U.S. Department of Transportation
Federal Highway Administration

Office of Operations
Research and Development

© oonal, iStock/ Getty Images Plus

Cooperative Driving Automation Transportation Systems Management and Operations Strategies and Use Cases—An Overview

The Federal Highway Administration (FHWA) Cooperative Driving Automation (CDA) Program is advancing the research and development of CDA to accelerate its market readiness and deployment. Through collaboration and open-source software development, the program allows researchers and engineers to research, develop, test, and evaluate CDA features on infrastructure and vehicles equipped with driving automation features. The focus is on using emerging automated driving and vehicle-to-everything technologies to improve the transportation system.

The CARMA Ecosystem of products provides the necessary software for conducting CDA research and testing. The CARMA product suite consists of CARMA Cloud^{SM}, CARMA Streets, CARMA Platform^{SM}, and CARMA Messenger, all of which are downloadable tools supporting cooperation between vehicles.

CARMA STREETS

CARMA Streets is a roadside interface and an edge-computing device that enables communication between infrastructure and various transportation modes and users. Developed as part of the FHWA Cooperative Automation Research: CARMA Proof-of-Concept Transportation Systems Management and Operations (TSMO) Use Case Testing project, CARMA Streets aims to enhance TSMO strategies to improve transportation efficiency and safety at intersections. The adoption of CARMA Streets at intersections may enable greater active transportation and demand management—increasing throughput, enhancing safety, and improving driver experience.

The SAE J3216 standard defines how cooperation between vehicles is regarded. The classes address different capabilities of a cooperative automated driving system (C–ADS)-equipped vehicle that would affect its ability to cooperate with other CDA participants (e.g., vehicles and infrastructure).

			Partial Automation of DDT*		Complete Automation of DDT		
		LEVEL 0	**LEVEL 1**	**LEVEL 2**	**LEVEL 3**	**LEVEL 4**	**LEVEL 5**
		No Driving Automation (human does all driving)	Driver Assistance (longitudinal OR lateral vehicle motion control)	Partial Driving Automation (longitudinal AND lateral vehicle motion control)	Conditional Driving Automation	High Driving Automation	Full Driving Automation
NO COOPERATIVE AUTOMATION		E.g., Signage, TCD	Relies on driver to complete the DDT and to supervise feature performance in real time		Relies on ADS to perform complete DDT under defined conditions (fallback condition performance varies between levels)		
CLASS A STATUS SHARING	Here I am and what I see	E.g., Brake lights, traffic signal	Potential for improved object and event detection**		Potential for improved object and event detection[2]		
CLASS B INTENT SHARING	This is what I plan to do	E.g., Turn signal, merge	Potential for improved object and event detection[1]		Potential for improved object and event detection[2]		
CLASS C AGREEMENT SEEKING	Let's do this together	E.g., Hand signals, merge	N/A		C-ADS designed to attain mutual goals through coordinated actions		
CLASS D PRESCRIPTIVE	I will do as directed	E.g., Hand signals, lane assignment by officials			C-ADS designed to accept and adhere to a command		

*Driving automation predictability is limited by potential human override (vs C-ADS), and vehicle motion control is limited to longitudinal OR lateral for L1.

**Driving automation sensing capabilities may be limited compared to C-ADS. DDT = dynamic driving task; TCD = traffic control device.

1. Improved object and event detection and prediction through CDA Class A and Class 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 to Level 3, 4, and 5 ADS-operated vehicles.
2. Class A and B communications are one of the many inputs to an ADS's object and event detection and prediction capability, which may not be improved by the CDA message.

© **2020 SAE International.** The summary table may be freely copied and distributed provided SAE International and J3216 are acknowledged as the source and must be reproduced AS-IS.

Figure 1. Relationship between the Society of Automotive Engineers Standard J3216 classes of CDA and level of automation Standard J3016.

