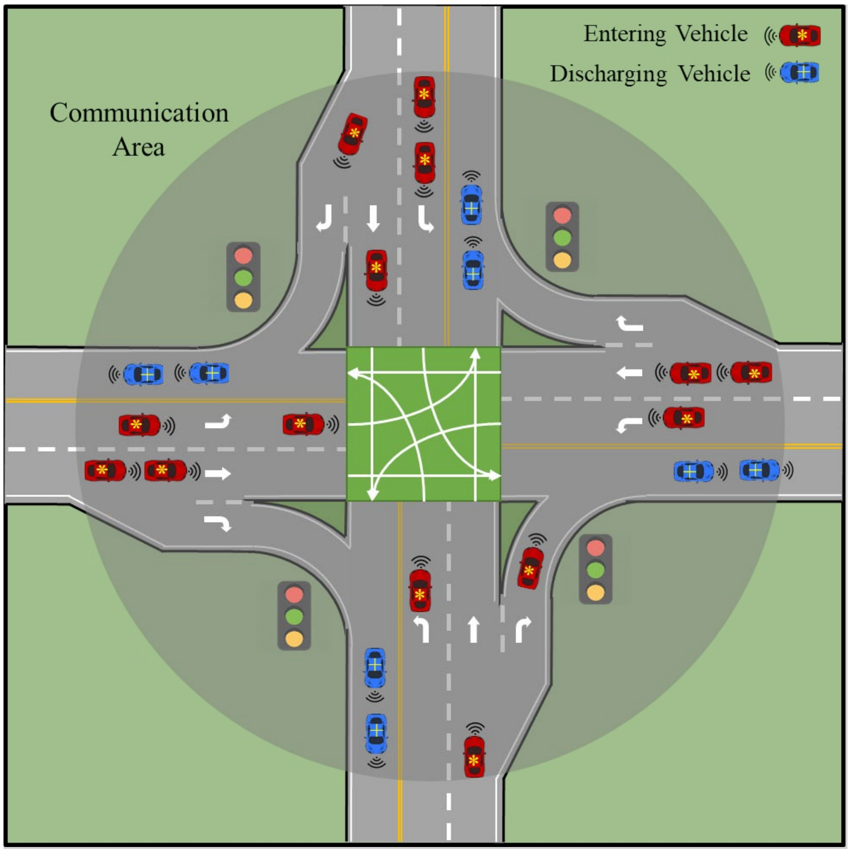
In this framework, all vehicles are assumed to be equipped with CDA technologies. The infrastructure at the intersection is assumed to be equipped with the needed software and hardware to allow it to transmit information to, and receive information from, all vehicles. The communication area of the intersection is then 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. This way, 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, vehicle type) and intents (e.g., entering time 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 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.

In TSMO UC2, no decision regarding the SPaT plan is required, and the SPaT plan at the investigated intersection is assumed to be given. The focus of this use case is to use the SPaT plan at the signalized intersection to smooth vehicle trajectories. The operational goal of this use case 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 hard safety constraints that avoids potential crash risks and uncomfortably high accelerations/decelerations.

- Mobility—within the feasible range allowed by the guaranteed safe/comfortable travel experience, the algorithm aims to maximize the throughput and minimize the overall travel delay at signalized intersections by minimizing vehicles' entering times to 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 further improve riding comfort.



Source: FHWA.

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

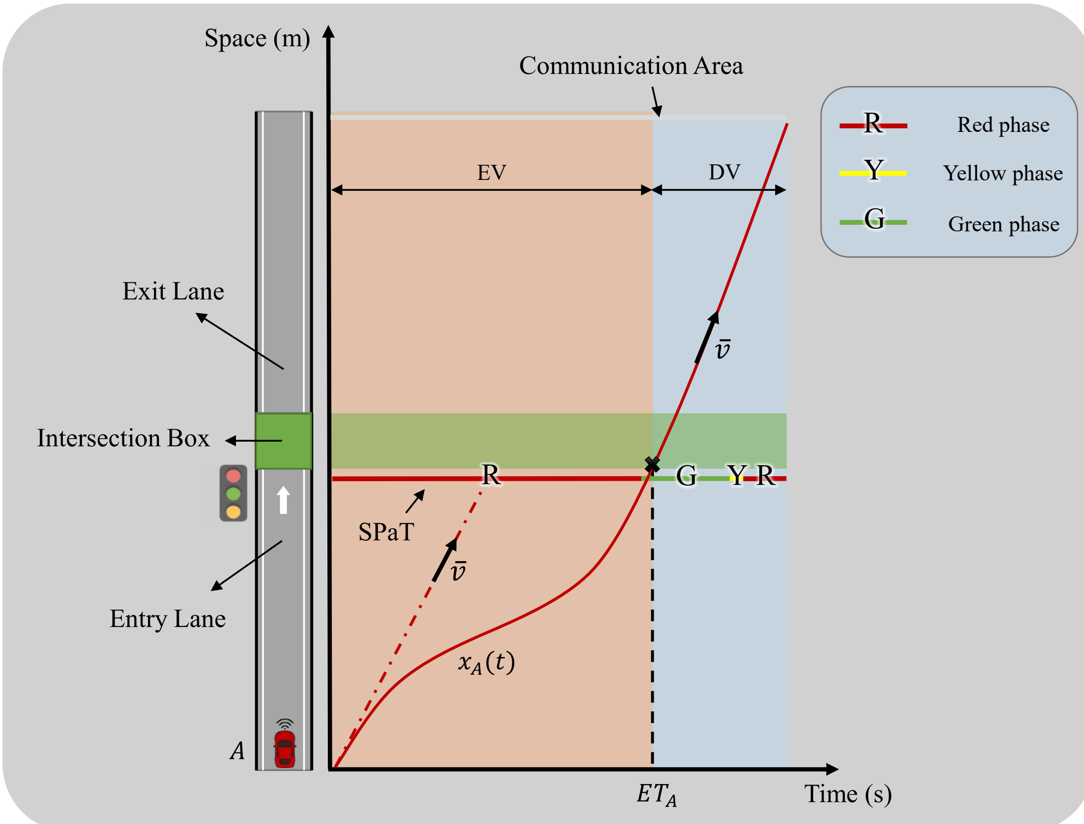
As illustrated in figure 1, at each time step of the algorithm, two different states can be defined for vehicles inside the communication area:

- Entering vehicles (EV)—vehicles that are approaching the signalized intersection and cannot enter the intersection box in the next time step (shown as red vehicles with star symbols in figure 1).

- Discharging vehicles (DV)—vehicles that have already departed the intersection box (shown as blue vehicles with plus symbols in figure 1).

A vehicle entering the communication area will initially join the EV set and begin transmitting information to RSE and other vehicles. While the vehicle is traveling through its associated entry lane and approaching the intersection, it might decide a desired entering time (ET) to enter the intersection box. 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. Note that 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 transition of a vehicle. Note that 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, however, DV trajectories might need to be controlled as well. In this case, DVs of one intersection might simply be seen as EVs by another intersection. This way, the proposed algorithm would be adaptable to handle a corridor of intersections.



Source: FHWA.

ET_A = entering time of vehicle A; xA (t) = trajectory of vehicle A; $\bar{v}$ = maximum speed.

