Cooperative Automation Research: CARMA Proof-of-Concept Transportation System Management and Operations Use Case 4 - Dynamic Lane Assignment

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

FOREWORD

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

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

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

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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, to enhance infrastructure performance, to improve network efficiency, and ultimately to reduce traffic congestion through transportation systems management and operations (TSMO) strategies on arterials. The focus of this concept of operations is TSMO Use Case 4 (UC4), or *Dynamic Lane Assignment,* which investigates active traffic management applied to traffic signal corridors. The proposed approach for TSMO UC4 has three main components: a signal and lane optimization (designed for roadside equipment [RSE]); a critical time step estimation (designed for RSE or CARMA Platform℠); and a trajectory smoothing for cooperative automated driving system (C–ADS)-equipped vehicles (designed for CARMA Platform) with the available vehicles' real-time information. Researchers expect the proposed control framework to increase throughput and reduce energy consumption while ensuring safety at signalized intersections by simultaneously optimizing the signal and lane settings.

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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 ABBREVIATIONS

ADS	automated driving system
CACC	cooperative adaptive cruise control
C–ADS	cooperative automated driving system
CDA	cooperative driving automation
ConOps	concept of operations
CT	control time
CTSE	critical time step estimation
C–V2X	cellular vehicle-to-everything
DLA	dynamic lane assignment
DSRC	dedicated short-range communication
DV	discharging vehicle
ECT	earliest control time
EET	earliest entering time
ET	entering time
EV	entering vehicle
FHWA	Federal Highway Administration
GHG	greenhouse gas
HRDO	Office of Operations Research and Development
HV	human-driven vehicles
I2V	infrastructure-to-vehicle
ID	identifier
IOO	infrastructure owner and operator
LAP	lane assignment plan
MPC	model predictive control
OBU	onboard unit
PID	proportional-integral-derivative
PV	processed vehicle
RSE	roadside equipment
RSU	roadside unit
SALO	signal and lane optimization
SPaT	signal phase and timing
STOL	Saxton Transportation Operations Laboratory
TS	trajectory smoothing
TSMO	transportation systems management and operations
UC4	Use Case 4
UPV	under-process vehicle
V2I	vehicle-to-infrastructure
V2V	vehicle-to-vehicle

CHAPTER 1. SCOPE AND SUMMARY

IDENTIFICATION

This document is a concept of operations (ConOps) for a transportation systems management and operations (TSMO) use case on arterials. The ConOps focuses 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 is conducted at the Saxton Transportation Operations Laboratory (STOL) established at Turner-Fairbank Highway Research Center. HRDO conducts operations research and development based upon a national perspective of the transportation needs of the United States.

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

A subsequent task order was designed to develop a new reference platform, CARMA2℠, using the Robot Operating System™ 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 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 nonautomated, 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 report will extend the research from Prototype II by enhancing CARMA Platform and CARMA Cloud to enable further capabilities of CDA participants to interact with the road infrastructure. All TSMO use cases in this project consider CDA operations on at-grade intersections. The use case discussed in this ConOps, *Cooperative Automation Research: CARMA Proof-of-Concept Transportation System Management and Operations Use Case 4* (UC4), focuses on active traffic management incorporating signal optimization, dynamic lane assignment (DLA), and trajectory smoothing (TS) at signalized corridors. This project addresses three high-level objectives: reduce traffic congestion, improve energy efficiency, and increase infrastructure efficiency. This project investigates to what extent these objectives can be achieved for different CDA cooperation classes, as given by the SAE J3216™ standard. This project is supported by a team of CARMA participants for development and testing.

Transportation System Management and Operations Arterial Use Cases

- Use Case 1—vehicle coordination and trajectory optimization—stop-controlled intersections.
- 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.
- UC4—DLA integrated with SPaT plan and trajectory optimization—active traffic management.

Audience

The intended audience for this ConOps is:

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

Document Structure

The structure of this document is generally consistent with the System Operational Concept described in "Annex A" of *ISO/IEC/IEEE Standard 29148:2011*.(1) A document conforming to this structure is called a ConOps in U.S. transportation systems engineering practice, and that title is retained for this document. Some sections of this ConOps have been enhanced to accommodate more detailed content than is described in *Standard 29148:2011*; titles of some sections may have been edited to capture those details.

- 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 UC4 system capabilities and their operations and presents detailed descriptions of operational concepts.

- Chapter 4 describes operational scenarios of TSMO UC4 at signalized intersections.

- Chapter 5 provides an analysis of the expected improvements, operational and research impacts, validation plans, disadvantages, and limitations.

- References provide a list of reference documents.

CHAPTER 2. CURRENT SITUATION AND OPPORTUNITIES FOR CHANGES

This chapter discusses existing approaches to congestion and energy consumption mitigation at signalized intersections. It also examines current applications of CDA technologies that reduce traffic congestion at signalized intersections. It will highlight advantages and disadvantages of the existing solutions because they are now motivating development of new CDA solutions to congestion and energy problems at signalized intersections.

BACKGROUND AND CURRENT SITUATION

Various roadway facilities intersect through the roadway network to provide access to commuters, causing conflicts among vehicles from various movement traffic streams. Inappropriate operations of a conflict area (e.g., signalized/unsignalized intersections, merging roadways) result in unstable traffic flow (i.e., stop-and-go traffic), which may exacerbate travel delay, energy consumption and emissions, driving discomfort, and safety risks. Operations of conflict movements at common conflict areas, however, may change in the advent of CDA technology. Cooperative automated driving system (C–ADS)-equipped vehicles have communication and automation technologies to allow them to coordinate with each other and with the infrastructure to maximize safety and network efficiency. C–ADS-equipped vehicles are parts of a connected ecosystem (that relies on 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 (e.g., DSRC systems) to help support C–ADS-equipped vehicle coordination.

A connected ecosystem combined with the current level of vehicle automation provides an opportunity for traffic flow improvements at a common conflict area that may produce mobility, safety, and environmental benefits. With these emerging technologies, the passing sequence of C–ADS-equipped vehicles at intersections can be further improved with proper coordination (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 aware of downstream traffic and the conflict area's conditions and determine the approximate time they can enter the conflict area. This way, vehicle speeds can be smoothed/optimized such that stop-and-go traffic and the backward shock wave propagation could be reduced or eliminated. Smoothed/optimized speeds would also create a reduction in energy consumption, harmful emissions, and crashes. At signalized intersections in particular, such an improvement becomes even more significant because vehicles must come to one or multiple complete stops before passing the intersection at red signal indications, which creates unstable stop-and-go traffic. Among various CDA applications related to conflict areas, control strategies near signalized intersections have received increasing attention because of the capability of communicating with traffic signal controllers and receiving the real-time SPaT information. These control strategies usually have two aspects. First, the traffic signal timing plan can be optimized to efficiently serve different traffic approaches according to their demands. Second, C–ADS-equipped vehicles can be controlled to simultaneously smooth their trajectories (i.e., paths vehicles follow in space as a function of time) to minimize fuel consumption, driving discomfort, and travel delay.

Many studies have been conducted on these two aspects. On the traffic signal side, several studies have aimed to optimize the signal timing plan to improve the traffic efficiency. (See references 2, 3, 4, 5, 6, and 7.) On the trajectory control side, centralized control scheme[8,9,10] and decentralized control scheme[11,12,13] are proposed to minimize speed/acceleration variations, which essentially reduces travel delay and increases energy efficiency. In the centralized control scheme, decisions are made by a single central controller in a global manner for all vehicles; in the decentralized control scheme, each vehicle is treated as an autonomous agent that determines its own operations based on the information sensed or received from other vehicles and roadside equipment (RSE) to maximize its own performance. Another class of studies integrates traffic signal optimization and vehicle trajectory optimization at signalized intersections simultaneously to further improve system performance of mobility, safety, and energy efficiency. (See references 14, 15, 16, and 17.)

Despite these breakthroughs, the performance of signal optimization and vehicle trajectory optimization is weakened with heavy traffic in one or more movement groups. One effective way to address this issue is called DLA, which has been widely studied for connected human-driven vehicles (HV) with pre-signals[18,19] and variable message signs.[20,21] Only a few studies have investigated DLA with C–ADS-equipped vehicles.[22] Sun et al.[22] maximizes intersection capacity by dynamically assigning lanes of one approach to different movement groups. However, neither signal optimization nor vehicle trajectory optimization is incorporated that may impair the best system performance. Also, Sun et al.[22] uses DLA in only one approach without considering multi-approach interactions at a signalized intersection. Motivated by these gaps, a real-time control algorithm integrating signal optimization, DLA, and vehicle trajectory optimization can be proposed.

From the real-time application perspective, only few studies have conducted field experiments and tested CDA operations at signalized intersections. (See references 23, 24, 25, and 26.) For instance, Altan et al.[23] developed, demonstrated, and evaluated a partially automated vehicle system with an eco-approach and departure feature. Omidvar et al.[24] deployed an intelligent real-time isolated intersection traffic control system in mixed traffic at a Florida Department of Transportation closed-course facility.

OPPORTUNITIES FOR CHANGES

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

Further, all these existing studies have simple assumptions of cooperation behaviors (e.g., assume all vehicles accept and follow a prescriptive plan), while the cooperation capabilities of C–ADS-equipped vehicles might be different. SAE already standardized how cooperation between vehicles is regarded. Similar to the levels of automation defined in SAE J3016™, the new standard, SAE J3216™,[27] defines classes of cooperation. The classes address different capabilities of a C–ADS-equipped vehicle that would affect its ability to cooperate with other CDA participants (e.g., vehicles and infrastructure).

Table 2 summarizes the cooperation classes and table 3 shows the opportunities provided by CDA technology by depicting examples of CDA features relating to cooperative traffic signals at intersection, considering different cooperation classes. A number of these examples are taken from the SAE J3216 standard. With this, the need for investigating the effects of different cooperation classes defined in SAE J3216 remains unaddressed.

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

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

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* = 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
Eco-Approach and Departure	A) Status Sharing/ B) Intent Sharing	One-way: RSE→ C–ADS-equipped vehicles	SPaT messages	Enabling C–ADS-equipped vehicles to plan their motions based on the future signal phase that would otherwise be unavailable
Tandem Approach and Departure	C) Agreement Seeking	Two way: 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 signalized intersection in the TSMO context. This ConOps serves as part of the CARMA framework and distinguishes between the levels of vehicle automation and classes of vehicle cooperation.

TRANSPORTATION SYSTEMS MANAGEMENT AND OPERATIONS STAKEHOLDERS

Stakeholders are 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 discusses 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 travelling from one location to another. For TSMO, motorized vehicles, whether human-driven or automated, are the main users of the traffic systems at intersections. Transportation users' needs include the following:

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

Integrating CDA technology into TSMO from the transportation user's perspective may support and enhance the following benefits:

- Smoother, faster, and lower-stress travel—controlling C–ADS-equipped vehicle trajectories at signalized intersections may increase intersection throughput and reduce friction and energy consumption in traffic flow by improving vehicle-following stability.

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

- Improved traffic safety—reducing crashes is a potential benefit of CDA technology. The National Highway Traffic Safety Administration estimates combined use of V2V and V2I communications has the potential to significantly reduce unimpaired driver crashes.[28] Smoothed vehicle trajectories with proper trajectory control may reduce risks and severity of rear-end collisions.

- More productive travel experience—incorporating CDA features such as signal optimization and TS may help eliminate stop-and-go movements, reduce travel delay and energy consumption, and increase travel time reliability, which can improve the overall travel experience.

Table 4 identifies four categories of transportation users and 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	Nonconnected ADS-equipped vehicle	Nonconnected ADS-equipped vehicles operate independently, relying on local sensor information and automated control software, and usually have conservative behavior to provide increased comfort and safety margin. 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, operate, and maintain roadways and supporting infrastructure for the mobility needs of transportation users. IOOs include public, public-private, or private-sector entities that operate in accordance with applicable laws at the Federal, State, 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, such as incidents, weather, intersections, dissemination of routing information, and other actions that increase traffic flow efficiency. Goals of IOOs may include the following:

- Reducing recurring congestion.
- Improving reliability and safety.
- Reducing travel times, fuel consumption, and emissions.
- Maintaining and increasing use of alternative and emerging transportation modes, such as car-sharing options (connected and automated vehicles are considered as a separate mode by travelers.[29]

From the perspective of IOOs, TSMO may support and enhance the following benefits:

- Faster realization of efficiency goals—early adoption of CDA at existing intersections may enable greater congestion management abilities to increase throughput, enhance safety, and improve driver experience. These benefits may increase as the fraction of C–ADS-equipped vehicles using the intersection, 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 facing funding constraints and inherent limitations in alleviating transportation problems. CDA technologies can be considered operational strategies that offer the potential for innovative solutions to congestion and travel time variability at intersections that plague facilities.

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

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

JUSTIFICATION FOR AND NATURE OF CHANGES

The transportation industry is moving toward improving safety with ADS by enhancing various vehicle technologies (i.e., levels of automation and ubiquitous sensing using automated vehicle sensors). As more advanced sensing and computing capabilities are integrated with ADS, a key consideration is what changes must take place to enable CDA system deployment and what additional capabilities and possibilities can be expected. This section discusses the nature of those changes.

