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

IEEE Vehicular Technology Society

Developed by the
Intelligent Transportation Systems Committee

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

Developed by the

Intelligent Transportation Systems Committee
of the
IEEE Vehicular Technology Society

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IEEE SA Standards Board

Abstract: This standard applies to road vehicles. It defines a minimum set of reasonable assumptions and foreseeable scenarios that shall be considered in the development of safety-related models that are part of an automated driving system (ADS).

Keywords: ADS, ADS-operated vehicle, automated driving system, assumption, automated vehicle, autonomous vehicles, AV, decision-making, IEEE 2846™

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When the IEEE SA Standards Board approved this standard on 24 March 2022, it had the following membership:

Introduction

This introduction is not part of IEEE Std 2846-2022, IEEE Standard for Assumptions in Safety-Related Models for Automated Driving Systems.

While automated driving system (ADS)-operated vehicles hold the potential for safety improvement compared to human drivers, the recognition that transportation will continue to entail some level of risk has to be considered.

Human drivers rely on extensive daily experience in their interactions with other agents on the road, which helps them craft assumptions about *reasonably foreseeable* behavior of other road users. For example, when following another vehicle, human drivers implicitly make assumptions about the behaviors of other road users (e.g., the possible deceleration rate of the vehicle in front of them), so that they may appropriately adjust their following distance. As illustrated in Figure A, the ego vehicle (blue vehicle) makes an assumption about the deceleration rate of the vehicle in the front (yellow vehicle) and adjusts its following distance as a consequence. Such assumptions enable human drivers to follow at a "natural" distance that allows for a smooth flow of traffic. A careful balance between conservativeness, safety considerations, and natural driving can be established, so that for this example, following distances may be adapted based on assumptions about reasonably foreseeable behaviors of other road users, not necessarily accounting for the theoretical worst-case capabilities at all times. Such a balance is needed for the efficiency and safety of the overall transportation system, without unnecessarily constraining vehicles on the road (e.g., drivers adopting a behavior based on worst case following distances under all circumstances). For example, studies have shown that even deceleration rates adopted by human drivers in the context of Figure A are often much lower than the maximum feasible decelerations achievable by the vehicles, so braking events in nominal driving conditions are likely to have even lower deceleration rates. If humans made driving decisions based primarily on the theoretical worst case, following distances would generally increase, and traffic flow could be negatively affected as a result of overly conservative driving behavior.

Figure A—An example scenario where the ego vehicle follows another vehicle

The same reasoning applies to interactions with other road users in addition to vehicles, such as pedestrians. Consider the situation depicted in Figure B, where the ego vehicle is being driven on a roadway next to a sidewalk where a pedestrian is walking in the same direction of travel. In this context, the ego vehicle driver implicitly evaluates how reasonable it may be to expect the pedestrian to continue their progression on the sidewalk versus turning into the road. In other words, the ego vehicle driver is making an assumption about how reasonably foreseeable it is that the pedestrian will keep moving in the current direction of travel without a sudden change of direction. Similar to the previously discussed car-following situation depicted in Figure A, accounting for theoretical worst cases (e.g., that every pedestrian could change heading with the fastest speed and agility possible for a human being) would lead to a state where an ADS-operated vehicle might never be able to pass the pedestrian.

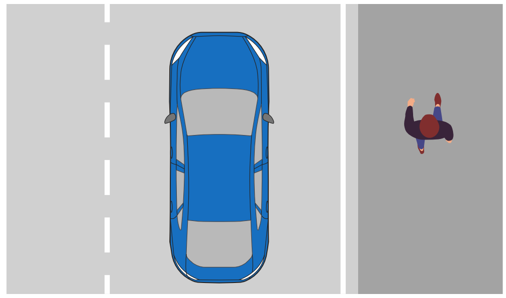

Figure B—An example scenario with the ego vehicle driving alongside a crosswalk with a pedestrian

The aforementioned examples illustrate how assumptions enable the balancing of efficient natural driving and safety considerations based on what is reasonably foreseeable to expect from other road users.

