



SURFACE VEHICLE INFORMATION REPORT

J3282™

JUN2024

Issued

2024-06

Cooperative Infrastructure CDA Feature: Cooperative Permissive Left Turn Across
Opposing Traffic with Infrastructure Guidance

RATIONALE

Cooperative driving automation (CDA) applications are expected to be enabled by the increasing penetration of Cooperative Automated Driving System (C-ADS) equipped vehicles, particularly fleet-operated ADS-dedicated vehicles (ADS-DVs) in urban areas (both ride-hailing and delivery fleets). These C-ADS-equipped vehicles (i.e., with SAE Levels 3 to 5 driving automation) may operate on signalized arterial roadways. Infrastructure Owners/Operators (IOOs) are also being encouraged through federal policy to equip signalized intersections with technology to provide information that could be used to support CDA applications. These applications can operate with greater safety and efficiency with a cooperative intersection infrastructure. This report provides a concept of operations needed to evaluate a CDA Feature for a permissive turn across opposing traffic.

NOTE: This CDA Feature concept of operations requires that vehicles involved are equipped both with an ADS and with requisite communications technology and that there is enabling V2X communications infrastructure at the intersection(s) where it is useful.

TABLE OF CONTENTS

1.	SCOPE	3
2.	REFERENCES	3
2.1	Applicable Documents	3
2.1.1	SAE Publications	3
2.1.2	IEEE Publications	3
2.1.3	Other Publications	4
3.	DEFINITIONS	5
4.	ABBREVIATIONS	8
5.	CONCEPT OF OPERATIONS	9
5.1	Tutorial	9
5.2	Current Situation and Problem Statement	10
5.3	Use Case Description	10
5.3.1	Capacity Model	11
5.3.2	Safety Measures	13
5.3.3	Cooperative Automated Driving System (C-ADS)	15
5.4	Reference Architecture	15
5.4.1	C-ADS-Equipped Vehicle	15
5.4.2	Cooperative Driving Automation Infrastructure (CDA-I)	18
5.5	Status-Sharing Cooperation (Class A) Scenario	19
5.5.1	Communication Interfaces	19

SAE Executive Standards Committee Rules provide that: "This report is published by SAE to advance the state of technical and engineering sciences. The use of this report is entirely voluntary, and its applicability and suitability for any particular use, including any patent infringement arising therefrom, is the sole responsibility of the user."

SAE reviews each technical report at least every five years at which time it may be revised, reaffirmed, stabilized, or cancelled. SAE invites your written comments and suggestions.

Copyright © 2024 SAE International

All rights reserved. No part of this publication may be reproduced, stored in a retrieval system, transmitted, in any form or by any means, electronic, mechanical, photocopying, recording, or otherwise, or used for text and data mining, AI training, or similar technologies, without the prior written permission of SAE.

TO PLACE A DOCUMENT ORDER: Tel: 877-606-7323 (inside USA and Canada)
Tel: +1 724-776-4970 (outside USA)
Fax: 724-776-0790
Email: CustomerService@sae.org
http://www.sae.org

SAE WEB ADDRESS:

Full document details: SAE J3282_202406

For more information on this standard, visit https://www.sae.org/standards/content/J3282_202406

