



SURFACE VEHICLE INFORMATION REPORT

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Cooperative Driving Automation (CDA) Feature - Infrastructure-Based Prescriptive Cooperative Merge

RATIONALE

Although still some years from being realized as a commercial product, automated driving system (ADS)-operated vehicles are expected to eventually become a common participant in road traffic. To help prepare for such a future, this document describes a cooperative driving automation (CDA) Feature and test procedure. The focus of the document is on producing a proof-of-concept-level infrastructure-based prescriptive CDA Feature and associated test procedures suitable for testing in both distributed virtual testing environments, as well as on test tracks, at the proof-of-concept level. (Note: This test procedure may also be suitable for testing on-road.)

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1. SCOPE

This SAE Information Report describes a concept of operations (CONOPS) for a Cooperative Driving Automation (CDA) Feature for infrastructure-based prescriptive cooperative merge. This work focuses on a Class D (Prescriptive; refer to J3216) CDA infrastructure-based cooperative merge Feature, supported by Class A (Status-Sharing) or Class C (Agreement-Seeking) messages among the merging cooperative automated driving system-operated vehicles (C-ADS-equipped vehicles). This document also provides a test procedure to evaluate this CDA Feature, which is suitable for proof-of-concept testing in both virtual and test track settings.

NOTE 1: This report was developed prior to SAE J3252. Future revisions of this report will align with the framework described in SAE J3252.

NOTE 2: The term “CDA Feature” as used in this report is defined in SAE J3216 as follows: “The design-specific functionality supported or enabled by M2M cooperation among CDA devices communicating with a C-ADS engaging in CDA.” Thus, the word “feature” here varies from its common English definition. To emphasize this variance and to avoid confusion, “Feature” is capitalized when modified by the adjective “CDA” or “C-ADS.”

2. REFERENCES

2.1 Applicable Documents

The following publications form a part of this specification to the extent specified herein. Unless otherwise indicated, the latest issue of SAE publications shall apply.

2.1.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or +1 724-776-4970 (outside USA), www.sae.org.

SAE J2735	V2X Communications Message Set Dictionary
SAE J2945	Dedicated Short Range Communication (DSRC) Systems Engineering Process Guidance for SAE J2945/X Documents and Common Design Concepts™
SAE J3016	Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles
SAE J3131	Definitions for Terms Related to Automated Driving Systems Reference Architecture
SAE J3161	LTE Vehicle-to-Everything (LTE-V2X) Deployment Profiles and Radio Parameters for Single Radio Channel Multi-Service Coexistence
SAE J3186	Application Protocol and Requirements for Maneuver Sharing and Coordinating Service
SAE J3216	Taxonomy and Definitions for Terms Related to Cooperative Driving Automation for On-Road Motor Vehicles
SAE J3224	V2X Sensor-Sharing for Cooperative and Automated Driving
SAE J3252	Process for Developing an Interoperable Cooperative Driving Use Case Test Framework and Test Procedures

2.1.2 FHWA Publications

Available from Federal Highway Administration, 1200 New Jersey Ave, SE, Washington, DC 20590, Tel: 202-366-4000, <https://www.fhwa.dot.gov/>.

CARMA CARMA Deployment of Cooperative Automated Vehicle Capabilities: Integrated Prototype II Architecture for CARMA System Version 4.0 - ROS 2, November 2021

FHWA-TSMO Transportation System Management and Operations Strategies, 2022

2.1.3 IEEE Publications

Available from IEEE Operations Center, 445 and 501 Hoes Lane, Piscataway, NJ 08854-4141, Tel: 732-981-0060, www.ieee.org.

IEEE 1362-1998 IEEE Guide for Information Technology - System Definition - Concept of Operations (CONOPS) Document, 1998

2.1.4 NHTSA PUBLICATIONS

Available from National Highway Traffic Safety Administration, 1200 New Jersey Avenue, SE, Washington, DC 20590, Tel: 1-888-327-4236, <https://www.nhtsa.gov/>.

NHTSA 2021 An Approach for the Selection and Description of Elements Used to Define Driving Scenarios, April 2021

2.1.5 Other Publications

5GAA 2019 5G Automotive Association (5GAA) Working Group 1, "C-V2X Use Cases - Methodology, Examples and Service Level Requirements," June 2019

ARC-IT Architecture Reference for Cooperative and Intelligent Transportation, United States Department of Transportation, Version 9.1

AVSC 2021 Best Practice for Metrics and Methods for Assessing Safety Performance of Automated Driving Systems (ADS), Automated Vehicle Safety Consortium, 2021

CTI 4001 Roadside Unit (RSU) Standard; American Association of State Highway and Transportation Officials, Institute of Transportation Engineers, National Electrical Manufacturers Association, SAE International, Version v01.01, September 2022

Euro NCAP 2021 European New Car Assessment Programme (Euro NCAP), Test Protocol - AEB VRU systems, Version 3.0.4, April 2021

NTCIP 8002 Annex B1 Content Outline for NTCIP 1200-Series Documents (for Standards Engineering Process Content), September 2016

VOICES Virtual Open Innovation Collaborative Environment for Safety (VOICES) Proof-of-Concept, USDOT, <https://usdot-voices.atlassian.net/wiki/spaces/VP/overview>.

Amersbach, C. and Winner, H. (2017). Functional decomposition: An approach to reduce the approval effort for highly automated driving. Institute of Automotive Engineering at the Technische Universität Darmstadt.

Beregi, S., Avedisov, S., He, C., et al. (2023). Connectivity-based delay-tolerant control of automated vehicles: Theory and experiments. *IEEE Transactions on Intelligent Vehicles*, 8(1), 275-289.