Similarly, ADS-operated vehicles will also need to make assumptions. The purpose of this standard is to define the assumptions about reasonably foreseeable behaviors of other road users that shall be considered for Automated Driving Systems. One use, presented in this standard, for instance, is the role that assumptions play within safety-related models, which provide a representation of safety-relevant aspects of driving behavior pertaining to both ADS-operated vehicles and other road users. In this context, assumptions are represented by bounds (i.e., maxima and/or minima) for a set of kinematic variables, which enable the ADS to make informed decisions with an understanding of what would be reasonably foreseeable behaviors of other road users. Kinematics are used to indicate both physical quantities such as speed/acceleration, but also non-mechanical quantities such as response time. Additional sources of uncertainty, such as prediction (e.g., existence of an occluded road user) or perception errors, are also important but are not explicitly covered in this standard.

Some safety-related models, which consider assumptions that an ADS-operated vehicle should take into account, have been released publicly and considered in development of this standard. The use of assumptions in these example models are varied, for example:

- Assumptions about the reasonable worst-case behaviors of other road users are used to calculate minimum safe longitudinal and lateral distances.
- Assumptions about road users can be used to formalize rules for reasonable driving behavior and help assess whether ADS-operated vehicle trajectories are safe and lawful.
- Assumptions can be used to determine the scope of acceptable vs. unacceptable actions.
- Assumptions on reasonably foreseeable accelerations provide a basis for modeling the bounds of the predicted behavior from other users and allow the model to restrict the predictive agents' profiles (i.e., the points in space occupied by agents in the future) used for the computation of the metrics of interest.

Regardless of the safety-related model utilized, the consideration of assumptions in safety-related models plays a central role in helping an ADS establish bounds for reasonably foreseeable behavior from other road users. The definition of the minimum set of assumptions for reasonably foreseeable behaviors of other roads users helps the ADS-operated vehicle navigate in real world environments more intelligently and safely, facilitating successful deployment and operation within the current transportation network.

While the set of values of the assumptions used in a safety-related model may be specified by regulation or selected by the ADS developer, this standard argues that a minimum set of kinematics-based assumptions can be taken into account under all circumstances, regardless of the model employed.

In this standard, an initial set of high-level scenarios is considered in order to derive a normative set of assumptions for consideration in safety-related models. The documented scenarios are not representative of all scenarios that an ADS-operated vehicle may encounter; instead, they were chosen as the starting contexts that would allow composability of more complex situations, and helped with the initial identification of the minimum set of assumptions for the road users present in each scenario of interest.

The considered scenarios and the derived minimum set of assumptions regarding the safety of the overall system are not exhaustive, but are proposed as a minimum set that can further increase the robustness of the behavior of an ADS-operated vehicle with respect to other road users.

The content of the standard is as follows:

- Clause 2 provides normative references to other important standards that are complementary to this standard.
- Clause 3 provides key terms and definitions, including key concepts that are central to this standard, such as “safety-related model” and “reasonably foreseeable.”
- Clause 4 defines the normative minimum set of assumptions that shall be considered by safety-related models.
- Clause 5 lists examples of attributes that are common to contributed safety-related models.
- Clause 6 describes methods for possible verification and validation of assumptions in safety-related models.
- Annex A provides further practical examples of how to apply the normative requirements to different application areas within an ADS.
- Annex B is the bibliography for this standard.

Contents

IEEE Standard for Assumptions in Safety-Related Models for Automated Driving System

1. Overview

1.1 Scope

This standard applies to road vehicles. For a set of scenarios, a minimum set of assumptions regarding reasonably foreseeable behaviors of other road users are defined that shall be considered in the development of safety-related models for automated driving systems (ADS).

This standard further defines a list of attributes common to contributed safety-related models and methods to help verify whether a safety-related model takes the minimum set of assumptions into consideration. An informative annex instantiates several examples of how the proposed minimum set of assumptions could be employed in ADS development.

Sources of uncertainty, such as prediction or perception errors, are out of scope to this standard.

This standard does not guarantee the safety of the overall system in all scenarios.

1.2 Purpose

Government and Industry alike need an open, transparent, and technology-neutral standard that provides guidance useful for evaluating the performance of an ADS. This guidance consists of a minimum set of assumptions with bounds on reasonably foreseeable behaviors of other road users used in the development of safety-related models.