Organizational/Institutional Changes

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

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

- Develop a performance management system—C–ADS-equipped vehicles aligned with agency performance standards and holistic data requirements can help transportation agencies leverage data sources across the organization. A performance management system collects and processes 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—all relevant data are obtained in real time from the various vehicles, onboard sensors, wireless devices, roadside units (RSUs), roadway traffic sensors, weather systems, message boards, and other related systems. These data can be placed in, or be accessible from, a common data environment.

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

    - Historical data—historical data can help 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:
    - Enhance the infrastructures at intersections by installing DSRC (or another RSU technology, such as cellular vehicle-to-everything [C–V2X]) and other hardware to support algorithms that enable CDA applications.
    - Equip vehicles that use the CDA system with DSRC radios (onboard units [OBU], vehicle awareness devices), camera, light detection and ranging technology, radar sensors, and other computational resources to implement the new control software.
- Develop/acquire new software. The application(s) should:
    - Make use of the frequently collected and rapidly disseminated multisource data drawn from connected travelers, vehicles, and infrastructure.
    - Include a vehicle awareness application (e.g., an OBU 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 that can collect, receive, and disseminate 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 and long-term storage of historical data).
    - Evolve and improve its algorithms and methods on the basis of performance measurements.
    - Include DSRC (or another RSU 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. Key questions to determine proper operational policies of intersections include:

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

All stakeholders should have clear expectations and incentives to participate. Improved throughput and smoother travel experience are shared goals between IOOs and CDA applications. Users can also create agreements or compacts to set expectations, encourage investments, and measure performance.

Facility Infrastructure Changes

Depending on the facility type, configuration, operations, 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 nonequipped 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 nonequipped vehicles at upstream of intersections.

- Striping and pavement markings.

- Appropriate signage—to convey relevant information to all drivers (both equipped and nonequipped).

For early CDA deployment, infrastructure equipped with existing communication devices offers the opportunity to begin integrating CDA systems into traffic. Because of the enabled cooperation capabilities, even a small number of C–ADS-equipped vehicles may 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 UC4. It describes how automated driving technology can be used in a cooperative manner from when C–ADS-equipped vehicles enter the communication area of signalized intersections with optimal signal and lane settings to when they exit. The chapter also discusses the roles of infrastructure in supporting and enabling automated driving technology to help manage the transportation system to address congestion and improve safety and energy efficiency during normal travel at arterials, especially in a high traffic demand scenario.

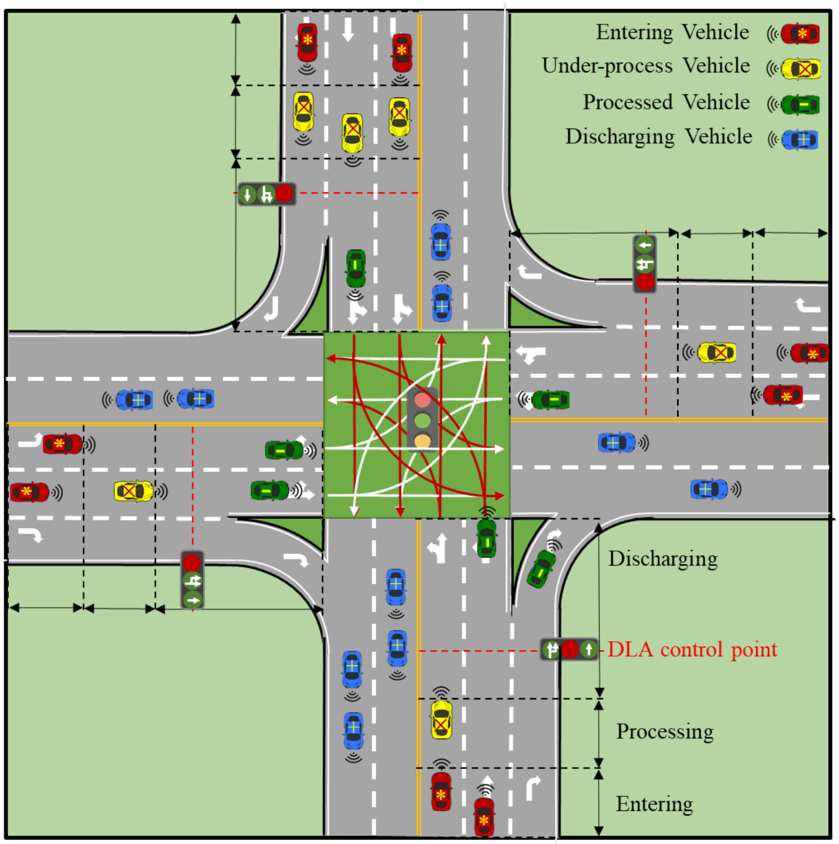
TECHNOLOGICAL FRAMEWORK FOR TRANSPORTATION SYSTEMS MANAGEMENT AND OPERATIONS BASIC ARTERIAL TRAFFIC USE CASE

This section describes the algorithm framework for an active traffic management feature to be used for TSMO UC4. This framework focuses on a signalized intersection with optimized signal and lane settings, formed by multilane approaches, as illustrated by 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 speed of each approach, lane width). Each lane of an entry approach before the control area is assigned to only one movement group (i.e., through, left-turn, and right-turn). Therefore, information regarding the current position and lane of a vehicle essentially determines the movement group of the vehicle. Also, right-turn-on-red is not allowed, and vehicles turning right must wait for the traffic signal to change to green phase. The two left-most lanes at the intersection are shared lanes for left-turn and through movement groups in the DLA module, and in the conventional signalized intersection (without DLA), each lane of an entry approach at the intersection is assigned to only one movement group. The speed limit of each lane is based on its associated movement groups. All C–ADS-equipped vehicles then will aim to pass the intersection box with a designed speed to maximize the throughput of the intersection.

In this framework, all vehicles are assumed to be equipped with CDA technologies. The infrastructure at the intersection is assumed to be equipped with the needed software and hardware to allow it to transmit information to, and receive information from, all vehicles. Therefore, 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, movement group, vehicle type) and intents (e.g., entering time [ET] and speed to the intersection box) to infrastructure and surrounding vehicles (i.e., following and preceding vehicles). Also, the infrastructure can assist the system by optimizing and transmitting the needed information (e.g., SPaT plan and lane assignment plan [LAP]) to the vehicles. This section also discusses the performance of the proposed control mechanism for different CDA cooperation classes.

The initial focus of TSMO UC4 is on optimizing the departure sequence of C–ADS-equipped vehicles and generating the optimal signal and lane settings (e.g., SPaT plan and LAP) accordingly at signalized intersections in real-time based on the received real-time operational information from C–ADS-equipped vehicles. Then, this use case aims to smooth C–ADS-equipped vehicle trajectories based on the SPaT and LAP by the infrastructure. The goal of this use case can be prioritized as follows:

- Safety—the primary goal of this algorithm is to maintain safety while traversing through a signalized intersection. The algorithm contains a set of hard safety constraints that avoids potential crash risks and uncomfortably high accelerations/decelerations.
- Mobility—within the feasible range allowed by the guaranteed safe/comfortable travel experience, the algorithm aims to maximize the throughput of signalized intersections by minimizing vehicles' departure times from 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.

DLA = dynamic lane assignment.

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

As illustrated in figure 1, the area of each entry approach is divided into three different segments of entering, processing, and discharging. There exists a virtual DLA control point in the discharging segment to direct C–ADS-equipped vehicles into different lanes (i.e., lateral trajectory planning). With this division, depending on the location of C–ADS-equipped vehicles inside the communication area at each time step of the algorithm, four different states are defined:

- Entering vehicles (EV)—vehicles that are approaching the signalized intersection, are located at the entering segment, and have not been processed by RSE, are shown as red vehicles with star symbol in figure 1.
- Under-process vehicles (UPV)—vehicles that are approaching the signalized intersection, are located either at the processing segment or at the entering segment, and are under process by RSE, are shown as yellow vehicles with multiplication dash symbol in figure 1.
- Processed vehicles (PV)—vehicles that are approaching the signalized intersection, are located either at the discharging segment or at the processing segment, and have already been processed by RSE, are shown as green vehicles with dash symbol in figure 1.

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

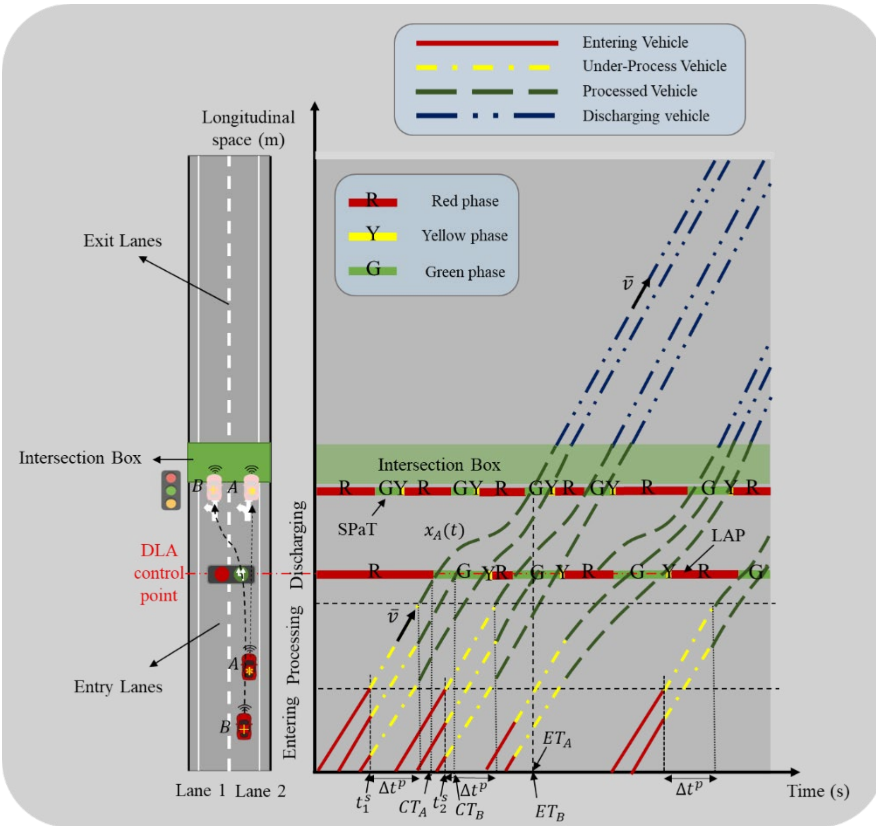
A vehicle entering the communication area will initially join the EV set and will start transmitting information to RSE and the other vehicles. EVs have not yet been processed by RSE; however, they will estimate their ETs to the intersection box based on the received information from the other vehicles and RSE to smooth their own trajectory while traversing through the entering segment.

As soon as an EV from an entry lane leaves the entering segment and enters the processing segment at a given time step (denoted by t_i^s for ith batch of vehicles), the status of all existing EVs inside the communication area will change to UPV, and RSE will start processing these vehicles. Note that this way, there might be UPVs inside the entering segment at a given time step. Also note that as the length of the entering segment increases, a higher throughput might be achieved because the vehicle batch size increases and RSE can schedule more vehicles at a time. This might also require a longer processing segment to handle the higher processing time required, however. While UPVs are traversing through the entering and processing segments, RSE will determine a proper departure sequence of them. The SPaT plan and LAP are then generated based on this departure sequence with the proposed signal and lane optimization (SALO) component. The length of these segments must be chosen properly such that the algorithm is able to schedule all UPVs before any of these UPVs enter the discharging segment and any EV enters the processing segment. One requirement needed to satisfy this condition is the processing segment must be no longer than the entering segment. The algorithm will then consider a maximum processing time, denoted by Δt^p, based on the chosen length for the processing segment and the maximum allowed speed. This way, by the time the maximum processing time is reached, the departure sequence of UPVs is available by RSE, and thus all existing UPVs at time step $t_i^s + \Delta t^p$ will change their states to PV.

Depending on the cooperation class of C–ADS-equipped vehicles, RSE will share the SPaT plan or a desired ET to the intersection box, and the LAP or a desired control time (CT) at the DLA control point with vehicles as soon as they join the PV set. PVs will smooth their longitudinal trajectories to enter the DLA control point at a desired CT. They then plan their lateral and longitudinal trajectories to enter the intersection box at a desired ET, estimated by RSE or the vehicle itself, at the speed limit or the highest speed allowed by safety constraints. Note that passing the intersection at the maximum possible speed improves the throughput of the intersection by reducing the time a vehicle occupies the intersection box. Also note that the length of the discharging segment must be chosen properly based on the range of communication area, maximum allowed speed, and average comfortable acceleration/deceleration rates such that vehicles can feasibly smooth their trajectories. As the range of communication area increases, the length of the discharging segment can increase, which increases the smoothness of the trajectories. Additionally, the location of the DLA control point must be chosen properly based on the length of the discharging segment, the maximum allowed speed, and the average comfortable acceleration/deceleration rates. At least, it should satisfy the requirement of lane changes before entering the intersection box.