Lin, Y., McPhee, J., and Azad, N. (2019). Longitudinal dynamic versus kinematic models for car-following control using deep reinforcement learning. *IEEE Intelligent Transportation Systems Conference (ITSC)*, 1504-1510.

Shalev-Shwartz, S., Shammah, S., and Shashua, A. (2017). On a formal model of safe and scalable self-driving cars. <https://doi.org/10.48550/arXiv.1708.06374>.

Wishart, J., Como, S., Elli, M., Russo, B. et al., "Driving Safety Performance Assessment Metrics for ADS-Equipped Vehicles," *SAE Int. J. Adv. & Curr. Prac. in Mobility* 2(5):2881-2899, 2020, <https://doi.org/10.4271/2020-01-1206>.

3. DEFINITIONS

3.1 AUTOMATED DRIVING SYSTEM (ADS) [refer to SAE J3016]

The hardware and software that are collectively capable of performing the entire dynamic driving task (DDT) on a sustained basis, regardless of whether it is limited to a specific operational design domain (ODD); this term is used specifically to describe a Level 3, 4, or 5 driving automation system. (For up-to-date definitions, notes, and examples, refer to the latest version of SAE J3016.)

3.2 COOPERATIVE DRIVING AUTOMATION (CDA) [refer to SAE J3216]

Automation that uses machine-to-machine (M2M) communication to enable cooperation among two or more entities with capable communications technology and is intended to facilitate the safer, more efficient movement of road users, including enhancing performance of the DDT for a vehicle with driving automation feature(s) engaged.

NOTE 1: For C-ADS-equipped vehicles engaged in cooperative automation, the M2M communications may enhance the performance of the DDT for the subject vehicle (e.g., object and event detection and response [OEDR], operational, and tactical maneuvers).

NOTE 2: For road operators engaged in cooperative automation, the M2M communications may provide situational awareness and influence performance of traffic management (e.g., signal phase and timing [SPaT], dynamic speed limits, and emergency response).

3.3 COOPERATIVE AUTOMATED DRIVING SYSTEM (C-ADS) [refer to SAE J3216]

An ADS capable of utilizing CDA.

NOTE: C-ADS may be considered a classification of a CDA Device Agent (defined under 3.8).

3.4 COOPERATIVE AUTOMATED DRIVING SYSTEM (C-ADS)-EQUIPPED VEHICLE [refer to SAE J3216]

A vehicle equipped with Level 3, 4, or 5 driving automation and capable of utilizing CDA. Note that Level 3 systems require human driver intervention upon ADS request. (Refer to SAE J3016 for additional information about driving automation systems.)

3.5 C-ADS-OPERATED VEHICLE

A C-ADS-equipped vehicle in which a C-ADS Feature is actively engaged in performance of the DDT.

NOTE 1: Additional ADS functions that are not specifically part of the C-ADS Feature function may also be actively engaged on a C-ADS-operated vehicle.

NOTE 2: A C-ADS-equipped vehicle may be operated by the ADS while the C-ADS Feature is disengaged (i.e., it can also be an ADS-operated vehicle).

3.6 CDA COOPERATION CLASSES [refer to SAE J3216]

Classes of cooperation facilitated by M2M communications among CDA devices that may influence DDT performance and traffic operations, defined as Classes A through D based on the increasing amount of cooperation entailed in each successive class.

NOTE: The use of CDA information to influence DDT performance by one or more C-ADS-equipped vehicle in any given situation depends upon the type of message provided, as well as other information used by the C-ADS-equipped vehicle(s).

3.6.1 STATUS-SHARING COOPERATION (CLASS A) [refer to SAE J3216]

Perception information about the traffic environment and information about the sending entity provided by the sending entity for potential utilization by receiving entities. ("Here I am, and here is what I see.")

NOTE 1: Status-sharing cooperation does not require the ability or consent of transmitting entities to employ the information provided via M2M communication, which may originate from any nearby traffic participant.

NOTE 2: Status-sharing cooperation may be used to enhance an entity's situational awareness.

NOTE 3: CDA devices that do not have direct control over the actions of the CDA device agent (e.g., pedestrians or conventional vehicles in which a human directly controls actions) may engage in status-sharing cooperation.

3.6.2 INTENT-SHARING COOPERATION (CLASS B) [refer to SAE J3216]

Information about planned future actions of the sending entity provided by that entity for potential utilization by receiving entities. ("This is what I plan to do.")

NOTE 1: Intent-sharing cooperation does not require the ability or consent of receiving entities to employ the information provided via M2M communication, which may originate from any nearby traffic participant. Receiving entities do not necessarily need to act on the shared intent, and all entities are expected to conduct competent operations regardless of others' actions.

NOTE 2: Intent-sharing cooperation may be used to augment prediction of future states to enhance models of the planned future actions of the sending entity.

NOTE 3: Intent-sharing cooperation may augment status-sharing cooperation by providing information that relates to a future state (rather than just the current state) of a sending entity.

NOTE 4: In some cases, intent information may be shared without M2M communication (e.g., turn signals), but in many cases (e.g., occlusion of taillights), this information could not otherwise be determined at all or as soon by a receiving entity that is not participating in CDA. These non-CDA forms of intent sharing (e.g., turn signals, human gestures, etc.) are beyond the scope of this document.

NOTE 5: CDA devices that do not have direct control over the actions of the CDA device agent (e.g., pedestrians or conventional vehicles in which a human directly controls actions) may engage in intent-sharing communication.

