



SURFACE VEHICLE RECOMMENDED PRACTICE

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Dynamic Driving Task Assessment (DA) Metrics for Automated Driving Systems

RATIONALE

As development of Automated Driving System (ADS) technologies progresses, the ability to assess the dynamic driving task (DDT)¹ performance of an on-road,² ADS-operated vehicle is critical. Further, this DDT assessment (DA) should be quantified using well-defined DA metrics. Establishing a set of DA metrics can help enable stakeholders, including the general public, to quantitatively understand various aspects of how well (i.e., the degree of competence with which) an ADS is executing the DDT, including its safety performance. Different stakeholders may use the DA metrics for various purposes, such as ADS-equipped vehicle development, third-party evaluation, and event reconstruction and analysis.

To address the need for DA metrics, this document provides a set of metrics, including definitions, taxonomy, and characteristics, to assess ADS DDT performance. The usage of the DA metrics is explicitly described, including examples, with alternative usages described as well.

This document has been developed according to the following guiding principles. Namely, it should:

- Be descriptive and informative rather than normative.
- Provide functional definitions.
- Be consistent with current industry practice.
- Be consistent with prior art to the extent practicable.
- Be useful in various areas, including engineering, law, media, and public discourse.

¹ The term DDT as defined in SAE J3016 [1].

² While the scope of this document includes on-road vehicles, the assessment could take place in simulation, on a closed course, and/or on public roads. The DA metrics could be applicable to off-road vehicles, but this is outside of the scope of this document.

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1. SCOPE

This SAE Recommended Practice provides DA metrics used to quantify the DDT performance of ADS-operated vehicles.³ Here, the primary focus is on the safety-related DDT performance and includes definitions, taxonomy, characteristics, and usage (along with alternatives) for each metric. DDT performance is a subset of overall operational performance of ADS-operated vehicles. Thus, assessments of DDT Fallback [1], cybersecurity, maintenance, interactions with passengers, etc., while important and could have an indirect impact on the DDT, are out of scope for this document. Note that the DA metrics do not specify the actions and/or maneuvers to be executed by the (ADS-operated) subject vehicle (SV).

While this document presents a set of individual DA metrics, it is important to note that it is out of the scope of this document to describe how these metrics should be applied in practice. This is because the overall context of the scenario or deployment must be considered during DA metrics implementation and different DA metrics could be applicable for different ADS applications. Implementation of the DA metrics recommended in this document may inform a safety assessment of an ADS's performance of the DDT, and this assessment in turn may inform a broader safety assessment of an ADS-operated vehicle. However, these metrics could be supplemented by additional input for both types of assessments.

A literature review of DA metrics that have been proposed and, in some cases, used in previous studies was conducted. From this literature review, a set of DA metrics has been created with example usage. Evidence of prior research indicating that a metric has a meaningful relationship with safety outcome(s) is included where applicable.⁴ The set of DA metrics is not necessarily comprehensive, and there may be additional metrics that can be used to assess DDT performance, particularly metrics that measure ADS subsystem performance.⁵

DA metrics might use parameterized variables, assumptions, and thresholds⁶ in their formulation. Defining or recommending values for these quantities used in the metrics formulation is outside the scope of this document. It is expected that the methodologies for collecting and assigning such values for these metrics will be developed based on implementation of the metrics in this document in field and other learned experiences with production and prototype vehicles and systems. Values could also be established by regulation, industry best practices, improved technology development, and academic research, among others, and may change based on the operating conditions within the operational design domain (ODD). In the interim, it will be the responsibility of the implementer of these metrics to choose values for these quantities.

The DA metrics can be implemented in both testing and commercialization phases and for various purposes, including for ADS-equipped vehicle development, third-party evaluation, and event reconstruction and analysis. For example, the metrics can be used as part of an ADS-equipped vehicle verification and validation (V&V) scenario-based testing process wherein individual scenarios are tested. A third-party evaluator could also aggregate measurements of the metrics measurements over a period of time or number of scenarios (i.e., a period of time could be considered to be a sequence of scenarios) in on-road operation (which could be during testing or commercialization) in order to monitor driving performance of an ADS-operated vehicle.

2. REFERENCES

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.

³ Some DA metrics may also be applicable to human-operated vehicles, but this is outside the scope of this document.

⁴ The DA metrics have not yet been applied to ADS-equipped vehicles on a broad scale; therefore, in order to validate the relationship of a DA metric to nominal driving behavior, crash avoidance, near-miss events, and/or collisions, additional research is necessary to better correlate the output of the DA metrics to such events.

⁵ Metrics that can be used to assess ADS subsystem performance (e.g., perception, path planning, etc.) would be White Box Metrics; see Section 5.

⁶ Recent work on metrics thresholds includes [46]. The thresholds in the Example Usage sections are for illustrative purposes only. Other approaches to metrics thresholds are discussed in [51].

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.

- [1] SAE J3016 - Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles
- [2] SAE J3164 - Ontology and Lexicon for Automated Driving System (ADS)-Operated Vehicle Behaviors and Maneuvers in Routine/Normal Operating Scenarios
- [3] National Highway Traffic Safety Administration, "Traffic Safety Facts - 2021 Data," DOT HS 813 515, 2021.
- [4] National Highway Traffic Safety Administration, "Traffic Safety Facts: Critical Reasons for Crashes Investigated in the National Motor Vehicle Crash Causation Survey," DOT HS 812 506, 2018.
- [5] SAE J3018 - Safety-Relevant Guidance for On-Road Testing of Prototype Automated Driving System (ADS)-Operated Vehicles
- [6] ISO 26262-1:2018 - Road vehicles - Functional safety - Part 1: Vocabulary
- [7] ISO 10393:2013 - Consumer product recall - Guidelines for suppliers
- [8] IEEE 2846 - Standard for Assumptions in Safety-Related Models for Automated Driving Systems
- [9] Vulnerable Road Users Safety Consortium, "Initial Research Summation Overview: Vehicle-VRU Safety Landscape," SAE ITC, 2023.
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- [11] Federal Register - New Car Assessment Program.
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3. DEFINITIONS

3.1 ACTUAL OPERATING CONDITIONS

The real-time conditions that the driving automation system is encountering on its trip, including, but not limited to, environmental, geographical, and/or the presence or absence of certain traffic or roadway characteristics.