1.3 Word usage

The word *shall* indicates mandatory requirements strictly to be followed in order to conform to the standard and from which no deviation is permitted (*shall* equals *is required to*).[1,2]

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[1] The use of the word *must* is deprecated and cannot be used when stating mandatory requirements; *must* is used only to describe unavoidable situations.
[2] The use of *will* is deprecated and cannot be used when stating mandatory requirements; *will* is only used in statements of fact.

The word *should* indicates that among several possibilities one is recommended as particularly suitable, without mentioning or excluding others; or that a certain course of action is preferred but not necessarily required (*should* equals *is recommended that*).

The word *may* is used to indicate a course of action permissible within the limits of the standard (*may* equals *is permitted to*).

The word *can* is used for statements of possibility and capability, whether material, physical, or causal (*can* equals *is able to*).

2. Normative references

The following referenced documents shall be understood and used for the application of this document, and each referenced document is cited in text and its relationship to this document is explained. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments or corrigenda) applies.

ISO 26262:2018, Road vehicles—Functional safety— Part 1: Vocabulary.

ISO/DIS 21448:2021, Road vehicles—Safety of the intended functionality.

ISO/TR 21974-1:2018, Naturalistic driving studies—Vocabulary—Part 1: Safety critical events.

SAE J3016, Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles.

SAE J3131, Automated Driving Reference Architecture.

SAE J3216, Taxonomy and Definitions for Terms Related to Cooperative Driving Automation for On-Road Motor Vehicles.

SAE J3164, Taxonomy and Definitions for Terms Related to Automated Driving System Behaviors and Maneuvers for On-Road Motor Vehicles.

The reference documents defined here are those applied most commonly throughout the document. Additional sources can be found in the bibliography in Annex B.

3. Definitions, acronyms, and abbreviations

3.1 Definitions

For the purposes of this document, the following terms and definitions apply. The *IEEE Standards Dictionary Online* should be consulted for terms not defined in this clause. [3] In order to maintain consistent terminology and definition usage, where quoted text is not available, relevant standards are indicated and should be referenced.

acceptable risk: Overall risk sufficient to satisfy the safety case.

automated driving system (ADS): *See:* SAE J3016, Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles: 2021.

[3] *IEEE Standards Dictionary Online* is available at: http://dictionary.ieee.org. An IEEE account is required for access to the dictionary, and one can be created at no charge on the dictionary sign-in page.

conflict: *See:* ISO/TR 21974-1:2018, Naturalistic driving studies—Vocabulary—Part 1: Safety critical events

controllability: *See:* ISO 26262:2018, Road vehicles—Functional safety— Part 1: Vocabulary.

driver: *See:* SAE J3016, Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles: 2021.

NOTE—As described in SAE J3016, the levels of driving automation are classified from Level 0 to Level 5, with an increasing level of driving automation from no automation to full automation.

driving policy: *See:* ISO/DIS 21448:2021, Road vehicles—Safety of the intended functionality.

dynamic driving task (DDT): *See:* SAE J3016, Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles: 2021.

event: Any change in ADS state or world state relevant to DDT performance.

emergency maneuver: A maneuver performed by a vehicle in case of an event in which the vehicle is at imminent collision risk and has the purpose of avoiding or mitigating a collision.

formal model: Model(s), expressed in formal notation, used in formal verification of system performance.

formal notation: *See:* ISO 26262:2018, Road vehicles—Functional safety— Part 1: Vocabulary.

formal verification: *See:* ISO 26262:2018, Road vehicles—Functional safety— Part 1: Vocabulary.

lateral vehicle motion control: *See:* SAE J3016, Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles: 2021.

longitudinal vehicle motion control: *See:* SAE J3016, Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles: 2021.

NOTE—See Figure 1 for different axes of vehicle motion.