3.6.3 AGREEMENT-SEEKING COOPERATION [AMONG CDA DEVICE AGENTS] (CLASS C) [refer to SAE J3216]

A sequence of collaborative messages among specific CDA devices intended to influence local planning of specific DDT-related actions. ("Let's do this together.")

NOTE 1: Agreement-seeking cooperation requires the ability and authority of the CDA device agents involved to cooperate and agree on plan(s) based on the information provided via M2M communication, which may originate from any nearby traffic participant.

NOTE 2: Agreement-seeking cooperation includes an interactive exchange of messages that may include plans, acceptance or rejection of plans, or considerations for arriving at consensus on a proposed plan. Depending on circumstances, CDA device agents may not follow a planned future action, and all entities must conduct competent operations regardless of others' actions.

NOTE 3: Agreement-seeking cooperation may utilize status-sharing and intent-sharing cooperation.

NOTE 4: This document does not consider planning for CDA devices that do not have direct control over the actions of the CDA device agent (e.g., pedestrians or conventional vehicles and driver support features in which a human directly controls actions), instead focusing on planning for systems with driving automation.

NOTE 5: Agreement-seeking cooperation includes proposing plans for other traffic participants (i.e., "What I want you to do."). In contrast, intent-sharing includes only sharing a plan for the sending entity (i.e., "What I plan to do.").

3.6.4 PRESCRIPTIVE COOPERATION (CLASS D) [refer to SAE J3216]

The direction of specific action(s) to specific traffic participants for imminent performance of the DDT or performance of a particular task by a road operator (e.g., changing traffic signal phase), provided by a prescribing CDA device agent(s) and adhered to by a receiving CDA device agent(s). ("I will do as directed.")

NOTE 1: CDA devices that do not have control over the actions of their corresponding CDA Agents (e.g., pedestrians or conventional vehicles and driver support features in which a human directly controls actions) cannot participate in prescriptive cooperation based CDA Features.

NOTE 2: Prescriptive cooperation does not require the willingness of the affected entities to cooperate. It relies on a pre-existing understanding between parties to adhere to commands, such as a specific aspect of DDT performance, under particular circumstances.

NOTE 3: Prescriptive cooperation may be performed by transportation authorities and/or fleet operations centers communicating with fleet vehicles under their control.

NOTE 4: Transportation authorities may have the ability to direct prescriptive cooperation to any relevant traffic participants.

NOTE 5: Prescriptive cooperation may utilize status-sharing, intent-sharing, and agreement-seeking cooperation to provide context for the understanding to cede control over actions that relate to the DDT performance.

3.7 CDA DEVICE [refer to SAE J3216]

A device equipped with requisite M2M communication technology that is used by traffic participants to perform CDA Features.

3.8 CDA DEVICE AGENT [refer to SAE J3216]

A traffic participant that authorizes its CDA device to send and receive communications enabling traffic participants to engage in CDA and authorizes CDA-related actions.

3.9 CDA FEATURE [refer to SAE J3216]

The design-specific functionality supported or enabled by M2M cooperation among CDA devices communicating with a C-ADS engaging in CDA.

NOTE 1: A given CDA device agent may employ multiple CDA Features simultaneously, where each Feature is associated with a particular data exchange, CDA device(s), and usage specification.

NOTE 2: CDA Features may be referred to by generic names (e.g., cooperative merging) or manufacturer-specific names.

3.10 CDA INFRASTRUCTURE (CDA-I) [adapted from SAE J3252]

Infrastructure capable of engaging in CDA Feature execution.

NOTE 1: CDA-I can be considered a classification of a CDA Device Agent (defined under 3.8).

NOTE 2: CDA-I can be located near a roadside (commonly referred to as “edge computing”) as well as far away from a roadside (e.g., cloud computing).

3.11 DYNAMIC DRIVING TASK (DDT) [refer to SAE J3016]

All of the real-time operational and tactical functions required to operate a vehicle in on-road traffic, excluding the strategic functions such as trip scheduling and selection of destinations and waypoints. (For up-to-date definitions, notes, and examples, refer to the latest version of SAE J3016.)

3.12 [DRIVING AUTOMATION SYSTEM] FEATURE [refer to SAE J3016]¹

A Level 1-5 driving automation system’s design-specific functionality at a given level of driving automation within a particular ODD, if applicable.

NOTE 1: Because the term “driving automation system” subsumes both driver support features and ADS features, it is also acceptable to refer to them as such.

NOTE 2: A given driving automation system may have multiple features, each associated with a particular level of driving automation and ODD.

NOTE 3: Each feature satisfies a usage specification.

NOTE 4: Features may be referred to by generic names (e.g., automated parking) or by proprietary names.

EXAMPLE 1: A Level 3 ADS feature that performs the DDT, excluding DDT fallback, in high-volume traffic on fully access-controlled freeways.

EXAMPLE 2: A Level 4 ADS feature that performs the DDT, including DDT fallback, in a specified geo-fenced urban center.

3.13 MESSAGE SUCCESS RATE

Percentage of messages received with respect to messages sent.

3.14 MINIMUM SAFE DISTANCE (MSD)

A safety boundary (aka safety envelope) between a vehicle and another vehicle or object to avoid a collision, as defined by current velocity(ies) and acceleration/deceleration capability(ies) of the vehicle(s) (see A.4.2).

3.15 MOBILE UNIT (MU) [refer to CTI 4001]

A device used to wirelessly communicate with other devices for safety and mobility purposes carried by a pedestrian, bicyclist, work zone worker, or other traveler.

3.16 ON-BOARD UNIT (OBU) [refer to CTI 4001]

A device used to wirelessly communicate with other devices for safety and mobility purposes installed in a vehicle as original equipment or as aftermarket equipment (sometimes referred to as an “aftermarket safety device (ASD).”