Further, as soon as the vehicle departs the intersection box, it will be removed from the PV set and will be added to the DV list. Finally, the vehicle will be removed from the DV list as soon as it leaves the communication area. The vehicles are classified into these different sets because the algorithm might control different vehicle sets with different logic.

Figure 2 illustrates the state of transition of a set of vehicles from entering the communication area of the intersection until leaving it. The time-space figure plots the vehicle trajectories in lane 2. As shown in figure 2, some trajectories (e.g., the second one) disappear after passing the DLA control point. This is because these C–ADS-equipped vehicles are assigned to other lanes, and thus they change their lanes to the assigned lanes. With this, vehicles A and B have the same ETs, and thus the traffic throughput increases compared with the conventional signalized intersections. Note that because this algorithm focuses on an isolated intersection (i.e., no bottleneck is considered at the end of communication area) and PVs aim to pass the intersection box at a high speed, the DVs are assumed to pass through the exit lanes with a constant speed. Also, DVs do not need any information regarding SPaT messages to plan their own trajectories. Therefore, the proposed algorithm does not consider controlling DV trajectories. For controlling a corridor of intersections, however, DV trajectories might need to be controlled as well. In this case, depending on the distance between two adjacent intersections and the considered segment lengths, 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.

CT_A / CT_B = control time of vehicle A/B; DLA = dynamic lane assignment; ET_A / ET_B = entering time of vehicle A/B; $x_A(t)$ = trajectory of vehicle A; $\bar{v}$ = maximum speed; t_i^s = the start time step of processing vehicle batch i; Δt^p= maximum processing time.

Figure 2. Illustration. Vehicle state transition.

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 the infrastructure and all vehicles to synchronize their movements. This way, vehicles can transmit their real-time information to RSE and receive the traffic signal information (e.g., current signal phase, planned SPaT), lane assignment information (e.g., accessible lanes, assigned lane), and their desired operations from RSE more accurately. The proposed framework is a real-time application of CDA; thus, the algorithm will be run at each real-time time step.

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

TSMO Use Case 4: Dynamic Lane Assignment Integrated with SPaT Plan and Trajectory Optimization (Active Traffic Management)

- UC4.1- SALO—determining a proper departure sequence of vehicles at the DLA control point and intersection box, and converting them to LAP and SPaT plan, respectively.
- UC4.2- CTSE—estimating a set of critical time steps for C–ADS-equipped vehicles based on the SPaT plan.
- UC4.3- TS—smoothing C–ADS-equipped vehicle trajectories with the estimated ETs.

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

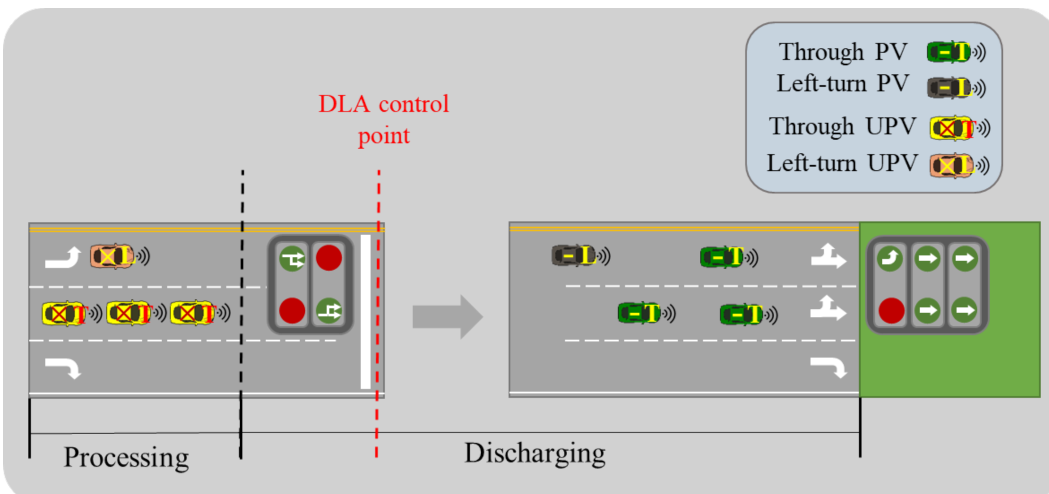
Signal and Lane Optimization

The SALO component is run at the intersection RSE in a centralized manner. Rather than optimizing the SPaT plan and LAP directly, RSE first determines a proper departure sequence of vehicles while considering all lanes from all approaches at the intersection. Then RSE estimates ETs to the intersection box and CTs at the DLA control point. Finally, RSE converts the estimated ETs and CTs to the SPaT plan and LAP, respectively, and shares them with vehicles, depending on the vehicles' cooperation classes.

At each iteration of the greedy algorithm, RSE selects the next vehicle in the departure sequence such that the increase in travel delay of vehicles from other entry lanes is minimized. The delay of a vehicle is defined as the difference between the estimated ET during scheduling and an estimated earliest entering time (EET) based on the speed and acceleration constraints and the departure sequence of the already scheduled vehicles (i.e., PVs). Further, the designed algorithm tends to clear the queue of a given entry lane before it switches the signal indication. Finally, when scheduling a given batch of UPVs at a given time step, the algorithm will reschedule those previous UPVs that could not enter the intersection box yet, if possible. This way, there will be some overlap between consecutive batches of UPVs, and thus the determined departure sequence will be improved. The greedy algorithm, however, is not the only available option for obtaining a proper departure sequence of vehicles at an intersection. Two alternative solutions to this problem are: using a neighborhood search from an initial solution (e.g., fixed-time signal setting, the obtained departure sequence from the proposed greedy algorithm) to improve the departure sequence of vehicles; and using machine learning techniques to learn the queueing pattern and predict a proper departure sequence of vehicles. The central RSE can be designed to follow one or more of these algorithms to obtain vehicles' departure sequences such that the best possible traffic performance can be achieved. The decision regarding the applied algorithm depends on a number of factors, including the intersection design (e.g., number of entry approach and lane), traffic demand, available computational resources, etc.

After determining the departure sequence of all UPVs, RSE will estimate vehicles' ETs and CTs, and then it will provide a SPaT plan and LAP based on the determined departure sequence. RSE then shares the determined SPaT plan and LAP with all existing UPVs. In cooperation class C and class D, RSE will also instruct UPVs with the estimated ET and CT. UPVs then use the received SPaT, LAP, and/or ETs from RSE to smooth their trajectories. Note that the algorithm tends to keep the determined departure sequence of vehicles rather than follow the exact SPaT plan and LAP. Therefore, the green phase of an entry lane at a given time step might be extended to ensure that the passing sequence of vehicles follows the determined one by RSE. Also, RSE will estimate the first time step that an EV can enter the intersection box and will share it with all existing and future EVs before they join the UPV set. EVs then will use this estimated time step to estimate their own ETs and smooth their trajectories.

Figure 3 illustrates the SALO. Because there are much more through vehicles than left-turn vehicles (i.e., high traffic demand on through lane), the optimal SPaT is planned such that the left-turn vehicles pass the intersection after through vehicles. Then the LAP is also designed such that the vehicles in the left-most lane pass the DLA control point after through vehicles from the middle lane.



Source: FHWA.

DLA = dynamic lane assignment; PV = processed vehicle; UPV = under-process vehicle.

Figure 3. Illustration. Signal and Lane Optimization.

Critical Time Step Estimation

The CTSE component aims to estimate ETs/CTs of vehicles based on the converted SPaT plan/LAP from the SALO component. At each time step *t*, DVs have already departed the intersection box and no decision regarding DVs is needed. PVs are already scheduled by RSE and need to estimate their ETs/CTs based on their associated SPaT plan/LAP. UPVs are under process by RSE and has to wait for their associated SPaT plan/LAP. EVs have not been scheduled yet, and thus they need to estimate their ETs/CTs based on the already determined SPaT plans/LAP and the first available time step to enter the intersection box. Note that the estimated ET/CT of an EV would be always greater than its estimated EET/earliest control time

(ECT), which is the earliest time that it can arrive and enter the intersection box/DLA control point while considering speed and acceleration constraints. This way, it will be always feasible for the vehicle to reach the estimated ET/CT of an EV. Depending on the cooperation class of C–ADS-equipped vehicles, the estimation of ETs/CTs might be done by the vehicles themselves based on the received SPaT plan/LAP and information from other vehicles, or it might be instructed by the deployed RSE around the intersection. The following subsections specify the algorithm framework of the CTSE component for each of the cooperation classes. It is assumed that all C–ADS-equipped vehicles inside the communication area are in the same cooperation class.

Class A Cooperation

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

Further, because no information regarding vehicles' intents is available in this cooperation class, vehicles cannot be aware of the estimated ETs/CTs of their preceding vehicles. Thus, the estimation of ETs/CTs in this cooperation class might not be as accurate as possible, and vehicles may face red signal indications because of this inaccurate estimation. Each vehicle will first determine the number of its preceding vehicles from the same entry lane. Then it will estimate the green time required for the determined number of vehicles to enter the intersection box or pass the DLA control point with free flow speed. With this, each vehicle estimates the first possible ET/CT with a simple search of green phases and durations.

Class B Cooperation

In this cooperation class, C–ADS-equipped vehicles will transmit their current status and intents to each other. As with those in class A, vehicles in this class lack negotiation capabilities, and thus the CTSE component at RSE cannot instruct EVs by estimating their ETs/CTs. Because the intents of all C–ADS-equipped vehicles are available in this cooperation class, C–ADS-equipped vehicles can be aware of the estimated ETs/CTs of their preceding vehicles. Therefore, each C–ADS-equipped vehicle can check whether it can enter the intersection box or pass the DLA control point at the same green phase with its preceding vehicle. Alternatively, it must wait for the next one with the received ET/CT from its preceding vehicle, SPaT plan, LAP, and estimated EET/ECT.

Classes C and D Cooperation

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

Further, the estimated/received ET/CT serves as the input of the TS component. With the available ET/CT, 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 based on the received information from RSE and other vehicles. It is intended to mitigate backward shock wave propagation and stop-and-go traffic patterns at signalized intersections, to increase the traffic throughput, and to improve energy efficiency. The TS component contains three main functions: longitudinal trajectory planning, lateral trajectory planning, and trajectory control.

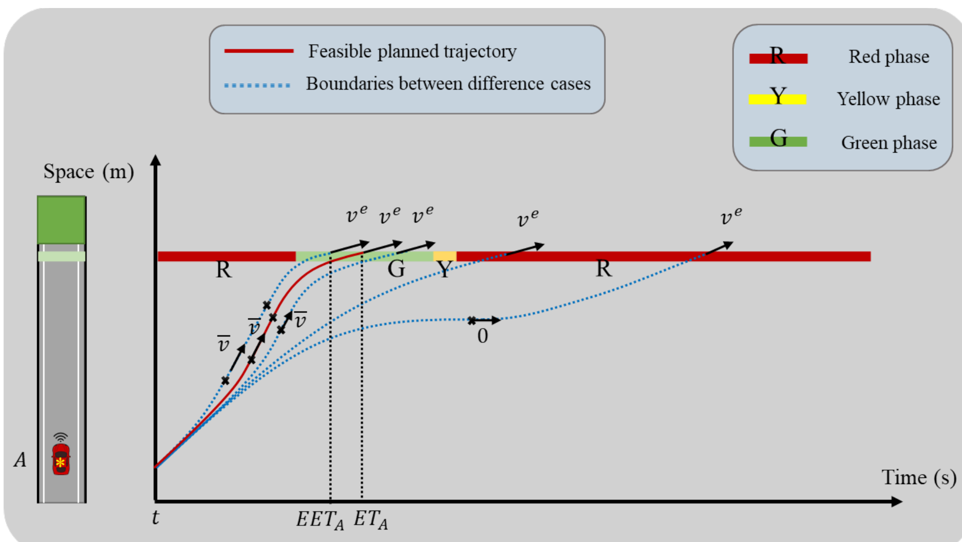
Longitudinal Trajectory Planning

This function will first plan a smooth longitudinal trajectory profile for each vehicle from an entry lane based on the received vehicles' status (e.g., current location, speed, acceleration, lane, maximum acceleration/deceleration rate), intent (e.g., target ETs and CTs and speeds), lane assignment information (e.g., accessible lanes, assigned lane), traffic signal information (e.g., SPaT plan), and the estimated/received ET/CT, while approaching the DLA control point/the intersection box. It will then determine a desired speed for the next time step based on the obtained smooth longitudinal trajectory.