Figure 2. Illustration. Vehicle state transition and entering time.

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

The proposed cooperative framework has two main components: 1) critical time step estimation (CTSE) and 2) TS. First, the CTSE component estimates an entering time to the intersection box for each C–ADS-equipped vehicle. This component is called either at each C–ADS-equipped vehicle in a decentralized manner, or at RSE in a centralized manner, depending on C–ADS-equipped vehicles' cooperation classes. Second, 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 critical time steps.

Transportation System Management and Operations Use Case 2: Trajectory Optimization (Fixed-Time and Actuated Signals)

- UC2.1- CTSE—estimating entering times to the intersection box for C–ADS-equipped vehicles based on the SPaT plan.
- UC2.2- TS—smoothing C–ADS-equipped vehicle trajectories with the estimated entering times.

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

Critical Time Step Estimation

The CTSE component aims to predict the entering times of vehicles to the intersection box, with the available SPaT plan, to improve traffic throughput and reduce traffic congestion. At each time step *t*, each EV needs to estimate/receive an ET based on the SPaT plan and the first available time step to enter the intersection box. If the signal actuation is triggered at any time, the new current and future status of the signal will be updated accordingly. Note that the estimated ET of an EV would 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. This way, the estimated ET of an EV will be always 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 SPaT plan and the received information from other vehicles, or it might be instructed by RSE deployed around the intersection. 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 may just serve as an information relay station to assist the information exchanges between vehicles.

Further, as no information regarding vehicles' intents is available in this cooperation class, vehicles are unaware of the estimated ETs of their preceding vehicles. Thus, the estimation of ETs in this cooperation class might be inaccurate, and vehicles may face red signal indications because of this inaccurate estimation. Each vehicle will first determine the number of its preceding vehicles from the same entry lane. Then they will estimate the green time required for the determined number of vehicles to enter the intersection box with free flow speed. With this, 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. As with those in class A, vehicles in this class lack negotiation capabilities, and thus the CTSE component at RSE cannot instruct EVs by estimating their ETs. Because 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 with its preceding vehicle or has to wait for the next one with the received ET from its preceding vehicle, SPaT plan, and its estimated EET.

Classes C and D Cooperation

In these cooperation classes, C–ADS-equipped vehicles have negotiation capabilities. Therefore, they will receive a desired ET from RSE. Although 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 cooperation class B C–ADS-equipped vehicles to estimate their ETs. Note that because the SPaT plan is assumed to be given and not adaptive in real time, no negotiation between the RSE and vehicles will take place. Thus, the estimated ET with the described procedure for class B C–ADS-equipped vehicles will be almost the same as the one RSE estimates. As a result, the difference between the traffic performances of cooperation classes B, C, and D are expected to be negligible.

Further, the estimated/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 at 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 to mitigate the backward shock-wave propagations and 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.

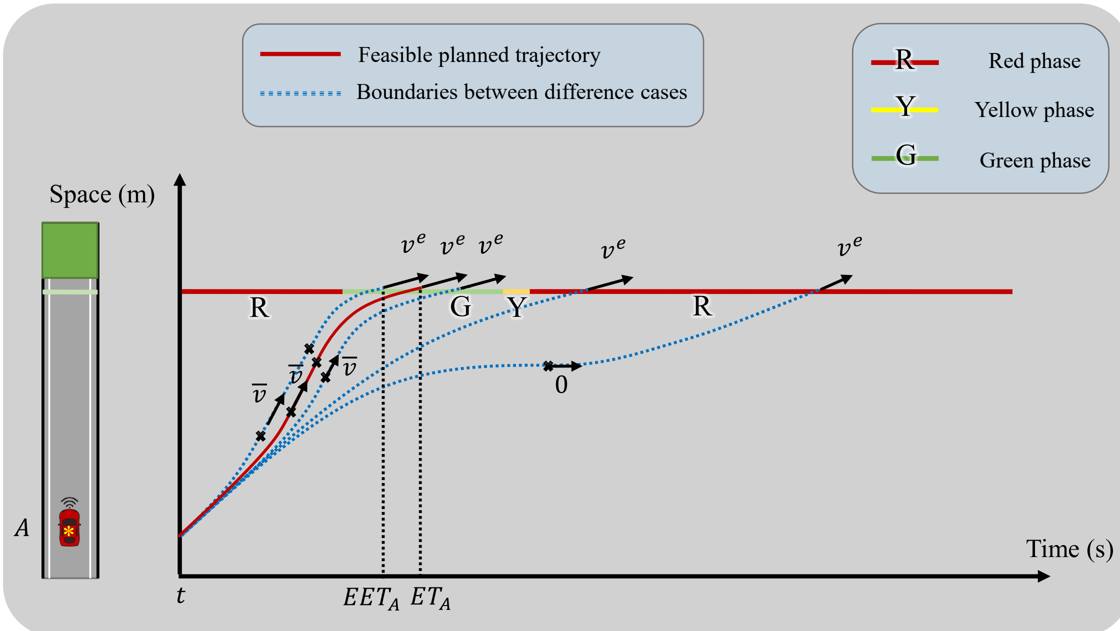
Trajectory Planning

This function will first plan a smooth trajectory profile for EVs based on the received vehicles' status (e.g., current location, speed, acceleration, lane, maximum acceleration/deceleration rate), intent (e.g., target departure time and speed), traffic signal information (e.g., SPaT plan), and the estimated/received ET. Then it will determine a desired speed for the next time step 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 and 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/comfortable travel experience as safety is the primary objective of this algorithm. Because all C–ADS-equipped vehicles with different cooperation classes receive the SPaT plan from RSE and subsequently are able to 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.

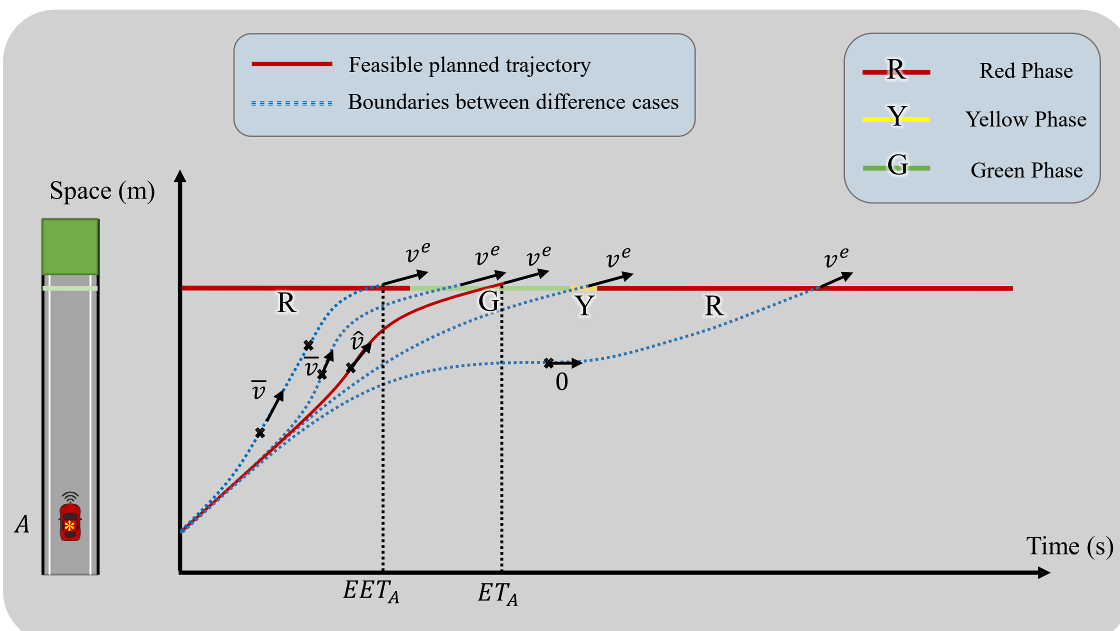
Regardless of the C–ADS-equipped vehicles' cooperation class, each EV aims to smooth its own trajectory to enter the intersection box at the estimated/received ET. The planned EV trajectory follows a third-, fourth-, or fifth-degree polynomial equation, depending on the available information as the entry and exit boundaries (e.g., current and target locations, speeds, and accelerations). The 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 rest (e.g., current and predicted entering accelerations, jerks) are optional (which enables the construction of higher order polynomial trajectories). Note that as the order of the polynomial equation increases, the planned trajectory becomes differentiable at a higher order and thus 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. It is obviously easier for C–ADS-equipped vehicles to accurately follow a smoother planned trajectory in the trajectory control function.

