Cooperative Automation Research: CARMA Proof-of-Concept Transportation System Management and Operations Use Case 1 - Basic Arterial Travel—Stop-Controlled Intersections

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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 support coordinated movement, with the aim of improving the safety, traffic throughput, and energy efficiency of the transportation network.

In 2015 the Office of Operations Research and Development at FHWA developed a cooperative adaptive cruise control proof-of-concept prototype, 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 support cooperative automation strategies by ADS-equipped vehicles. This project expands CARMA functionality to include transportation systems management and operations (TSMO) strategies on surface arterials with intersections. The intended audience for this report is CDA stakeholders such as system developers, analysts, researchers, and application developers.

This is the first in a series of four proof-of-concept reports exploring research and development for the basic TSMO use cases on arterials. This report focuses on the *Basic Arterial Travel–Stop-Controlled Intersections* use case.

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)		8. Performing Organization Report No.
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16. Abstract Cooperative driving automation (CDA) aims to improve the safety, traffic throughput, and energy efficiency of the transportation network by allowing vehicles and infrastructure to work together to coordinate movement. The objective of this project is to advance the CARMA ecosystem to enable further capabilities for CDA participants to interact with the road infrastructure, enhance infrastructure performance, improve network efficiency, and, ultimately, reduce traffic congestion through transportation systems management and operations (TSMO) strategies on arterials. The focus of this concept of operations is TSMO Use Case 1 (UC1), or *Basic Arterial Travel–Stop-Controlled Intersections*. The proposed approach for TSMO UC1 has two main components. The first component is designed to run on the roadside equipment, and the second component is designed to run on vehicles (designed for CARMA Platform℠). It is expected that this approach will increase throughput and reduce energy consumption while ensuring safety at unsignalized intersections.		

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

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

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2,000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	2.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

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

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LIST OF ACRONYMS

ACC	adaptive cruise control
ADS	automated driving system
CACC	cooperative adaptive cruise control
C–ADS	cooperative automated driving system
CDA	cooperative driving automation
ConOps	concept of operations
CTSE	critical time step estimation
C–V2X	cellular vehicle-to-everything
DDT	dynamic driving task
DSRC	dedicated short-range communication
DV	discharging vehicle
EAD	eco-approach and departure
EST	earliest stopping time
ET	entering time
EV	entering vehicle
FCFS	first come, first served
FHWA	Federal Highway Administration
GHG	greenhouse gas
HRDO	Office of Operations Research and Development
Hz	hertz
I2V	infrastructure-to-vehicle
ID	identifier
IOO	infrastructure owner and operator
MPC	model predictive control
OBU	onboard unit
PID	proportional-integral-derivative
RDV	ready-to-depart vehicle
RSE	roadside equipment
SPaT	signal phase and timing
ST	stopping time
STOL	Saxton Transportation Operations Laboratory
TS	trajectory smoothing
TSMO	transportation system management and operations
UC1	Use Case 1
V2I	vehicle-to-infrastructure

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 International® 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). Onsite research and development are 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 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™ 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 ADS, first to the SAE Level 3 (conditional driving automation) and then to full automation. The approach takes advantage of an open-source ADS platform, Autoware®, to enable ADS functionality to be used for cooperative automation strategies.

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 with infrastructure 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 the CDA research at universities and with other research groups. Table 1 lists various projects associated with this development effort.

Table 1. Projects associated with this development effort.

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

STOL = Saxton Transportation Operations Laboratory.

Objective

This project, *FHWA Cooperative Automation Research: CARMA Proof-of-Concept TSMO Use Case Testing*, will extend the research from Prototype II (693JJ318F000225) 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. This particular use case discussed in this document, TSMO Use Case 1 (UC1), focuses on incorporating vehicle coordination with C–ADS-equipped vehicle trajectory optimization at stop-controlled intersections. The aim of this project is to address three, high-level objectives on a tactical level: reduce traffic congestion, improve energy efficiency, and increase infrastructure efficiency. This project investigates to what extent these objectives can be achieved for different cooperation classes as given by the SAE J3216™ standard. This project is be supported by a team of CARMA participants for development and testing.

Transportation System Management and Operations Arterial Use Cases

- UC1—vehicle coordination and trajectory optimization – stop-controlled intersections.
- Use Case 2—trajectory optimization – fixed-time and actuated signals.
- Use Case 3—signal phase and timing (SPaT) plan and trajectory optimization – adaptive traffic signals.
- Use Case 4—dynamic lane assignment integrated with SPaT plan and trajectory optimization – active traffic management.

Audience

The intended audience for this document includes:

- U.S. Department of Transportation and CDA stakeholders, including program managers, assistant managers, research engineers, 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 ConOps 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 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 UC1 system capabilities and their operations and presents detailed descriptions of operational concepts.
- Chapter 4 describes operational scenarios of TSMO UC1 at stop-controlled 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 stop-controlled intersections (i.e., unsignalized intersections with stop signs). It examines the current application of CDA technologies that reduce traffic congestion at intersections, highlighting some of the advantages and disadvantages of the existing solutions, which are now motivating the development of new CDA solutions to congestion and energy problems at stop-controlled 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 a common conflict area that may produce widespread mobility, safety, and environmental benefits. With these emerging technologies, the passing sequence of C–ADS-equipped vehicles at an intersection can be further improved with proper coordination (e.g., allowing movements without conflict to take place simultaneously at an intersection instead of only allowing one vehicle to proceed at the intersection at a time) to increase traffic throughput.

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.

In light of these benefits, researchers have conducted studies on CDA operations at various stop-controlled intersections. They seek a proper departure sequence of C–ADS-equipped vehicles by applying either decentralized or centralized control. In decentralized control, each individual C–ADS-equipped vehicle approaching a conflict area determines its own operations based on the information received from the coordinator and/or other C–ADS-equipped vehicles.

(See references 2, 3, 4, 5, 6, 7, and 8.) In centralized control, the best departure sequence of all C–ADS-equipped vehicles in the traffic stream is determined to maximize the system performance in terms of optimizing a systematic objective, e.g., minimizing total travel time delay and maximizing the throughput of the traffic flow at a conflict area. (See references 9, 10, 11, 12, 13, 14, 15, and 16.)

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.[(17)] 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 with two corridors with six connected signalized intersections that could communicate their SPaT information. Ma et al.[(18)] tested and verified the newly developed algorithms on an innovative CDA platform and quantified the fuel saving benefits of eco-drive. Furthermore, the project Integrated Prototype I also developed the Glidepath Prototype System,[(19)] which developed, demonstrated, and evaluated a partially automated vehicle system with an eco-approach and departure (EAD) feature. In terms of vehicle coordination and real-time vehicle operations at stop-controlled intersections, however, no studies have been implemented on real vehicles and infrastructures.

OPPORTUNITIES FOR CHANGES

Although the existing studies bring advantageous insights into CDA operations at intersections, they face several 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 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), but 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,[(20)] defines classes of cooperation. The classes address different capabilities of a C–ADS-equipped 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 at intersections, considering different cooperation classes. Several 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.

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

[*] = improved object and event detection prediction through CDA class A and B status and intent sharing may not always be realized, given that Level 1 and 2 driving automation features may be overridden by the driver at any time, and otherwise have limited sensing capabilities compared with Level 3, 4, and 5 ADS-operated vehicles. [**] = class A and B communications are one of many inputs to an ADS's object and event detection and prediction capability, which may not be improved by the CDA message. ADS = automated driving system; C–ADS = cooperative automated driving system; 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
EAD	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: C–ADS-equipped vehicles → RSE RSE → C–ADS-equipped vehicles C–ADS-equipped vehicles → C–ADS-equipped vehicles	SPaT messages Velocity profile 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 will typically send the message to multiple CDA devices in the vicinity. C–ADS = cooperative automated driving system; CDA = cooperative driving automation; RSE = roadside equipment; SPaT = signal phase and timing.