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

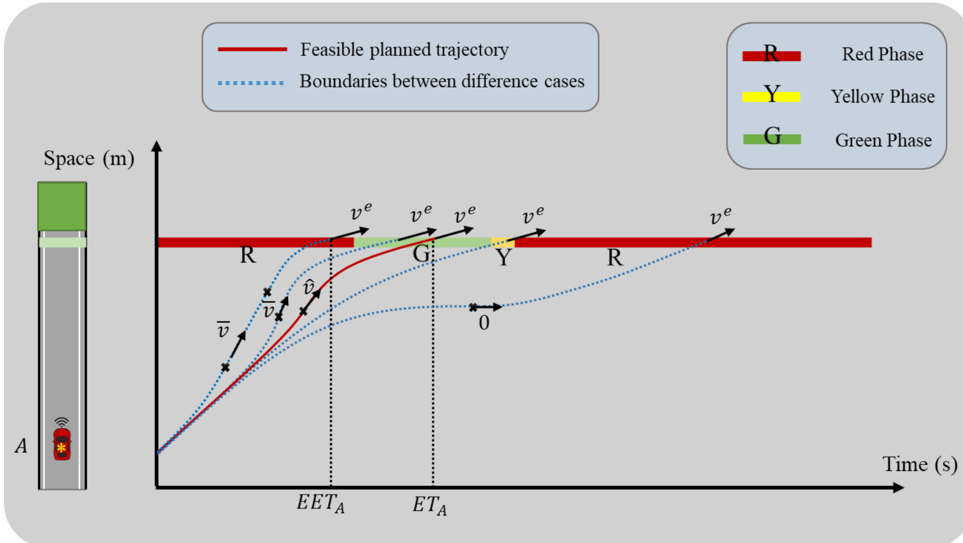
Regardless of the C–ADS-equipped vehicles' cooperation class, each vehicle from an entry lane aims to smooth its own trajectory to pass the DLA control point or enter the intersection box at the estimated/received CT/ET. The planned vehicle trajectory follows a third-, fourth-, or fifth-degree polynomial 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 CTs/ETs, locations, and speeds (which enable the construction of third-order polynomial trajectories) and the rest (e.g., current and predicted entering accelerations, jerks) are optional (which enables the construction of higher order polynomial trajectories). Note that as the order of the polynomial equation increases, the planned trajectory becomes differentiable at a higher order and thus smoother. For example, a second-order polynomial trajectory has continuous speed but jumping acceleration at transition points, but a third-order polynomial trajectory would have both continuous speed and acceleration everywhere. It is obviously easier for C–ADS-equipped vehicles to accurately follow a smoother planned trajectory in the trajectory control function.

Although the safety constraints are absent in this function, the planned smoothed trajectories are guaranteed to be feasible in terms of speed and acceleration constraints. Figure 4 shows an illustrative example of possible cases for planned longitudinal trajectory while aiming to catch the estimated/received ET. As shown in figure 4, depending on the estimated EET, the estimated/received ET, and the vehicle's current location and speed, the constructed smooth trajectory might fall in one the illustrated four cases to ensure the speed and acceleration feasibility. Without loss of generality, these cases are applied for planning vehicles' longitudinal trajectories while aiming to catch the estimated/received CT at the DLA control point.



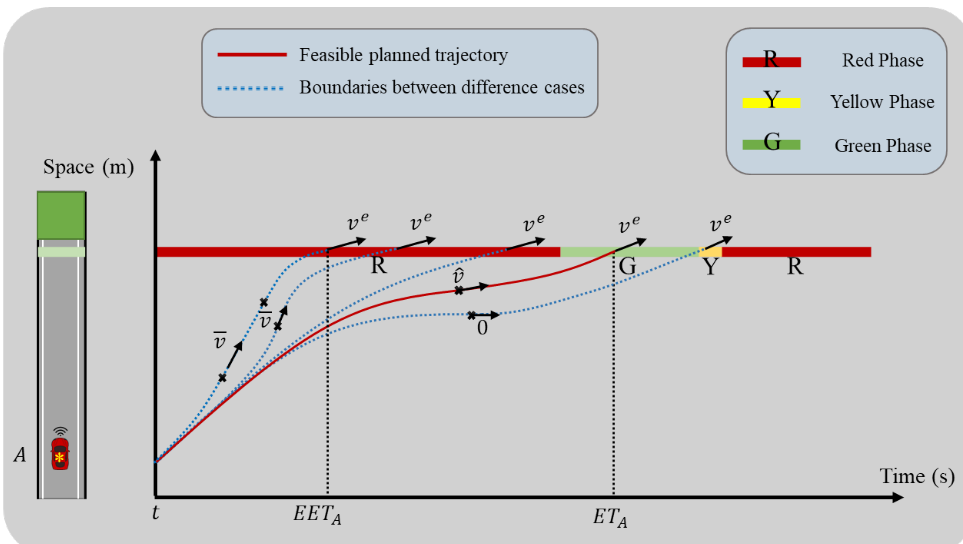
Source: FHWA.

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



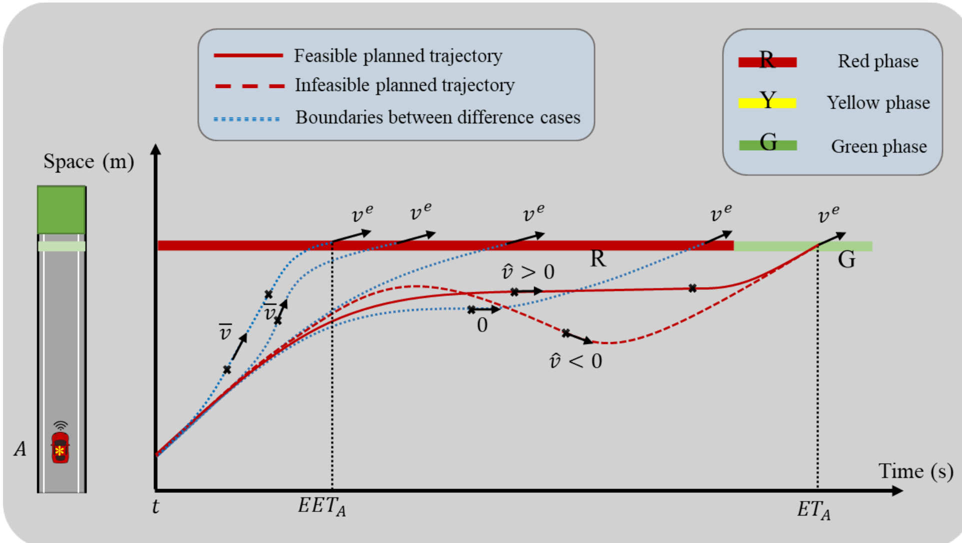
Source: FHWA.

B. Case 2: Acceleration, deceleration.



Source: FHWA.

C. Case 3: Deceleration, acceleration.



Source: FHWA.

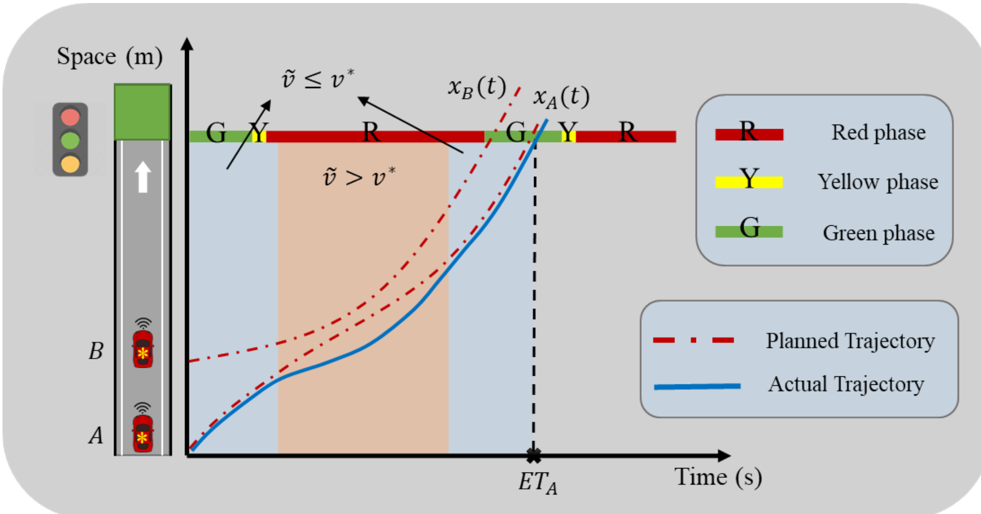
D. Case 4: Deceleration, cruising, acceleration.

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

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

Longitudinal Safety Feature

Although the proposed trajectory planning feature smooths vehicle motions and improves fuel/energy consumption, it fails to 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), as well as 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 5.



Source: FHWA.

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

Figure 5. Illustration. Safety feature.

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

Lateral Trajectory Planning

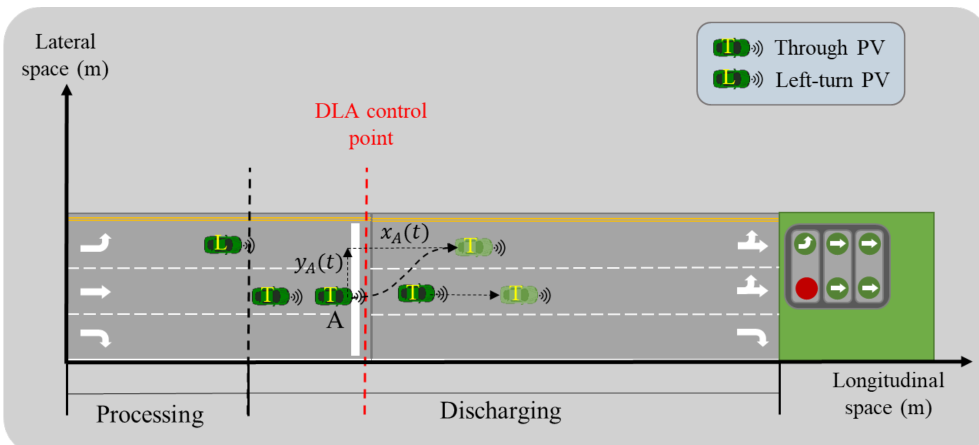
With the smooth longitudinal trajectory from the above section, this function will plan a smooth lateral trajectory profile for each vehicle based on the received vehicles' status (e.g., current location, speed, acceleration, lane, maximum acceleration/deceleration rate), intent (e.g., estimated CT and speed), and lane assignment information (e.g., accessible lanes, assigned lane) at the DLA control point. The smooth lateral trajectories are constructed with a high-order polynomial equation based on the longitudinal trajectories. With this, the control mechanism of the lateral trajectory planning function for different CDA classes is illustrated in the following subsections.

Cooperative Driving Automation Classes A and B

In classes A and B, RSE transmits the accessible lanes to all vehicles regarding the LAP. Because vehicles are unaware of the assigned lanes, they would choose their preferable lanes based on their locations, speeds, and the accessible lanes. Therefore, vehicles cannot smooth their own trajectories and will follow a predefined lane-changing model. As demonstrated in the car-following model, if a vehicle is the leader in its associated lane and the signal is red, the entry of the intersection box with zero speed and acceleration will be considered as the preceding obstacle.

Cooperative Driving Automation Classes C and D

In classes C and D, the RSE transmits the LAP that provides the future states of the lanes (e.g., assigned lane to each vehicle) to all vehicles. Each vehicle constructs its own smooth lateral trajectory profile with a high-order polynomial equation based on the smooth longitudinal trajectory. As shown in figure 6, the required variables for constructing lateral trajectories with polynomial equations are the start location of lane changing at the current lane, the final location of lane changing at the desired lane, and current and final speeds and times. Note that as the order of the polynomial equation increases, the planned lateral trajectory becomes differentiable at a higher order, and thus smoother. In class C, if vehicles reject the assigned lanes, they will follow the predefined lane-changing model, as described in classes A and B.



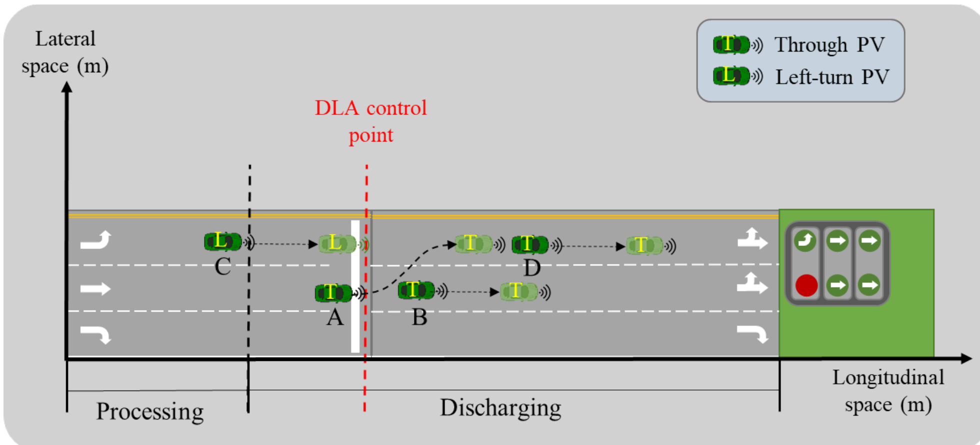
Source: FHWA.

DLA = dynamic lane assignment; PV = processed vehicle; $x_A(t)$ = longitudinal trajectory of vehicle A; $y_A(t)$ = lateral trajectory of vehicle A.

Figure 6. Illustration. Lateral trajectory planning.