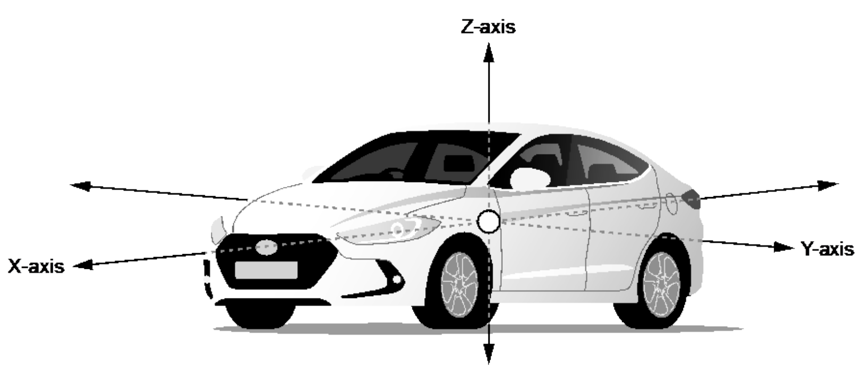


Figure 1—Diagram showing axes of vehicle motion

object and event detection and response (OEDR): *See:* SAE J3016 ,Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles: 2021.

operational design domain (ODD): *See:* SAE J3016, Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles: 2021.

reasonably foreseeable: *See:* ISO 26262:2018, Road vehicles—Functional safety— Part 1: Vocabulary.

NOTE—For the purpose of this standard, reasonably foreseeable is considered to be both credible and measurable.

representation: Collection of information perceived about a scene and all its elements including dynamic agents.

NOTE—May be subjective or objective. Only a representation in a simulated world can be all-encompassing (objective). In the real world, it is varied and from one or several observers' points of view (subjective).

response time: The time it takes for a road user to perceive a specific stimulus and start executing a response (e.g., braking/steering/accelerating/stopping) in a given scenario.

NOTE—The definition of response time is compatible with that of SAE J2944 [B27].

risk: *See:* ISO 26262:2018, Road vehicles—Functional safety— Part 1: Vocabulary.

road operators: *See:* SAE J3216, Taxonomy and Definitions for Terms Related to Cooperative Driving Automation for On-Road Motor Vehicles: 2020.

road user: *See:* SAE J3216, Taxonomy and Definitions for Terms Related to Cooperative Driving Automation for On-Road Motor Vehicles: 2020.

safety envelope: A set of limits and conditions, within which the system is designed to operate, subject to constraints or controls, in order to maintain operations within a level of acceptable risk.

safety-related model: Representation of safety-relevant aspects of driving behavior based on assumptions about reasonably foreseeable behaviors of other road users.

NOTE 1—Examples of safety-related models can include those related to motion planning, as well as on-board and off-board safety checkers and analyzers.

NOTE 2—Safety-related models could apply to both an ADS and representations of other road users.

NOTE 3—Safety-related models can take many forms. Example formulations may include: definition of a driving policy; definitions as a formal mathematical equation, or as a set of more conceptual rules, or as a set of scenario-based behaviors, or a combination thereof.

safety-relevant object: Any object (excluding ego vehicle), dynamic or static, that may have relevance for the safety performance of the DDT.

safety validation: *See:* ISO 26262:2018, Road vehicles—Functional safety— Part 1: Vocabulary.

scenario: *See:* ISO/DIS 21448:2021, Road vehicles—Safety of the intended functionality.

scene: *See:* ISO/DIS 21448:2021, Road vehicles—Safety of the intended functionality.

traffic participant: *See:* SAE J3216, Taxonomy and Definitions for Terms Related to Cooperative Driving Automation for On-Road Motor Vehicles: 2020.

[human] user: *See:* SAE J3016, Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles: 2021.

[dynamic driving task] vehicle behavior: *See:* SAE J3164, Taxonomy and Definitions for Terms Related to Automated Driving System Behaviors and Maneuvers for On-Road Motor Vehicles: 2022.

verification: *See:* ISO 26262:2018, Road vehicles—Functional safety— Part 1: Vocabulary.

vulnerable road user (VRU): A road user who is not occupying a vehicle such as a passenger car, a public transit vehicle, or a train.

world model: *See:* SAE J3131, Automated Driving Reference Architecture: 2022.