Although 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 3, 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.



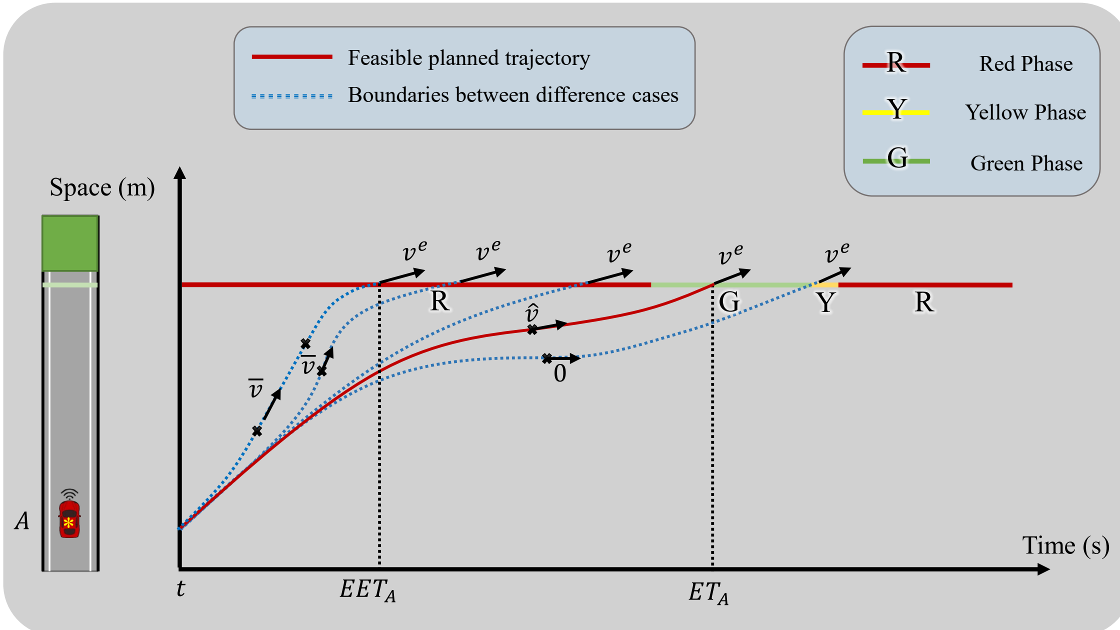
Source: FHWA.

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



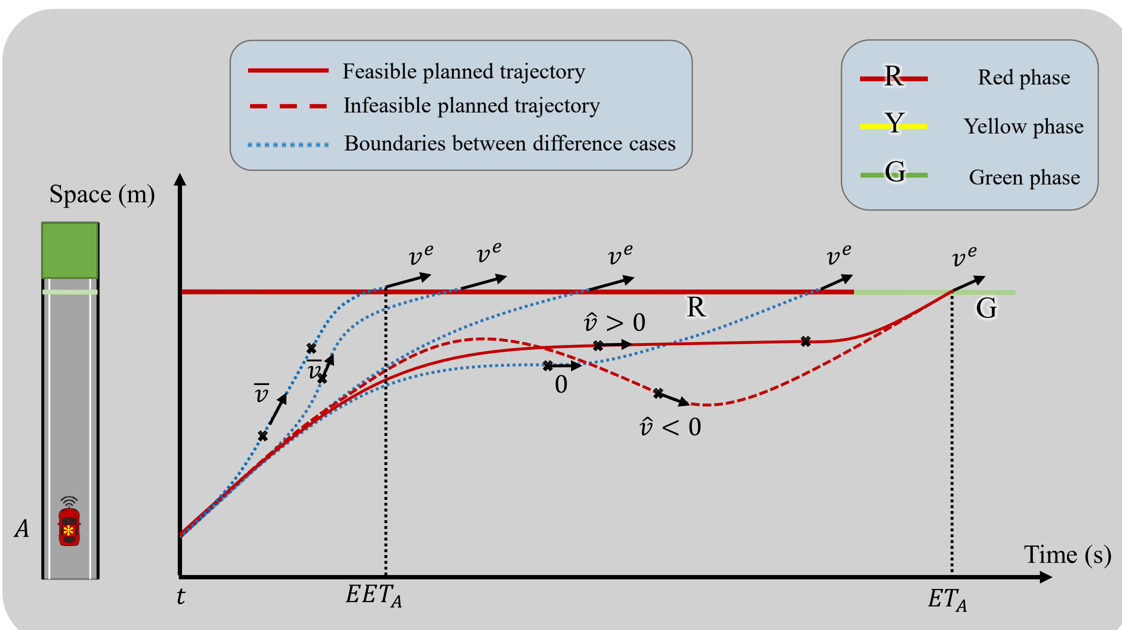
Source: FHWA.

B. Case 2: Acceleration, deceleration.



Source: FHWA.

C. Case 3: Deceleration, acceleration.



Source: FHWA.