USE CASES

The introduction of CDA is expected to improve several existing TSMO strategies, as well as enable new strategies through driving automation. Each use case framework examines actions that the entity responsible for TSMO activities (i.e., an organization operating a transportation management service (TMS) will perform to achieve the TSMO strategy. Six TSMO strategy groups serve as use cases:

1.	**Stop-Controlled Intersections**
2.	**CDA Optimization at Fixed Time and Actuated Traffic Signals**
3.	**Traffic Signal Optimization with CDA at Adaptive Traffic Signals**
4.	**Dynamic Lane Assignment at Signalized Intersections**
5.	**Transit Signal Priority (TSP) at Signalized Intersections**
6.	**Traffic Incident Management (TIM) at Signalized Intersections**

The goals of these use cases are prioritized as follows:

SAFETY

The primary goal of these algorithms are to maintain safety while traversing an intersection. The algorithms contain a set of hard safety constraints that avoid potential crash risks and uncomfortably high accelerations/decelerations.

MOBILITY

Within the feasible range allowed by the guaranteed safe/comfortable travel experience, these algorithms aim to maximize the throughput of intersections by minimizing vehicles' departure times from the intersection box (and maximizing their departure speeds for signalized intersections).

ENERGY EFFICIENCY

Within the feasible range allowed by the safety and mobility priorities, these algorithms seek to smooth vehicle trajectories to minimize energy consumption as well as further improve riding comfort.

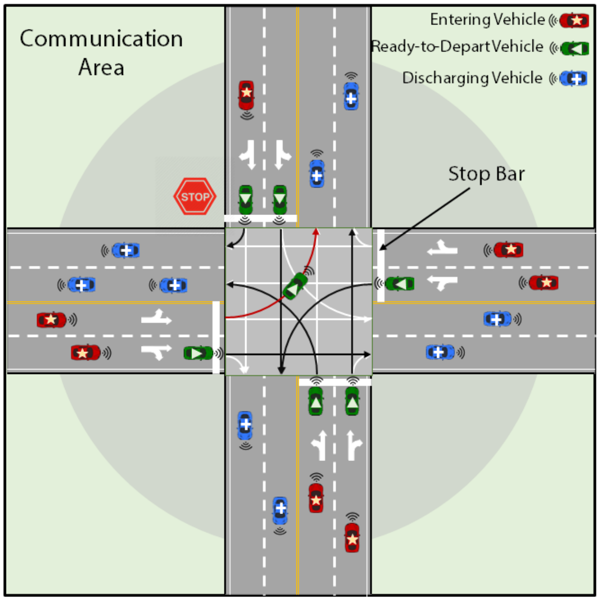
Automated driving technology can be used in a cooperative manner from when C-ADS-equipped vehicles enter the communication area of intersections to when they exit. CDA infrastructure supports and enables automated driving technology to help manage the transportation system to address congestion and improve safety and energy efficiency during normal travel at arterials, especially in a high traffic demand scenario.

1. Stop-Controlled Intersections

Framework: Focuses on improving the departure sequence of vehicles and smoothing vehicle trajectories at a stop-controlled intersection.

This use case has two main components:

- Critical time step estimation (CTSE).
  - o Designed to run on CARMA Streets or CARMA Platform, depending on the cooperation class of the C-ADS equipped vehicles.
  - o Targeted to estimate crucial points in a vehicle's journey through an intersection, such as stopping at a stop sign and traversing an intersection.
- Trajectory smoothing (TS).
  - o Designed to run on C-ADS-equipped vehicle.
  - o Aims to streamline vehicle paths.
  - o Determined by the vehicle itself.



Source: FHWA.

Figure 2. Stop-Controlled Intersections.

In this use case, when vehicles enter the communication area of a stop-controlled intersection, they begin transmitting real time operational status (such as location and speed) and intents (such as movement group and a few points of the vehicle's future path) to CARMA Streets. CARMA Streets processes this information and broadcasts critical high-level input regarding when vehicles will perform specific actions to navigate through the intersection, and enables vehicle control over trajectories and collision avoidance.