3.2 Acronyms and abbreviations

ADS	automated driving system
DDT	dynamic driving task
ODD	operational design domain
OEDR	object and event detection and response
SOTIF	safety of the intended functionality
VRU	vulnerable road user
V&V	verification and validation
RSS	Responsibility Sensitive Safety
SFF	Safety Force Field

4. Minimum set of assumptions about reasonably foreseeable behaviors of other road users to be used in scenarios

4.1 Assumptions

This clause introduces the minimum set of assumptions about reasonably foreseeable behavior of other road users that shall be considered in safety-related models for an initial set of scenarios to help demonstrate absence of unacceptable risk within a given operational design domain (ODD). The absence of unacceptable risk can be demonstrated through high controllability from other road users, low rates of occurrence, and/or low severity of the outcome of a particular scenario. The definition of the minimum set of assumptions about reasonably foreseeable behaviors of other road users helps the ADS-operated vehicle navigate through the real world more intelligently and safely without unnecessarily constraining its behavior on the road. Scenarios may exist in which acceptable driving behaviors of other road users do not align with these assumptions, and, in these cases, additional refinements may be needed on the part of the ADS developer.

This standard considers scenarios that cover safety-relevant driving situations that an ADS-operated vehicle may encounter in real traffic and in which the use of assumptions about reasonably foreseeable behaviors of other road users can help it to drive more naturally and safely. Safety-related models that are part of or used in the evaluation of an ADS shall consider the minimum set of assumptions made about the behaviors of other road users described within the defined scenarios. This requirement does not imply that all safety-related models consider the assumptions, but instead, assumptions may be considered by some combination of safety-related models. Assumptions about other road users should be continuously in place and updated regularly as required by the safety-related model implementation, taking into consideration information from the most current scene representation.

Within the scope of this standard, the following high-level road user classification shall be considered:

a) Ego vehicle
b) Other road users, including:

1) Pedestrians: For example, a person walking on a sidewalk next to a road
2) Cyclists: For example, a person riding a bicycle
3) Other VRUs: For example, a person using a wheelchair, a golf cart, or riding a motorcycle or motor scooter
4) Vehicles (human-driven or ADS-operated): For example, passenger vehicles, commercial motor vehicles, buses

Other road users and/or objects like light rail, animals, or obstacles are out of the scope of this standard.

NOTE—The "vehicle" under road user's category defined in this standard could be further subclassed into different road vehicle types via regulation or implementation, e.g., passenger vehicle or freight truck.

The minimum set of assumptions about reasonably foreseeable behaviors of other road users considered in this standard is mainly based on kinematic properties of other road users, such as braking capabilities or rate of change of the heading angle. Assumptions on the response time of road users, while not based on kinematics, are still included in the standard because response time has a direct and immediate impact on the kinematic behaviors of road users. A list with notation, description, and measurement unit of the road users' properties considered in this standard is presented in Table 1.

Table 1—Notation and descriptions of road users' properties

Notation	Description	Measurement unit
v^{lon}, v^{lat}	Longitudinal and lateral velocity of a road user	m/s
$\alpha^{lon}, \alpha^{lat}$	Magnitude of longitudinal and lateral acceleration of a road user	m/s^2
β^{lon}, β^{lat}	Magnitude of longitudinal and lateral deceleration of a road user	m/s^2
h	Heading angle (yaw) of a road user	° (degrees)
h'	Heading angle rate of change (yaw rate) of a road user	°/s
ρ	Response time of a road user	s
λ	Lateral fluctuation margin for lateral movements within a lane performed by a road user when moving in forward motion	m

The meaning of longitudinal/lateral position/velocity/acceleration and their sign for the properties of Table 1 is defined according to a reference coordinate system defined in 4.2.2.

The purpose of making assumptions about kinematic properties of other road users is to aid the ADS decision-making in safety-relevant situations, such as those defined in 4.2.3. ADS implementations may have additional assumptions for other road users' properties that are not based on kinematics, such as other road users' intention, which may impact the assumptions in this standard; however, those are out of the scope of this standard.

Assumptions considered in safety-related models may be used to define a safety envelope around the ego vehicle. A safety envelope around the ego vehicle comprises a variety of characteristics, such as longitudinal and lateral distances derived from kinematics with consideration of traffic laws and their regional and/or temporal dependencies. A safety envelope, then, may function as an onboard or off-board checker to evaluate the ADS-operated vehicle safety performance. Safety envelopes based on these assumptions may also be utilized in the development of safety performance indicators that are computed in aggregate from simulation, track, or on-road testing. Additionally, assumptions may be used by the ADS to inform prediction models of the range of potential behaviors of other road users, which usually work in a future time horizon.