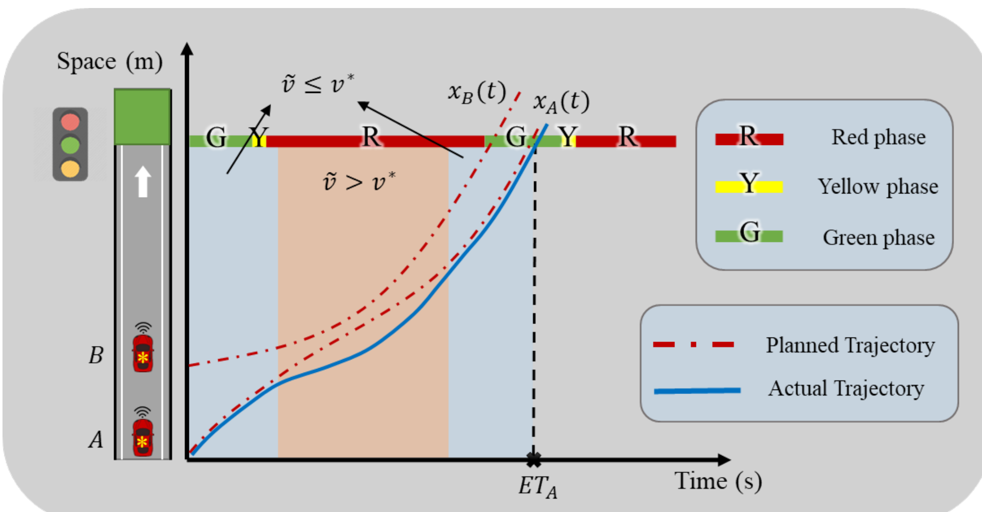
t = current time step; EET_A = earliest entering time of vehicle A; $\hat{v}$ = the joint speed between the acceleration and deceleration pieces; *ve* = the entering speed.

D. Case 4: Deceleration, cruising, acceleration.

Figure 3. Illustration. Different cases of planned trajectory.

Safety Feature

Although the proposed trajectory planning feature smooths vehicle motions and improves fuel/energy consumption, it fails to guarantee the planned trajectory is safe. Moreover, in the actuated signal setting, the signal status may change anytime, and therefore, some vehicles may need to change their plans to decelerate instead. Thus, the target vehicles shall maintain a sufficient gap from the preceding vehicles to avoid collision. Therefore, there is a need for a safety feature 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). It 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 processes 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 illustrative example is presented in figure 4.



Source: FHWA.

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

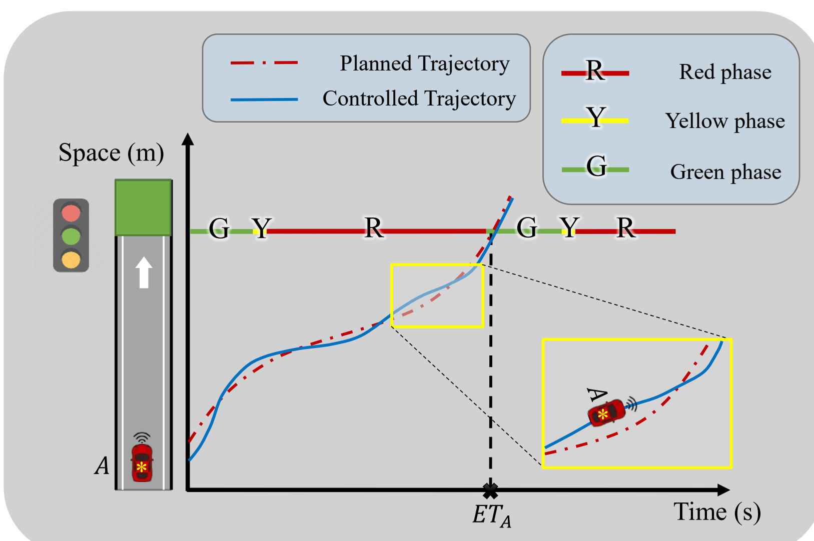
Figure 4. Illustration. Safety feature.

Also, for all of the cooperation classes, a safety constraint is considered when the light turns yellow. Regardless of the vehicles' cooperation classes, when the light turns yellow, an EV will first test to plan a trajectory to come to stop within its safe deceleration. If the trajectory is feasible, the EV will slow down to a full stop at the intersection according to the planned trajectory. Otherwise, if the EV is too close to the intersection and the test trajectory is infeasible, it 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 in hand and the determined maximum safe speed, researchers can determine the advisory speed profile of each vehicle. 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. Note that each vehicle may need to frequently (e.g., every 20 ms) 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. This 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 5, 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 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 control. Note that the control error can be quantified only 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.

Figure 5. Illustration. Trajectory control function.

INFRASTRUCTURE CONFIGURATION AND NEEDS

This section describes technological and institutional infrastructure, and it explains the role of IOOs in developing the rule strategies for addressing congestion problems at signalized intersections.

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 can be used to emulate an intersection controller for functions proposed in this use case. RSE can communicate to C–ADS-equipped vehicles, irrespective of the particular communication technologies, 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 constitutes the foundation of CDA, which includes both cooperative perception and cooperative vehicle control/traffic management. CDA participants, vehicles, and infrastructure, may use this information to improve situational awareness and expand their operational design domain. The algorithm for this particular use case does not require a cloud-based service as the focus of the algorithm is on an isolated intersection. The algorithm certainly can be extended to use a cloud-based service, however, especially when an entire corridor of intersections is under investigation.

With this background and perspective, there is then a limited set of user needs relevant to the interactions between traffic management center (operator) and vehicle (traveler). Although 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 it with all other available information, and then send the resulting pertinent information back to C–ADS-equipped vehicles. A list of needs for both road users and IOOs are shown in table 5. Note that road users are C–ADS-equipped vehicles such that one-way or two-way information exchanges 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 entering time
Get information on the estimated entering time	Inform travelers of the SPaT plan
Estimate the entering time to the intersection box	Inform travelers of traffic condition
Inform IOOs of observed traffic condition	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	—

C–ADS = cooperative automated driving system; SPaT = signal phase and timing; IOO = infrastructure owner and operator.

Further, 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. • Mapping rules. • SPaT plan. • Estimated entering times. • Other vehicles' information.	• Vehicle current status, intent, etc. • Local world information sensed by each C–ADS-equipped vehicle.

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

SUMMARY OF TRANSPORTATION SYSTEMS MANAGEMENT AND OPERATIONS NEEDS

To summarize key features of TSMO UC2 and inform future development of the TSMO UC2 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. Note that 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 MAP, speed limits, lane restrictions, etc.
- A C–ADS-equipped vehicle's status and intent data may include vehicle identifier (ID) (e.g., license plate or a temporary anonymous ID), vehicle type, location, speed, braking status, heading, priority position, entering time to the intersection box, departing time from the intersection box, etc. This data set may various across different cooperation classes.
- Further, RSE advisory data may include the desired entering time for each C–ADS-equipped vehicle, and RSE signal data include the SPaT plan. Note that the central computer and RSEs in all cooperation classes are needed because C–ADS-equipped vehicles need to receive the SPaT plan. They might not be used for transferring information from one C–ADS-equipped vehicle to another, however, if 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 2.

C–ADS-Equipped Vehicle System	ID#	Operational Need	Cooperation Classes
CTSE	TSMO UC2-N01	Need for static infrastructure data (e.g., MAP, speed limits, lane restrictions)	A and above
CTSE	TSMO UC2-N02	Need for signal data (e.g., planned SPaT) and advisory data (e.g., desired entering time to the intersection box) from the central RSE	A and above
CTSE	TSMO UC2-N03	Need to process the status and intent data from other C–ADS-equipped vehicles and/or RSE advisory data to estimate the entering time to the intersection box	A, B, and C
TS	TSMO UC2-N04	Need to plan and follow the future trajectory and speed profile from the current location and speed to the target location, speed at the target time	A and above
TS	TSMO UC2-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	TSMO UC2-N06	Needs to store static infrastructure data (e.g., MAP, speed limits, lane restrictions)	A and above
Central Computer	TSMO UC2-N07	Need for C–ADS-equipped vehicle status and intent information data received from all RSE	A and above
Central Computer	TSMO UC2-N08	Need for the capability to process relevant data to estimate vehicles' entering time to the intersection box	A and above
RSE	TSMO UC2-N09	Need for 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 UC2-N010	Need for relay data received from other RSE sent from the central computer	A and above
RSE	TSMO UC2-N011	Need for vehicle-specific advisory data and the 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; RSE = roadside equipment; SPaT = signal phase and timing; TS = trajectory smoothing; TSMO = transportation systems management and operations; UC2 = use case 2.