Documents



Standard, visit Sharing Hub

5.5.2	Service Level Requirements	19
5.5.3	Security	20
5.5.4	CDA Message and Event Flow	20
5.6	Operational Policies and Constraints	21
5.7	Relationship to the Architecture Reference for Cooperative and Intelligent Transportation (ARC-IT)	21
5.8	Operational Scenarios	22
5.8.1	Functional Scenario	22
5.8.2	Logical Scenario	24
5.8.3	Concrete Scenario	29
5.8.4	Performance Metrics	34
APPENDIX A	CONCRETE TEST DESIGN AND SYNCHRONIZATION	37
APPENDIX B	AGREEMENT-SEEKING COOPERATION (CLASS C) SCENARIO	42
APPENDIX C	RECOMMENDATIONS FOR FURTHER RESEARCH	45
Figure 1	Illustration of permissive left turns with opposing traffic	10
Figure 2	Effective green time in a traffic signal timing cycle	12
Figure 3	Time to collision (TTC)	13
Figure 4	Gap time (GT)	14
Figure 5	Architecture for C-ADS-equipped vehicle	17
Figure 6	SV left turn steps and modules	17
Figure 7	Architecture for CDA-I	18
Figure 8	Status-sharing cooperation: V2V message flow	19
Figure 9	Status-sharing cooperation: V2I message flow	19
Figure 10	Class A: CDA message and event flow	21
Figure 11	Speed profiles of SVs and POVs	34
Table 1	National architecture mapping for status-sharing cooperation (Class A)	22
Table 2	Functional scenario: permissive left turn with status-sharing cooperation	23
Table 3	Logical scenario: initialization and end conditions	25
Table 4	Logical scenario: environment properties	26
Table 5	Logical scenario: connectivity properties	27
Table 6	Logical scenario: C-ADS-equipped vehicle properties	28
Table 7	Logical scenario: CDA-I properties	29
Table 8	Concrete scenario: initialization and end conditions	30
Table 9	Concrete scenario: environment properties	31
Table 10	Concrete scenario: connectivity properties	32
Table 11	Concrete scenario: C-ADS-equipped vehicle properties	33
Table 12	Concrete scenario: CDA-I properties	34

1. SCOPE

This report provides a concept of operations needed to evaluate a CDA Feature for a permissive left turn across opposing traffic, with infrastructure guidance. The Feature uses CDA cooperation levels including status-sharing and agreement-seeking, and a set of test scenarios (functional, logical, and concrete) is developed to evaluate this CDA Feature.

NOTE 1: While this report refers to the permissive *left* turn from hereon, jurisdictions that drive on the left can also apply the concepts herein for a permissive *right* turn.

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 J2945/1	On-Board System Requirements for V2V Safety Communications
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 J3161/1	On-Board System Requirements for LTE-V2X V2V Safety Communications
SAE J3164	Ontology and Lexicon for Automated Driving System (ADS)-Operated Vehicle Behaviors and Maneuvers in Routine/Normal Operating Scenarios
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 IEEE Publications

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

IEEE 2846	IEEE Standard for Assumptions in Safety-Related Models for Automated Driving Systems
-----------	--

2.1.3 Other Publications

5GAA 2019	5G Automotive Association (5GAA) Working Group 1, C-V2X Use Cases - Methodology, Examples and Service Level Requirements, June 2019.
AASHTO Greenbook	A Policy on Geometric Design of Highways and Streets 7th Edition, AASHTO Publication, 2018.
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 4501	Connected Intersections Implementation Guide; American Association of State Highway and Transportation Officials, Institute of Transportation Engineers, National Electrical Manufacturers Association, SAE International, Version v01.01, June 2022.
DOT-HS-812-623	A Framework for Automated Driving System Testable Cases and Scenarios, NHTSA Publication, September 2018.
DOT-HS-812-815	Review of Simulation Frameworks and Standards Related to Driving Scenarios, NHTSA Publication, October 2019.
DOT-HS-812-893	Test Procedures with Countermeasure Timing Constraints for Intersection Movement and Left Turn Assist Safety Applications, NHTSA Publication, May 2021.
DOT-HS-813-073	An Approach for the Selection and Description of Elements Used to Define Driving Scenarios, NHTSA Publication, April 2021.
ETSI 302 324	Intelligent Transport Systems (ITS); Vehicular Communications; Basic Set of Applications; Collective Perception Service; Release 2.
ETSI 302 637-2	Intelligent Transport Systems (ITS); Vehicular Communications; Basic Set of Applications; Part 2: Specification of Cooperative Awareness Basic Service.
FHWA-HRT-04-091	Signalized Intersections: Informational Guide, FHWA Publication, August 2004.
FHWA-JPO-16-405	A Framework for Validating Traffic Simulation Models at the Vehicle Trajectory Level, FHWA Publication, March 2017.
FHWA-JPO-16-420	Connected Vehicle Impacts on Transportation Planning, FHWA Publication, June 2016.
FHWA-RD-03-050	Surrogate Safety Measures From Traffic Simulation Models, FHWA Publication, 2003.
FHWA-TSMO	Transportation System Management and Operations Strategies, FHWA Publication, 2022.
HCM 2022	Highway Capacity Manual 7th Edition: A Guide for Multimodal Mobility Analysis, National Academies of Sciences, Engineering, and Medicine, 2022.
NHTSA-0102-0006	Intersection Safety Assist System Confirmation Test, NHTSA Publication, September 2019.
NCST-UCR-RR-23-09	Eco-friendly Cooperative Traffic Optimization at Signalized Intersections, National Center for Sustainable Transportation (NCST) Publication, 2023.
STM 2015	Signal Timing Manual - Second Edition, National Academies of Sciences, Engineering, and Medicine, 2015.