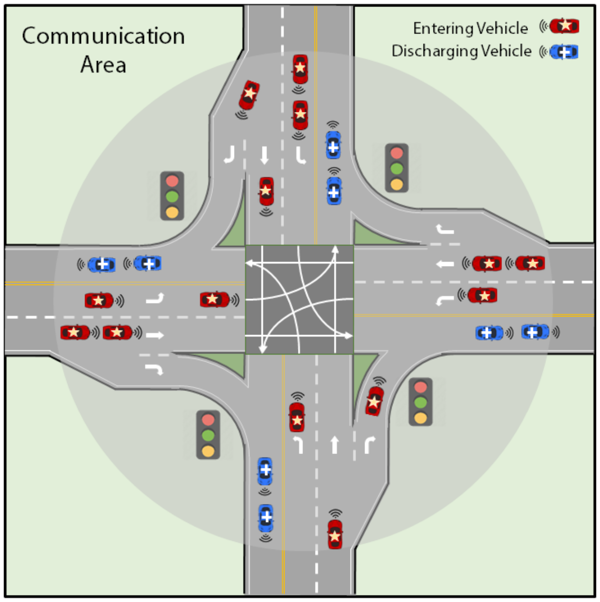
2. CDA Optimization at Fixed Time and Actuated Traffic Signals

Framework: Focuses on smoothing vehicle trajectories at a signalized intersection by sharing the Signal Phase and Timing (SPaT) plan with vehicles.

This use case has two main components:

- CTSE.
- TS.

When a vehicle enters the communication area, it will receive the SPaT information from the roadside unit (RSU). Then, the vehicle will plan the trajectory for passing through the intersection, either at the highest speed safely allowed to get through the intersection, or at a lower speed, such as when the vehicle cannot make it to the green signal.



Source: FHWA.

Figure 3. CDA Optimization at Fixed Time and Actuated Traffic Signals.

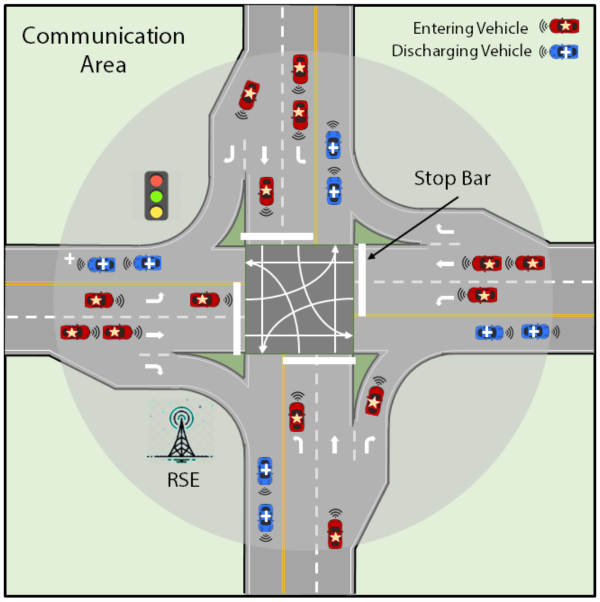
3. Traffic Signal Optimization with CDA at Adaptive Traffic Signals

Framework: Focuses on optimizing the SPaT plan and smoothing vehicle trajectories at a signalized intersection.