The derivation and definition of assumptions about reasonably foreseeable behaviors of other road users followed a sequential methodology depicted in Figure 2. While other methodologies could be applied, the methodology used in this standard consists of the following key steps:

a) A set of foundational scenarios were identified following the rationale presented in 4.2.1.

b) For each scenario, its high-level description, the relevant scenery, and the applicable dynamic elements (i.e., other road users) were identified and described.

c) For each other road user other than ego vehicle in a given scenario, the relevant kinematic properties that govern their motion were identified for the driving situation described within the scenario. For example, lateral motion-related kinematics become relevant when another road user is on an adjacent lane, next to the ego vehicle.

d) For each relevant kinematic property of a given road user, an assessment of their applicability and their safety relevance was done. In general terms, the safety relevance of a kinematic property was evaluated by checking whether a given property could result in other road user's motion toward the ego vehicle or not. For example, if a road user traveling in the opposite direction in front of the ego vehicle exhibits a longitudinal acceleration in its direction of travel, this would result in a motion toward the ego vehicle. Thus, longitudinal acceleration is considered a safety-relevant kinematic property in the situation considered. If a kinematic property is deemed not safety-relevant, then it is not considered applicable to the given scenario for the purpose of this standard.

e) For each safety-relevant kinematic property of a given road user, assumptions about reasonably foreseeable behaviors of other road users were developed for the given scenario. Assumptions were defined by setting boundaries on what are reasonably foreseeable behaviors of other road users in the particular driving situation under consideration (see Figure 2). For example, it is reasonably foreseeable to assume a deceleration no greater than a maximum for a vehicle driving in front and in the same direction as the ego vehicle.

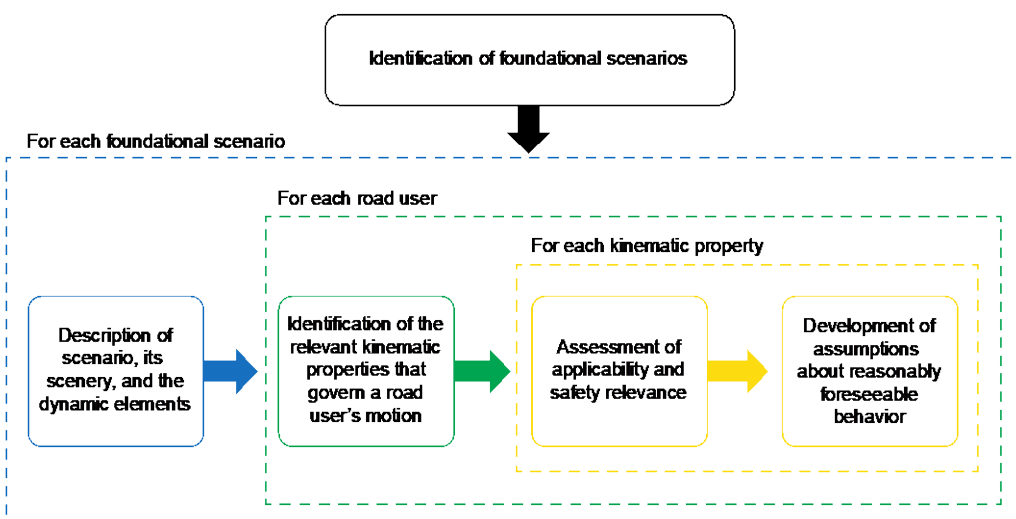


Figure 2—Diagram of methodology for deriving assumptions about reasonably foreseeable behaviors of other road users

Assumptions take the form of bounding limits as described in Table 2, which gives a summary list of constraints that bound the reasonably foreseeable behavior of road users that shall be considered by safety-related models. Assumptions specified in Table 2 that are functions of time t are denoted as $f(t)$, as they might change (or not) during a given scenario. Note that not all of the assumptions about reasonably foreseeable behaviors of other road users listed in Table 2 are safety relevant in all driving situations. Subclause 4.2.3 specifies the minimum subset of assumptions about reasonably foreseeable behaviors of other road users that shall be considered in each of the scenarios contemplated by this standard.