¹ J3016 also defines the following three specific types of driving automation system features: (1) maneuver-based, (2) sub-trip, and (3) full-trip.

3.17 OPERATIONAL DESIGN DOMAIN (ODD) [refer to SAE J3016]

Operating conditions under which a given driving automation system or feature thereof is specifically designed to function, including, but not limited to, environmental, geographical, and time-of-day restrictions, and/or the requisite presence or absence of certain traffic or roadway characteristics. (For up-to-date definitions, notes, and examples, refer to the latest version of SAE J3016.)

3.18 [A] PLAN [refer to SAE J3216]

A sequence of tasks defined to achieve or maintain a DDT-relevant goal during a trip.

NOTE 1: Planning may occur at strategic, tactical, and operational timescales. This may include outputs from mission planning (e.g., selected route segments and strategies to achieve a given destination or waypoint given certain goals) and behavior planning (e.g., trajectory - i.e., path and speed - of vehicles to competently perform the DDT given a particular driving situation).

NOTE 2: The terms “task,” “goal,” and “trip” are not further defined here. These concepts are discussed in other documents, such as the NIST 4D-RCS Framework provided in the references in SAE J3216.

3.19 TRAFFIC PARTICIPANT [refer to SAE J3216]

Entities whose actions influence travel in the transportation environment, which may include road users engaged in travel upon or across publicly accessible roadways and road operators.

3.19.1 ROAD USERS [refer to SAE J3216]

A traffic participant on or adjacent to an active roadway for the purpose of travelling from one location to another.

NOTE 1: Road users may include motor vehicles (including emergency vehicles), vehicle occupants, pedestrians, pedal cyclists, and users of motorized and non-motorized personal mobility devices, such as scooters, wheelchairs, and mobility carts.

NOTE 2: Road users are governed by local traffic laws.

3.19.2 ROAD OPERATOR [refer to SAE J3216]

A traffic participant who provides, operates, and maintains the roadways and supporting infrastructure that enable and support the mobility needs of road users.

NOTE: Road operators may include infrastructure owner operators as public, public-private, or private sector entities that operate in accordance with applicable laws at the federal, state, and/or local level.

3.19.3 ROADSIDE UNIT (RSU) [refer to CTI 4001]

A transportation infrastructure communications device located on the roadside that provides V2X connectivity between OBUs or MUs and other parts of the transportation infrastructure including traffic control devices, traffic management systems, and back-office systems.

NOTE: Devices that are not part of the transportation infrastructure, such as cellular base stations or satellites, are not RSUs.

3.19.4 CERTIFICATE AUTHORITY [refer to SAE J3216]

An entity that issues digital certificates that confirm authenticity of the certificate owner.

3.19.5 COMMUNICATIONS SERVICE PROVIDER (CSP) [refer to SAE J3216]

A traffic participant who provides and maintains the hardware and software necessary to support secure, low-latency communication M2M between and among traffic participants.

NOTE: CSPs may include public, public-private, or private sector entities that operate in accordance with applicable laws at the federal, state, and/or local level.

3.20 TIME-TO-COLLISION (TTC)

The time interval required for a vehicle to collide with another vehicle or object if one or both continue on their current paths and at the same speed (see A.4.1).

3.21 VEHICLE-TO-INFRASTRUCTURE (V2I) COMMUNICATION

A type of M2M wireless communication between local infrastructure and one or more vehicles.

NOTE 1: Communication can be initiated by either the vehicle or the local infrastructure.

NOTE 2: It is communication technology and radio spectrum agnostic so long as the reliability and latency requirements are met. Examples are Dedicated Short-Range Communications (DSRC) per SAE J2945 or Cellular V2X (C-V2X) per SAE J3161.

3.22 VEHICLE-TO-VEHICLE (V2V) COMMUNICATION

A type of M2M wireless communication between two or more vehicles.

NOTE: It is communication technology and radio spectrum agnostic so long as the reliability and latency requirements are met. Examples are DSRC per SAE J2945 or C-V2X per SAE J3161.

3.23 VEHICLE-TO-EVERYTHING (V2X) COMMUNICATION

A type of M2M wireless communication between a vehicle and any traffic participant, including other vehicles and infrastructure.

NOTE: V2X communications include V2I and V2V, as well as other types of M2M communications, such as vehicle-to-network.

4. ABBREVIATIONS

ADS	automated driving system
ARC-IT	Architecture Reference for Cooperative and Intelligent Transportation
AVSC	Automated Vehicle Safety Consortium
BSM	basic safety message
C-ADS	cooperative-automated driving system
CARMA	Cooperative Automation Research Mobility Applications
CDA	cooperative driving automation
CDA-I	cooperative driving automation infrastructure
CONOPS	concept of operations

CSP	communication service provider
C-V2X	cellular V2X
CVRE	connected vehicle roadside equipment
DDT	dynamic driving task
DSRC	dedicated short range communications
FHWA	Federal Highway Administration
GNSS	global navigation satellite system
ID	identification
INS	inertial navigation system
ITS	intelligent transportation system
LIDAR	light detection and ranging
M2M	machine-to-machine
MSCM	maneuver sharing and coordinating message
MSCS	maneuver sharing and coordinating service
MSD	minimum safe distance
MUTCD	Manual on Uniform Traffic Control Devices
NHTSA	National Highway Traffic Safety Administration
OBU	on-board unit
ODD	operational design domain
OEDR	object and event detection and response
QoS	quality of service
RSU	roadside unit
SDSM	sensor data sharing message
TTC	time-to-collision
V2I	vehicle-to-infrastructure
V2V	vehicle-to-vehicle
V2X	vehicle-to-everything
VOBE	vehicle on-board equipment
WLAN	wireless local area network

5. CONCEPT OF OPERATIONS

5.1 Tutorial

A CONOPS describes a proposed system from the users' perspective. Typically, a CONOPS is used on a project to ensure that the system developers understand the users' needs. In this document, the CONOPS describes a specific CDA use case in sufficient operational detail to enable exploratory testing during development of a CDA Feature that fulfils the use case. As such, this document stops short of developing requirements for a specific CDA Feature and instead supports the exploratory testing needed to develop such requirements. This exploratory testing and development require cooperation among distinct entities, whose participation is necessary for the CDA Feature in question to function.