This use case has three main components:

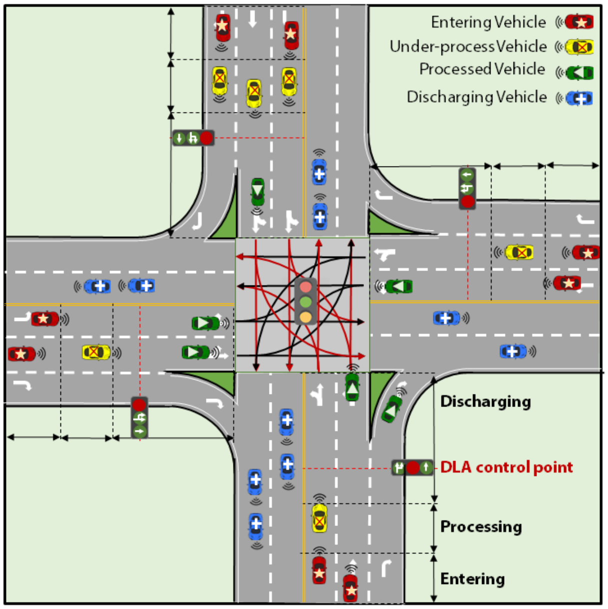
- CTSE.
- TS.
- Signal optimization: runs on CARMA Streets.

CARMA Streets gathers the vehicle's status and intent information and uses them for optimizing the SPaT plan in real time. The SPaT plan optimization algorithm aims to reduce the average travel delay and increase throughput at the intersection. Additionally, CARMA Streets continuously shares the updated SPaT information with the vehicle inside the communication area. Then, the vehicle will plan the trajectory for passing through the intersection, either at the highest speed safely allowed to get through the intersection, or at a lower speed, such as when that the vehicle cannot make it to the green signal.



Source: FHWA.

Figure 4. Traffic Signal Optimization with CDA at Adaptive Traffic Signals.



Source: FHWA.

Figure 5. Dynamic Lane Assignment at Signalized Intersections.

4. Dynamic Lane Assignment at Signalized Intersections

Framework: Focuses on optimally assigning the entry lanes to different vehicle movement groups while optimizing the SPaT plan at a signalized intersection.

This use case has three main components:

- CTSE.
- TS.
- Signal and Lane Optimization.
  - Runs on CARMA Streets to support real time vehicle information.
  - Assists with assigning vehicles to specific lanes.

Similar to use case 3, in this use case, CARMA Streets also gathers vehicle status and intent information and uses them for optimizing the SPaT plan in real time. The difference between this use case and use case 3, however, is that the entry lanes in this use case can be dynamically assigned to different movement groups. This way, the intersection resources can be allocated to different traffic streams more efficiently in the case of unbalanced and dynamic traffic flow patterns.

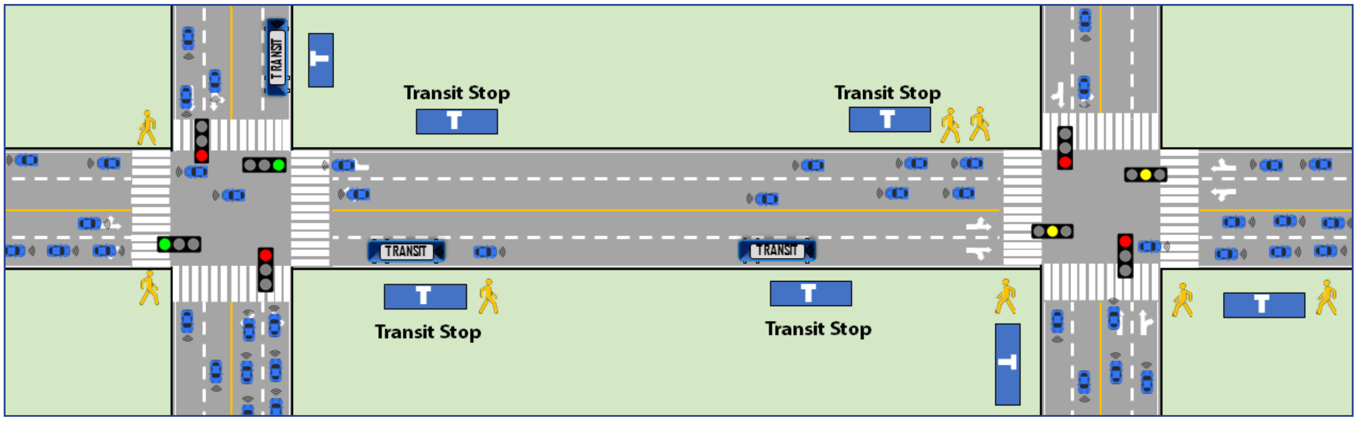


Figure 6. TSP at Signalized Intersections.