Table 8 lists the functional requirements of the C–ADS-equipped vehicles, RSE, and 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 2.

Functional Requirement Identifier	Functional Requirement	Cooperation Class
TSMO UC2-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 UC2-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 UC2-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)

Functional Requirement Identifier	Functional Requirement	Cooperation Class
TSMO UC2-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 road segment to relay the data.	A and above
TSMO UC2-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 UC2-R06	The central computer has storage and computational functions.	A and above

Functional Requirement Identifier	Functional Requirement	Cooperation Class
TSMO UC2-R07	The central computer relays vehicle intent and status information between RSE within certain geo-fenced area 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 UC2-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 UC2-R09	The central computer sends vehicle-specific advisory data and the SPaT plan to the corresponding RSE in real time. The connection between the central computer and the RSE is through cables.	A and above
TSMO UC2-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
TSMO UC2-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 CDA communication range is not enough and needs relay with the RSE)

Functional Requirement Identifier	Functional Requirement	Cooperation Class
TSMO UC2-R12	RSE sends vehicle-specific advisory data and the 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; UC2 = use case 2; 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 2.

C–ADS-Equipped Vehicle System	Operational Need Identifier	Operational Need	Functional Requirement Identifier	Functional Requirement
CTSE	TSMO UC2-N01	Need for static infrastructure data (e.g., MAP, speed limits, lane restrictions)	TSMO UC2-R01	A C–ADS-equipped vehicle with at least cooperation class A shall have an onboard computer with storage and computing functions.
CTSE	TSMO UC2-N02	Need for signal data (e.g., planned SPaT and advisory data (e.g., desired entering time to the intersection box) from the central RSE	TSMO UC2-R12	RSE shall be able to send vehicle-specific advisory data and the SPaT plan through DSRC or C–V2X communications within its communication range. The communication frequency should be approximately 10 Hz or more.

C–ADS-Equipped Vehicle System	Operational Need Identifier	Operational Need	Functional Requirement Identifier	Functional Requirement
CTSE	TSMO UC2-N03	Need to process the status and intent data from other C–ADS-equipped vehicles and/or RSE advisory data to estimate some the entering time to the intersection box	TSMO UC2-R01	A C–ADS-equipped vehicle with at least cooperation class A shall have an onboard computer with storage and computing functions.
CTSE	TSMO UC2-N03	Need to process the status and intent data from other C–ADS-equipped vehicles and/or RSE advisory data to estimate some the entering time to the intersection box	TSMO UC2-R03	A C–ADS-equipped vehicle with at least cooperation class A shall be able to broadcast its location, speed, heading, and brake status. The communication frequency should be approximately 10 Hz or more.

C–ADS-Equipped Vehicle System	Operational Need Identifier	Operational Need	Functional Requirement Identifier	Functional Requirement
CTSE	TSMO UC2-N03	Need to process the status and intent data from other C–ADS-equipped vehicles and/or RSE advisory data to estimate some the entering time to the intersection box	TSMO UC2-R04	A C–ADS-equipped vehicle with at least cooperation class A shall be able to receive, decode, process, analyze, and use locations, speeds, and headings from other preceding C–ADS-equipped vehicles with at least cooperation class A on the same lane. The communication frequency should be approximately 10 Hz or more. If the range of V2V communications is smaller than the worst-case communication distance, RSE may be installed along each road segment to relay the data.
CTSE	TSMO UC2-N03	Need to process the status and intent data from other C–ADS-equipped vehicles and/or RSE advisory data to estimate some the entering time to the intersection box	TSMO UC2-R11	RSE shall be able to broadcast the status and intent data among C–ADS-equipped vehicles through DSRC or C–V2X communications within the communication range. The communication frequency should be approximately 10 Hz or more.

C–ADS-Equipped Vehicle System	Operational Need Identifier	Operational Need	Functional Requirement Identifier	Functional Requirement
TS	TSMO UC2-N04	Need to plan and follow the future trajectory and speed profile from the current location and speed to the target location, speed at the target time	TSMO UC2-R01	A C–ADS-equipped vehicle with at least cooperation class A shall have an onboard computer with storage and computing functions.
TS	TSMO UC2-N04	Need to plan and follow the future trajectory and speed profile from the current location and speed to the target location, speed at the target time	TSMO UC2-R02	A C–ADS-equipped vehicle with at least cooperation class A shall have 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 UC2-N05	Need to plan and follow the future trajectory and speed profile from the current location and speed to the target location, speed at the target time	TSMO UC2-R01	A C–ADS-equipped vehicle with at least cooperation class A shall have an onboard computer with storage and computing functions.
TS	TSMO UC2-N05	Need to plan and follow the future trajectory and speed profile from the current location and speed to the target location, speed at the target time	TSMO UC2-R02	A C–ADS-equipped vehicle with at least cooperation class A shall have a drive-by-wire control system, a navigation system, and corresponding algorithms (e.g., PID or MPC) to follow a given space-time trajectory.

C–ADS-Equipped Vehicle System	Operational Need Identifier	Operational Need	Functional Requirement Identifier	Functional Requirement
TS	TSMO UC2-N05	Need to plan and follow the future trajectory and speed profile from the current location and speed to the target location, speed at the target time	TSMO UC2-R05	A C–ADS-equipped vehicle with at least cooperation class A shall provide 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 shall be 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 should be approximately 10 Hz or more.
Central Computer	TSMO UC2-N06	Needs to store static infrastructure data (e.g., MAP, speed limits, lane restrictions)	TSMO UC2-R06	The central computer shall have storage and computational functions.

C–ADS-Equipped Vehicle System	Operational Need Identifier	Operational Need	Functional Requirement Identifier	Functional Requirement
Central Computer	TSMO UC2-N07	Need for C–ADS-equipped vehicle status and intent information data received from all RSE	TSMO UC2-R07	The central computer shall be able to relay vehicle intent and status information between RSE within certain geo-fenced areas in real time through DSRC or C–V2X communications. The connection between the central computer and the RSE is through cables.
Central Computer	TSMO UC2-N08	Need for the capability to process relevant data to estimate vehicles' entering time to the intersection box	TSMO UC2-R06	The central computer shall have storage and computational functions.
Central Computer	TSMO UC2-N08	Need for the capability to process relevant data to estimate vehicles' entering time to the intersection box	TSMO UC2-R08	The central computer shall be able to process and analyze C–ADS-equipped vehicle status and intent information data received from each RSE to compute the vehicle-specific advisory data.