To fill the existing research gaps, this ConOps proposes an edge-computing-based cooperative control framework for C–ADS-equipped vehicles at a stop-controlled 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 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 users' perspective:

- Smoother, faster, and more efficient travel—together, cooperative coordination of vehicles at intersections and controlling trajectories 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—the combination of cooperative vehicle coordination and trajectory control can substantially reduce travel delay and uncertainty in travel times by better scheduling vehicles at intersections, 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.(21) Further smoothed vehicle trajectories with proper trajectory control reduce risks and the 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 the

elimination of stop-and-go movements, reduction in travel delay and energy consumption, and improvement of travel time reliability, among others.

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

Table 4. Transportation user characteristics and needs.

Driving Mode	Transportation User Categories	User Characteristics and Needs
Human Driving	Regular human driver	Regular human drivers have neither connectivity nor automation capability, and have uncertain driver behavior. Needs alignment with general transportation user needs as defined.
Human Driving	Connected human driver	Connected human drivers receive additional traveler information and can make better informed travel decisions. Needs alignment with general transportation user needs as defined.
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).(22)

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, enhanced safety, and improved driver experience. These benefits will increase as the fraction of C–ADS-equipped vehicles using the intersection, as compared with the total number of users, increases.

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

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

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

JUSTIFICATION FOR AND NATURE OF CHANGES

The transportation industry is moving toward improving safety with automated driving systems 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—a 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 includes vehicle speed and location data collected and disseminated by vehicles as part of a connected system. These data also include traditional detection sources (e.g., inductive loop detectors, overhead radar, and closed-circuit television cameras) that provide traffic data for the system.
    - 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., roadside units), 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) and the computational resources to implement the new control software.
- Develop/acquire new software—the application(s) should:
  - Make use of the frequently collected and rapidly disseminated multisource data drawn from connected travelers, vehicles, and infrastructure.
  - Include a vehicle awareness device (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 needed CDA data.
  - Enable systems and algorithms that can generate traffic condition predictions, alternative scenarios, and solution evaluations in real time.
  - Contain microscopic and macroscopic traffic simulations.
  - Incorporate real-time and historical data.
  - Utilize traffic optimization models.
  - Encourage the constant evaluation, adjustment, and improvement of traffic optimization models (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 operational policy 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 will activities be performed?
- Why are the strategies being used?
- How will the system be operated and maintained?

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 UC1. It describes how automated driving technology can be used in a cooperative manner from when CDA vehicles enter the communication area of stop-controlled intersections (i.e., unsignalized intersections with stop signs) until they exit the communication area. 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 TSMO BASIC ARTERIAL TRAFFIC USE CASE

This section describes the tentative algorithm framework of CDA applications for TSMO UC1. In this framework, the focus is on a stop-controlled intersection formed by multilane approaches, as illustrated in figure 1. The proposed algorithm is developed for the fully connected and fully 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 speeds of approaches, lane width). There exists a stop bar—the location vehicles must stop completely before entering the intersection box—on each entry lane right before the intersection box. Each lane of an entry approach might be assigned to one or more movement groups (i.e., through, left-turn, and right-turn). Therefore, the information regarding the current position and lane of a vehicle does not determine the movement group of the vehicle; thus, each vehicle’s movement group is considered as intent information. Further, no lane-changing process is allowed in the communication area of the intersection.

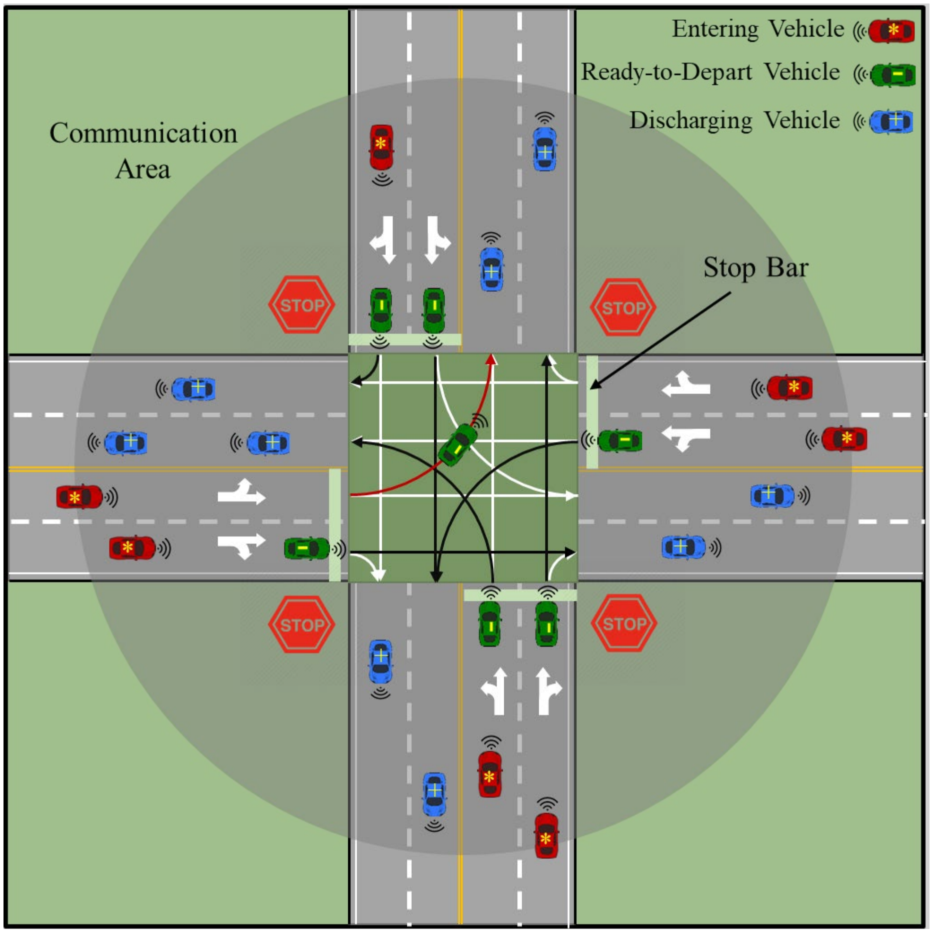
In this framework, all vehicles are assumed to be equipped with CDA technologies. The infrastructure at the intersection is assumed to be equipped with the needed software and hardware to allow it transmit information to, and receive information from, all vehicles. The communication area of the intersection is defined as the area around the intersection in which the infrastructure can communicate with vehicles. If needed, the communication area can be expanded by adding more RSE to relay the communications. This way, all vehicles inside the communication area of the intersection can broadcast their real-time information regarding their operational status (e.g., location, speed, acceleration, vehicle type) and intents (e.g., movement group, stopping time [ST] at the stop line, entering time [ET] 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., the first available time to enter the intersection box) to the vehicles. This section also discusses the performance of the proposed control mechanism for different CDA cooperation classes.

Further, 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 stop-controlled intersection. The algorithm contains a set of hard safety constraints that avoid 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 stop-controlled intersections by minimizing vehicles' ETs 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 stop-controlled intersection.

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

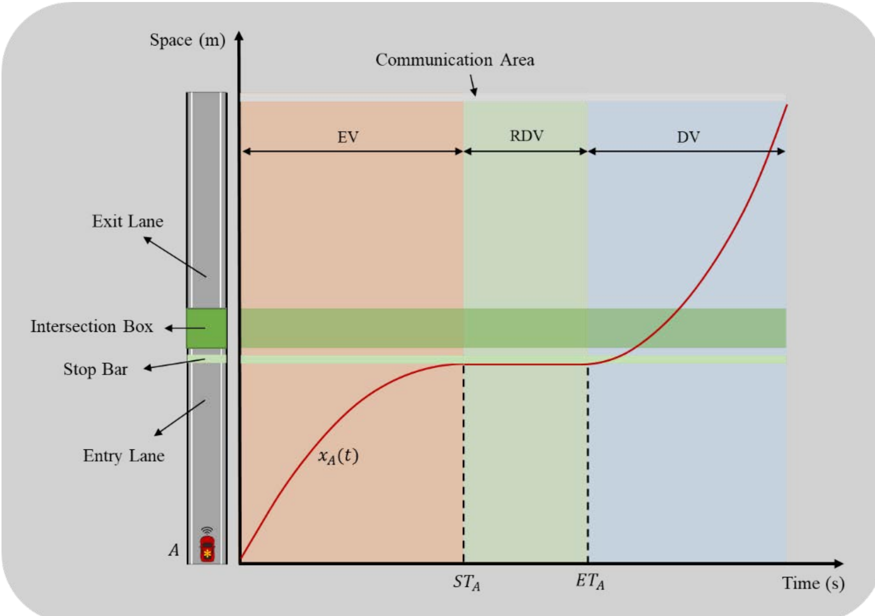
- Entering vehicles (EV)—vehicles that are approaching the intersection and cannot enter the intersection box in the next time step (shown as red vehicles with star symbol in figure 1).