NOTE: This is used for comparison with its ODD constraints.

3.2 ADS DATA

Data originating in the ADS or ADS subsystems, either unmodified or processed.

3.3 ADS STATUS DATA

The subset of ADS data that reflects specific attributes of ADS operation at a given point in time.

NOTE: For the purposes of this document, the following ADS status data are included as part of Grey Box DA metrics:

- a. Whether an ADS feature⁷ is engaged and executing the DDT.
- b. Intervention request/prompt to take over has been made (including time stamp of request).

3.4 [ADS-OPERATED VEHICLE] BEHAVIORAL COMPETENCY [2] [QUOTED]

A description of an expected capability(ies) of an ADS feature operating a vehicle within the feature's ODD.

NOTE: See SAE J3164 [2] for more details.

3.5 CRASH [3] [ADAPTED]

An event involving the physical impact between two or more in-transport road users or between an in-transport road user and property, roadway infrastructure, or objects on the road that results in detectable physical injury, fatality, and/or property or road infrastructure damage.

NOTE 1: The term includes unintended road departures and single-vehicle crashes.

NOTE 2: The detection of a crash (by the ADS or by humans), including physical injury and/or property damage, may not be uniform and may also vary in reporting thresholds and requirements for events involving ADS-operated vehicles and human-driven vehicles.

3.6 CRITICAL REASON [4] [ADAPTED]

The last event in the causal chain that leads to an incident.

3.7 [DRIVING AUTOMATION SYSTEM] DISENGAGEMENT

The act of changing the operational state of the driving automation feature, from the state in which it is executing all or part of the DDT to the state in which it is performing none of the DDT.

NOTE 1: The term “disengagement” is intended to be used in conjunction with the corresponding term, “engagement.”

NOTE 2: A disengagement may, for example, be initiated by the driving automation system or by a human. During the testing phase, the human intervening may be a fallback test driver (in-vehicle or remote). In the commercial deployment phase, the human intervening may be a remote assistant, a passenger, or fallback-ready user.

NOTE 3: As this document addresses ADS, i.e., Level 3 to Level 5, the driving automation feature is executing all of the DDT prior to disengagement.

3.8 DDT ASSESSMENT (DA) METRIC

A quantifiable measure of one or more DDT performance-related aspects of an ADS-operated vehicle.

⁷ The engaged ADS feature(s) should be identified so that the level of driving automation according to [1] can be understood. See 6.1.

3.9 [ADS] DDT PERFORMANCE-RELEVANT SYSTEM FAILURE [1] [QUOTED]

A malfunction in a driving automation system and/or other vehicle system that prevents the driving automation system from reliably performing its portion of the DDT on a sustained basis, including the complete DDT, that it would otherwise perform.

NOTE: See SAE J3016 [1] for more details.

3.10 DYNAMIC DRIVING TASK (DDT) [1] [QUOTED]

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, and including, without limitation, the following subtasks:

1. Lateral *vehicle* motion control via steering (*operational*).
2. Longitudinal *vehicle* motion control via acceleration and deceleration (*operational*).
3. Monitoring the driving environment via object and event detection, recognition, classification, and response preparation (*operational* and tactical).
4. Object and event response execution (*operational* and tactical).
5. Maneuver planning (tactical).
6. Enhancing conspicuity via lighting, sounding the horn, signaling, gesturing, etc. (tactical).

3.11 [DRIVING AUTOMATION SYSTEM] ENGAGEMENT

The act of changing the operational state of the driving automation feature, from the state in which it is performing none of the DDT to the state in which it is performing all or part of the DDT.

NOTE 1: The term “engagement” is intended to be used in conjunction with the corresponding term “disengagement.”

NOTE 2: An engagement may, for example, be initiated by the driving automation system or by a human. During the testing phase, the human intervening may be a fallback test driver (in-vehicle or remote). In the commercial deployment phase, the human intervening may be a remote assistant, a passenger, or fallback-ready user.

NOTE 3: As this document addresses ADSs, i.e., Level 3 to Level 5, the driving automation feature is executing all of the DDT when it is engaged.

3.12 FALLBACK TEST DRIVER [5] [QUOTED]

A person specially trained and skilled in supervising the performance of prototype ADS-operated vehicles in on-road traffic for testing purposes.

NOTE: See SAE J3018 [5] for more details.

3.13 HARM [6] [ADAPTED]

Physical injury and/or damage to the health of persons or property.

3.14 HAZARDOUS EVENT [6] [QUOTED]

Combination of a hazard and an operational situation.

3.15 HUMAN TRAFFIC CONTROLLER

A person who directs traffic through gestures or signals.

NOTE: A human traffic controller (HTC) may be an authorized person (e.g., first responder or construction zone worker) or may be an unauthorized person such as another road user (e.g., a pedestrian indicating the subject vehicle should proceed). The ADS developer may decide whether the behavioral competency includes responding only to directions from authorized persons or both authorized and unauthorized persons.

3.16 INCIDENT [ADAPTED] [7]

Event that could have caused or actually caused harm.

NOTE 1: A traffic incident is any non-recurrent event, such as a vehicle crash, vehicle breakdown, or other special event, that causes a reduction in highway capacity and/or an increase in traffic congestion.

NOTE 2: Incidents include loss-of-control events.

NOTE 3: Some safety envelope infringements/violations may be considered incidents.