C–ADS-Equipped Vehicle System	Operational Need Identifier	Operational Need	Functional Requirement Identifier	Functional Requirement
RSE	TSMO UC2-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 UC2-R03	A C–ADS-equipped vehicle with at least cooperation class A shall be able to broadcast its location, speed, heading, and brake status. The communication frequency should be approximately 10 Hz or more.
RSE	TSMO UC2-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 UC2-R10	RSE shall be able to receive status and intent data from C–ADS-equipped vehicles with at least cooperation class A within the communication range. The communication frequency should be approximately 10 Hz or more.
RSE	TSMO UC2-N10	Need for vehicle-specific advisory data and the SPaT plan sent from the central computer	TSMO UC2-R07	The central computer shall be able to relay vehicle intent and status information between RSE within certain geo-fenced area in real time through DSRC or C–V2X communications. The connection between the central computer and the RSE is through cables.

C–ADS-Equipped Vehicle System	Operational Need Identifier	Operational Need	Functional Requirement Identifier	Functional Requirement
RSE	TSMO UC2-N11	Need for the status and intent data from C–ADS-equipped vehicles in the communication area	TSMO UC2-R09	The central computer shall be able to send vehicle-specific advisory data and the SPaT plan to the corresponding RSE in real time. The connection between the central computer and the RSE is through cables.

C–ADS = cooperative automated driving system; C–V2X = cellular vehicle-to-everything; CDA = cooperative driving automation; CTSE = critical time step estimation; DSRC = dedicated short-range communication; Hz = hertz; MPC = model predictive control; PID = proportional-integral-derivative; RSE = roadside equipment; SPaT = signal phase and timing; TS = trajectory smoothing; TSMO = transportation systems management and operations; UC2 = use case 2; V2V = vehicle-to-vehicle.

PERFORMANCE METRICS AND TARGETS

The effectiveness of TSMO use cases must be evaluated by measuring their capability to positively impact 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—separation distances are the 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—travel speeds driven are the speeds driven by each vehicle during the tests, which will be used for evaluating the driving smoothness within the control area.

- Acceleration profile—acceleration profile is the accelerations of each vehicle at different time steps during the tests, which will be used for approximating fuel/energy consumption.

- Speed control error—speed control error refers to the 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—CTSE error refers to the differences between the estimated critical time steps and the actual critical time steps 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—this performance metric captures all data exchanges from V2V, V2I, and I2V to determine whether communication and/or the 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 difference between message origination on vehicle A and the reading of the message by infrastructure, and vice versa. The latency time includes the time to compose the message, send the message from vehicle A's computer to vehicle A's OBU, the queuing time on vehicle A's OBU, the radio transmission from vehicle A to infrastructure, the message constitution and queueing

on RSE, message transmission from RSE to the infrastructure's computer, and the time for infrastructure's decomposition and reading time.

Performance Metrics for Traffic Performance

This subsection identifies the performance measures on traffic performance to be used to evaluate the impact of TSMO use cases on traffic flow at intersections. Five main categories of impacts(20) are identified and summarized in table 10.

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

Safety

Safety is an essential factor in evaluating the impacts of CDA technologies. Because human errors cause the majority of crashes(21), automated vehicles have the potential to significantly decrease the number of crashes, particularly at high-market-penetration levels. One may quantify safety improvements by calculating safety surrogate measures (e.g., time to collisions).

Throughput

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

Stability

Several stability indices developed in the literature can be used. For example, string stability is stability with respect to intervehicular spacing 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 because of a perturbation (e.g., accident or sudden braking). CDA technologies are expected to improve traffic flow reliabilities by providing smoother, safer, and more responsive vehicle operations. The use case can employ multiple measures to quantify CDA impacts on flow breakdown and reliability, such as occurrence of shock waves and the severity of shock waves formed.

Sustainability

The environmental impacts of CDA are uncertain. On one hand, smoother operations associated with CDA can lead to lower greenhouse gas emissions and energy consumption. On the other hand, the CDA impacts on travel demand are uncertain and could result in higher overall travel volume, which would increase emissions and energy consumption. The trade-offs between the higher efficiency of flows and higher demand require further research.

Calculating emissions and energy consumption is usually an offline process that uses data previously obtained by simulation or observed data.[22] Several methods are available in the literature for that purpose at different data aggregation levels. For the proposed use case, 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 measures include carbon dioxide, nitrogen oxide, and 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 number of crashes	Number of crashes
Safety	Improvement in safety outcome of crashes	Severity of crashes
Throughput	Increase in traffic flow volumes	Number of vehicles passing through the intersection per 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 greenhouse gas emissions	Level of carbon dioxide, nitrogen oxide, and particulate matter equivalent emissions
Sustainability	Reduction in energy consumption	Amount of energy consumed

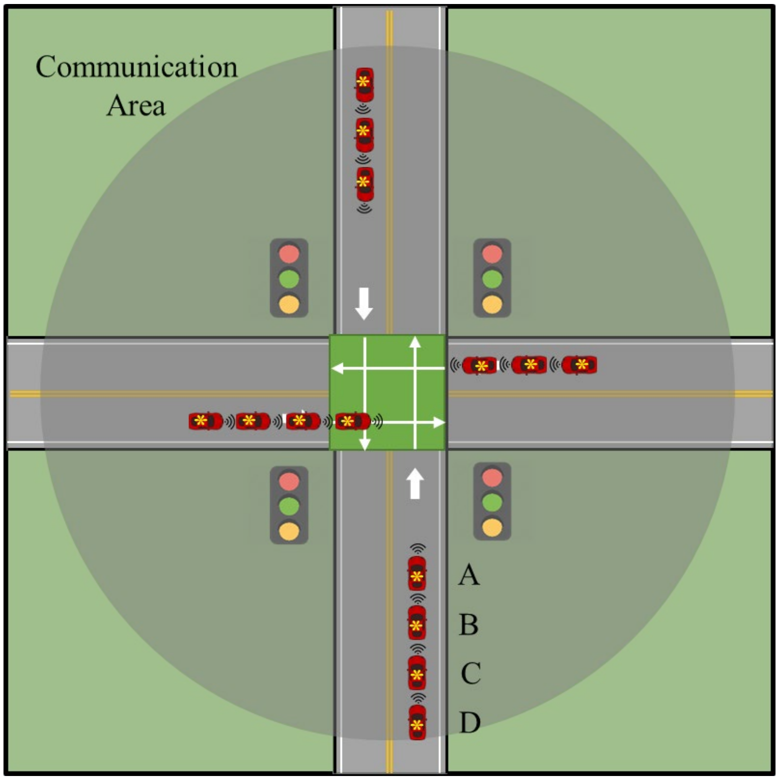
CHAPTER 4. OPERATIONAL SCENARIOS

This chapter identifies TSMO UC2's operational scenarios to enhance TSMO at signalized intersections with fixed-time/actuated signal settings, as well as to understand the impact of early deployment of CDA on traffic operations. An illustrative operational scenario is described wherein a set of vehicles enter the communication area of an isolated, four-way one-lane (in each direction) signalized intersection with a fixed-time/actuated signal setting. They engage in the CDA features described in the previous chapter and move through the intersection. This scenario is described for the existing human-driven vehicles and C–ADS-equipped vehicles with different cooperation classes. This scenario is designed to cover all key features of the proposed control framework and to illustrate their potential benefits.