- Ready-to-depart vehicles (RDV)—vehicles that are stopped at the stop bars or moving within the intersection box (shown as green vehicles with dash symbol in figure 1). Note that if there is more than one vehicle from an entry lane stopped at the intersection, only the leading vehicle will be considered as RDV and the rest will be still considered as EVs. Each RDV is associated with a fixed order index in the RDV departure sequence.

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

A vehicle entering the communication area will initially join the EV set and start transmitting information to RSE and other vehicles. As soon as the vehicle comes to a complete stop at the stop bar and is ready to depart (i.e., the vehicle is stopped at the intersection and is the leading vehicle on the corresponding entry lane), it will be removed from the EV set and will be added to the RDV list. The time step at which an EV joins the RDV set—referred to as the stopping time (ST)—will be stored by the vehicle to be used later in the algorithm. It is part of the status information of RDVs. Each RDV will then enter the intersection box at a given ET. Further, as soon as the vehicle departs the intersection box, the state of the vehicle will change to DV. Finally, the vehicle will be removed from the DV list as soon as it leaves the communication area. The vehicles are placed into these three different sets because the algorithm might control different vehicle sets with different logic.

Figure 2 illustrates the state transition of a vehicle and the definition of ST and ET. Note the focus of this algorithm is on an isolated intersection, which indicates that no bottleneck is considered at the end of 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.

EV = entering vehicle; RDV = ready-to-depart vehicle; DV = discharging vehicle; ST_A = stopping time of vehicle A; ET_A = entering time of vehicle A; $x_A(t)$ = trajectory of vehicle A.

Figure 2. Illustration. Vehicles' state transition, stopping time, and entering time.

The algorithm framework in this ConOps is designed to run on both vehicles and the 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 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 a set of critical time steps (e.g., ST at the stop bar, ET 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 1: Vehicle Coordination and Trajectory Optimization (Stop-Controlled Intersections)

- UC1.1- CTSE—estimating a set of critical time steps for C–ADS-equipped vehicles.
- UC1.2- TS—smoothing C–ADS-equipped vehicle trajectories with the estimated critical time steps.

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

Critical Time Step Estimation

The CTSE component aims to predict the future states of the intersection to improve traffic throughput and reduce traffic congestion. At the intersection box, the first come, first served (FCFS) rule is imposed. This FCFS rule is applied based on the sequence of vehicles stopping at the stop bar (joining the RDV set) to represent a real-world stop-controlled intersection. This indicates that as soon as a vehicle stops at the stop bar (joining the RDV set), it will reserve the next position in the departure sequence and cannot enter the intersection box earlier than the already stopped vehicles.

At each time step *t*, each EV needs to estimate/receive an ST based on the traffic condition inside the communication area, and each RDV needs to estimate/receive an ET based on the stopping sequence of existing RDVs at the stop bars. Note that the estimated ST of an EV would be always greater than or equal to its estimated earliest stopping time (EST), which is the earliest time that it can arrive and stop at the stop bar, considering speed and acceleration constraints. This way, the estimated ST 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 these time steps might be done by the vehicles themselves based on 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 cooperation class. 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 transmit their current status only 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 make any changes in the sequence of EVs coming to stop at the stop bar, and RSE may just serve as an information relay station to assist the information exchanges between vehicles. Note that the vehicles' directions are considered as vehicles' intents and are not shared across vehicles in this cooperation class. Therefore, only one vehicle at a time can enter the intersection box.

The departure sequence of RDVs in this class follows the FCFS rule depending on their STs. Further, with the information received from the other vehicles, each EV estimates an earliest possible ST depending on the preceding vehicles' current status and the departure sequence of the existing RDVs. This way, each EV will try to reach the stop bar as soon as possible to reserve the intersection at the first possible time.

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 make any changes in the sequence of EVs coming to stop at the stop bar. The only difference from class A is that the information regarding vehicles' directions are shared across all vehicles in this cooperation class. Therefore, while satisfying the FCFS rule at the intersection, multiple vehicles may use the intersection box simultaneously if their movement directions do not conflict with each other.

The estimation of ETs for RDVs and STs for EVs follow a similar procedure to the one used in class A cooperation. As the vehicles' intents are shared across all vehicles in this class of cooperation, however, the estimation of these time steps becomes more accurate compared with the one in class A cooperation.

Class C Cooperation

In this cooperation class, C–ADS-equipped vehicles will transmit their current status and intents to each other. As opposed to class A and class B, vehicles in this class have negotiation capabilities; and thus, the CTSE component at RSE can assist the traffic system and EVs by deciding a proper sequence of EVs coming to stop at the stop bar. Vehicles might reject the instruction of RSE and follow their own plan, however, like those in class B. Further, as with that in class B, the information regarding vehicles' directions is shared across all vehicles in this cooperation class. Therefore, while satisfying the FCFS rule at the intersection, multiple vehicles may use the intersection box simultaneously if their movement directions do not conflict with each other.

The departure sequence of RDVs in this class follows the FCFS rule depending on their STs and the estimation of ETs for RDVs follows the same procedure described for class B cooperation. EVs in class C and class D cooperation, however, are the main beneficiaries of the CDA technology. At each time step, RSE follows a defined greedy algorithm to schedule all EVs to a set of STs such that: first, vehicles without conflicting directions be grouped together and pass the intersection box simultaneously; and second, as soon as a vehicle stops at the stop bar, it can enter the intersection box (i.e., the estimated ST be equal to the estimated ET). This will minimize the unnecessary stop-and-go traffic patterns and backward shock wave propagations. Now, if a vehicle is unwilling to accept RSE's suggestion, it will estimate its own ST with the same procedure defined for class B cooperation.

Class D Cooperation

In this cooperation class, C–ADS-equipped vehicles will transmit their current status and intents to each other. As with those in class C, C–ADS-equipped vehicles in this cooperation class have negotiation capabilities; and thus, the CTSE component at RSE can assist the traffic system and EVs by deciding a proper sequence of EVs coming to stop at the stop bar. As opposed to those in class C, vehicles cannot reject and must obey the instructions of RSE. Further, similar to that in classes B and C, the information regarding vehicles' directions is shared across all vehicles in this cooperation class. Therefore, while satisfying the FCFS rule at the intersection, multiple vehicles may use the intersection box simultaneously if their movement directions do not conflict with each other.

The CTSE component follows the exact procedure described for class C cooperation. The only difference here is that all EVs are forced accept the RSE's suggestions and will follow the received STs from RSE. Therefore, the traffic performance in this class of cooperation is expected to be improved compared with other class of cooperation.

Further, these estimated/received critical time steps serve as the inputs of the TS component. With these available critical time steps, 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 the stop-and-go traffic patterns at stop-controlled 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.