UCB-ITS-PRR-2010-20 Cooperative Intersection Collision Avoidance System (CICAS): Signalized Left Turn Assist and Traffic Signal Adaptation, California PATH Research Report, 2010.

Allen, B., Shin, B., and Cooper, P. (1978). Analysis of Traffic Conflicts and Collisions. *Transportation Research Record*, 667, 67-74.

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.

Chan, C. (2006). *Defining Safety Performance Measures of Driver-Assistance Systems for Intersection Left-Turn Conflicts* [Conference paper]. IEEE Intelligent Vehicles Symposium.

Chen, W., Xie, Y., Huang, H., and Liu, P. (2021). A Review of Surrogate Safety Measures and their Applications in Connected and Automated Vehicles Safety Modeling. *Accident Analysis and Prevention*.

Khan, S. and Chowdhury, M. (2021). Situation-Aware Left-Turning Connected and Automated Vehicle Operation at Signalized Intersections. *IEEE Internet of Things Journal*, 8(16), 13077-13094.

Lin, Y., McPhee, J., and Azad, N. (2019). *Longitudinal Dynamic versus Kinematic Models for Car-Following Control Using Deep Reinforcement Learning* [Conference paper]. IEEE Intelligent Transportation Systems Conference (ITSC).

Morando, M., Tian, Q., Truong, L., and Vu, H. (2018). Studying the Safety Impact of Autonomous Vehicles Using Simulation-Based Surrogate Safety Measures. *Journal of Advanced Transportation*.

Nobukawa, K. (2011). *A Model Based Approach to the Analysis of Intersection Conflicts and Collision Avoidance Systems* [PhD Thesis, University of Michigan].

Sharath, M. and Mehran, B. (2021). A Literature Review of Performance Metrics of Automated Driving Systems for On-Road Vehicles. *Frontiers in Future Transportation*.

Wu, J. and Qu, X. (2022). Intersection Control with Connected And Automated Vehicles: A Review. *Journal of Intelligent and Connected Vehicles*, 5(3). 260-269.

3. DEFINITIONS

3.1 AUTOMATED DRIVING SYSTEM (ADS) [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.

3.2 COOPERATIVE DRIVING AUTOMATION (CDA) [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.

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

An ADS capable of utilizing CDA.

3.4 C-ADS-EQUIPPED VEHICLE [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 CDA INFRASTRUCTURE (CDA-I) [adapted from SAE J3252]

Infrastructure capable of engaging in CDA Feature execution.

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

3.6 CDA COOPERATION CLASSES [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.

3.6.1 STATUS-SHARING COOPERATION (CLASS A) [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.”)

3.6.2 INTENT-SHARING COOPERATION (CLASS B) [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.”)

3.6.3 AGREEMENT-SEEKING COOPERATION (CLASS C) [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.”)

3.6.4 PRESCRIPTIVE COOPERATION (CLASS D) [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(s) and adhered to by a receiving CDA device(s). (“I will do as directed.”)

3.7 CDA DEVICE [SAE J3216]

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

3.8 CDA FEATURE [SAE J3216]

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

3.9 CRITICAL HEADWAY

The minimum time interval between two successive vehicles in the opposing direction of traffic that will allow a vehicle to complete a left turn (see 5.3.1).