3.17 [ADS-OPERATED VEHICLE] MANEUVER [2] [QUOTED]

Goal-oriented vehicle movement directed by an ADS in order to achieve a specific result/outcome.

NOTE: See SAE J3164 [2] for more details.

3.18 OBSERVABLE VARIABLE

An element of a DA metric formulation that can be perceived and/or calculated through some method of measurement.

NOTE: The observable variable adheres to the taxonomy of its governing metric (see Section 5). For example, if a metric is Black Box, no ADS data are required for the observable variable measurement (although ADS data can be used and could result in a different measurement uncertainty).

3.19 OPERATIONAL DESIGN DOMAIN (ODD) [1] [QUOTED]

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.

NOTE: See SAE J3016 [1] for more details.

3.20 REASONABLY FORESEEABLE [6] [QUOTED]

Technically possible and with a credible and measurable rate of occurrence.

NOTE: See ISO 26262 [6] for more details.

3.21 SAFETY-RELEVANT [OBJECT, EVENT, OR ROAD FEATURE] [8] [ADAPTED]

An object, event, or road feature that is relevant to the performance of the DDT.

NOTE: Safety-relevant objects, events, or road features may be observed using onboard sensors, vehicle to vehicle communication, vehicle to infrastructure communication, etc.

3.22 [OPERATING] SCENARIO [2] [QUOTED]

A description of the temporal development through several consecutive scenes in a sequence of scenes.

NOTE: See SAE J3164 [2] for more details.

3.23 [OPERATING] SCENE [2] [ADAPTED]

A representation of the operating environment at a given point in time that includes salient static (including signage and road boundaries) and dynamic objects (including vehicles) and the relationships among them.

NOTE: See SAE J3164 [2] for more details.

3.24 [OPERATING] SITUATION [2] [ADAPTED]

A scene augmented with the perspective, including goals, values, and assumptions, of the SV.

NOTE 1: See SAE J3164 [2] for more details.

NOTE 2: Since this term involves the perspective of the SV, ADS data are required, and the term is associated with White Box metrics.

3.25 SPATIOTEMPORAL SAFETY ENVELOPE

A set of distance or time-based limits and conditions computed by the ADS with respect to the SV and the safety-relevant objects in its surroundings, even as a given scenario unfolds and the SV and safety-relevant objects move with different kinematics.

NOTE 1: The limits and conditions are defined in relation to a given level of acceptable risk. For example, a distance-based limit decrease could impact the level of risk.

NOTE 2: The spatiotemporal safety envelope may vary based on numerous factors, e.g., safety-relevant objects' characteristics, environmental conditions, local traffic laws, etc.

3.26 SUBJECT VEHICLE (SV)

The ADS-operated vehicle of interest.

3.27 TRIP [1] [QUOTED]

The traversal of an entire travel pathway by a vehicle from the point of origin to a destination.

NOTE: See SAE J3016 [1] for more details.

3.28 VEHICLE MANEUVER [2] [QUOTED]

Goal-oriented vehicle movement directed by an ADS or human driver in order to achieve a specific result/outcome.

NOTE: See SAE J3164 [2] for more details.

3.29 VULNERABLE ROAD USER (VRU) [9] [QUOTED]

Any human road user not occupying a vehicle.

NOTE: In this document, the "vehicle" term is reserved for powered vehicles starting from the light-duty passenger car and light truck classification and extending to the classifications of heavier, powered vehicles. Therefore, powered micromobility (e.g., e-scooter and e-bike) users, bicycle users, and motorcycle users are considered VRUs in this document.

4. DISCLAIMERS

At the time of the writing of this Recommended Practice, the DA metrics described have not yet been applied to ADS-equipped vehicles on a broad scale. As a result, substantial data linking the metrics to safety outcomes for ADS-operated vehicles do not yet (and might not) exist. The intent of this document is to introduce and recommend these metrics to be used for DDT performance evaluation. As more data are gathered on the DA metrics, especially correlated to nominal driving behavior, crash avoidance, near-miss events and/or crashes, the list of metrics may be amended, including potentially the formulations and adding/removing metrics.

5. TAXONOMY

The DA metrics included in this document are categorized by a taxonomy containing three types (Black Box, Grey Box, and White Box). The taxonomy is based on the minimum data (i.e., from observable variables) required from the ADS to compute the metric. It should be noted that in some cases it is possible to obtain data from multiple sources or make assumptions, which could result in a different measurement uncertainty. For example, the distance between the SV and a safety-relevant object can be obtained from the ADS perception data⁸ or from an infrastructure-based sensor system. This could result in different measurement uncertainty in the measured distance, for example, due to relative sensor locations, the sensor technology used, etc.

[ADS] Black Box Metrics

DA metrics that can be calculated without ADS data.

NOTE: While the minimum information needed to calculate Black Box metrics does not require ADS data, metrics calculations could be performed using ADS data, using onboard sources (outside the ADS) such as speed and steering wheel torque sensors, using off-board sources such as infrastructure cameras, or using assumptions for formulation variables. The metrics calculation uncertainty will be impacted by the data source. Using assumptions about the ADS, SV, and/or safety-relevant object may lead to greater metrics calculation uncertainty.

EXAMPLE 1: An implementer uses data originating in an infrastructure-based camera to calculate a safety envelope metric.

EXAMPLE 2: An implementer uses ADS data for the ADS' reaction time rather than an assumed ADS reaction time value and assumes reaction time values for safety-relevant objects that impact its safety envelope determination.

[ADS] Grey Box Metrics

DA metrics for which ADS status data are required for their calculation.

NOTE 1: ADS status data can be obtained if they are made available by the ADS developer.

NOTE 2: ADS status data could be supplemented by data originating onboard or off-board the vehicle.