The CONOPS starts with a discussion of the "current situation and problem statement" that has led to the need to deploy the CDA Feature. This discussion permits both potential users and system developers to understand the situation.

The CONOPS then documents key aspects of the proposed system, including:

- Reference Architecture (see 5.4) - The reference physical architecture defines the overall context of the proposed system and defines which specific interfaces are addressed.
- Architectural Needs (see 5.5) - The architectural needs discuss issues and needs relative to the system architecture.
- Features (see 5.6) - The features identify and describe the various functions that users may want the system to perform. These features are derived from the high-level user needs identified in the problem statement but are refined and organized into a more manageable structure that forms the basis of the traceability table that would otherwise be included in a "Functional Requirements" section. However, this document defines a CDA Feature concept of operations only and, therefore, does not establish functional requirements.

Architectural needs and features are collectively called "user needs."

The CONOPS concludes by:

- Identifying security needs for the CDA Feature under development (see 5.7).
- Describing the extent to which policies or constraints relative to the operational environment have a direct impact on the implementation of the CDA Feature under test (see 5.8).
- Providing a description of how the CDA Feature under test relates to the National ITS Architecture (see 5.9).
- Describing the process for deriving operational scenarios that facilitate the development of this CDA Feature (see 5.10).

A test procedure including test metrics and a test design is presented in Appendix A.

5.2 Use Case and Feature Description

The use case for this document is: Cooperative Driving Automation (CDA) Feature - CDA infrastructure-based prescriptive cooperative merge (Class D). It describes a CDA-I directed cooperative lane merge among C-ADS-equipped vehicles, including a large truck. Figure 1 provides a situational depiction of the C-ADS-equipped vehicles performing a merge into an adjacent lane with other C-ADS-equipped vehicles using the prescriptive message with the merge order provided by the CDA-I. After directing C-ADS-equipped vehicle 1 to merge in front of C-ADS-equipped vehicle 2, the CDA-I then directs C-ADS-equipped vehicle 3 to merge after C-ADS-equipped vehicle 2 and ahead of C-ADS-equipped vehicle 4, while directing C-ADS-equipped vehicles 5 and 6 to drop behind C-ADS-equipped vehicle 4 before attempting to merge. The relative speeds and distances of and between C-ADS-equipped vehicles 1-6, as well as path planning and maneuvering, are managed by the C-ADS-equipped vehicles with support of V2V communications; however, the order, and to some degree the timing, of the merges are commanded by the CDA-I. The C-ADS-equipped vehicles comply with the CDA-I commands, i.e., perform a CDA Class D - Prescriptive merge (directed by the CDA-I).

In addition, two V2V merge implementation approaches are supported:

1. In the first, the predicted speed profiles of the C-ADS-equipped vehicles are computed at the CDA-I and transmitted from it to assist the merging vehicles in executing the merge maneuvers safely. It may be possible in this case for the C-ADS-equipped vehicles to perform the merging relying only CDA Class A - Status-Sharing (e.g., using BSMS per SAE J2735) among the vehicles. This implementation approach lends itself to early testing to validate its feasibility and safety.
2. In the second implementation approach, the C-ADS-equipped vehicles perform a CDA Class C - Agreement-Seeking merge to coordinate the details of the merge maneuvers, utilizing the Maneuver Sharing and Coordination Messages (MSCMs) from SAE J3186, guided by the merge order, timing, and speed profile information provided by the CDA-I.

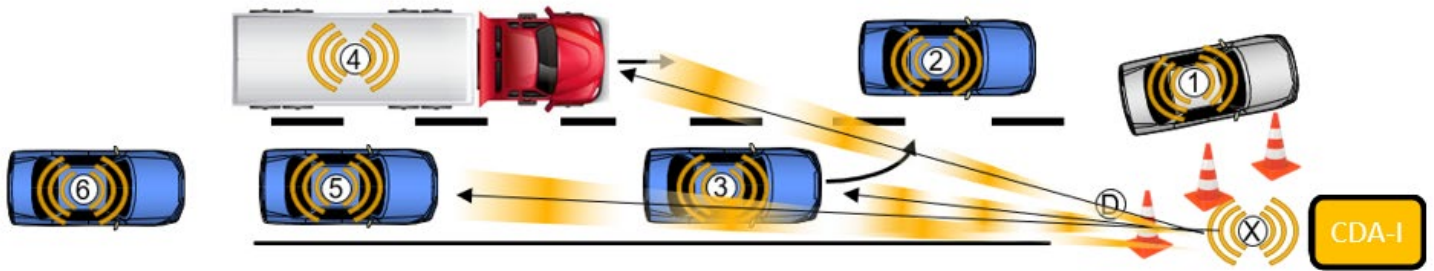


Figure 1 - Cooperative traffic management use case

5.3 Current Situation and Problem Statement

Numerous studies have shown and demonstrated the congestion mitigation and energy consumption reduction benefits associated with coordinated merge technologies that optimize relative speeds and merge timing of proximal vehicles. Such features work by mitigating, or even eliminating, the “accordion” or “slinky” effect that occurs because of short-cycle slowing and accelerating traffic speeds caused by merging traffic.