As shown in figure 6A, vehicles A, B, C, and D 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 D. As shown in figure 6B, if vehicles are without CDA systems, they are unaware of the SPaT information and will proceed according to the predefined car-following model. If all vehicles are equipped with CDA systems with cooperation class A or higher, however, they will receive the SPaT plan and other vehicles' status and intents. And therefore, they will be able to predict their own ETs and plan their smooth trajectories (figure 6C).

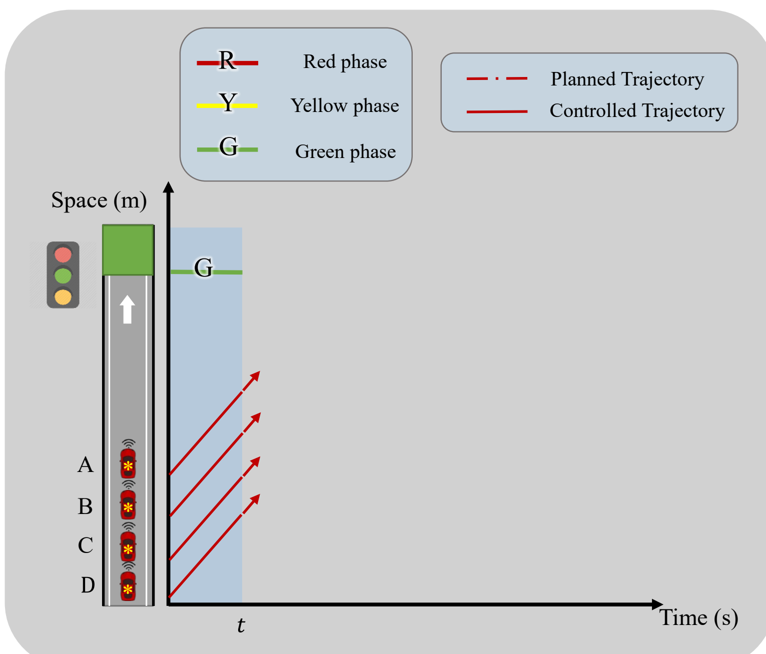
Further, figure 6D and figure 6E show the investigated scenarios after the first green phase for vehicles A, B, C, and D. As shown in figure 6D where vehicles are without CDA systems, vehicles A, B, C, and D must stop at the red signal indication and wait for the light to turn green. After the light turns green for these vehicles, they will accelerate to pass the intersection box. The time it takes for vehicles A, B, and C to accelerate from zero speed will prohibit vehicle D from entering the intersection box at the green signal indication. Therefore, vehicle D has to stop at the red signal indication again and wait for the next green signal indication. As shown in figure 6E, however, because vehicles are aware of the SPaT plan, they control their trajectories such that they can enter the intersection box at the green signal indication at the maximum speed. Therefore, vehicle D can also pass the intersection at the first green signal indication and can proceed before the next cycle.

Overall, this operational scenario illustrates the effectiveness of the proposed control framework at signalized intersections. It is shown by this operational scenario that the combination of V2V and vehicle-to-RSE cooperation both enhances the overall traffic system performance and also improves individual vehicle travel experiences.



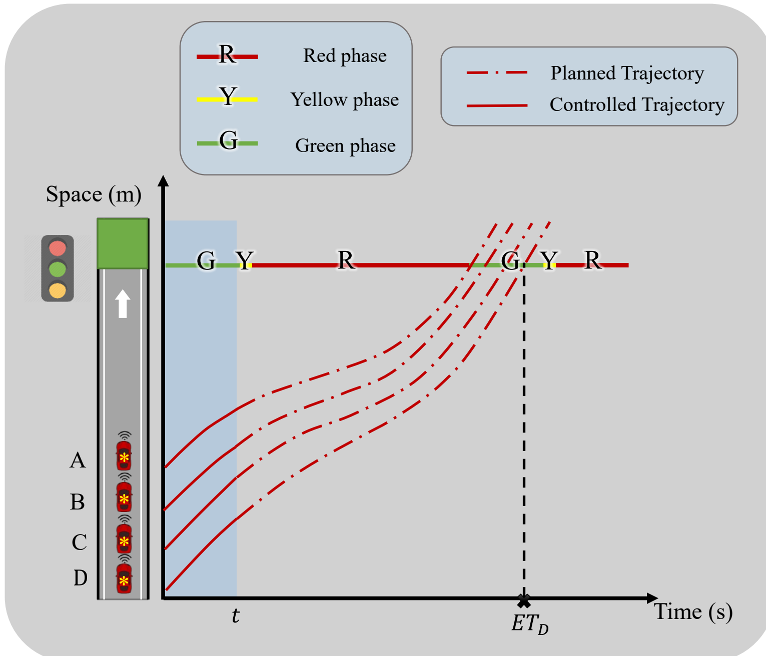
Source: FHWA.

A. Four-way single-lane signalized intersection with a fixed-time/actuated signal setting.



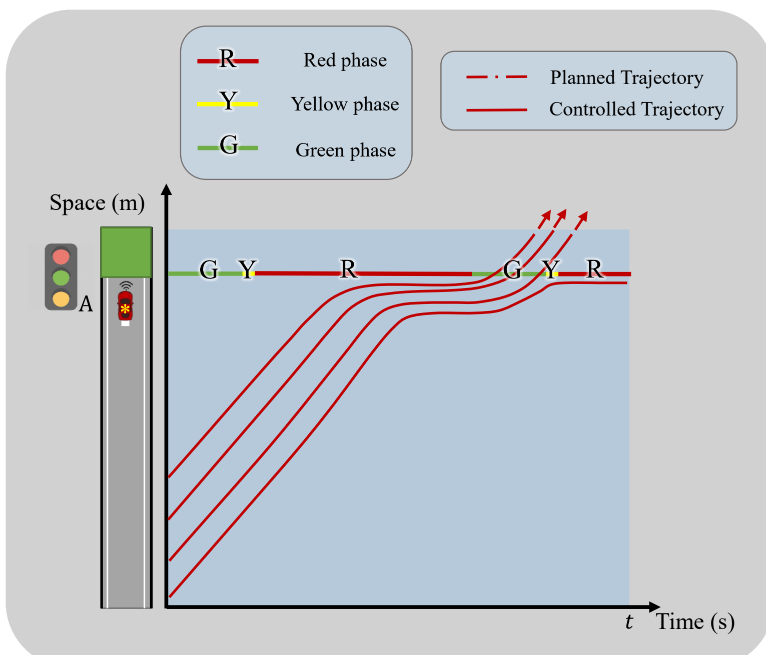
Source: FHWA.