EXAMPLE: An implementer uses ADS status data indicating that the ADS is executing the DDT as part of an ADS performance evaluation.

[ADS] White Box Metrics

DA metrics for which ADS data (beyond ADS status data) are required for their calculation.

NOTE 1: ADS data can be obtained if they are made available by the ADS developer.

NOTE 2: ADS data could be supplemented by data originating onboard or off-board the vehicle.

EXAMPLE: An implementer compares the ADS' calculation of its safety envelope against a ground truth value as part of an ADS performance evaluation.

⁸ ADS perception could be augmented or supplemented via connectivity. Connectivity considerations are outside the scope of this document.

6. DA METRICS

The set of recommended DA metrics is presented in this section and listed in [Table 1](#), categorized by the taxonomy, indicating the document sections that contain further details on each metric:

- Section 7: Black Box Metrics
- Section 8: Grey Box Metrics
- Section 9: White Box Metrics

The DA metrics are structured in one of three ways: (1) a binary violation⁹/no violation (i.e., with a value of 1 or 0, respectively), (2) an error (with a value between 0 and 1)¹⁰, or (3) a combination of the binary violation/no violation and a stand-alone formula underlying the violation.¹¹

The binary violation/no violation approach is advantageous because it conforms to the approach followed by existing automotive industry regulations, such as the Federal Motor Vehicle Safety Standards (FMVSS) [10], U.S. New Car Assessment Program (NCAP) [11], and European NCAP [12], as well as by some of the latest regulations concerning automated driving systems and automated driving assistance systems, such as UN Regulation No. 157 [13] and European Union Regulation 2022/1426 [14]. Some binary metrics incorporate a numerical threshold, determined by the implementer, to indicate a violation. This threshold can be adjusted based on the specific requirements and/or tolerances of the ADS being evaluated (e.g., assigning different violation thresholds to a DA metric under different weather conditions), providing a further layer of customization to the assessment process.¹²

The combination approach is advantageous because, in addition to the binary violation/no violation utility, the underlying formula (used to calculate the violation or error rate) can be used in a variety of ways, such as to compare the performance of two ADSs or of a single ADS over time or after a design change. The underlying formula provides granular information that the binary approach may obscure, such as when knowledge that ADS performance is close to a threshold (or to that of another ADS) is important or in order to contrast and compare in more depth the performance disparities between two ADS-equipped vehicles from different manufacturers, rather than solely depending on a binary result.

The DA metrics can be used in a variety of test methods as described in [15], Section 7.2. For example, these metrics can be used as part of V&V strategies utilizing scenario-based testing in simulation or controlled track testing. In a given scenario test using the binary violation/no violation approach, the violation of a DA metric by an ADS-operated vehicle could constitute a test failure and would inform root cause analysis of the ADS. Executing the same scenario with a different ADS-operated vehicle could provide valuable insights into the relative strengths and weaknesses of the designs. Another possible implementation is testing on road with an in-vehicle fallback test driver (IFTD) with the combination approach. Over the testing period, the binary output can be augmented by calculating the duration, magnitude (e.g., the extent of the violation, with greater extents potentially indicating lower DDT performance), or frequency of violations (e.g., violations per mile traveled). The underlying formula calculations can provide greater detail on the violations and also support a more comprehensive evaluation of the ADS DDT performance from on-road operations.

⁹ For the DA metric related to vehicle crashes (see 7.2), “violation” is modified to “instance.”

¹⁰ The error approach is used for the two DA metrics that involve human traffic controllers (HTCs): one Black Box and the other White Box. This approach is also used in one other White Box metric.

¹¹ The combination approach is implemented wherever applicable, i.e., whenever an underlying formula exists. This is true for six out of the 17 DA metrics. The Example Usage sections of the six applicable metrics include illustrations of both approaches.

¹² There are many possible threshold approaches, such as those mentioned in [51], that are useful where the existence of fluctuations in the metrics measurements would result in potential false positives of a violation. The implementer of the DA metrics may wish to use alternate violation thresholds beyond those shown in this document.

While this document presents individual DA metrics, it is important to note that they are not intended to be used in isolation, and the overall context of the scenario or deployment must be considered during DA metrics implementation. For example, comparing the performance of two ADSs with a single DA metric in which one ADS generates more violations but is operating in a more complex scenario could result in a skewed perspective on the DDT performance. Many metrics could be applicable and used based on the particulars of a given scenario to achieve the intended evaluation of the DDT performance. However, not all metrics will be applicable in all scenarios. For example, there are two metrics involving interactions with a human traffic controller (HTC) that will only be applicable when an HTC is present in the scenario. Furthermore, for the DA metrics to be applicable, the ADS must have the behavioral competency of following HTC directions in its behavioral competency portfolio.

A framework and/or methodology for interpreting the combination of applicable metrics measurements to achieve an overall assessment of the DDT performance of the ADS is out of the scope of this document. Further, the scope of this document does not include guidance on how the metrics violation(s) (including the frequency, duration, and magnitude of the violation) or the quantity of the error might influence the overall DDT performance assessment.

In summary, the DA metrics in this document allow for flexibility of implementation tailored for different implementation purposes, expanding their usability to a variety of applications and enhancing their overall utility and value in the evaluation process.

Table 1 - DA metrics grouped by metrics taxonomy

Section	Taxonomy	Metric
7.1	Black Box	Safety Envelope Metrics¹³: 1. Safety Envelope Ratio Violation 2. Safety Envelope Infringement 3. Safety Envelope Violation 4. Safety Envelope Restoration Time Violation
7.2		Crash Instance
7.3		Lane Departure Violation
7.4		Traffic Law Violation
7.5		Aggressive Acceleration Violation
7.6		Compliance Error Rate to Human Traffic Controller Directions
7.7		Event Response Time Violation
8.1	Grey Box	[Inside the ODD] ADS DDT Non-Execution Violation
8.2		[Outside the ODD] ADS DDT Execution Violation
8.3		Intervention Request/Prompt to Take Over Violation
9.1	White Box	Instantiation of Behavioral Competency Violation
9.2		Identification Error Rate to Human Traffic Controller Directions
9.3		ODD Recognition Violation
9.4		DDT-Relevant Object Distance Calculation Error Rate

¹³ The Safety Envelope Metrics are intended to be neutral to the Safety Envelope Formulation selected to calculate the spatiotemporal boundaries. See Appendix A for more details on the Safety Envelope Formulations.