Lateral Safety Feature

For safety reasons, a lateral safety feature is proposed to ensure the avoidance of collisions when following the planned lateral trajectory. The lateral safety feature in this study is considered for each vehicle by checking the safe accelerations/gaps of surrounding vehicles (e.g., preceding vehicle in the current lane, preceding and following vehicles in the target lane). It is a function of the subject vehicle's current location, speed, minimum spacing, and communication delay (i.e., the time needed for sensors and the computer to processes data added to the actuator time) and its surrounding vehicle's current location, speed, and acceleration. Figure 7 illustrates an example. Vehicle A is considered the subject vehicle, and before vehicle A passes the DLA control point, it will check the safety features between itself and vehicles B and D at each time step. The safety features of vehicle C will also be checked during the process. If vehicle C accepts the planned lateral trajectory, the safety features between vehicle C and vehicles A and D are checked. Otherwise, vehicle C will just check the safety features between vehicle C and vehicle D. If vehicle C is too close to vehicle A (i.e., safety checks fail) during the lateral control process, a lateral control abortion process will be applied, and thus vehicle A will give up the planned lateral trajectory and will stay in its current lane.



Source: FHWA.

DLA = dynamic lane assignment; PV = processed vehicle.

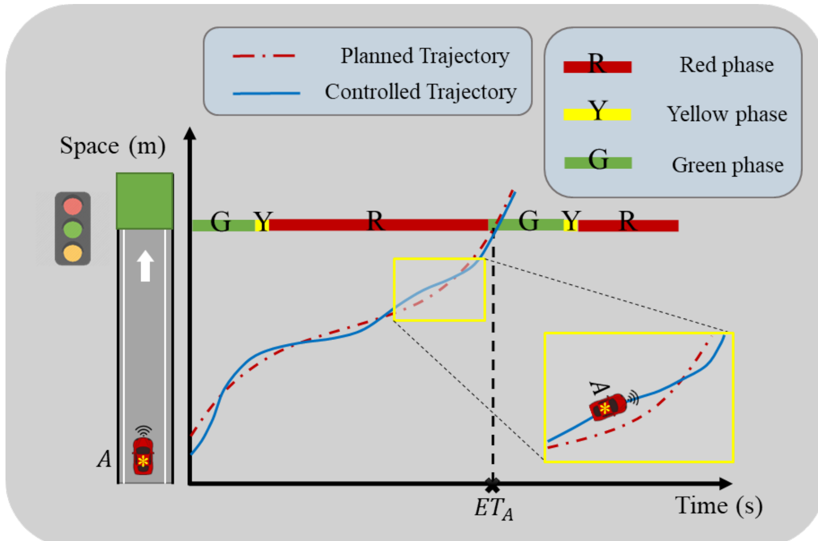
Figure 7. Illustration. Lateral safety feature.

With the planned longitudinal and lateral trajectories in hand, the advisory speed profile of each vehicle can be determined. Each vehicle will then seek 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 adjust (e.g., every 20 ms) 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 8, 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 squared errors of location and speed). In the PID control, each control variable is a simple linear function of the discrepancies of the states (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 states (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 only quantified after the field experiments with the specific C–ADS-equipped vehicles. Different sensing, computing, and vehicle mechanics may result in different control errors.



Source: FHWA.

ET_A = entering time of vehicle A.

Figure 8. Illustration. Trajectory control function.

INFRASTRUCTURE CONFIGURATION AND NEEDS

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

A key feature of CDA operations is the dynamic vehicle-infrastructure interactions, particularly the exchange of real-time vehicular and roadway information that an ADS-equipped vehicle can understand and share. This project considers RSE that can be used to emulate an intersection controller for functions proposed in this use case. RSE can communicate to C–ADS-equipped vehicles, irrespective of the particular communication technologies, using the appropriate protocols. C–ADS-equipped vehicles can also share their status and what they sense about the surrounding dynamic traffic environment for better static and dynamic world models. The two-way information exchange constitutes the foundation of CDA, which includes both cooperative perception and cooperative vehicle control. 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 algorithm focuses on an isolated intersection. The algorithm can be extended to use a cloud-based service, however, especially when an entire corridor of intersections is under investigation.

There is a limited set of user needs relevant to the operator-traveler interactions. Travelers are the primary beneficiaries but can also be 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 out the resulting pertinent information back to C–ADS-equipped vehicles. Table 5 shows a list of needs for road users and IOOs. In this table, road users are C–ADS-equipped vehicles, such that one-way or two-way information exchange can occur between them 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/assigned lanes	Control access to lanes
Get information on current local speed limits	Control speed limits
Get information on the SPaT plan and LAP	Optimize SPaT plan and LAP
Get information on the estimated control and ETs	Estimate vehicles' control and ETs
Estimate the CT at the DLA control point	Inform travelers of the planned SPaT
Estimate the ET to the intersection box	Inform travelers of the accessible lanes/assigned lanes
Inform IOOs of observed traffic condition	Inform travelers of their estimated control and ETs
Inform IOOs of observed weather conditions	Inform travelers of traffic condition
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
Control trajectory	Inform travelers of current local speed limits
–	Inform travelers of any special rules that are currently being enforced

C–ADS = cooperative automated driving system; DLA = dynamic lane assignment; ET = entering time; LAP = lane assignment plan; SPaT = signal phase and timing; IOO = infrastructure owner and operator.

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

Table 6. Exchanges between roadside equipment and vehicles.

RSE-to-vehicle	Vehicle-to-RSE
Planning rules	**Cooperative perception**
• Speed rules. • Mapping rules. • SPaT plan and LAP. • Estimated ET and CT. • Other vehicles' information.	• Vehicle current status, intent, etc. • Local world information sensed by each C–ADS-equipped vehicle.

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

SUMMARY OF TRANSPORTATION SYSTEMS MANAGEMENT AND OPERATIONS NEEDS AND REQUIREMENTS

To summarize key features of TSMO UC4 and guide future development of requirements of the TSMO UC4 system, this section describes the operational needs and functional requirements for both C–ADS-equipped vehicles and infrastructures. These needs and requirements are specified for different CDA cooperation classes and different components of the proposed control algorithm. Note that a central computer (e.g., CARMA Streets) might be needed to connect a set of RSEs deployed around the intersection box to store information and transfer them from one RSE to another and essentially from and to all C–ADS-equipped vehicles. In these operational needs and functional requirements:

- Static infrastructure data may include MAP, speed limits, lane restrictions, etc.

- A C–ADS-equipped vehicle's status and intent data may include vehicle identifier (ID) (e.g., license plate or a temporary anonymous ID), vehicle type, location, speed, braking status, heading, priority position, departure time from the DLA control point, ET to the intersection box, departing time from the intersection box, etc. This dataset may vary across different cooperation classes.

- Further, RSE advisory data may include the desired departure time from the DLA control point and ET to the intersection box for each C–ADS-equipped vehicle. RSE signal data include the SPaT plan. Note that the central computer and RSEs in all cooperation classes are needed because C–ADS-equipped vehicles need to receive the SPaT plan. They might not be used for transferring information from one C–ADS-equipped vehicle to another, however, if V2V communication range is sufficient in the control area.

Table 7 provides a list of operational needs. Functional requirements for the C–ADS-equipped vehicles, RSEs, and the central computer are provided in table 8. These requirements are also specified for different cooperation classes. Finally, table 9 provides the functional requirements described in table 8 for each operational need in table 7.

Table 7. Operational needs for vehicles and infrastructure in Transportation Systems Management and Operations Use Case 4.

C–ADS-Equipped Vehicle System	ID#	Operational Need	Cooperation Classes
CTSE	TSMO UC4-N01	Need for static infrastructure data (e.g., MAP, speed limits, lane restrictions).	A and above.
CTSE	TSMO UC4-N02	Need for signal data (e.g., planned SPaT, LAP) and advisory data (e.g., desired ETs to the intersection box, desired CT at the DLA control point) from the central RSE.	A and above.
CTSE	TSMO UC4-N03	Need for lane assignment (e.g., accessible lanes in cooperation classes A and B, and assigned lanes in cooperation classes C and D) and advisory data (e.g., desired CTs at the DLA control point) from the central RSE.	A and above.
CTSE	TSMO UC4-N04	Need to process the state and intent data from other C–ADS-equipped vehicles and/or the RSE advisory data to estimate some critical time steps.	A, B, and C.
TS	TSMO UC4-N05	Need to plan and follow the future trajectory and speed profile from the current location and speed to the target location, speed at the target time.	A and above.
TS	TSMO UC4-N06	Need for the state 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 (SALO)	TSMO UC4-N07	Need to store static infrastructure data (e.g., MAP, speed limits, lane restrictions).	A and above.
Central Computer (SALO)	TSMO UC4-N08	Need for C–ADS-equipped vehicle status and intent-information data received from all RSE.	A and above.

C–ADS-Equipped Vehicle System	ID#	Operational Need	Cooperation Classes
Central Computer (SALO)	TSMO UC4-N09	Need for the capability to process relevant data to estimate critical time steps and determine the SPaT and LAP.	A and above.
RSE	TSMO UC4-N10	Need for 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 UC4-N11	Need for relay data received from other RSE sent from the central computer.	A and above.
RSE	TSMO UC4-N12	Need for vehicle-specific advisory data, the planned SPaT and LAP sent from the central computer.	A and above.

C–ADS = cooperative automated driving system; C–V2X = cellular vehicle-to-everything; CTSE = critical time step estimation; DLA = dynamic lane assignment; DSRC = dedicated short-range communication; LAP = lane assignment plan; RSE = roadside equipment; SPaT = signal phase and timing; SALO = signal and lane optimization; TS = trajectory smoothing; TSMO = transportation systems management and operations; UC4 = Use Case 4.

Table 8. Functional requirements for vehicles and infrastructure in Transportation Systems Management and Operations Use Case 4.

Functional Requirement Identifier	Functional Requirement	Cooperation Classes
TSMO UC4-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 UC4-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 UC4-R03	A C–ADS-equipped vehicle with at least cooperation class A broadcasts its location, speed, heading, and brake status. The communication frequency is approximately 10 Hz or more.	A and above (status data only for class A).

Functional Requirement Identifier	Functional Requirement	Cooperation Classes
TSMO UC4-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 UC4-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 components are installed within each C–ADS-equipped vehicle. These safety components can be built upon in-vehicle sensors and may be enhanced with status and intent information shared by the surrounding vehicles. If communications are used to assist the safety component, the communication frequency is approximately 10 Hz or more.	A and above.
TSMO UC4-R06	The central computer has storage and computational functions.	A and above.
TSMO UC4-R07	The central computer relays vehicle intent and status information between RSE within certain geo-fenced areas in real time through DSRC or C–V2X communications. The connection between the central computer and RSE has minimum latency.	A and above.
TSMO UC4-R08	The central computer processes and analyzes C–ADS-equipped vehicle status and intent-information data received from each RSE to compute the vehicle-specific advisory data and determine the SPaT and LAP.	A and above.
TSMO UC4-R09	The central computer sends vehicle-specific advisory data and the determined SPaT and LAP to the corresponding RSE in real time. The connection between the central computer and RSE is through cables.	A and above.

Functional Requirement Identifier	Functional Requirement	Cooperation Classes
TSMO UC4-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 UC4-R11	RSE broadcasts the status and intent data among C–ADS-equipped vehicles through DSRC or C–V2X communications within the communication range. The communication frequency is approximately 10 Hz or more.	A and above (optional for when CDA communication range is not enough and needs relay with the RSEs).
TSMO UC4-R12	RSE shall be able to send vehicle-specific advisory data and the determined SPaT and LAP through DSRC or C–V2X communications within its communication range. The communication frequency should be approximately 10 Hz or more.	A and above.

C–ADS = cooperative automated driving system; CDA = cooperative driving automation; DLA = dynamic lane assignment; LAP = lane assignment plan; MPC = model predictive control; PID = proportional-integral-derivative; RSE = roadside equipment; SPaT = signal phase and timing; TSMO = transportation systems management and operations; UC4 = Use Case 4; V2V = vehicle-to-vehicle.

Table 9. Needs-to-requirements traceability matrix for Transportation Systems Management and Operations Use Case 4.

C–ADS-Equipped Vehicle System	Operational Need Identifier	Operational Need	Functional Requirement Identifier	Functional Requirement
CTSE	TSMO UC4-N01	Need for static infrastructure data (e.g., MAP, speed limits, lane restrictions).	TSMO UC4-R01	A C–ADS-equipped vehicle with at least cooperation class A shall have an onboard computer with storage and computing functions.
CTSE	TSMO UC4-N02	Need for signal data (e.g., SPaT plan, LAP) and advisory data (e.g., desired ETs to the intersection box, desired CT at the DLA control point) from the central RSE.	TSMO UC4-R12	RSE shall be able to send vehicle-specific advisory data and the determined SPaT and LAP through DSRC or C–V2X communications within its communication range. The communication frequency should be approximately 10 Hz or more.
CTSE	TSMO UC4-N03	Need for lane assignment (e.g., accessible lanes in cooperation classes A and B, and assigned lanes in cooperation classes C and D) and advisory data (e.g., desired CTs at the DLA control point) from the central RSE.	TSMO UC4-R12	RSE shall be able to send vehicle-specific advisory data and the determined SPaT and LAP through DSRC or C–V2X communications within its communication range. The communication frequency should be approximately 10 Hz or more.
CTSE	TSMO UC4-N04	Need to process the state and intent data from other C–ADS-equipped vehicles and/or the RSE advisory data to estimate some critical time steps.	TSMO UC4-R01	A C–ADS-equipped vehicle with at least cooperation class A shall have an onboard computer with storage and computing functions.