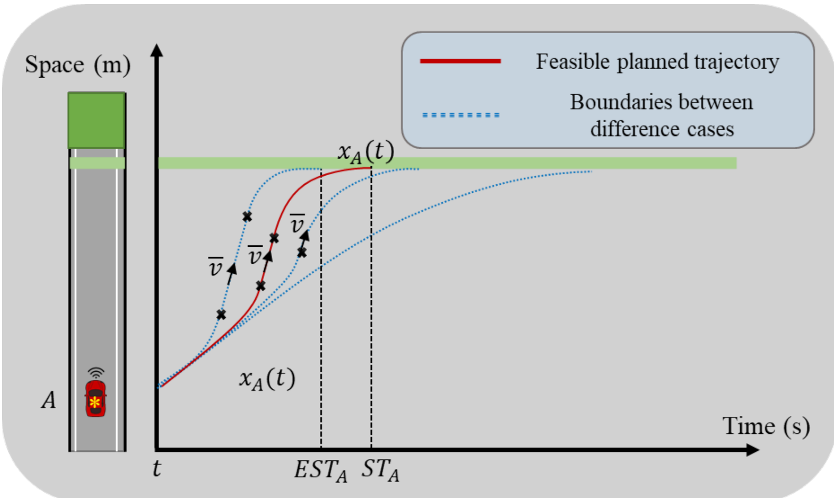
Trajectory Planning

This function will first plan a smooth trajectory profile for each vehicle approaching the intersection (i.e., each EV) based on the received vehicle's status (e.g., current location, speed, acceleration, lane, maximum acceleration/ deceleration rate), intents (e.g., directions), and the estimated/received critical time steps from the CTSE component (e.g., ST, ET). Then it will determine a desired speed for the next time step based on the obtained smooth trajectory. Note that RDVs that are allowed to enter the intersection box aim to pass the intersection box with maximum possible speed, and DVs that already have departed the intersection box will not face any bottleneck and simply will follow their predefined car-following behavior. Therefore, RDVs and DVs do not need to plan their detailed trajectories.

The smooth vehicle trajectories are constructed with a polynomial equation using the entry and exit boundaries. This function constructs a smooth trajectory for each vehicle individually, without considering safety constraints. The safety constraints, however, are considered in a safety feature after the smoothed trajectory is planned; the safety feature will guarantee a safe/comfortable travel experience, as safety is the primary objective of this algorithm. Because all C–ADS-equipped vehicles with different cooperation classes are able to estimate their own STs, 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.

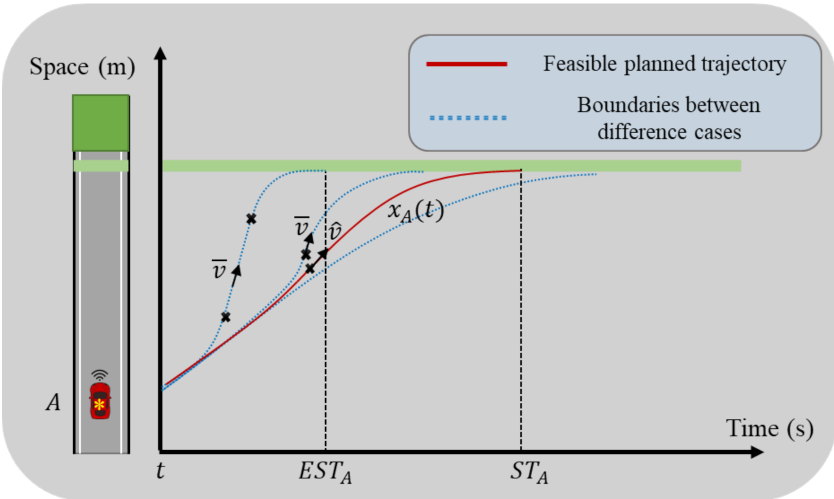
Regardless of the C–ADS-equipped vehicles' cooperation class, each EV aims to smooth its own trajectory to stop at the stop bar at the estimated/received ST. The planned EV trajectory follows a third-, fourth-, or fifth-degree polynomial equation, depending on the available information as the entry and exit boundaries (e.g., current and target locations, speeds, and accelerations). The required variables for constructing trajectories with polynomial equations are the current and predicted STs, locations, and speeds (which enable the construction of third-order polynomial trajectories) and the rest (e.g., current and predicted departure 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 follow accurately 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 EST, the estimated/received ST, and the vehicle's current location and speed, the constructed smooth trajectory might fall in one of the illustrated three cases to ensure the speed and acceleration feasibility.



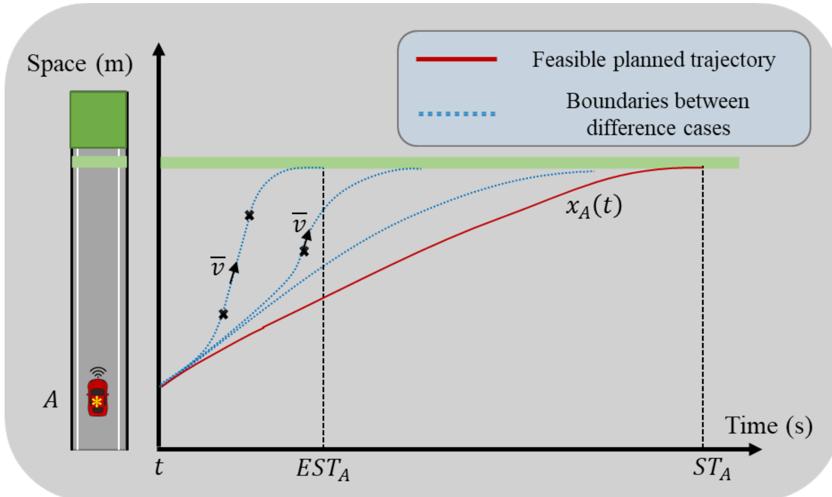
Source: FHWA.

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



Source: FHWA.

B. Case 2: Acceleration, deceleration.



Source: FHWA.

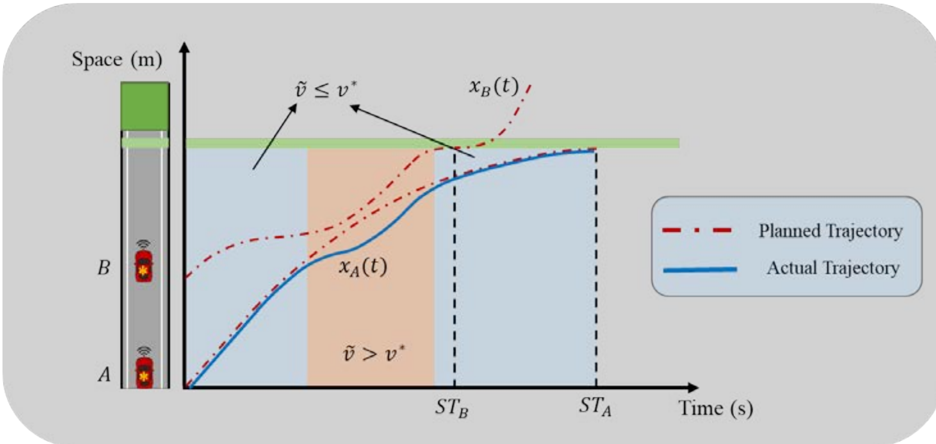
C. Case 3: Deceleration.

t = current time step; EST_A = earliest stopping time of vehicle A; ST_A = stopping time of vehicle A; $x_A(t)$ = trajectory of vehicle A; $\bar{v}$ = maximum speed; $\hat{v}$ = the joint speed between the acceleration and deceleration pieces.

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 does not guarantee that the planned trajectory is safe. 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 process data added to the actuator time), and its preceding vehicle's current location, speed, and acceleration. This way, if the speed obtained from a vehicle's planned trajectory, denoted by $\tilde{v}$, is greater than the determined maximum safe speed, the vehicle will follow the maximum safe speed. Otherwise, the vehicle will follow the speed obtained from the planned trajectory. An illustrative example is presented in figure 4.



Source: FHWA.