This particular use case was also selected based on its ability to challenge a distributed virtual test platform that enables multiple entities to simultaneously test CDA Features by emphasizing the role of CDA devices. In this use case, CDA-I is capable of adapting commands to also address vehicle classes that necessitate both two-way communications with vehicles to gather relevant data (class/size, location, velocity, distance to relevant vehicles) as well as to command deviations from a single-vehicle by single-vehicle “zipper” merge to accommodate large trucks.

5.4 Reference Architecture

In this use case, the CDA-I gathers relevant data regarding vehicle type/class, location, and velocity from C-ADS-equipped vehicles 1-6 via wireless means; the information is used by the CDA-I to coordinate the merge order and timing of C-ADS-equipped vehicles 1, 3, 5, and 6 to accomplish an efficient lane merge. A high-level depiction of this simple architecture is displayed in Figure 2.



Figure 2 - Cooperative traffic management high-level architecture

The major components of the cooperative traffic management use case include:

- **C-ADS-Equipped Vehicles:** For the purposes of this document, the C-ADS-equipped vehicles include the light-duty vehicles and the heavy-duty vehicle. The C-ADS-equipped vehicles have connectivity capabilities using OBUs.
- **CDA-I:** An infrastructure device installed along the roadway used to exchange data with each of the C-ADS-equipped vehicles.
- **Communication Interfaces:** The two-way communications technology is the interface between the C-ADS-equipped vehicles and the CDA-I providing temporary CDA-I's traffic management messages as well as vehicle status messages.

5.4.1 C-ADS-Equipped Vehicles

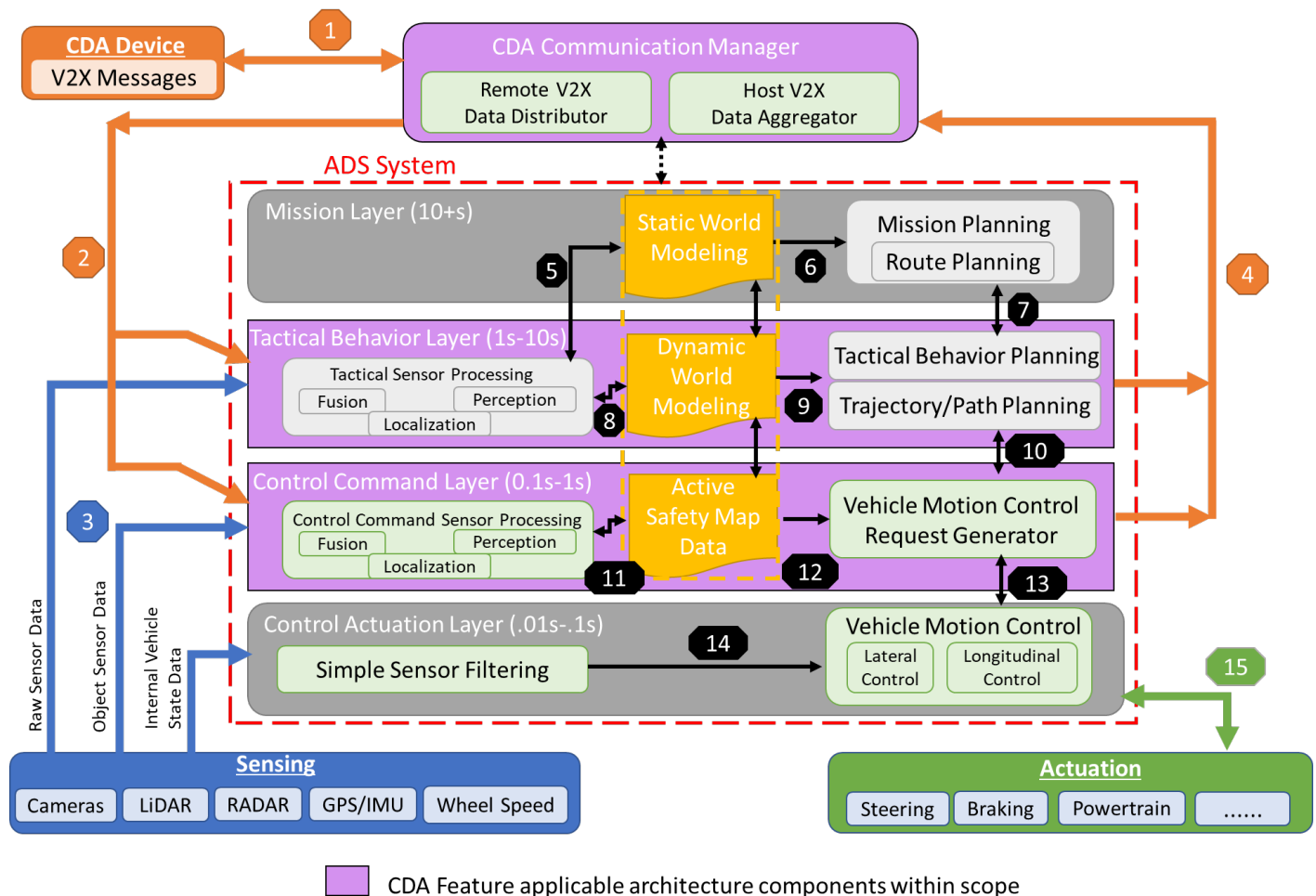


Figure 3 - C-ADS functional reference architecture for cooperative traffic management
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Figure 3 provides a functional architecture for a C-ADS-equipped vehicle which is based on the ADS model provided in SAE J3131. This architecture illustrates the various subsystems and how data is transferred between different layers within a C-ADS system.