C–ADS-Equipped Vehicle System	Operational Need Identifier	Operational Need	Functional Requirement Identifier	Functional Requirement
CTSE	TSMO UC4-N04	Need to process the state and intent data from other C–ADS-equipped vehicles and/or the RSE advisory data to estimate some critical time steps.	TSMO UC4-R03	A C–ADS-equipped vehicle with at least cooperation class A shall be able to broadcast its location, speed, heading, and brake status. The communication frequency should be approximately 10 Hz or more.
CTSE	TSMO UC4-N04	Need to process the state and intent data from other C–ADS-equipped vehicles and/or the RSE advisory data to estimate some critical time steps.	TSMO UC4-R04	A C–ADS-equipped vehicle with at least cooperation class A shall be able to receive, decode, process, analyze, and use locations, speeds, and headings from other preceding C–ADS-equipped vehicles with at least cooperation class A on the same lane. The communication frequency should be approximately 10 Hz or more. If the range of V2V communications is smaller than the worst-case communication distance, RSE may be installed along each road segment to relay the data.
CTSE	TSMO UC4-N04	Need to process the state and intent data from other C–ADS-equipped vehicles and/or the RSE advisory data to estimate some critical time steps.	TSMO UC4-R11	RSE shall be able to broadcast the status and intent data among C–ADS-equipped vehicles within the communication range. The communication frequency should be approximately 10 Hz or more.

C–ADS-Equipped Vehicle System	Operational Need Identifier	Operational Need	Functional Requirement Identifier	Functional Requirement
TS	TSMO UC4-N05	Need to plan and follow the future trajectory and speed profile from the current location and speed to the target location, speed at the target time.	TSMO UC4-R01	A C–ADS-equipped vehicle with at least cooperation class A shall have an onboard computer with storage and computing functions.
TS	TSMO UC4-N05	Need to plan and follow the future trajectory and speed profile from the current location and speed to the target location, speed at the target time.	TSMO UC4-R02	A C–ADS-equipped vehicle with at least cooperation class A shall have a drive-by-wire control system, a navigation system, and corresponding algorithms (e.g., PID or MPC) to follow a given space-time trajectory.
TS	TSMO UC4-N06	Need for the state and intent data from the preceding C–ADS-equipped vehicles on the same lane for a car following/collision avoidance mechanism.	TSMO UC4-R01	A C–ADS-equipped vehicle with at least cooperation class A shall have an onboard computer with storage and computing functions.
TS	TSMO UC4-N06	Need for the state and intent data from the preceding C–ADS-equipped vehicles on the same lane for a car following/collision avoidance mechanism.	TSMO UC4-R02	A C–ADS-equipped vehicle with at least cooperation class A shall have a drive-by-wire control system, a navigation system, and corresponding algorithms (e.g., PID or MPC) to follow a given space-time trajectory.

C–ADS-Equipped Vehicle System	Operational Need Identifier	Operational Need	Functional Requirement Identifier	Functional Requirement
TS	TSMO UC4-N06	Need for the state and intent data from the preceding C–ADS-equipped vehicles on the same lane for a car following/collision avoidance mechanism.	TSMO UC4-R05	A C–ADS-equipped vehicle with at least cooperation class A shall provide for the capability to avoid crashes with other vehicles (vehicles with or without cooperation class capabilities) prior to, during, and after completion of the intersection control. Valid car-following and collision avoidance components shall be installed within each C–ADS-equipped vehicle. These safety component can be built upon in-vehicle sensors and may be enhanced with status and intent information shared by the surrounding vehicles. If communications are used to assist the safety component, the communication frequency should be approximately 10 Hz or more.
Central Computer (SALO)	TSMO UC4-N07	Need to store static infrastructure data (e.g., MAP, speed limits, lane restrictions).	TSMO UC4-R06	The central computer shall have storage and computational functions.
Central Computer (SALO)	TSMO UC4-N08	Need for CAD vehicle status and information data received from all RSE.	TSMO UC4-R07	The central computer shall be able to relay vehicle intent and status information between RSE within certain geo-fenced areas in real time. The connection between the central computer and RSE are through cables.

C–ADS-Equipped Vehicle System	Operational Need Identifier	Operational Need	Functional Requirement Identifier	Functional Requirement
Central Computer (SALO)	TSMO UC4-N09	Need for the capability to process relevant data to estimate critical time steps and determine the SPaT and LAP.	TSMO UC4-R06	The central computer shall have storage and computational functions.
Central Computer (SALO)	TSMO UC4-N09	Need for the capability to process relevant data to estimate critical time steps and determine the SPaT and LAP.	TSMO UC4-R08	The central computer shall be able to process and analyze C–ADS-equipped vehicle status and intent-information data received from each RSE to compute the vehicle-specific advisory data and determine the SPaT and LAP.
RSE	TSMO UC4-N10	Need for status and intent data from C–ADS-equipped vehicles in the communication area (covered by DSRC or C–V2X devices).	TSMO UC4-R03	A C–ADS-equipped vehicle with at least cooperation class A shall be able to broadcast its location, speed, heading, and brake status. The communication frequency should be approximately 10 Hz or more.
RSE	TSMO UC4-N10	Need for status and intent data from C–ADS-equipped vehicles in the communication area (covered by DSRC or C–V2X devices).	TSMO UC4-R10	RSE shall be able to receive status and intent data from C–ADS-equipped vehicles with at least cooperation class A within the communication range. The communication frequency should be approximately 10 Hz or more.

C–ADS-Equipped Vehicle System	Operational Need Identifier	Operational Need	Functional Requirement Identifier	Functional Requirement
RSE	TSMO UC4-N11	Need for relay data received from other RSE sent from the central computer.	TSMO UC4-R07	The central computer shall be able to relay vehicle intent and status information between RSE within certain geo-fenced areas in real time. The connection of between the central computer and RSE are through cables.
RSE	TSMO UC4-N12	Need for vehicle-specific advisory data sent from the central computer.	TSMO UC4-R09	The central computer shall be able to send vehicle-specific advisory data and the determined SPaT and LAP to the corresponding RSE in real time. The connection between the central computer and RSE is through cables.

C–ADS = cooperative automated driving system; CDA = cooperative driving automation; CTSE = critical time step estimation; DLA = dynamic lane assignment; LAP = lane assignment plan; MPC = model predictive control; PID = proportional-integral-derivative; RSE = roadside equipment; SPaT = signal phase and timing; SALO = signal and lane optimization; TS = trajectory smoothing; TSMO = transportation systems management and operations; UC4 = Use Case 4; V2V = vehicle-to-vehicle.

PERFORMANCE METRICS AND TARGETS TRAFFIC FLOW

Effectiveness of TSMO use cases can be evaluated by measuring the capability in positively impacting the performance. Performance metrics in this ConOps are presented from two perspectives: vehicle behavior and traffic flow.

Performance Metrics for Vehicle Behavior

Performance metrics for monitoring and evaluating vehicle operations during execution of this situation include:

- Separation distances—the longitudinal distances between the vehicles in the test. This performance metric determines the frequency of minimum safe distance violations.
- Travel speeds driven—speeds driven by each vehicle during the tests evaluate 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 approximates fuel/energy consumption.
- Speed control error—the differences between the advised speed and actual speed driven by each vehicle during the tests 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 ones during the test. This performance metric investigates how accurately the CTSE component can estimate the critical time steps and how accurately vehicles can follow them.
- Data exchanges during communication/negotiation—capture all data exchanges from V2V, V2I, and I2V to determine whether communication and/or the maneuver negotiations took place as designed. Data exchanges include the following data types:
    - Frequency of packet loss.
    - Total duration of negotiation process.
    - Frequency of negotiation success/failure.
    - Number of attempts before a plan is accepted by all affected neighbors.
    - Message latency—time difference between message origination on vehicle A to reading of message by infrastructure, and vice versa. Latency time includes the time it takes to compose the message and send it from vehicle A's computer to vehicle A's OBU, the queuing time on vehicle A's OBU, the radio transmission time from vehicle A to infrastructure, the message constitution and queueing time on infrastructure's RSE, the transformation time from infrastructure's RSE to infrastructure's computer, and the time for infrastructure's decomposition and reading time.

Performance Metrics on Traffic Performance

Performance metrics on traffic performance are used to evaluate TSMO use cases' impact on traffic flow at intersections. The following 5 categories of impacts[30] are summarized in table 10:

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

Safety

Safety is an important factor in evaluating the impacts of CDA-technologies. Because the majority of crashes are caused by human errors,[31] automated vehicles have the potential to decrease the number of crashes, specifically at high market penetration levels. One way to quantify safety improvements is 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 are dependent on the cooperation level of those technologies, however. 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

There are several stability indices developed in the literature that 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 breaks). CDA technologies are expected to improve traffic flow reliabilities by providing smoother, safer, and more responsive vehicle operations. Multiple measures can be used to quantify CDA impact on flow breakdown and reliability, such as occurrence of shock waves and severity of shock waves formed.

Sustainability

The environmental impacts of CDA require further research. On one hand, smoother operations associated with CDA could lead to lower greenhouse gas (GHG) emissions and energy consumption. On the other hand, the CDA impacts on travel demand could result in higher overall travel volume, which would increase GHG emissions and energy consumption. The tradeoffs between the higher efficiency of flows and higher demand requires further research. Calculating GHG emissions and energy consumption is usually an offline process that uses data previously obtained by simulation or observed data.(32) 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 oxides, 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

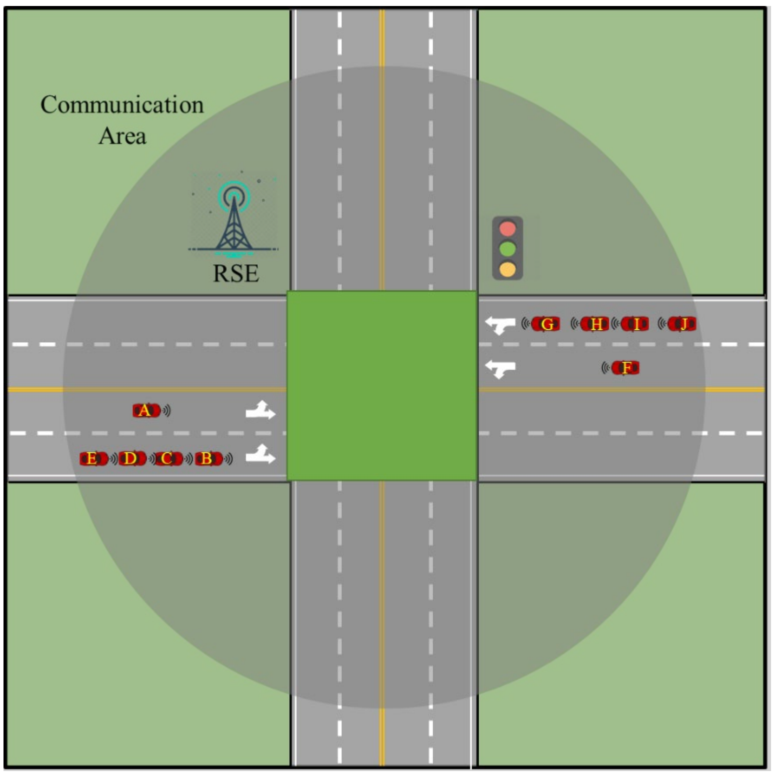
CHAPTER 4. OPERATIONAL SCENARIOS

This chapter identifies important TSMO UC4 operational scenarios to enhance TSMO at signalized intersections with the incorporation of traffic SALO, CTSE, and TS. The operational scenarios also help to understand the impact of early deployment of CDA participants. Described are two illustrative operational scenarios in which a set of vehicles enter the communication area of an isolated four-way signalized intersection with the optimal signal settings, engage in the CDA features described in chapter 3, and move through the intersection. These scenarios are described for the existing HVs and C–ADS-equipped vehicles with different cooperation classes. These scenarios are designed to cover all key features of the proposed control framework and to illustrate their potential benefits.