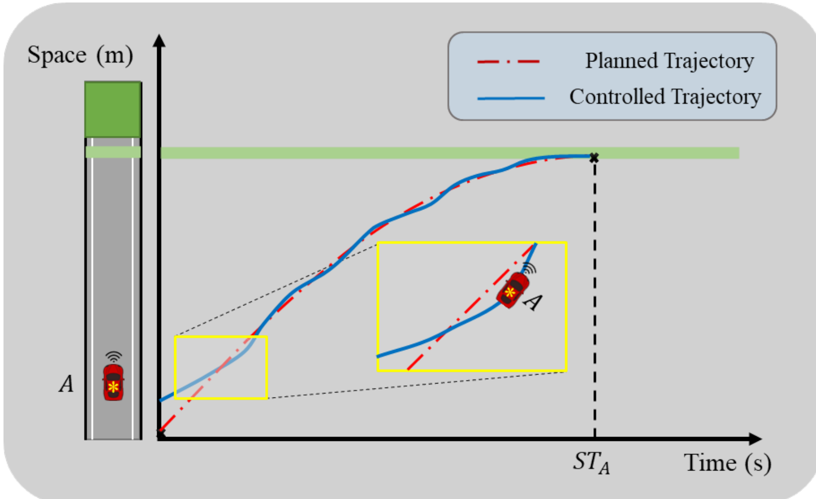
ST_A/ST_B = stopping time of vehicle A/B; $x_A(t)/x_B(t)$ = space-time trajectory of vehicle A/B; v^* = the maximum safe speed; $\tilde{v}$ = the speed obtained from the planned trajectory.

Figure 4. Illustration. Safety feature.

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

Trajectory Control

This function minimizes the control error of a vehicle following its planned trajectory profile. 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.

ST_A = stopping time of vehicle A.

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 stop-controlled 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 communications technology, 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 because 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 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 them with all other available information, and send the resulting pertinent information back to C–ADS-equipped vehicles. A list of needs for both road users and IOOs is shown in table 5. Note that in this table, road users are C–ADS-equipped vehicles, such that one-way or two-way information exchange can occur between road users and IOOs.

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

Road Users (C–ADS-Equipped Vehicles)	IOOs
Get maps for navigating to their destination, including turns	Monitor traffic conditions
Get information on traffic conditions ahead	Monitor environmental conditions
Get information on weather conditions	Receive traffic condition information from travelers
Get information on accessible lanes	Control access to lanes
Get information on current local speed limits	Control speed limits
Get information on the estimated critical time steps	Control vehicles' arrival sequence to the stop bar
Get information on any special rules that are currently being enforced	Control vehicles' entry sequence to the intersection box
Inform IOOs of observed traffic conditions	Inform travelers of their estimated critical time steps
Inform IOOs of observed weather conditions	Inform travelers of traffic conditions
Inform IOOs of their planned trajectories	Inform travelers of weather conditions
Inform IOOs of their status, intents, and what they see	Inform travelers of accessible lanes
	Inform travelers of current local speed limits
	Inform travelers of any special rules that are currently being enforced

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 • Estimated critical time steps • Other vehicles' information	• Vehicle current status, intent, etc. • Local world information sensed by each C–ADS-equipped vehicle

SUMMARY OF TRANSPORTATION SYSTEMS MANAGEMENT AND OPERATIONS NEEDS AND REQUIREMENTS

To summarize the discussion on key features of TSMO UC1 and guide the future development of requirements of the TSMO UC1 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. Also, transfer the information 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, stop bar's location, 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, ST at the stop bar, ET to the intersection box, departing time from the intersection box, etc. This data set may vary across different cooperation classes.

- Further, RSE advisory data may include the desired ST and desired ET for each C–ADS-equipped vehicle. Note that the central computer and RSEs in cooperation classes A and B are only needed for relay information purposes. They are not needed 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 1.

C–ADS-Equipped Vehicle System	ID#	Operational Need	Cooperation Classes
CTSE	TSMO UC1-N01	Need for static infrastructure data (e.g., MAP, speed limits, lane restrictions).	A and above.
CTSE	TSMO UC1-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.

C–ADS-Equipped Vehicle System	ID#	Operational Need	Cooperation Classes
CTSE	TSMO UC1-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 UC1-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 UC1-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 UC1-N06	Needs to store static infrastructure data (e.g., MAP, speed limits, lane restrictions).	A and above.
Central Computer	TSMO UC1-N07	Need for C–ADS-equipped vehicle status and intent information data received from all RSE.	A and above.
Central Computer	TSMO UC1-N08	Need for the capability to process relevant data to estimate vehicles' entering time to the intersection box.	A and above.
RSE	TSMO UC1-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 UC1-N010	Need for relay data received from other RSE sent from the central computer.	A and above.
RSE	TSMO UC1-N011	Need for vehicle-specific advisory data and the SPaT sent from the central computer.	A and above.

Table 8 illustrates 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 1.

Functional Requirement Identifier	Functional Requirement	Cooperation Classes
TSMO UC1-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 UC1-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 UC1-R03	A C–ADS-equipped vehicle with at least cooperation class A broadcasts its location, speed, heading, and brake status. The communication frequency is approximately 10 Hz or more.	A and above (status data only for class A).
TSMO UC1-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 UC1-R05	A C–ADS-equipped vehicle with at least cooperation class A avoids 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 modules are installed within each C–ADS-equipped vehicle. These safety modules 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 module, the communication frequency is approximately 10 Hz or more.	A and above.
TSMO UC1-R06	The central computer has storage and computational functions.	A and above.

Functional Requirement Identifier	Functional Requirement	Cooperation Classes
TSMO UC1-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 RSE is through cables.	A and above.
TSMO UC1-R08	The central computer processes and analyzes C–ADS-equipped vehicle status and intent information data received from RSE to compute the vehicle-specific advisory data.	A and above.
TSMO UC1-R09	The central computer sends vehicle-specific advisory data to the corresponding RSE in real time. The connection between the central computer and RSE is through cables.	A and above.
TSMO UC1-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 UC1-R11	RSE broadcasts the status and intent data among C–ADS-equipped vehicles through DSRC or C–V2X communications within the communication range. The communication frequency is approximately 10 Hz or more.	A and above (optional for when the CDA communication range is not enough and needs relay with RSE).
TSMO UC1-R12	RSE sends vehicle-specific advisory data through DSRC or C–V2X communications within its communication range. The communication frequency is approximately 10 Hz or more.	A and above.

Finally, the functional requirements described in table 8 for each of the operational needs illustrated in table 6 are presented in table 9.

Table 9. Needs-to-requirements traceability matrix for Transportation Systems Management and Operations Use Case 1.

C–ADS-Equipped Vehicle System	Operational Need Identifier	Operational Need	Functional Requirement Identifier	Functional Requirement
CTSE	TSMO UC1-N01	Need for static infrastructure data (e.g., MAP, speed limits, stop bar's location, lane restrictions).	TSMO UC1-R01	A C–ADS-equipped vehicle with at least cooperation class A has an onboard computer with storage and computing functions.
CTSE	TSMO UC1-N02	Need for advisory data (e.g., stopping time and entering time at the intersection box) from RSE.	TSMO UC1-R12	RSE sends vehicle-specific advisory data within its communication range. The communication frequency is approximately 10 Hz or more.
CTSE	TSMO UC1-N03	Need to process the status and intent data from other C–ADS-equipped vehicles and/or RSE advisory data to estimate some critical time steps.	TSMO UC1-R01	A C–ADS-equipped vehicle with at least cooperation class A has an onboard computer with storage and computing functions.
CTSE	TSMO UC1-N03	Need to process the status and intent data from other C–ADS-equipped vehicles and/or RSE advisory data to estimate some critical time steps.	TSMO UC1-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.

C–ADS-Equipped Vehicle System	Operational Need Identifier	Operational Need	Functional Requirement Identifier	Functional Requirement
CTSE	TSMO UC1-N03	Need to process the status and intent data from other C–ADS-equipped vehicles and/or RSE advisory data to estimate some critical time steps.	TSMO UC1-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, RSEs are installed along each road segment to relay the data.
CTSE	TSMO UC1-N03	Need to process the status and intent data from other C–ADS-equipped vehicles and/or RSE advisory data to estimate some critical time steps.	TSMO UC1-R11	RSE broadcasts the status and intent data among C–ADS-equipped vehicles through DSRC or C–V2X communications within the communication range. The communication frequency is approximately 10 Hz or more.
TS	TSMO UC1-N04	Need to plan and follow the future trajectory and speed profile from the current location and speed to the target location and speed at the target time.	TSMO UC1-R01	A C–ADS-equipped vehicle with at least cooperation class A has an onboard computer with storage and computing functions.
TS	TSMO UC1-N04	Need to plan and follow the future trajectory and speed profile from the current location and speed to the target location and speed at the target time.	TSMO UC1-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.