NOTE 1: The static world model is either pre-downloaded or pre-cached by the vehicle or received via V2X communications. It has no direct impact on C-ADS operations and is not considered in this document.

NOTE 2: In general, cooperation will not have a direct impact on the control actuation layer. Direct control over vehicle actuation, such as remote vehicle operation, is not considered in this document.

Within the ADS system (depicted as the red dashed box), there are four layers outlined in SAE J3131. (1) The mission layer ensures the ADS achieves its primary objective for the trip; for example, mission planning tracks the static world model to identify effective routes. (2) The tactical behavior layer uses the dynamic world model to plan tactical behavior and trajectory/path. (3) The control command layer uses active safety map data to generate the motion control request specifying actions needed to implement a specific path. (4) Finally, the control actuation layer provides lateral and longitudinal vehicle motion control inputs to the actuation components.

Sensing outputs from various sensors are provided to different layers within the ADS system. Internal vehicle state data, such as the readiness or diagnostic status of electronic control units, is provided to the control actuation layer to filter data for noise. Object sensor data, including size, classification, state, and other relevant object parameters, is provided to the control command layer, while raw sensor data (e.g., three-dimensional LiDAR tracks) is sent to the tactical behavior layer, given the additional time required to process complex sensor outputs with larger sizes.

The CDA device is typically an OBU. The CDA communication manager interacts with the ADS system and performs two main functions:

(1) Remote V2X Data Distributor: When the CDA communication manager receives remote V2X messages from the CDA device, it can distribute the message content to the layers within the ADS system, depending on the remote V2X message type and/or content. For example:

- For status-sharing messages such as BSMs, the message content is data similar to the object sensor data and is distributed to the control command layer.
- For prescriptive merge order messages, the merge order content has the information influencing both tactical behaviors and vehicle motions and is distributed to both the tactical behavior layer and the control command layer.

(2) Host V2X Data Aggregator: The CDA communication manager collects the data from the tactical behavior layer and the control command layer, prepares the host V2X message content as needed, and sends the content to the CDA device for transmission.

The purple areas indicate the CDA Feature applicable components for this specific merge feature. In this use case, the CDA communication manager, along with the tactical behavior and control command layers, are the essential aspects for performing the merge. The numbers aligned to each arrow (specified below) indicate the type of data transfer occurring between any two components of the diagram.

1. The CDA communication manager receives remote V2X messages from the CDA device for distribution and also sends host V2X message content to the CDA device for transmission.
2. Depending on the remote V2X message type and/or content, the message content is distributed to the tactical behavior layer and/or the control command layer within the ADS system.
3. Sensing outputs, together with remote V2X message content, are incorporated into the control command layer to enable a C-ADS-equipped vehicle to send vehicle motion control requests and actuate promptly in case of concerns with nearby vehicles. This information is also integrated into the tactical behavior layer to perform trajectory or path.
4. The CDA communication manager collects data from the tactical behavior layer and the control command layer, prepares the host V2X message content as needed, and sends the content to the CDA device for transmission as described in 1.
5. The tactical sensor processing block interacts with the static world model to identify potential updates to static objects such as road closures, placement of new traffic control devices, and work zones.
6. The static world model provides information about the static objects within a scene to the mission planning block, allowing the ADS to update its mission objective as needed based on semi-permanent changes in the operating environment as described in 5.
7. The mission planning block interacts with the tactical behavior planning block to ensure that the ADS plans tactical behaviors that meet the desired objective. Upon receiving a prescriptive merge order message, the tactical behaviors are guided by the merge order.

8. The tactical sensor processing block interacts with the dynamic world model to update dynamic objects or actors within a scene, such as vehicles, pedestrians, bicyclists, and animals. This includes updating various pieces of their state information, including size, location, kinematic state, and other relevant object parameters. This provides more real-time adjustments to dynamic objects.
9. Dynamic world model outputs are provided to the tactical behavior planning block to update the needed trajectory/path for the vehicle based on the information about the dynamic objects within the scene.
10. The trajectory/path planning block interacts with the vehicle motion control request generator to ensure that the ADS determines what motion control actions need to be taken to achieve the desired trajectory/path. Upon receiving a prescriptive merge order message with predicted speed profiles, the motion control actions are guided by the predicted speed profiles.
11. The control command sensor processing block interacts with the active safety map data to update safety-critical aspects of a scene (whether static or dynamic). An example is pothole information. To avoid traversing over a pothole, this information needs to be included in the active safety map data to avoid potentially developing a flat tire. This type of information is determined in the control command layer and updated in the active safety map data.
12. Active safety map data is provided to the vehicle motion control request generator to timely update the vehicle motion control.
13. The vehicle motion control request generator interacts with the vehicle motion control block to adjust the longitudinal and lateral control of the vehicle to either achieve the desired trajectory or potentially avoid incidents based on the active safety map data.
14. At the lowest layer (control actuation), internal vehicle state data is filtered and then sent to the vehicle motion control block to adjust the controls based on the vehicle's current pose and the readiness and diagnostic status of different components. The vehicle may need to perform an immediate lane change to pull over if certain components have failed (e.g., minimal risk condition).
15. The vehicle motion control block interacts with the vehicle actuation to achieve the desired motions, just as a human driver would operate the steering wheel, the brake, and powertrain.