The characteristics included for each DA metric are:

- A. Definition
- B. Key References¹⁴
- C. Assumptions and Subjectivity
- D. Observable Variables
- E. Formulation
- F. Applicability
- G. Example Usage

6.1 Additional Pertinent Information

To assess DDT performance, information that is additional to the DA metrics can be useful in providing additional context. For all DA metrics, it is important to know whether the ADS is engaged and executing the DDT; otherwise, if there is a human driver executing the DDT, the DDT performance of the ADS is not being measured. (The situation is more complex at lower levels of SAE J3016 driving automation when the human driver and driving automation system combine to execute the DDT.) Note that knowing whether the ADS is executing the DDT is a requirement for the calculation of the [Inside the ODD] ADS DDT Non-Execution Violation (IADNEV) and [Outside the ODD] ADS DDT Execution Violation (OADEV) metrics (see 8.1 and 8.2, respectively).

The level of driving automation¹⁵, as described in SAE J3016 [1], of each of the ADS feature(s) is information that can clarify, for example, if the ADS has the capability of achieving a minimal risk condition in the event of an ODD exit. The current level of driving automation does not indicate the maximum level of automation that may be achieved by an ADS. Rather, it indicates the level of the ADS feature(s) presently engaged and could be provided as a time-stamped level of driving automation. The level of driving automation for an ADS-operated vehicle may vary during a single trip (as defined in [1]: SAE J3016) either by a single ADS feature having multiple possible levels of driving automation or by engagement of another ADS feature. Note that knowing the feature level of driving automation is a requirement for the calculation of the Intervention Request/Prompt to Take Over Violation (IRPTOV) DA metric (see 8.3).

It is also useful to know whether the ADS-operated vehicle is operating in an on-road testing or commercialization capacity.¹⁶ On-road testing operation may include the presence of a fallback test driver according to [5]: SAE J3018.¹⁷ If the operation is at the commercialization stage, the human user is a fallback-ready user for Level 3 driving automation and a passenger for Level 4/Level 5 driving automation, according to [1]. In general, an ADS-equipped vehicle's development will proceed from testing to commercialization. However, it is possible that a previously deployed vehicle undergoing an update may be operating in a testing phase.

¹⁴ The Key References characteristic includes documents that have been used in the development of the particular DA metric section. Some of the DA metrics are novel, while some contain varying degrees of content from the referenced documents.

¹⁵ There may be multiple methods for the ADS to convey the feature level of driving automation.

¹⁶ The distinction between "testing" and "commercialization" lies in the stage of development of the ADS. Testing occurs during development and corresponds to Technology Readiness Level (TRL) 8 and below; on-road operation of an ADS-equipped vehicle would be described as testing. Commercialization would occur once development is complete and corresponds to TRL 9; the manufacturer operating an ADS-equipped vehicle as part of a commercial service and/or operation by a customer would constitute a commercialization. The distinction for a particular jurisdiction must be understood by all stakeholders in order for the information to be useful.

¹⁷ While the fallback test driver is expected to maintain situational awareness due to the prototype nature and testing and development phase of the subject vehicle, a fallback-ready user is not expected to maintain situational awareness when the ADS is engaged.

Comprehensive knowledge of the ODD of an ADS-equipped vehicle feature ODD is critical to understanding the context of its operation, particularly in assessing the ADS' DDT performance. Note that knowledge of the ODD is a requirement for the calculation of several DA metrics. The ADS may be expected to be executing the DDT inside the ODD (see [Inside the ODD] ADS DDT Non-Execution Violation in 8.1) but should not be executing the DDT outside of its ODD (see [Outside the ODD] ADS DDT Execution Violation in 8.2). Knowledge of the ODD is also a requirement to establish a ground truth against which the actual operating conditions can be compared (see ODD Recognition Violation in 9.3).

These examples of additional information are applicable in all ODDs and thus are pertinent for all situations where DA metric measurements are obtained. How this information is communicated between stakeholders is beyond the scope of this document.

7. BLACK BOX METRICS

7.1 Spatiotemporal Safety Envelope Formulations and Metrics

Safety envelope metrics capture a kinematic relationship between the state space of the SV and the boundary established by a given spatiotemporal safety envelope formulation. These spatiotemporal safety envelope formulations, which are defined in terms of distance or time, are defined using kinematic equations that describe the SV and/or safety-relevant object's motion and interactions within the environment.

The structure of 7.1 is different from those pertaining to the other DA metrics of this document, wherein every other metric is described in a single section. For the safety envelope concept, the desired properties of spatiotemporal safety envelope formulations are first described in 7.1.1. Next, the recommended spatiotemporal safety envelope metrics are presented in 7.1.2. Finally, the safety envelope formulations are defined and described in detail in Appendix A.

7.1.1 Desired Properties of Spatiotemporal Safety Envelope Formulations

Spatiotemporal safety envelope formulations play an important role in the safety performance of the ADS as they define the time and space the SV has for performing maneuvers and responding to the actions of nearby safety-relevant objects, aiming to reduce the likelihood and/or severity of a potential crash.