C–ADS-Equipped Vehicle System	Operational Need Identifier	Operational Need	Functional Requirement Identifier	Functional Requirement
TS	TSMO UC1-N05	Need for the status and intent data from the preceding C–ADS-equipped vehicles on the same lane for a car following/collision avoidance mechanism.	TSMO UC1-R01	A C–ADS-equipped vehicle with at least cooperation class A has an onboard computer with storage and computing functions.
TS	TSMO UC1-N05	Need for the status and intent data from the preceding C–ADS-equipped vehicles on the same lane for a car following/collision avoidance mechanism.	TSMO UC1-R02	A C–ADS-equipped vehicle with at least cooperation class A has a drive-by-wire control system, a navigation system, and corresponding algorithms (e.g., PID or MPC) to follow a given space-time trajectory.
TS	TSMO UC1-N05	Need for the status and intent data from the preceding C–ADS-equipped vehicles on the same lane for a car following/collision avoidance mechanism.	TSMO UC1-R05	A C–ADS-equipped vehicle with at least cooperation class A avoids 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 modules shall be installed within each C–ADS-equipped vehicle. These safety modules 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 module, the communication frequency is approximately 10 Hz or more.

C–ADS-Equipped Vehicle System	Operational Need Identifier	Operational Need	Functional Requirement Identifier	Functional Requirement
Central Computer	TSMO UC1-N06	Need to store static infrastructure data (e.g., MAP, speed limits, stop bar's location, lane restrictions).	TSMO UC1-R06	The central computer has storage and computational functions.
Central Computer	TSMO UC1-N07	Need for C–ADS-equipped vehicle status and information data received from RSE.	TSMO UC1-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 RSE is through cables.
Central Computer	TSMO UC1-N08	Need for the capability to process relevant data to estimate critical time steps (e.g., stopping time and entering time at the intersection box).	TSMO UC1-R06	The central computer has storage and computational functions.
Central Computer	TSMO UC1-N08	Need for the capability to process relevant data to estimate critical time steps (e.g., stopping time and entering time at the intersection box).	TSMO UC1-R08	The central computer processes and analyzes C–ADS-equipped vehicle status and intent information data received from RSE to compute the vehicle-specific advisory data.
RSE	TSMO UC1-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 UC1-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.

C–ADS-Equipped Vehicle System	Operational Need Identifier	Operational Need	Functional Requirement Identifier	Functional Requirement
RSE	TSMO UC1-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 UC1-R10	RSE receives status and intent data from C–ADS-equipped vehicles with at least cooperation class A within the communication range. The communication frequency is approximately 10 Hz or more.
RSE	TSMO UC1-N10	Need for relay data received from other RSE sent from the central computer.	TSMO UC1-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 RSE is through cables.
RSE	TSMO UC1-N11	Need for vehicle-specific advisory data sent from the central computer.	TSMO UC1-R09	The central computer sends vehicle-specific advisory data to the corresponding RSE in real time. The connection between the central computer and RSE is through cables.

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 safe distances and the frequency of infringement of those distances.

- 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 are identified[23] and summarized in table 10:

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

Safety

Safety is a key factor in evaluating the impacts of CDA technologies. Because human errors cause the majority of crashes,[24] automated vehicles have the potential to significantly decrease the number of crashes, particularly at high-market-penetration levels. One may quantify safety improvements is 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 technology 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 (GHG) 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 tradeoffs between the higher efficiency of flows and higher demand requires further research.

Calculating emissions and energy consumption is usually an offline process that uses data previously obtained by simulation or observed data.(25) 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 GHG 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 key TSMO UC1's operational scenarios to enhance TSMO at stop-controlled intersections with the proposed control framework, 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) stop-controlled intersection. 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 6-A, three vehicles at each entry approach are situated in the communication area at the current time step *t*. As shown in figure 6-B, the stopping sequence of vehicles inside the communication area, and subsequently their departure sequence, follows the alphabetical order (i.e., $ST_A < ST_B < \ldots < ST_L$ and $ET_A < ET_B < \ldots < ET_L$) in the existing human-driven traffic scenario. Because vehicles in this scenario are unable to predict their STs and smooth their trajectories, a stop-and-go pattern before the stop bar can be observed.

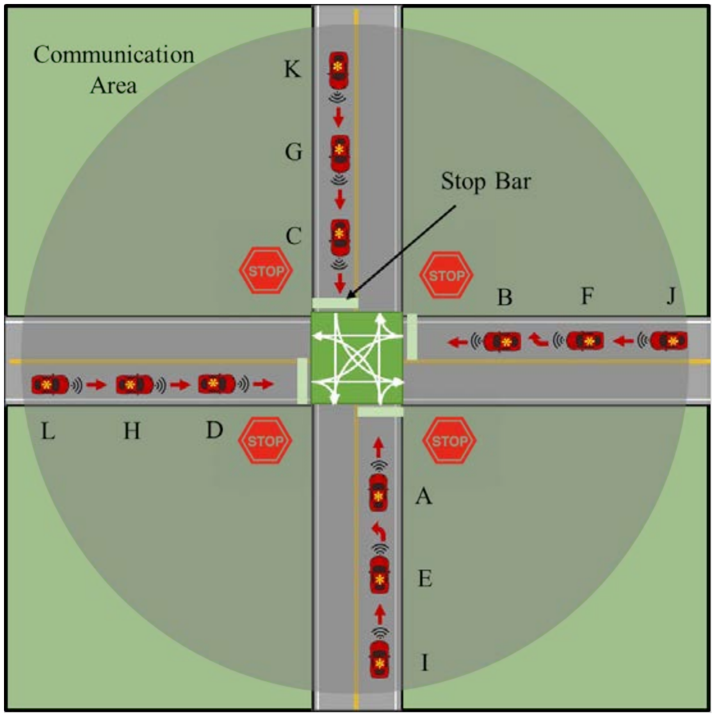
In the class A scenario, the departure sequence of vehicles is the same as the one in the existing human-driven traffic scenario. As shown in figure 6-C, however, as vehicles in this cooperation class are able to predict their approximate STs and smooth their trajectories, a reduction in the stop-and-go traffic pattern can be observed.

In the class B scenario, the availability of information on vehicle directions enables vehicles E and F to use the intersection box simultaneously, which improves the throughput. Also, as shown in figure 6-D, the higher accuracy of ST estimation increases the smoothness of the trajectories and decreases the stop-and-go traffic pattern.

In the class C scenario, the RSE's instructions help vehicles without conflicting directions to form groups and pass the intersection box simultaneously. As shown in figure 6-E, the stopping sequence of vehicles is decided by RSE in a way that vehicle A is coupled with vehicle C and vehicle B is coupled with vehicle D, which further improves the throughput at the intersection. Further, it is assumed that vehicles I is unwilling to accept RSE's instructions and will stop at the stop bar after vehicle H and before vehicle J, which prohibits vehicle H and vehicle J from being coupled. Those vehicles that are willing to accept RSE's suggestions receive the most accurate estimation of their STs (which is expected to be the same as their ETs) from RSE, which reduces the stop-and-go traffic pattern.