B. Existing human-driven vehicles—before green.



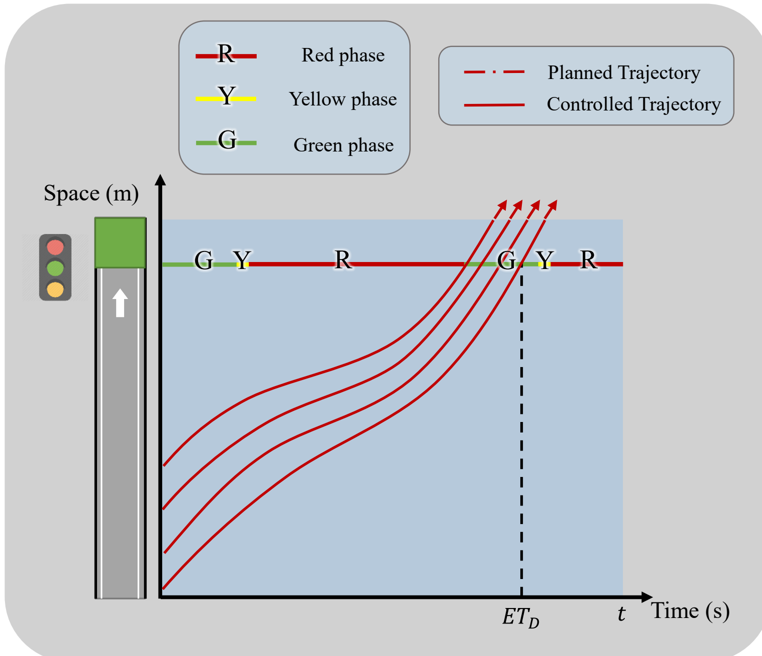
Source: FHWA.

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



Source: FHWA.

D. Existing human-driven vehicles—after green.



Source: FHWA.

ET_D = entering time of vehicle D.

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

Figure 6. Illustration. Cooperative driving automation operational scenario.

CHAPTER 5. ANALYSIS OF THE PROPOSED SYSTEM

This chapter provides an analysis of the benefits, advantages, limitations, and disadvantages of TSMO UC2 at signalized intersections with a fixed-time/actuated signal setting. A high-level system validation plan is also discussed.

SUMMARY OF POTENTIAL BENEFITS AND OPPORTUNITIES

CDA technologies enable mobility applications that individual ADS-operated vehicles cannot achieve. They do so by sharing information that can be used to increase the safety, efficiency, and reliability of the transportation system. They 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. This is accomplished, for example, by sharing information that can be used directly or indirectly to influence DDT by one or more nearby road users. Vehicles and infrastructure elements engaged in CDA may share information, such as status (e.g., vehicle position, speed) and intent (e.g., estimated entering time, the 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 UC2, a cooperative control framework is proposed to control C–ADS-equipped vehicles at signalized intersections efficiently with a fixed-time/actuated signal setting. The proposed framework is illustrated for different cooperation classes defined in SAE J3216 and contains two main components: 1) CTSE and 2) TS. The CTSE component aims to estimate an entering time to the intersection box for each individual vehicle with the available SPaT plan, which will be called by either RSE or the vehicle itself, depending on its cooperation class. The TS component aims to smooth vehicle trajectories with the estimated entering time, which will be 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, it much reduces operational complexity and associated risks and liabilities for traffic operators. Also, it distributes the computational burden among different entities in an edging computing structure and thus makes it much more suitable for real-time applications. Further, as illustrated by an operational scenario in chapter 4, the combination of cooperation between vehicles and between vehicles and RSE can enhance the overall traffic system performance (as a result of the shared SPaT plan, the CTSE component, and the TS component together) and improve individual vehicle travel experiences (as a result of the TS component). It is expected from the proposed control framework to reduce the stop-and-go traffic pattern and the backward shock wave propagations, increase the throughput, and maintain safety for each vehicle at signalized intersections with a fixed-time/actuated 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 UC2. The purpose of the validation testing is to ensure the developed TSMO UC2 system can meet all of the operational needs listed in table 7 of chapter 3.

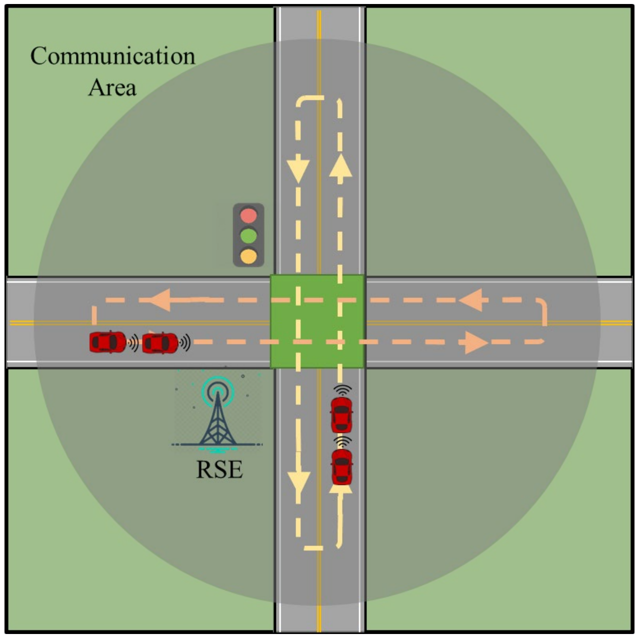
Simulation Testing

Simulations can be designed to test the developed algorithm for TSMO UC2 using the performance metrics identified in chapter 3 in terms of vehicle behavior and traffic system performance. Different types of simulation 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 with the limited number of vehicles and length of roadway for ADS simulators) to 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 information, and intersection geometry. Usually, the CDA control algorithms will be simplified from real software and parsimonious to calibrated/validated CDA behavioral models/algorithms that are implementable for large-scale testing.

Field Testing

To ensure 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. This can be demonstrated onsite at a signalized intersection with a fixed-time/actuated signal setting typical of anywhere in the United States. Depending on participation by partners, multiple CARMA vehicles loaded with feature groups can be instructed to run loops on the test track to represent continuous driving, as shown in figure 7. The operational scenario discussed in chapter 4 can be tested. The purpose of testing can be to verify the software, collect vehicle behavior performance measures, and to validate if the software meets the requirements. Note that 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. This can enable better validated evaluation of CDA’s traffic impacts in simulation.



Source: FHWA.

RSE = roadside equipment

Figure 7. Illustration. Experimental plan for signalized intersection control.

SUMMARY OF IMPACTS

The proposed control strategy for TSMO UC2 will have a significant impact on research and operations of future transportation systems management. From a research perspective, TSMO UC2 offers a unique approach to manage efficiently transportation systems at signalized intersections and reduce any type of disutilities, such as excessive delay and emissions. The benefits of TSMO UC2 can be realized only when cooperative control can be enabled by effective algorithms, including those for 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 UC2 presents significant changes to how TSMO is conducted at signalized intersections. Intelligent transportation system infrastructure 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. CDA technologies can enhance those conventional strategies for TSMO with which agencies are already familiar.

DISADVANTAGES AND LIMITATIONS

Although the proposed control strategy for TSMO UC2 provides advantageous insights to CDA operations at signalized intersections, it might suffer from a number of disadvantages and limitations that need to be further investigated:

- The proposed CTSE component requires a centralized unit.
- The cooperation level of C–ADS-equipped vehicles highly affects the performance of the traffic.
- The proposed algorithm focuses on pure automated traffic, and the full benefits of the proposed control framework 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 because the signal timing plan is not adaptive to real-time traffic information.

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