5.4.2 CDA Infrastructure (CDA-I)

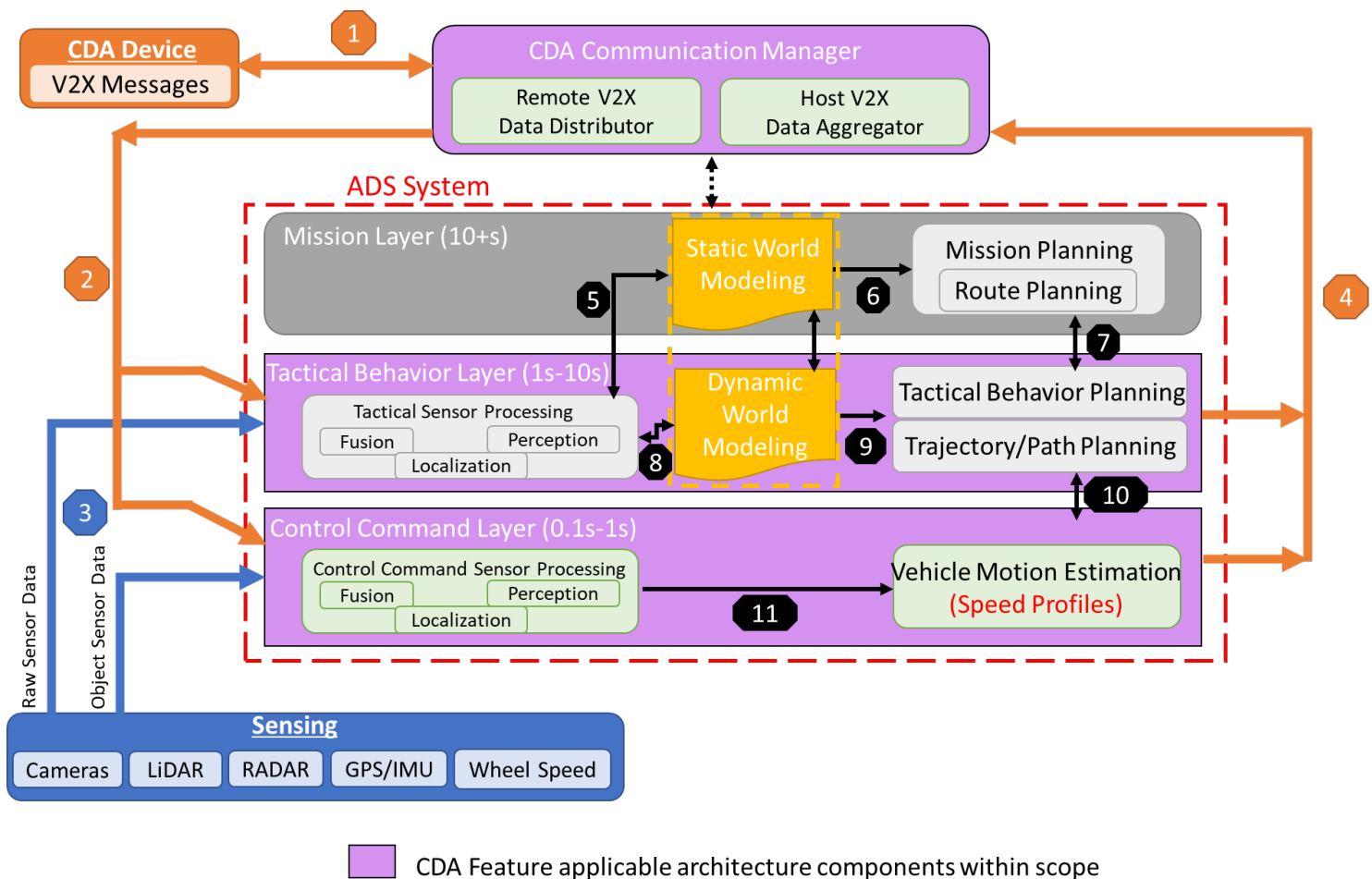


Figure 4 - CDA-I functional reference architecture for cooperative traffic management
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Similar to the reference architecture developed for the C-ADS-equipped vehicle in 5.4.1, the CDA-I has a functional reference architecture describing the specific subcomponents for this particular use case, as shown in Figure 4. A priori static world model is either pre-downloaded or pre-cached by the CDA-I.

The CDA-I can have sensors that enable it to determine the kinematic state information about each vehicle approaching the lane closure. Note that the sensors for this specific application are optional. There could be cases where the CDA-I simply processes V2X messages received from the C-ADS-equipped vehicles. Alternatively, there may be cases where the CDA-I has sensors and can perform local functions (perception and localization) to fuse with data received from the C-ADS-equipped vehicles. The data can be incorporated into the control command layer where detected objects are localized into a world model by the CDA-I and data sources are fused to more accurately perceived objects, as well as into the tactical behavior layer to take raw sensor data and fuse data which takes more time. After developing a world model, the CDA-I uses the mission planning layer as the objective to help determine the tactical behavior of each vehicle and what their estimated trajectory or path is. This allows the CDA-I to develop an appropriate merge order request that is then sent out to each vehicle to perform the cooperative merge.

The CDA device is typically an RSU. The CDA communication manager performs some similar functions as the C-ADS system:

(1) Remote V2X Data Distributor: When the CDA communication manager receives remote V2X messages from the CDA device, it can distribute the message content to the layers within the ADS system. For status-sharing messages such as BSMs from the C-ADS-equipped vehicles, the message content is data similar to the object sensor data and is distributed to the control command layer.