3.10 DYNAMIC DRIVING TASK (DDT) [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.

3.11 FOLLOW-UP HEADWAY

The headway between two vehicles when multiple vehicles are making a left-turn within the same gap in opposing traffic (see 5.3.1).

NOTE: Headway is defined in 3.14.

3.12 GAP

The space or time between two vehicles, measured from the rear bumper of the front vehicle to the front bumper of the second vehicle.

3.13 GAP TIME (GT)

The time interval between completion of encroachment by a turning vehicle and the arrival time of an opposing vehicle if both vehicles continue with the same speed and path (see 5.3.2).

3.14 HEADWAY

The time between successive vehicles as they pass a point on a lane or roadway, measured from the same common feature of both vehicles (for example, the front axle or the front bumper).

3.15 MESSAGE SUCCESS RATE

Percentage of messages received with respect to messages sent.

3.16 OPERATIONAL DESIGN DOMAIN (ODD) [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.

3.17 PERMISSIVE LEFT TURN

A type of left turn at an intersection without a dedicated left turn signal or arrow, where a vehicle is allowed to turn left when there is a sufficient gap in opposing traffic.

NOTE: A permissive left turn is sometimes called an “unprotected left turn.”

3.18 SATURATION FLOW RATE

The hourly rate at which left-turn vehicles can traverse an intersection approach, assuming that a green traffic signal is available at all times; in other words, it is the maximum capacity of the intersection for left-turn vehicles (see 5.3.1).

3.19 TIME TO COLLISION (TTC)

The time that it would take for two vehicles to collide if they continue on their current paths and maintain a constant velocity (see 5.3.2).

3.20 TRAFFIC PARTICIPANT [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.

3.20.1 ROAD USER [SAE J3216]

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

3.20.2 ROAD OPERATOR [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.

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 J2945/1 or Cellular V2X (C-V2X) per SAE J3161/1.

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 J2945/1 or Cellular V2X (C-V2X) per SAE J3161/1.

3.23 VEHICLE-TO-EVERYTHING (V2X) COMMUNICATION

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

NOTE: V2X communications include V2I and V2V, as well as other types, for example, Vehicle-to-Network.

4. ABBREVIATIONS

ADS	Automated Driving System
ARC-IT	Architecture Reference for Cooperative and Intelligent Transportation
BSM	Basic Safety Message
C-ADS	Cooperative Automated Driving System
CAM	Cooperative Awareness Message
C-V2X	Cellular V2X
CDA	Cooperative Driving Automation
CDA-I	Cooperative Driving Automation Infrastructure
CVRE	Connected Vehicle Roadside Equipment
DDT	Dynamic Driving Task
DR	Deceleration Rate
DSRC	Dedicated Short Range Communications
GNSS	Global Navigation Satellite System
GT	Gap Time

INS	Inertial Navigation System
M2M	Machine-to-Machine
MSCM	Maneuver Sharing and Coordinating Message
OBU	Onboard Unit
ODD	Operational Design Domain
PET	Post Encroachment Time
POV	Principal Other Vehicle
RSU	Roadside Unit
SDSM	Sensor Data Sharing Message
SPaT	Signal Phase and Timing
SV	Subject Vehicle
TTC	Time to Collision
V2I	Vehicle-to-Infrastructure
V2V	Vehicle-to-Vehicle
V2X	Vehicle-to-Everything
VOBE	Vehicle Onboard Equipment

5. CONCEPT OF OPERATIONS

5.1 Tutorial

A concept of operations describes a proposed system from the users' perspective. Typically, a concept of operations is used on a project to ensure that the system developers understand the users' needs. In this information report, the concept of operations 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. This exploratory testing and development require cooperation among distinct entities, whose participation is necessary for the CDA Feature to function.

The concept of operations starts with a discussion of the current situation and problem statement (see 5.2) that have led to the need to deploy the use case (see 5.3), then documents key aspects of the proposed system, including:

- Reference Architecture (see 5.4) - Defines the overall context of the proposed system and defines which specific functions are addressed.
- Status-Sharing Cooperation (see 5.5) - Addresses architectural needs, features, security, and CDA message and event flow relative to the system architecture.
- Agreement-Seeking Cooperation (see Appendix B) - Describes two types: one is vehicle-centric and the other is infrastructure-centric.
- Operational policies and constraints (see 5.6).