Source: FHWA.

5. Transit Signal Priority (TSP) at Signalized intersections

Framework: Focuses on a signalized arterial with several transit vehicles traveling on the arterial or on the cross streets.

This use case uses CDA technologies to provide signal priority to transit vehicles as they enter the communications radius of signalized intersections. The CDA technologies reduce travel delays and improve the quality of service of transit vehicles. The CARMA Ecosystem and the multimodal intelligent traffic signal system are two key technological advances that enable a CDA approach to TSMO transit using TSP.

At any time, there may be several transit vehicles traveling on the arterial or cross streets. It is assumed that all transit vehicles are equipped with CDA technologies and that each intersection is similarly equipped with an RSU, an edge processor (CARMA Streets), and a traffic signal controller that provides SPaT data and is capable of providing priority for transit vehicles when requested.

If the transit vehicle does send a request for transit signal priority, the RSU will forward the message to CARMA Streets, where it will be considered along with requests from other priority eligible vehicles. At any single intersection, several transit vehicles may have requested priority.

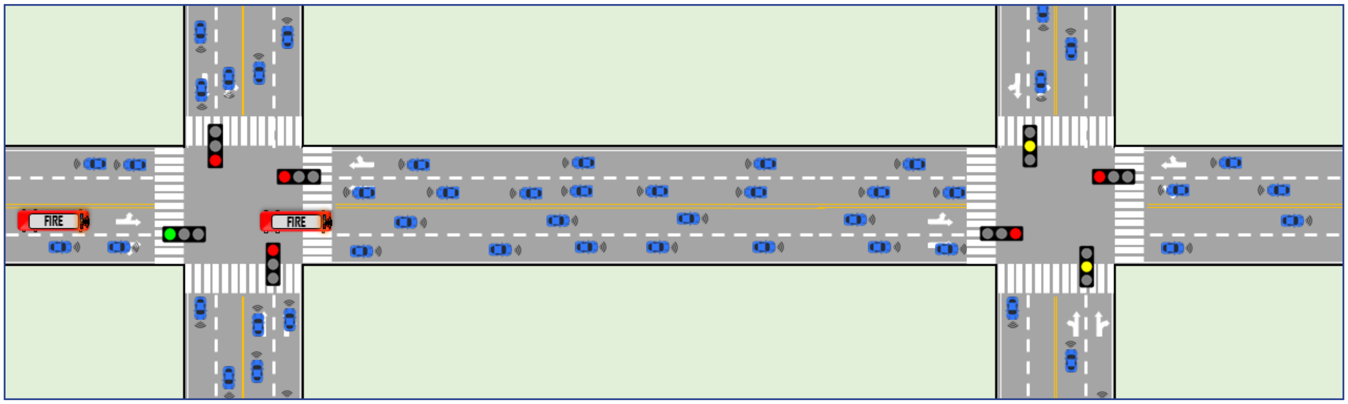


Figure 7. TIM at Signalized Intersections.

Source: FHWA.

6. Traffic Incident Management (TIM) at Signalized Intersections

Framework: Focuses on an arterial with several signalized intersections and one or more active incident response vehicles.

This use case demonstrates how CDA technologies can be used to reduce delays and improve safety of incident response vehicles as soon as they enter the communication radius of signalized intersections. The CARMA Ecosystem and the multimodal intelligent traffic signal system are key advances that enable a CDA appraoch to TSMO TIM using traffic signal perception.