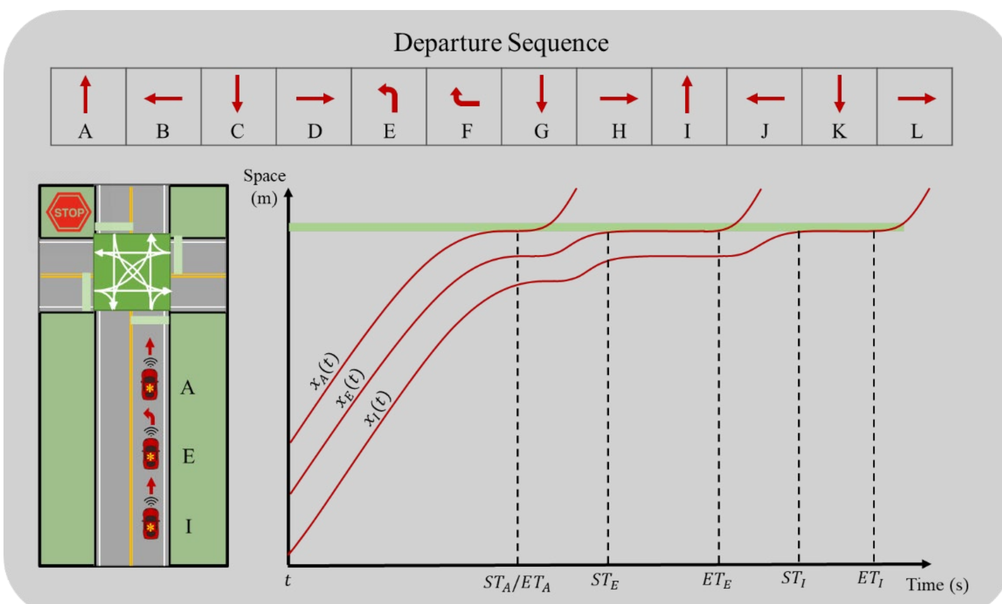
In the class D scenario, all vehicles are forced to accept RSE's instructions. Therefore, the best performance can be achieved in this cooperation class, as shown in figure 6-F.

Overall, this operational scenario illustrates the effectiveness of the proposed control framework with different cooperation classes. 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 improves individual vehicle travel experiences.



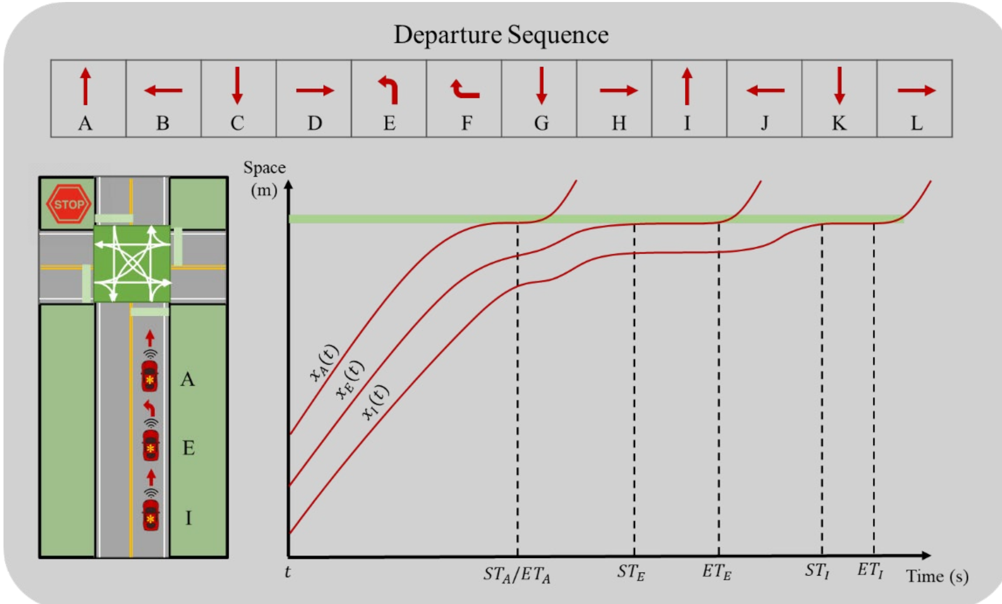
Source: FHWA.

A. Four-way one-lane stop-controlled intersection.



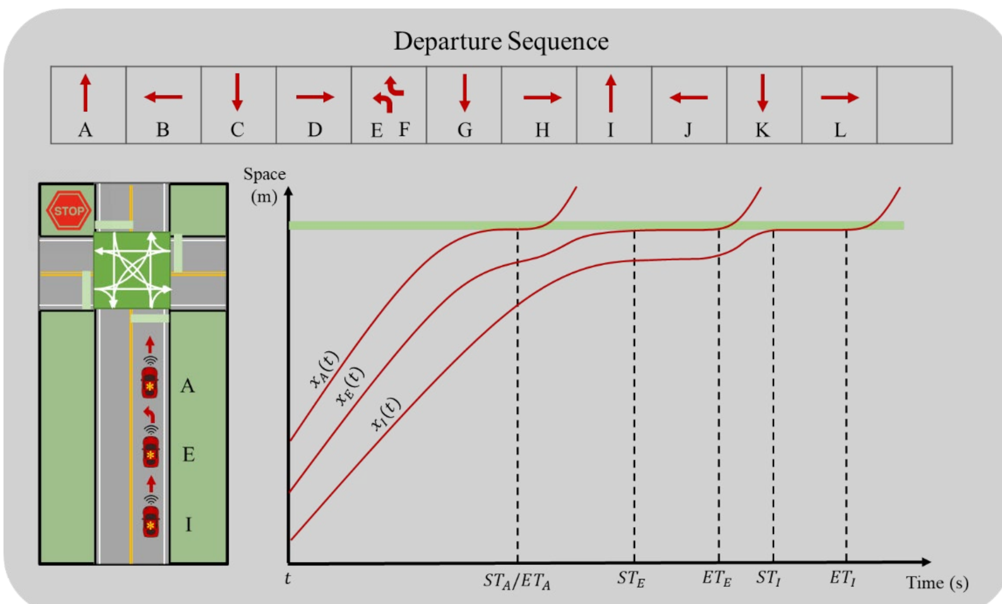
Source: FHWA.

B. Existing human-driven vehicles.



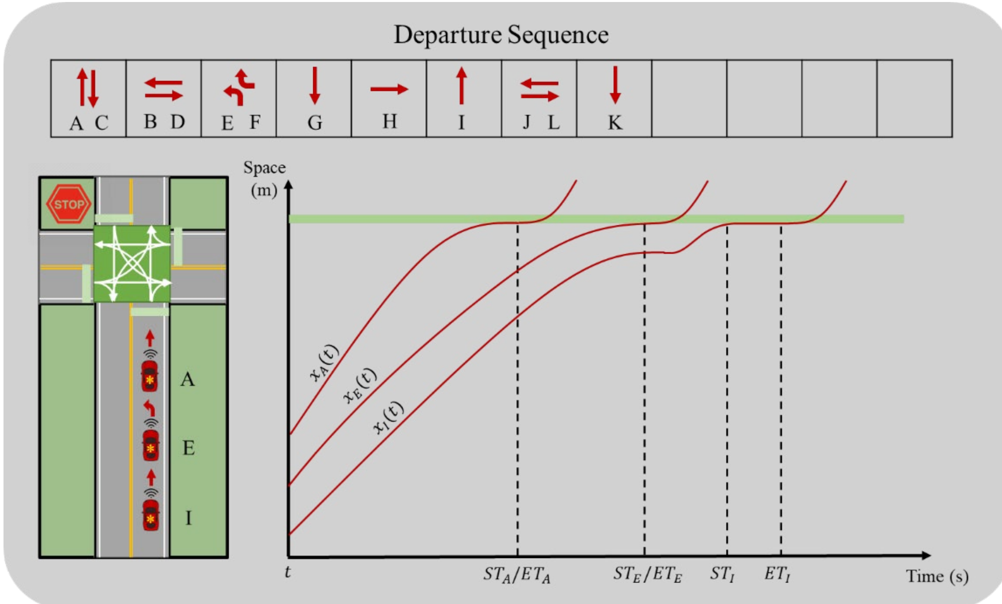
Source: FHWA.