- A description of how the CDA Feature relates to the National ITS Architecture (see 5.7 and B.2.2).
- The process for deriving operational scenarios that facilitate the development of this CDA Feature (see 5.8) and the test design for a concrete scenario of two-vehicle platooning (see Appendix A).
- Recommendations for further research (see Appendix C).

5.2 Current Situation and Problem Statement

A permissive left turn is a type of left turn at an intersection where a driver is allowed to turn left when there is a gap in opposing traffic without a dedicated signal or arrow. One of the main challenges is the difficulty in accurately judging the gap in opposing traffic. This is especially true when there is a high volume of traffic or when the driver's view of opposing traffic is obstructed.

CDA applications (refer to SAE J3216), such as the permissive left turn as described in this information report, can be expected to address these challenges, improve traffic flow, and reduce corresponding crashes. This particular use case and a set of test scenarios have been developed based on their ability to evaluate the CDA performance in a simulated platform or a test track setting without undertaking a large development effort.

5.3 Use Case Description

According to FHWA-HRT-04-091, there are three basic types of left-turn phasing at a signalized intersection: permissive, protected, and protected/permissive. Permissive left-turn phasing allows two opposing approaches to time concurrently, with left turns allowed after yielding to conflicting traffic and pedestrians. "Permissive" displays are signified by a green ball indication with the option of using the sign ("LEFT TURN YIELD ON GREEN [symbolic green ball]"). Protected left-turn phasing provides a separate phase for left-turning traffic and allows left turns to be made only on a green left arrow signal indication, with no pedestrian movement or vehicular traffic conflicting with the left turn. A combination of protected and permissive left-turn phasing is referred to as protected/permissive left-turn operation.

Permissive left-turn phasing is common with low left-turn volumes on rural or urban roads. Permissive left turns may also be allowed at intersections of major-to-major streets, but they are more common for major-to-minor streets. Cooperative permissive left turn is the scope of this information report.

Figure 1 provides an illustration of vehicles performing permissive left turns while opposing traffic is present. The traffic light phase of the CDA-I is green (permissive). The subject vehicles (SVs) in the depicted scenario are the vehicles making a permissive left turn across the path of oncoming principal other vehicles (POVs), which are traveling straight through the intersection from the opposite direction. SVs must yield to POVs in the opposing direction of traffic before making left turns. An SV makes the left turn from a major street to a minor street if there is a sufficient time gap in the opposing traffic. Otherwise, it decelerates to a stop and waits for the next sufficient time gap.