Spatiotemporal safety envelope formulations can help identify potentially hazardous events. Therefore, it is important to evaluate the formulations to select the appropriate one(s) for the intended scenario. In this document, safety envelope formulations are chosen to:

- P.1 Include relevant kinematic components (i.e., positions, velocities, and accelerations) and the reasonably foreseeable behaviors of road users that affect the DDT of the ADS (e.g., response time, assumed braking behavior, etc.).
- P.2 Be inclusive of salient dynamic components of the ODD in which the ADS feature of the SV is intended to operate (e.g., changing assumptions or parameter values based on environmental or geographical factors).
- P.3 Have an output that is always defined for the scenario for which it is being used and have a computation that is repeatable.
- P.4 Include the conditions and assumptions where the safety envelope formulation is applicable.
- P.5 Have a logical relation to hazardous events (e.g., near-miss events and/or crashes) such that it can account for safety performance and functionality¹⁸ of the ADS.

¹⁸ The functionality in this case refers to the usability of the subject vehicle in completing its intended mission (e.g., reach its destination), as well as the impact of the subject vehicle on the surrounding environment and road users (e.g., traffic flow).

P.6 Have a definition that is readily available and without excessive specificity such that is broadly applicable (e.g., applicable to more than one scenario¹⁹).

P.7 Have an implementation that relies on variables that are measurable with readily available, off-the-shelf equipment.

The intent of these properties is to serve as a guideline that can be followed to assess different black box safety envelope formulations used for the driving assessment of an ADS. However, developers and manufacturers of ADS may utilize safety envelope formulations that deviate from one or more of the properties mentioned above. Additionally, safety envelope formulations should be applicable to scenarios encountered in simulation, closed course, and/or on road and could incorporate the inherent measurement uncertainty related to the implementation. Ultimately, it is worth noting that a thorough evaluation and data analysis are needed to assess the effectiveness of a safety envelope formulation for a given scenario.

The Comprehensive Safety Envelope Formulations in this document are the result of a non-exhaustive literature review of definitions that meet the properties listed above and are defined in detail in Appendix A. Additionally, the appendix presents Traditional Formulations (also known as “surrogate safety measures”) that have been widely used in the literature and in fields like Traffic Engineering Safety for characterizing near-miss and crash events, as well as for characterizing human driving behavior [16], [17], [18]. While relevant, these formulations do not meet one or more of the desired properties. It is important to note that the list of safety envelope formulations in this document can be extended as new formulations develop through innovation and research. Although the desired properties are a guideline, any new safety envelope formulation could be evaluated against them to determine if it is comprehensive enough to aid with the dynamic driving task evaluation of an ADS. [Table 2](#) presents which properties are met by the safety envelope formulations and by the traditional formulations.

Table 2 - Evaluation of met (✓) properties of safety envelope formulations

	P.1	P.2	P.3	P.4	P.5	P.6	P.7
Comprehensive Safety Envelope Formulations							
Minimum Distance Safety Envelope	✓	✓	✓	✓	✓	✓	✓
Model Predictive Instantaneous Safety Envelope	✓	✓	✓	✓	✓	✓	✓
Reachability-Based Drivable Area	✓	✓	✓	✓	✓	✓	✓
Traditional Formulations							
Time Gap			✓	✓	✓	✓	✓
Post-Encroachment Time			✓	✓	✓	✓	✓
Time-to-Collision				✓	✓	✓	✓
Modified Time-to-Collision				✓	✓	✓	✓

NOTE: See Appendix A for detailed explanation of met and unmet properties of Safety Envelope Formulations.

7.1.2 Safety Envelope Metrics

As previously stated, safety envelope metrics capture a kinematic relationship between the state space of the SV and the boundary established by a given spatiotemporal safety envelope formulation; therefore, the metrics defined in this section are generic in their definitions as they do not depend on a specific safety envelope formulation. The implementer of this document can decide how to use these metrics and which spatiotemporal safety envelope formulation to apply, as these decisions depend on the specific scenario or deployment context.

The safety envelope metrics in this document can serve as quantifiable measures to evaluate the DDT performance of an ADS based on the occurrence of specific behaviors or events in relation to the SV's state space and the boundary defined by a particular spatiotemporal safety envelope formulation during the DDT execution. Ideally, safety envelope metrics should be able to accurately identify undesired driving outcomes with a high True Positive Rate and a low False Negative Rate; however, in practice, there may be a trade-off in achieving these outcomes. Additionally, safety envelope metrics could be generalizable to different ADS implementations; e.g., at different stages of development (testing versus commercialization) and in different test methods (on-road testing, closed course testing, and simulation testing).

¹⁹ Widely applicable safety envelope formulations may be preferable from a usability perspective. Note, however, that certain situations may lend themselves to a choice of specific formulation that only applies to single scenarios (e.g., usage of TTC in consumer rating testing protocols).

It is important to reiterate that while the safety envelope metrics result in a binary indication (i.e., a metric violation), their application can be further augmented by assessing the frequency, duration, and/or magnitude of the violations, where applicable, to support a more comprehensive evaluation. Additionally, the underlying formulations used to compute a violation could be used to compare the performance of two or more ADS-equipped vehicles rather than relying purely on binary outcomes. Moreover, even if the numerical results of some metrics may be the same in certain cases, the significance is in how each metric is interpreted and used in combination with additional metrics and scenario information since they each shed light on different aspects of the ADS performance.

7.1.2.1 Safety Envelope Ratio Violation

A. Definition

Safety Envelope Ratio Violation (SERV) is a comparison of the ratio of the measured spatiotemporal boundaries to the calculated spatiotemporal safety envelope boundaries between the SV and a safety-relevant object against minimum and maximum thresholds.

NOTE 1: The SERV is calculated by first calculating the Safety Envelope Ratio (SER), which is the ratio of the measured spatiotemporal boundaries to the calculated spatiotemporal safety envelope boundaries between the SV and a safety-relevant object.