C. Class A cooperative automated driving system-equipped vehicles.



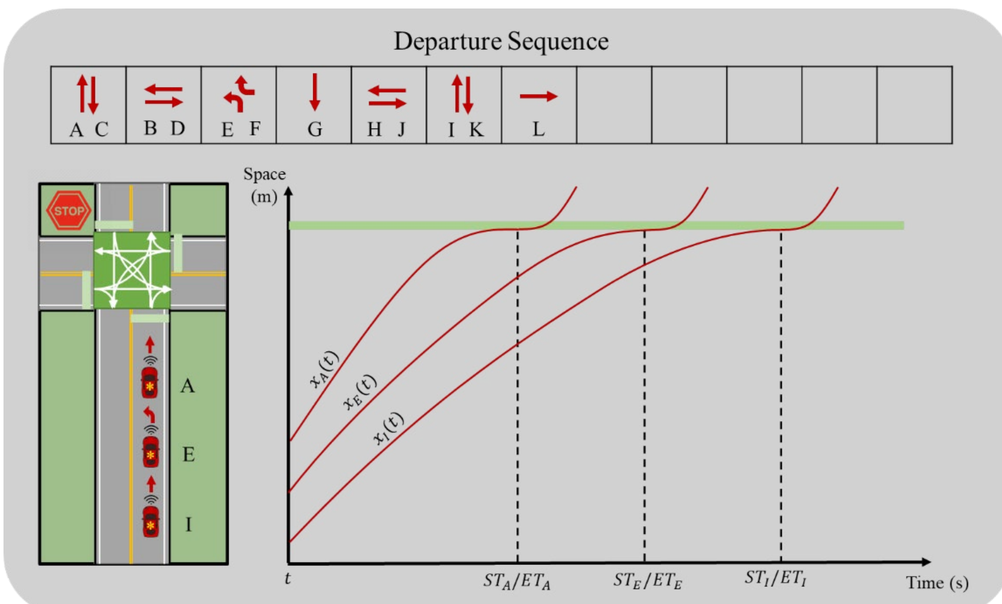
Source: FHWA.

D. Class B cooperative automated driving system-equipped vehicles.



Source: FHWA.

E. Class C cooperative automated driving system-equipped vehicles.



Source: FHWA.

F. Class D cooperative automated driving system-equipped vehicles.

ST_A / ST_E / ST_I = stopping time of vehicle A/E/I; ET_A / ET_E / ET_I = entering time of vehicle A/E/I; $x_A(t)$ / $x_E(t)$ / $x_I(t)$ = space-time trajectory of vehicle A/E/I.

Figure 6. Illustration. CDA operational scenario for different cooperation classes.

CHAPTER 5. ANALYSIS OF THE PROPOSED SYSTEM

This chapter provides an analysis of the benefits, advantages, limitations, and disadvantages of TSMO UC1 at stop-controlled intersections. A high-level system validation plan is also discussed.

SUMMARY OF POTENTIAL BENEFITS AND OPPORTUNITIES

CDA technologies enable mobility applications unachievable by individual ADS-operated vehicles. They do so by sharing information that can be used to increase the safety, efficiency, and reliability of the transportation system and 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 to directly or indirectly influence DDT performance by one or more nearby road users. Vehicles and infrastructure elements engaged in cooperative automation may share information, such as status (e.g., vehicle position, speed) and intent (e.g., estimated critical time steps) 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 UC1, a cooperative control framework is proposed to control C–ADS-equipped vehicles at a stop-controlled intersection efficiently. The proposed framework is illustrated for different cooperation classes defined in SAE J3216 and contains two main components: CTSE and TS. The CTSE component aims to estimate a set of critical time steps (e.g., ST at the stop bar, ET to the intersection box) for each individual vehicle, 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 critical time steps, 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 CTSE component and 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 individual vehicle at stop-controlled intersections.

SYSTEM VALIDATION PLAN

This section describes system validation methods that will be used to validate the developed algorithms and software systems for TSMO UC1. The purpose of the validation testing is to ensure that the developed TSMO UC1 system can meet all the operational needs listed in table 7 of chapter 3.

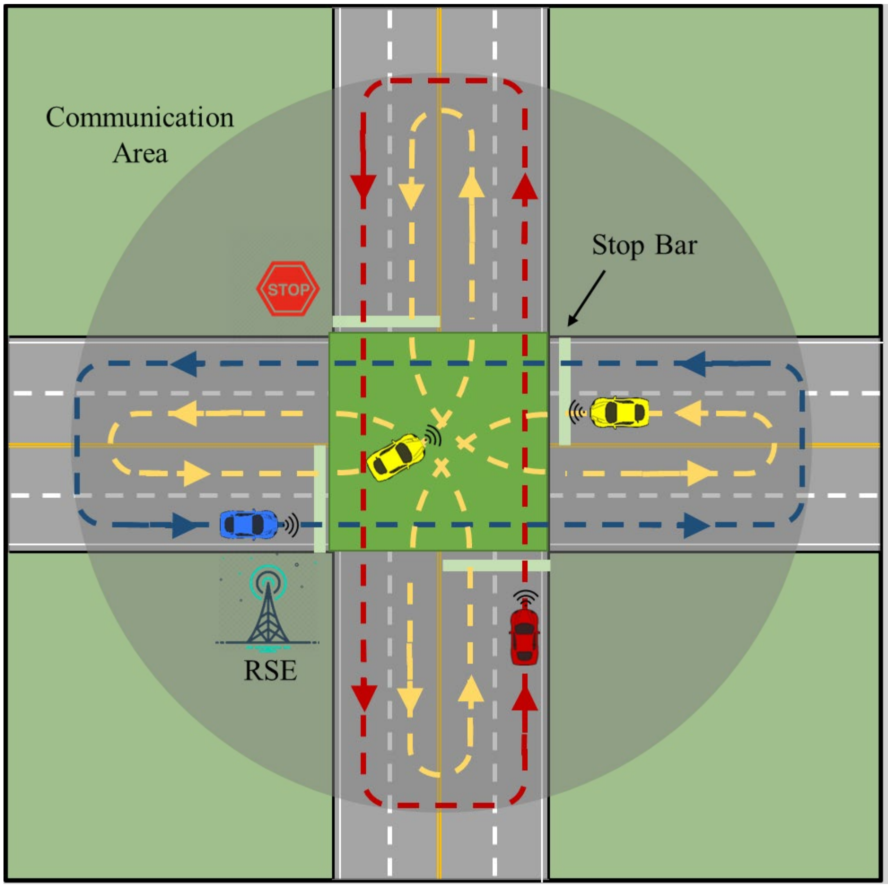
Simulation Testing

Simulations can be designed to test the developed algorithm for TSMO UC1 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 the 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 the 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, scheduling policy, and intersection geometry. Usually, the CDA control algorithms will be simplified to calibrated/validated CDA behavioral models/algorithms that are implementable for large-scale testing.

Field Testing

To ensure that the developed algorithm can be reliably and easily implemented into CARMA Platform, a set of proof-of-concept testing can be conducted on a closed test track. This can be demonstrated onsite at a stop-controlled intersection typical of anywhere in the United States. Depending on participation by partners, multiple CARMA vehicles loaded with the necessary 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 validate if the software meets the requirements. Note that data collected from the test track can be used both to calculate vehicle behavior performance metrics and 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 stop-controlled intersection control.

SUMMARY OF IMPACTS

The proposed control strategy for TSMO UC1 will have a significant impact on research and operations of future transportation systems management. From a research perspective, TSMO UC1 offers a unique, efficient approach to manage transportation systems at stop-controlled intersections and reduce any type of disutilities, such as excessive delay and emissions. The benefits of TSMO UC1 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, 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 UC1 presents significant changes to how TSMO are conducted at stop-controlled intersections. Intelligent transportation infrastructure systems must be upgraded with RSE services and supporting information technologies to accommodate the CDA system's needs. Agencies also need to evaluate and build capabilities for operating such emerging systems. The conventional process of transportation system performance monitoring and reporting would be revolutionized with the prevalence of C–ADS-equipped vehicles and advanced sensors. Conventional strategies for TSMO with which agencies are already familiar can be significantly enhanced by CDA technologies.

DISADVANTAGES AND LIMITATIONS

Although the proposed control strategy for TSMO UC1 provides advantageous insights to CDA operations at stop-controlled intersections, it might suffer from a number of disadvantages and limitations that need to be further investigated. Some of these disadvantages and limitations are as follows:

- The proposed CTSE component requires a centralized unit.
- The cooperation level of C–ADS-equipped vehicles highly affects the performance of traffic.
- The proposed algorithm focuses on pure automated traffic and the full benefits of the proposed control framework, which might not be achieved in a mixed traffic environment.
- The proposed control framework cannot accommodate pedestrians or bicyclists.

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