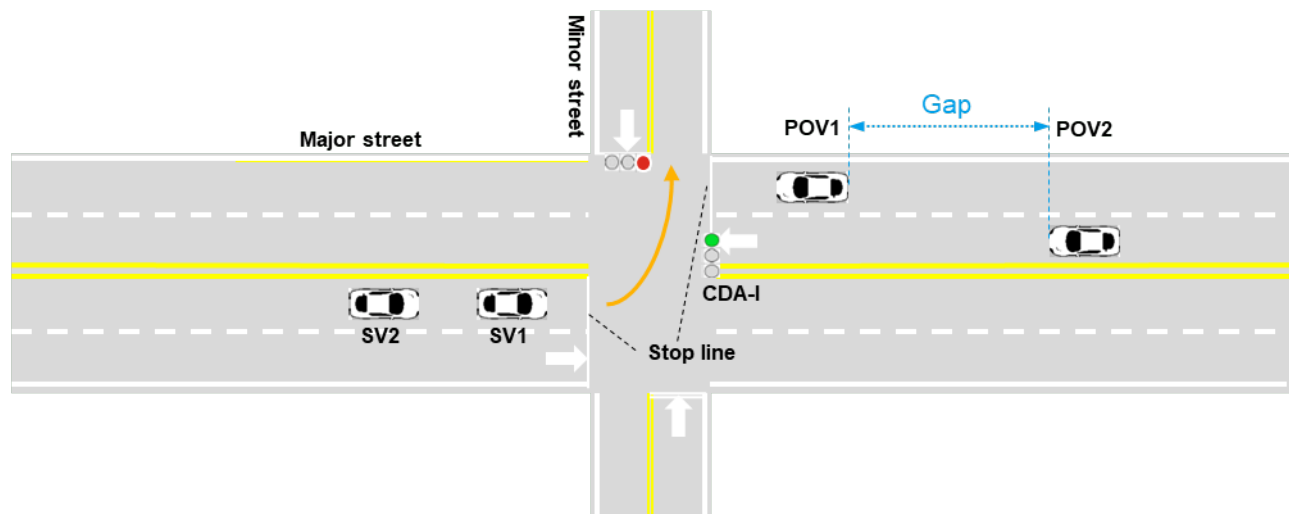


Figure 1 - Illustration of permissive left turns with opposing traffic



In this report, movement generally refers to the actions of vehicles as they traverse the intersection during the green phase, including both the movement of vehicles turning left and the movement of vehicles in the opposing direction of traffic.

A capacity model, within the realm of transportation engineering, refers to a mathematical or analytical representation used to estimate the maximum flow rate or capacity of a transportation facility, such as a roadway, intersection, or transit system. Within a capacity model, two terms - namely headway and gap - are often used. While related, the two terms are distinct (refer to HCM 2022 and STM 2015). As defined in 3.14, headway is the time between two successive vehicles as they pass a point on the roadway, measured from the same common feature of both vehicles (for example, the front axle or the front bumper). Meanwhile, as defined in 3.12, gap refers to the space or time between two vehicles, measured from the rear bumper of the front vehicle to the front bumper of the second vehicle.

In 5.3.1, key parameters for the capacity model of a permissive left-turn movement are introduced. Improving these key parameter values (thereby enhancing the permissive left-turn capacity) is one of the focal points of the rest of this report.

In 5.3.2, safety measures for vehicles making left turns are presented. These safety measures can be utilized by an ADS in real-time to identify areas for improvement or adjustment, with the aim of avoiding or reducing safety risks.

In 5.3.3, the potential benefits provided by a C-ADS are outlined and summarized.

5.3.1 Capacity Model

The critical headway and follow-up headway are key parameters to determine the potential capacity of a permissive left-turn movement.

As defined in 3.9, the critical headway is the minimum time interval between two successive vehicles (POV1 and POV2) in the opposing direction of traffic that will allow a vehicle (SV1) to complete a left turn from the major street to the minor street. The gap in Figure 1 must be greater than the critical headway to allow for a turn.

When more than one left-turn vehicle (SVs) use a gap in the opposing traffic on the main street (see the gap between POV1 and POV2 in Figure 1), the headway between the two left-turn vehicles (SV1 and SV2) is termed follow-up headway (see 3.11).

As defined in 3.18, the saturation flow rate is the hourly rate at which left-turn vehicles can traverse an intersection approach, assuming that a green traffic signal is constantly available, i.e., it is the maximum capacity of the intersection for left-turn vehicles.

The gap acceptance model used in the Highway Capacity Manual (HCM 2022) assumes that vehicles arrive in both traffic streams (left turn and opposing) at random and conform to a Poisson distribution with a constant rate. Hence, the saturation flow rate of a left-turn traffic stream is computed in accordance with Equation 1:

$$S_{LT} = S_{Opp} \frac{e^{-t_c * S_{Opp}/3600}}{1 - e^{-t_f * S_{Opp}/3600}} \quad (\text{Eq. 1})$$

where:

S_{LT} = the saturation flow rate of the left-turn movement (vehicles/hour)

S_{Opp} = the flow rate of the opposing movement (vehicles/hour)

t_c = the critical headway of the left-turn movement (seconds)

t_f = the follow-up headway of the left-turn movement (seconds)

The critical headway and follow-up headway are considered representative of a statistical average of the driver population. The default values t_c and t_f for passenger vehicles are 4.5 and 2.5 seconds, respectively. Operational impacts of these two parameters on C-ADS-equipped vehicles are examined in the concrete test design and synchronization (see Appendix A), where Equation 1 is used in determining relative left-turn capacity improvements for specific scenario parameters.