Let us assume the maximum allowed speed, the average maximum comfortable acceleration rate, and the average maximum comfortable deceleration rate are set to 30 mph, 3.28 ft/s^2, and −3.28 ft/s^2, respectively. With this, a minimum of $(30 \text{ x } 1.46)^2 \div 3.28 \cong 580$ ft length is required for the discharging segment to enable C–ADS-equipped vehicles to plan and smooth their trajectories feasibly. The required length of the processing segment depends on the computational time of algorithm, which is probably in the order of seconds because the algorithm has a greedy nature. Considering 1.5 s as the lane-changing time, the length to implement lane changes (i.e., the distance between the DLA control point and the intersection box) must be no shorter than $(30 \text{ x } 1.46) \text{ x } 1.5 \cong 65$ ft. Considering 5 s as the maximum computational time for the algorithm, the processing segment must be no shorter than $(30 \text{ x } 1.46) \text{ x } 5 \cong 220$ ft. Further, the only requirement for the length of the entering segment is that it must not be shorter than the processing segment's length. Therefore, the length of the entering segment can take any value greater or equal to 220 ft. As the length of the entering segment increases, however, the sizes of vehicle batches might increase, enabling RSE to schedule more vehicles at a time and further improve the throughput at the intersection box. In this example, however, we consider the same length for all segments without loss of generality.

The proposed control method improves the traffic performance at the intersection in two aspects. First, optimizing the departure sequence (i.e., optimizing signal and lane settings) increases the possibility of having more vehicles passing the intersection box on average during a time interval, which consequently increases the throughput and decreases the average travel delay. Second, smoothing vehicle trajectories both decreases the fuel consumption and increases the throughput as vehicles try to pass the intersection box at the maximum allowed speed without having stop. In this section, two examples are presented to illustrate these two benefits. For illustration purposes, these examples are specified for only one batch of vehicles from two approaches. The benefits of the proposed control algorithm would be expected to increase as the number of considered approaches, directions, and vehicles increases.

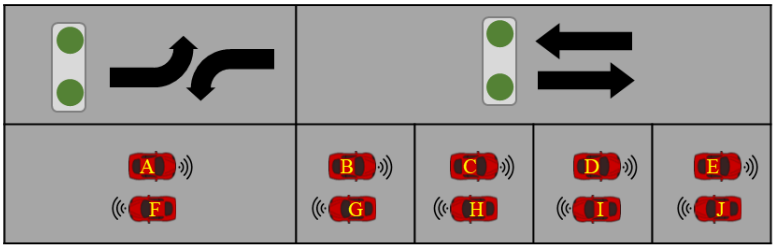
The first example focuses on how dynamically assigning lanes to different movement groups with an optimized signal setting can increase the throughput at intersections and decrease the average travel delay. Figure 9-A shows an isolated four-approach, two-lane intersection. The traffic demand of the through lane is assumed to be much higher than the one on the left-turn lane (i.e., four through vehicles and one left-turn vehicle on each approach). This example focuses on only two phases of left-turn and through for eastbound and westbound vehicles. The goal is to compare the throughput at the intersection box for two cases of fixed and optimized signal and lane settings. As figure 9-B shows, without DLA (i.e., all green-pass message for all lanes), even with an optimized signal setting, all through vehicles can pass the intersection box only from their current and only available lane sequentially. This might introduce an unnecessary delay to through vehicles, while the left-turn lane is free to use. Figure 9-C, however, shows that such an unnecessary delay can be eliminated by enabling different lanes to be assigned to vehicles with different movement groups. As shown in figure 9-C, the throughput at the intersection can increase by allowing through vehicles to use the left-turn lane. Note that this is an illustrative example of how optimizing the signal and lane settings can eliminate unnecessary delays. As the number vehicles and approaches increases, the opportunity for eliminating unnecessary delays is expected to increase.



Source: FHWA

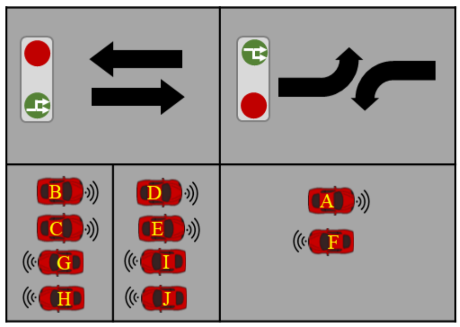
RSE = roadside equipment.

A. Illustration. Four-approach, two-lane signalized intersection.



Source: FHWA.

B. Illustration. Planned signal without DLA and the corresponding departure sequence.



Source: FHWA.

C. Illustration. Planned signal with DLA and the corresponding departure sequence.

Figure 9. Illustration. Cooperative driving automation operational scenario 1.

The second example, shown in figure 10, illustrates how smoothing vehicle trajectories and the available SPaT and LAP in CDA environment can improve the traffic performance at intersections. As specified by the SALO component, RSE determines a near-optimum departure sequence of vehicles at the intersection, estimates their ETs/CTs to the intersection box/DLA control point, and converts the estimated ETs/CTs to a SPaT plan/LAP, regardless of vehicles' cooperation class. Therefore, the determined SPaT plan and LAP for scenarios with different cooperation classes will be the same. Also, regardless of vehicles' cooperation classes, the determined SPaT plan is shared among all vehicles. Further, the difference in TS component of different cooperation classes is the source of ET estimation (i.e., the ET will be estimated by the C–ADS-equipped vehicles in cooperation classes A, B, and C, and will be estimated by RSE in cooperation classes C and D). Therefore, the negotiation capabilities enabled in cooperation classes C and D just assist C–ADS-equipped vehicles by eliminating the need for estimation of the ETs. Thus, the TS component in all cooperation classes essentially follows the same procedure. With this, the example is specified for two cases: existing HVs (without TS component); and C–ADS-equipped vehicles (with TS component).

Just to present the TS operations, only the through vehicles are considered in the second example. As shown in figure 10-A, through vehicles A, B, C, D, and E enter the communication area and are approaching the intersection box. This operational scenario focuses on this set of vehicles, especially vehicle C. As soon as the first EV from an entry lane leaves the entering segment (vehicle D in figure 10-B), all existing EVs will change their state to UPV. While UPVs are traversing through the entering and processing segments, RSE will determine a near-optimum departure sequence of UPVs, estimate their CTs and ETs, and convert them to the SPaT plan. RSE will also determine the LAP for the case with C–ADS-equipped vehicles.

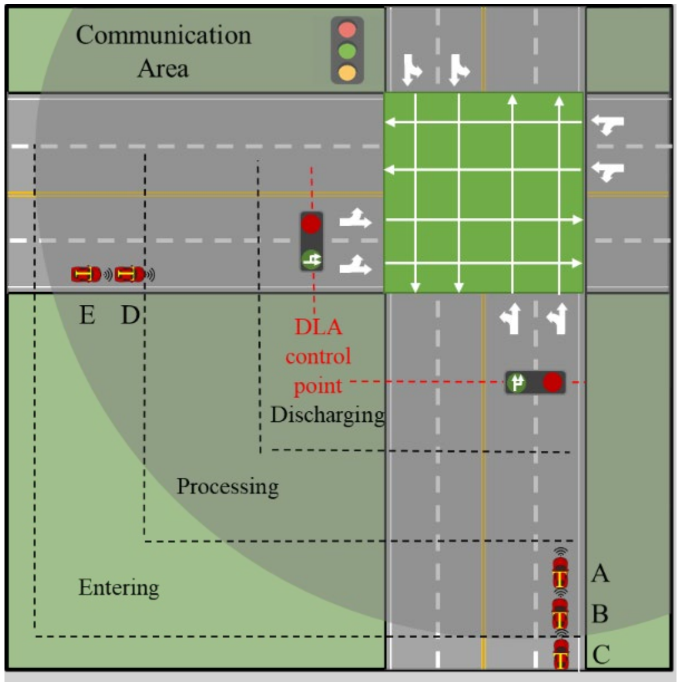
As soon as the SPaT and LAP are available, UPVs change their states to PV. For the longitudinal trajectory planning, as shown in figure 10-C, if all vehicles are HVs, they are unaware of the SPaT plan and other vehicles' information, and they will proceed according to their predefined car-following model. If all vehicles are C–ADS-equipped vehicles, however, they will receive the planned SPaT and LAP as well as other vehicles' statuses and intents, and therefore they will be able to predict their own CTs and ETs, as shown in figure 10-D, and plan their smooth longitudinal trajectories.

For the lateral trajectory planning, figure 10-E and figure 10-F show the C–ADS-equipped vehicle operations for cooperation classes A and B and cooperation classes C and D, respectively. As shown in figure 10-E, if all vehicles are equipped with class A or B cooperation, they receive the accessible lanes from RSE and thus proceed according to the predefined lane-changing model (e.g., the straight line trajectory of vehicle B in figure 10-E). If all vehicles are CDA class C or D cooperation, however, they will receive the assigned lanes from RSE and thus follow the planned smooth lateral trajectories as shown in figure 10-F (e.g., the smooth curve trajectory of vehicle B in figure 10-F).

Figure 10-G and figure 10-H show the investigated scenarios after the first green phase for vehicles A, B, and C. As shown in figure 10-G, where all vehicles are HVs, vehicles A, B, and C will follow their predefined car-following model and thus will come to full stop at the departure line and wait for the green phase. Therefore, their entry speed to the intersection box might not be the maximum possible speed, and vehicles might need more time to pass through the intersection box. Thus, vehicle C cannot enter the intersection box at the given green phase, must stop at the red phase again, and must wait for the next green phase.

As shown in figure 10-H, however, because vehicles are aware of the other vehicles' information, SPaT plan, and LAP, they control their trajectory such that they can pass the intersection at the green phase at the maximum speed. Note that vehicle B changes to another lane so that vehicles A and B can pass the intersection at the same time. Therefore, vehicle C can also pass the intersection at the first green phase and does not need to wait for the next cycle. Figure 10-H shows there is still some time for another vehicle to enter the intersection box at the given green phase, however. This shows that even without DLA, vehicle A would still be able to enter the intersection box at the given green phase, which is a result of the proposed TS component.

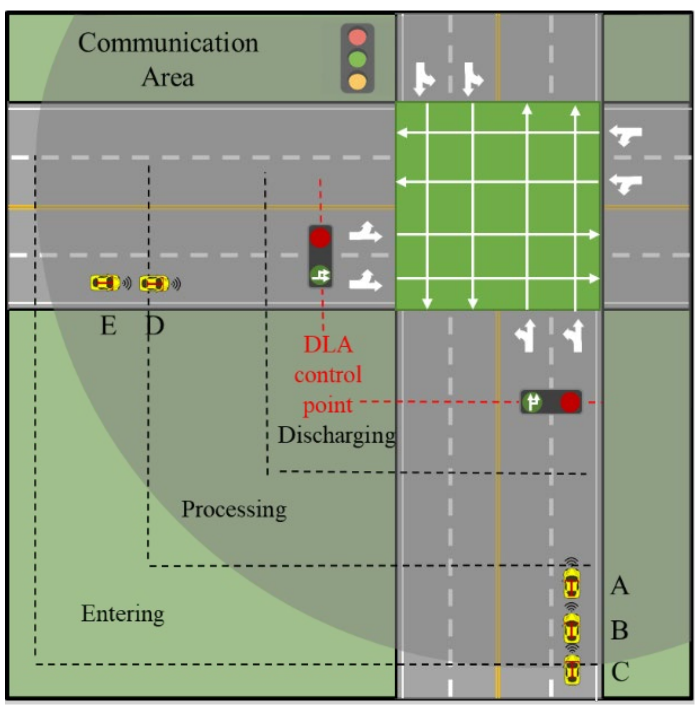
Overall, these operational scenarios illustrate the effectiveness of the proposed control framework at signalized intersections. It is shown by these operational scenarios that the combination of V2V and vehicle-to-RSE cooperation both enhances the overall traffic system performance and improves individual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



Source: FHWA.

DLA = dynamic lane assignment.

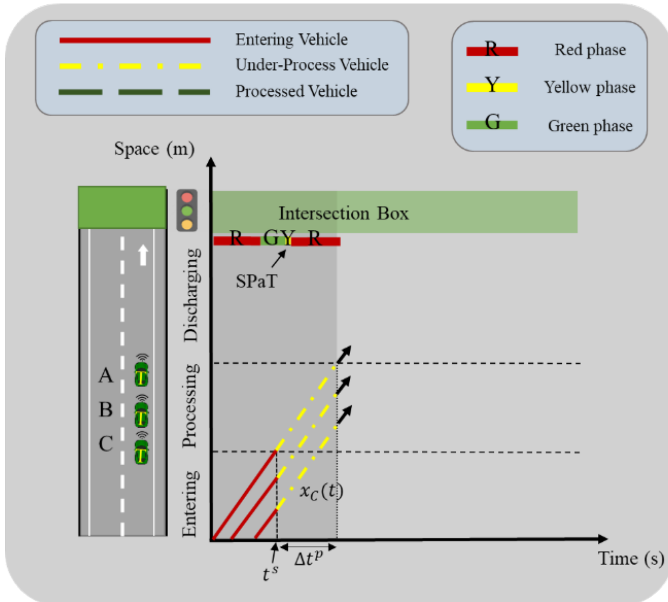
A. Illustration. Four-approach two-lane signalized intersection.



Source: FHWA.

DLA = dynamic lane assignment.