NOTE 2: The SERV is calculated by determining how much or how little of a defined safety envelope the SV is maintaining with respect to another safety-relevant object and comparing it against predefined minimum and maximum ratio thresholds.

B. References

Adapted from [19].

C. Assumptions and Subjectivity

The formulation of SERV is based on a particular Safety Envelope formulation, which may or may not have assumptions or a subjective definition.

D. Observable Variables

The formulation of SERV is based on a particular Safety Envelope formulation. Observable variables will vary depending on such formulation.

E. Formulation

$$SER = \frac{\text{measured boundary}}{\text{safety envelope boundary}} \quad (\text{Eq. 1})$$

$$SERV = \begin{cases} 1 & \text{else} \\ 0 & \text{if } SER_{min} < SER < SER_{max} \end{cases} \quad (\text{Eq. 2})$$

where:

measured boundary = measured spatiotemporal boundary between the SV and a safety-relevant object (e.g., headway distance)

safety envelope boundary = calculated spatiotemporal safety envelope between the SV and a safety-relevant object as defined by a given safety envelope formulation

NOTE 1: The implementer of this metric could use the SER value to compare against another deployment, against the performance of another version of the ADS software, against another ADS, etc.

NOTE 2: The practical implication of defining an SER_{max} threshold is to identify situations where one could have the unintended outcome of selecting too big of a spatiotemporal safety envelope that induces undesirable behavior from the surrounding traffic. For example, selecting too conservative assumptions about the braking tendency of a lead vehicle may lead to a long trailing distance, unintentionally inducing other vehicles to cut in front of the SV. Therefore, the definition of an SER_{max} threshold needs to be considered in the context of a given scenario and underlying safety envelope formulation to avoid unintended results.

F. Applicability

This metric is applicable to all scenarios to which the underlying safety envelope formulation is applicable. For example, a safety envelope formulation could be defined for longitudinal-only scenarios; therefore, the SERV metric would only apply to those scenarios.

G. Example Usage

Consider the example depicted in [Figure 1a](#), where the SV is driving behind a safety-relevant object (denoted as SO).

At a given point in time ($t = 3$), the SV starts accelerating, and the distance between the SV and the SO starts decreasing. After infringing upon the calculated distance-based safety envelope ($t = 7$), the SV starts reducing its speed until restoring its safety envelope distance at $t = 14$ (see [Figure 1b](#)). The distance between both vehicles keeps increasing due to the reduced speed of the SV.

The calculated SER and SERV are shown in [Figure 1c](#) with $SER_{min} = 1.0$ and $SER_{max} = 1.5$. An analysis of this scenario test result could focus on the violation and/or its duration; the analysis could also use the SER values to examine the SV behavior more closely (e.g., by seeing how the SER value changes over time and what its minimum is).

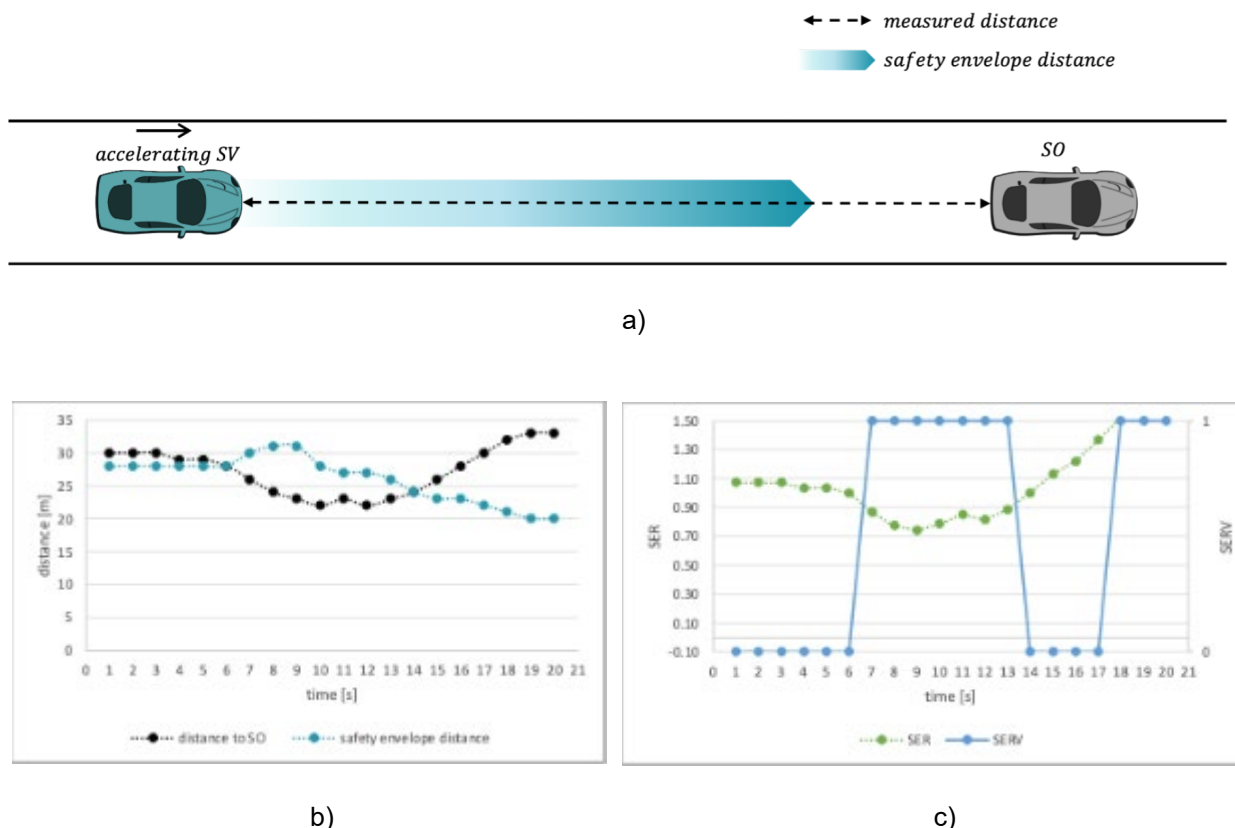


Figure 1 - Example driving situation and resulting computation of SERV

NOTE 1: The time interval resolution used in the figures (i.e., 1 second) is for illustration purposes and could differ from actual ADS implementation.