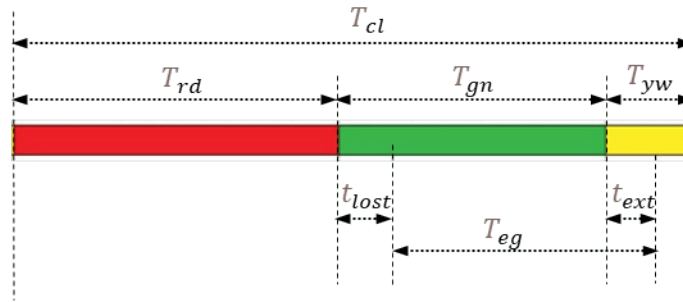


Figure 2 - Effective green time in a traffic signal timing cycle

The capacity of a left-turn movement is impacted by traffic signal phase timings. In Figure 2, the sum of T_{rd} , T_{gn} , and T_{yw} is T_{cl} , where:

T_{cl} = the traffic signal timing cycle (seconds), which is the total time for a traffic signal to complete one cycle

T_{rd} = the red time (seconds), which is the duration of the red interval

T_{gn} = the green time (seconds), which is the duration of the green interval

T_{yw} = the yellow time (seconds), which is the duration of the yellow interval

Effective green time is also illustrated in Figure 2 and computed in accordance with Equation 2:

$$T_{eg} = T_{gn} - t_{lost} + t_{ext} \quad (\text{Eq. 2})$$

where:

T_{eg} = the effective green time (seconds)

t_{lost} = the start-up lost time (seconds), which is the additional time consumed by the first few vehicles in a queue because of the need to react to the initiation of the green interval and accelerate

t_{ext} = the extension of an effective green (seconds), which is the initial portion of a yellow interval during which a combination of traffic movements is considered to proceed effectively

Hence, the capacity of a left-turn movement is computed in accordance with Equation 3:

$$C_{LT} = S_{LT} \frac{T_{eg}}{T_{cl}} \quad (\text{Eq. 3})$$

where:

C_{LT} = the capacity of the left-turn movement (vehicles/hour)

S_{LT} = the saturation flow rate of the left-turn movement (vehicles/hour)

T_{eg} = the effective green time (seconds)

It is clearly shown in Equation 3 that larger effective green time directly translates into higher capacity of the left-turn movement. When the flow rates of the left-turn and opposing streams can be estimated, the signal controller can change the green time accordingly to increase the capacity as discussed in 5.4.2.

5.3.2 Safety Measures

Conflict in traffic is used to describe potential crash risk between road users. When two or more vehicles approach each other in both space and time, a collision may occur if their movements do not change. This is relevant in the case of permissive left-turn scenarios, where a left-turning vehicle and an opposing vehicle intersect paths. To predict the level of safety, various metrics have been developed. For left-turn conflict events, two of the most commonly used metrics are Time to Collision (TTC) and Gap Time (GT).

As defined in 3.19, TTC is the time it would take for two vehicles to collide if they continue on their current paths and maintain a constant velocity. Referring to FHWA-RD-03-050 and Morando et al. (2018), TTC is illustrated in Figure 3 and computed in accordance with Equation 4:

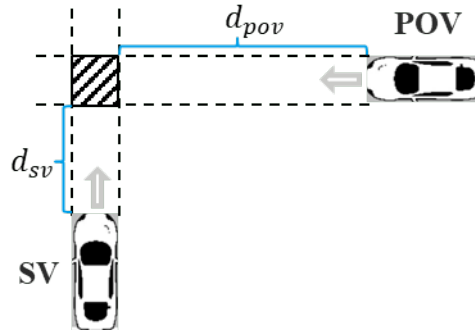


Figure 3 - Time to collision (TTC)

$$TTC = \frac{d_{pov}}{v_{pov}} \quad \text{if } \frac{d_{sv}}{v_{sv}} < \frac{d_{pov}}{v_{pov}} < \frac{d_{sv} + l_{sv} + w_{pov}}{v_{sv}}$$