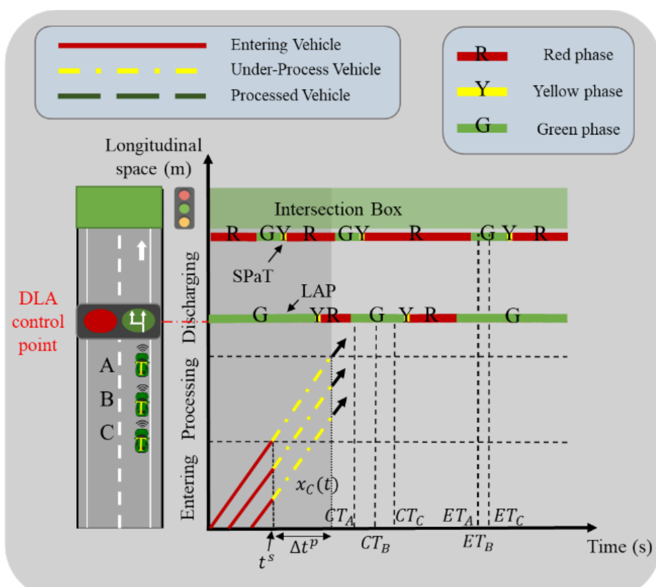
B. Illustration. Change of states from EV to UPV.



Source: FHWA.

SPaT = signal phase and timing; $x_c(t)$ = trajectory of vehicle C;
t^s = the start time step of processing; Δt^p = maximum processing time.

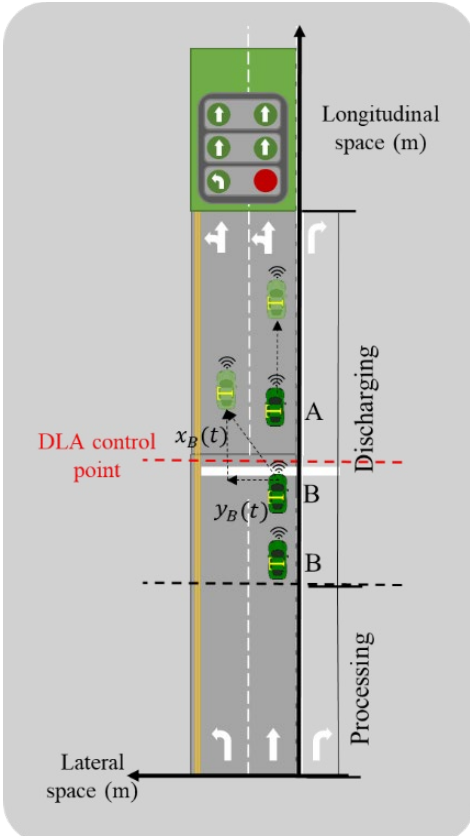
C. Illustration. Class A—before green.



Source: FHWA.

DLA = dynamic lane assignment; ET_A / ET_B / ET_C = entering time of vehicle A/B/C; CT_A / CT_B / CT_C = entering time of vehicle A/B/C; $x_C(t)$ = trajectory of vehicle C; t^s = the start time step of processing; Δt^p = maximum processing time.

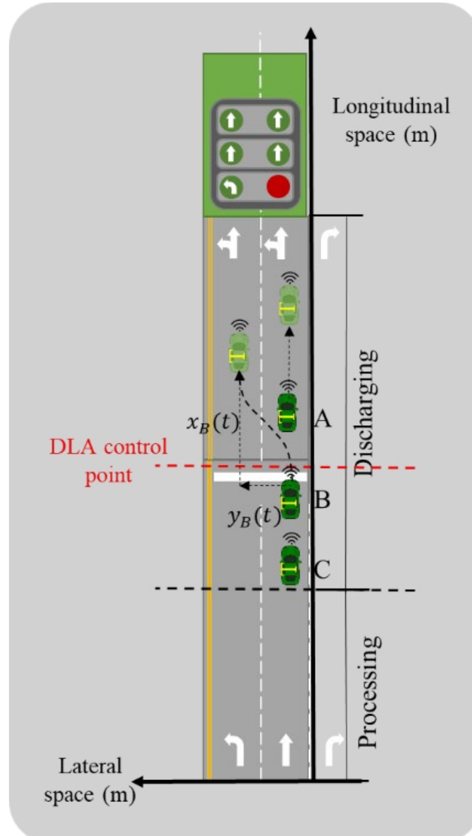
D. Illustration. Classes B, C, and D—before green.



Source: FHWA.

DLA = dynamic lane assignment; $x_B(t)$ = longitudinal trajectory of vehicle B.
$y_B(t)$ = lateral trajectory of vehicle B.

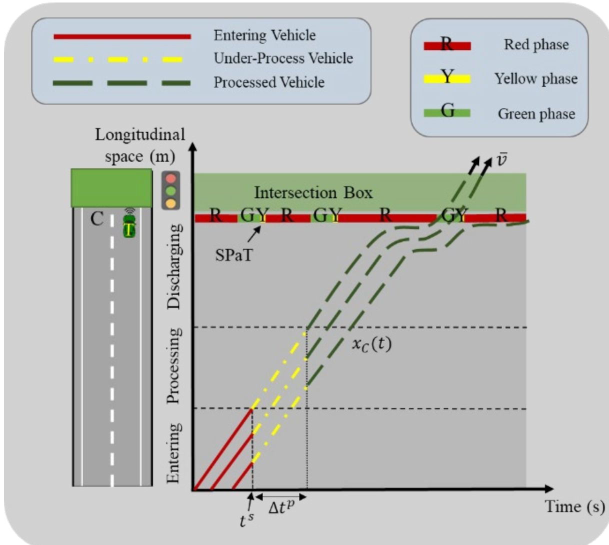
E. Illustration. Classes A and B—lateral trajectory planning.



Source: FHWA.

DLA = dynamic lane assignment; $x_B(t)$ = longitudinal trajectory of vehicle B.
$y_B(t)$ = lateral trajectory of vehicle B.

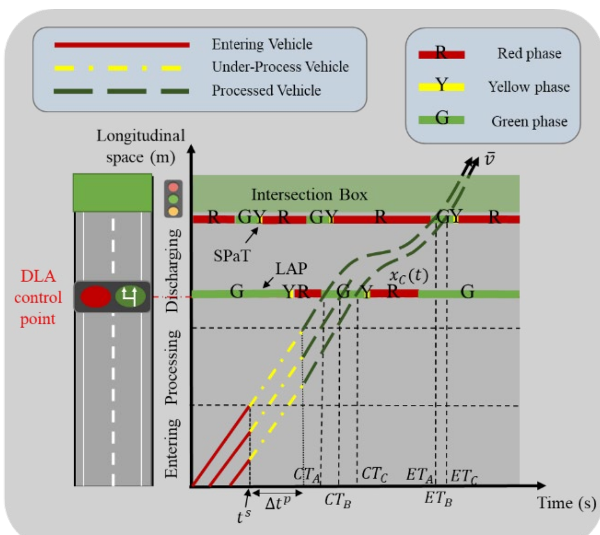
F. Illustration. Classes C and D—lateral trajectory planning.



Source: FHWA

$x_C(t)$ = trajectory of vehicle C; t^s = the start time step of processing;
Δt^p = maximum processing time.

G. Illustration. Class A—after green.



Source: FHWA

DLA = dynamic lane assignment; ET_A / ET_B / ET_C = entering time of vehicle A/B/C;
CT_A / CT_B / CT_C = entering time of vehicle A/B/C; $x_C(t)$ = trajectory of vehicle C;
t^s = the start time step of processing; Δt^p = maximum processing time.

H. Illustration. Classes B, C, and D—after green.

Figure 10. Illustration. Cooperative driving automation operational scenario 2.

CHAPTER 5. ANALYSIS OF THE PROPOSED SYSTEM

This chapter provides an analysis of the benefits, advantages, limitations, and disadvantages of TSMO UC4 at signalized intersections with an integration of traffic SALO and C–ADS-equipped vehicle TS. A high-level system validation plan is also discussed.

SUMMARY OF POTENTIAL BENEFITS AND OPPORTUNITIES

CDA technologies enable mobility applications that individual ADS-operated vehicles cannot achieve. They do so by sharing information that can be used to increase the safety, efficiency, and reliability of the transportation system, and that may serve to 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 dynamic driving task by one or more nearby road users. Vehicles and infrastructure elements engaged in cooperative automation may share information, such as status (e.g., vehicle position, speed) and intent (e.g., estimated ET, SPaT plan, lane assignments) 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 UC4, a cooperative control framework is proposed to efficiently control C–ADS-equipped vehicles at signalized intersections with an optimal signal setting. The proposed framework is illustrated for different cooperation classes defined in SAE J3216 and contains three main components: SALO, CTSE, and TS. First, the signal optimization component runs at a centralized RSE server to optimize SPaT and LAP with real-time information from all C–ADS-equipped vehicles. Second, the CTSE component aims to estimate an ET to the intersection box and a CT at the DLA control point for each individual vehicle with the available SPaT plan and LAP, which will be called by either RSE or the vehicle itself, depending on its cooperation class. Finally, the TS component aims to smooth vehicle trajectories with the estimated ET and CT, 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 the operational scenarios in chapter 4, the combination of cooperation between vehicles and between vehicles and RSE can enhance the overall traffic system performance (as a result of the SALO component, the CTSE component, and the TS component together) and improve individual vehicle travel experiences (as a result of the TS component). It is expected from the proposed control framework to reduce the stop-and-go traffic pattern and the backward shock wave propagations, increase the throughput, decrease travel delay, and maintain safety for each individual vehicle at signalized intersections with an optimal signal and lane setting.

SYSTEM VALIDATION PLAN

This section describes system validation methods to validate the developed algorithms and software systems for TSMO UC4. The purpose of the validation testing is to ensure the developed TSMO UC4 system can meet all the operational needs listed in table 7.

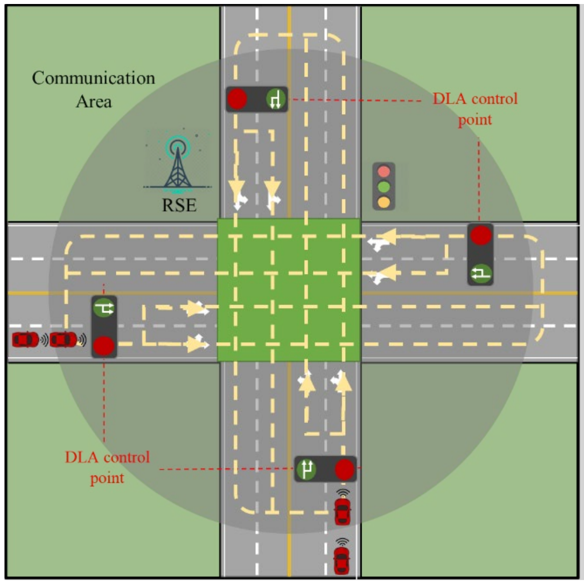
Simulation Testing

Simulations can be designed to test the developed algorithm for TSMO UC4 using the performance metrics, identified in chapter 3, of vehicle behavior and traffic system performance. Different types of simulations can be used and combined for testing purposes.

Traffic simulators offer the possibility to scale up the evaluation to an intersection corridor/network level (as compared with the limited number of vehicles and length of the roadway for ADS simulators) to study the CDA impact on transportation system performance (as measured by traffic performance metrics such as safety, efficacy, stability, and sustainability). Traffic simulators can evaluate different scenarios, such as various traffic demand, SPaT, LAP, 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 the developed algorithm can be reliably and easily implemented into CARMA Platform, a set of proof-of-concept tests will be conducted on a closed test track. This can be demonstrated onsite at a signalized intersection typical of anywhere in the United States. Depending on participation by partners, multiple CARMA vehicles loaded with necessary feature groups can be instructed to run loops on the test track to represent continuous driving, as shown in figure 11. The operational scenarios discussed in chapter 4 can be tested. The purpose of testing can be to verify the software, collect vehicle behavior performance measures, and to validate software requirements. Data collected from the test track can be used not only to calculate vehicle behavior performance metrics, but also to calibrate traffic simulation CDA behavior models. This may enable better validated evaluation of CDA's traffic impacts in simulations.



Source: FHWA.

DLA = dynamic lane assignment; RSE = roadside equipment.

Figure 11. Illustration. Experimental plan for signalized intersection control.

SUMMARY OF IMPACTS

The proposed control strategy for TSMO UC4 can have an impact on research and operations of future transportation systems management. From a research perspective, TSMO UC4 offers an approach to managing transportation systems efficiently at signalized intersections and reducing any type of disutilities, such as excessive delay and emissions. The benefits of TSMO UC4 can be realized only when cooperative control can be enabled by effective algorithms, including those for SALO, 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 UC4 presents changes to how TSMO is conducted at signalized intersections. Intelligent transportation systems infrastructures would need to be upgraded to accommodate the CDA system needs, such as RSE services and supporting information technologies. Agencies would also need to evaluate and build up capabilities for operating such emerging systems. The conventional process of transportation system performance monitoring and reporting could be revolutionized with the prevalence of C–ADS-equipped vehicles and advanced sensors. Conventional strategies for TSMO with which agencies are already familiar may be enhanced by CDA technologies.

DISADVANTAGES AND LIMITATIONS

The proposed control strategy for TSMO UC4 provides advantageous insights to CDA operations at signalized intersections but might face limitations that could be further investigated. The following are some of those limitations:

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

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