At any time, there may be one or more incident response vehicles in route to an incident. It is assumed that all incident response vehicles are equipped with CDA technologies and that each intersection is similarly equipped with an RSU, an edge processor (e.g., CARMA Streets), and a traffic signal controller that provides SPaT data and is capable of providing preemption for incident response vehicles when requested.

Having active incident response vehicles is an exception to the assumption of "normal" traffic operating conditions, and special considerations are made for traffic signal operations including traffic signal preemption. If the incident response vehicle does send a request for transit signal priority (i.e., signal preemption), the RSU will forward the message to CARMA Streets, where it will be considered along with requests from other priority eligible vehicles. At any single intersection, several incident response vehicles may have requested priority.

COOPERATIVE PERCEPTION (CP)

In addition to work on the six use cases described in the previous section, the CDA Program is also developing a CP feature that will be integrated into the CARMA ecosystem.

CP Framework: The CP feature enables various CDA participants (e.g., vehicles and infrastructure) to exchange information about roadway objects they have detected in their surrounding environments. The roadway objects can be detected by a vehicle's extrospective onboard sensors (e.g., cameras and LiDARs) and/or similar infrastructure-based sensors.

These roadway objects include, but are not limited to, vulnerable road users (VRUs), vehicles on the road, and obstacles on the roadway. This feature is expected to improve the perception capabilities of CDA participants, and as a result, transportation safety and efficiency.

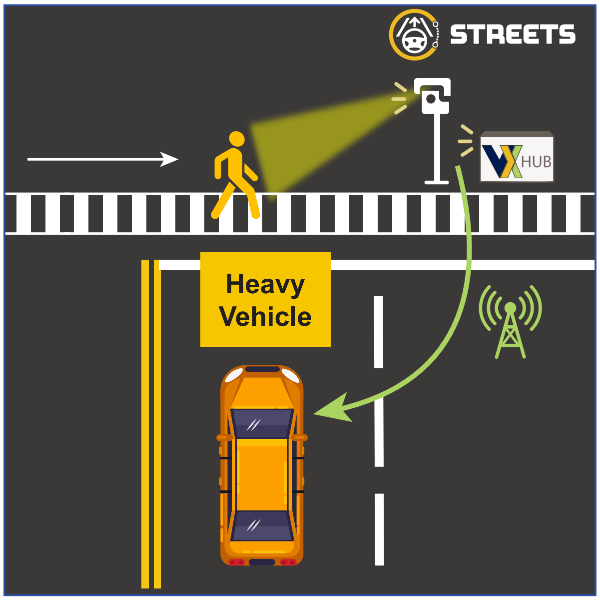


Figure 8. CP. Source: FHWA.

Fourteen potential use case scenarios are discussed in the CP high-level concept of operations to be published by FHWA. The use case scenarios are classified into four categories: VRU applications, collision avoidance, conflict avoidance and cooperative driving, and general enhancement of situational awareness. An example scenario is described below.

Application: Interacting with VRUs
Scenario: VRUs Crossing at Controlled Conflict Areas

- When traffic volume is relatively high, or when the number of conflict points is large, VRUs can be easily missed by human drivers. Autonomous vehicles could also have a limited line of sight and may not be able to detect VRUs sufficiently early.
- In the example shown in Figure 8 above, a roadside sensor (e.g., camera or LiDAR) located at the intersection detects and perceives the pedestrian (represented by the yellow triangle). It could then share its perception with the passenger vehicle whose line of sight is blocked (in this case, by a heavy vehicle) using vehicle-to-infrastructure communication as indicated by the curved green arrow.

REFERENCES

SAE International. 2020. Relationship Between Classes of Cooperative Driving Automation (CDA) J3216 and Levels of Automation J3016. Warrendale, PA: SAE International.

U.S. Department of Transportation
Federal Highway Administration

For more information, please contact: g.vadakpat@dot.gov

Digital Object Identifier (DOI): https://doi.org/10.21949/1521869
FHWA-HRT-22-067
HRSO-50/05-22(WEB)E