(Eq. 4)

$$TTC = \frac{d_{sv}}{v_{sv}} \quad \text{if } \frac{d_{pov}}{v_{pov}} < \frac{d_{sv}}{v_{sv}} < \frac{d_{pov} + l_{pov} + w_{sv}}{v_{pov}}$$

where:

d_{sv} and d_{pov} = the distances from SV and POV to the conflict zone, respectively

v_{sv} and v_{pov} = the velocities of SV and POV, respectively

l_{sv} and l_{pov} = the lengths of SV and POV, respectively

w_{sv} and w_{pov} = the widths of SV and POV, respectively

The shadowed area defines a conflict zone. The first equation in Equation 4 is applicable if SV would cross through the conflict zone first. The second equation in Equation 4 is applicable if SV would cross through the conflict zone second.

When the conditions for Equation 4 do not hold, no potential collision is predicted. Otherwise, when the conditions hold, a potential collision event is predicted with a TTC value:

- When the TTC value is 0, it is a crash-imminent event.
- When the TTC value is small, the SV has little time to take action so that a potential collision may occur.
- When the TTC value is large, the SV has sufficient time to take action so that a potential collision event is prevented.

The smaller value of TTC indicates the higher risk of a potential collision event. However, in the situation where no potential collision is predicted, TTC has no value and the urgency of potential conflicts is unknown. This can be predicted by GT.

As defined in 3.13, GT is the time interval between completion of encroachment by a turning vehicle and the arrival time of an opposing vehicle if both vehicles continue with the same speed and path. Referring to Allen et al. (1978) and Chan (2006), Figure 4 illustrates situations for GT calculation:

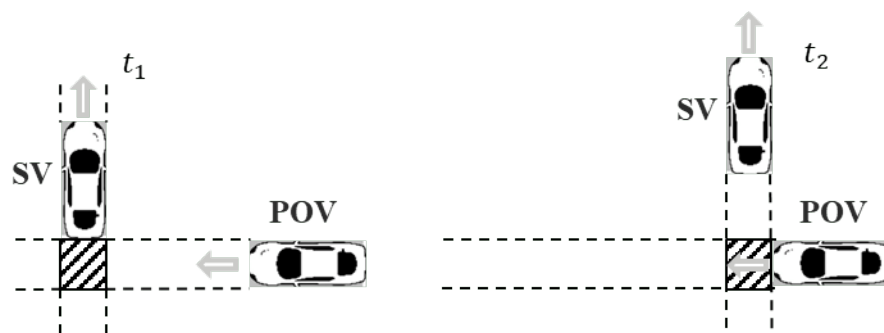


Figure 4 - Gap time (GT)

$$GT = t_2 - t_1 \quad (\text{Eq. 5})$$

where:

t_1 = the time when SV would cross through the conflict zone with the same speed and path

t_2 = the time when POV would arrive at the conflict zone with the same speed and path

The shadowed area defines a conflict zone. $GT > 0$ if SV would cross through the conflict zone first. $GT < 0$ if SV would cross through the conflict zone second. According to Chan (2006), the following safety thresholds were suggested:

- If $GT = 0$, it is a crash-imminent event.
- If the absolute value of $GT < 1$ second, it is considered as a near-miss event.
- If the absolute value of $GT < 2$ seconds, it is considered as a potential conflict.

The combined use of TTC and GT provides a comprehensive picture of the risk of conflicts (crash-imminent, near-miss, and potential conflict) and can be used to identify areas for improvement/adjustment in terms of reducing the safety risk.

The shadowed area in Figures 3 and 4 is the conflict zone between SV and POV. For the use case depicted in Figure 1, there are two conflict zones: one between SV and POV1, and the other between SV and POV2. For a permissive left turn, the motion planning of SV can use TTC and GT to predict safety conditions in real time and thus prevent severe conflicts ahead of time.

More discussions on safety measures can be found in 5.8.4.