NOTE 2: To further analyze the performance of the ADS in either scenario-based testing or deployment, the implementer of this metric may wish to use the value of the underlying SER or the count, frequency, duration, or magnitude of any violations.

7.1.2.2 Safety Envelope Infringement

A. Definition

Safety Envelope Infringement (SEI) is the loss of the safety envelope when the measured boundaries between the SV and a safety-relevant object are less than those defined by the spatiotemporal safety envelope formulation.

NOTE 1: The SEI is calculated by first calculating the Safety Envelope Ratio (SER), which is the ratio of the measured spatiotemporal boundaries to the calculated spatiotemporal safety envelope boundaries between the SV and a safety-relevant object.

NOTE 2: An SEI might be due to actions of the SV or the safety-relevant object. In the former case, the SEI also constitutes as a Safety Envelope Violation (SEV) (see 7.1.2.3).

B. References

Adapted from [19] and [15].

C. Assumptions and Subjectivity

The formulation of SEI is based on a particular Safety Envelope formulation, which may or may not have assumptions or a subjective definition.

D. Observable Variables

The formulation of SEI is based on a particular Safety Envelope formulation. Observable variables will vary depending on such formulation.

E. Formulation

$$SER = \frac{\text{measured boundary}}{\text{safety envelope boundary}} \quad (\text{Eq. 3})$$

$$SEI = \begin{cases} 1 & \text{if } 0 < SER < 1 \\ 0 & \text{if } SER \geq 1 \end{cases} \quad (\text{Eq. 4})$$

where:

measured boundary = measured spatiotemporal boundary between the SV and a safety-relevant object (e.g., headway distance)

safety envelope boundary = calculated spatiotemporal safety envelope between the SV and a safety-relevant object as defined by a given safety envelope formulation.

F. Applicability

This metric is applicable to all scenarios to which the underlying safety envelope formulation is applicable. For example, a safety envelope formulation could be defined for longitudinal-only scenarios; therefore, the SEI metric would only apply to those scenarios.

G. Example Usage

Consider again the example depicted in [Figure 1a](#), where the SV is driving behind a safety-relevant object (denoted as SO).

At a given point in time ($t = 3$), the SV starts accelerating, and the distance between the SV and the SO starts decreasing. After infringing upon the calculated distance-based safety envelope ($t = 7$), the SV starts reducing its speed until restoring its safety envelope distance ($t = 14$) (see [Figure 2a](#)). The distance between both vehicles keeps increasing due to the reduced speed of the SV.

The calculated SEI is shown in [Figure 2b](#).

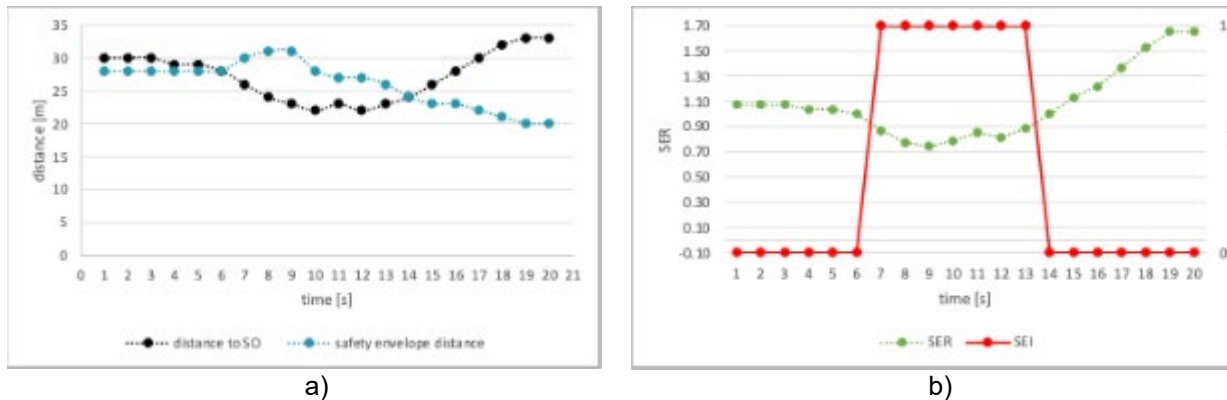


Figure 2 - Example driving situation and resulting computation of SEI

NOTE 1: The time interval resolution used in the figures (i.e., 1 second) is for illustration purposes, and it could differ from actual ADS implementation.

NOTE 2: To further analyze the performance of the ADS in either scenario-based testing or deployment, the implementer of this metric may wish to use the value of the underlying SER or the count, frequency, duration, or magnitude of any violations.

7.1.2.3 Safety Envelope Violation

A. Definition

Safety Envelope Violation (SEV) is an instance of an SEI that was precipitated by either an initial, unexpected maneuver or the lack of an expected maneuver by the SV, making the SV's action or inaction the critical reason for the incident.

NOTE: In practice, it may not always be possible to determine whether an SEI also constitutes an SEV. This determination is related to the assignment of Crash Instance roles: An SEV indicates that the SV is the initiator of the SEI.

EXAMPLE 1: An SEV may result from a maneuver by the SV; for example, a cut-in maneuver in front of an adjacent vehicle with insufficient headway.

EXAMPLE 2: An SEV may result from inaction by the SV; for example, a failure to brake for a decelerating vehicle in front.

B. References

Adapted from [19] and [15].