Table 2—Summary list of minimum set of assumptions about reasonably foreseeable behaviors of other road users

Minimum set of assumptions	
Assumption	**Description**
$v^{lon}(t) \leq v^{lon}_{max}$	v^{lon}_{max} is the reasonably foreseeable maximum assumed longitudinal velocity other road users could exhibit
$v^{lat}(t) \leq v^{lat}_{max}$	v^{lat}_{max} is the reasonably foreseeable maximum assumed lateral velocity that other road users could exhibit
$\alpha^{lon}(t) \leq \alpha^{lon}_{max}$	α^{lon}_{max} is the reasonably foreseeable maximum assumed longitudinal acceleration other road users could exhibit
$\alpha^{lat}(t) \leq \alpha^{lat}_{max}$	α^{lat}_{max} is the reasonably foreseeable maximum assumed lateral acceleration other road users could exhibit
$\beta^{lon}(t) \leq \beta^{lon}_{max}$	β^{lon}_{max} is the reasonably foreseeable maximum assumed longitudinal deceleration other road users could exhibit when moving in front of the ego vehicle
$\beta^{lon}(t) \geq \beta^{lon}_{min}$	β^{lon}_{min} is the reasonably foreseeable minimum assumed longitudinal deceleration other road users could exhibit when moving in the opposite direction of the ego vehicle or behind the ego vehicle
$\beta^{lat}(t) \geq \beta^{lat}_{min}$	β^{lat}_{min} is the reasonably foreseeable minimum assumed lateral deceleration other road users could exhibit
$\lvert h(t)\rvert \leq h_{max}$	h_{max} is a reasonably foreseeable maximum assumed heading angle other road users could exhibit
$\lvert h'(t)\rvert \leq h'_{max}$	h'_{max} is a reasonably foreseeable maximum assumed heading angle rate change other road users could exhibit
$\lvert \lambda(t)\rvert \leq \lambda_{max}$	λ_{max} is a reasonably foreseeable maximum assumed lateral position fluctuation other road users could exhibit
$\rho \leq \rho_{max}$	ρ_{max} is the reasonably foreseeable maximum assumed response time other road users could exhibit

Note that the maximum denoting assumptions' bounds (e.g., β^{lon}_{max}) in Table 2 are not intended as the physical/kinematics maximum achievable by a given road user but do represent a reasonably foreseeable bound for the given scenario.

The values of the assumptions about reasonably foreseeable behaviors of other road users can be scenario dependent and may not be defined as one fixed value. As the scene representation evolves, the set of assumptions to be considered should be updated at regular intervals depending on the most-current information available (for example, the current scene). Values for assumptions about reasonably foreseeable behaviors of other road users can be defined as bounding limits or with other appropriate methods. For example, the reasonably foreseeable deceleration of a vehicle driving longitudinally in front of the ego vehicle at a point in time t may be bounded by $\beta^{lon}(t) \leq \beta^{lon}_{max}$ (see scenario V1-S2) or with scenario-dependent probabilistic distributions on β^{lon}.

The values of the assumptions about reasonably foreseeable behaviors of other road users may vary for different road users. For example, the value for β^{lon}_{max} may be different for a person using a wheelchair, a person riding a motorcycle (both within the same VRU category), or a vehicle; therefore, the assumptions listed in 4.2.3 are explicitly defined for each road user category. The values of the assumptions may also change due to other reasons. Examples include, but are not limited to, differences in cultural norms, as is exhibited in more aggressive driving behavior in certain cities, or different traffic laws, such as those specified by speed limits. Additionally, the values of the assumptions may change due to variations in the parameters that define the ODD in which the ADS-operated vehicle is operating, such as changes on the external environmental conditions. For example, the assumed value for β^{lon}_{max} could vary under dry, rainy, or snowy road conditions. However, the need to make assumptions about kinematic characteristics of other road users in a particular scenario remains the same, independent of the ODD and other conditions, unless otherwise stated.

Finally, depending on the scenario, a number of assumptions are specified to be considered within the safety-related model. In addition, when one scenario is used in combination with others to represent more complex driving situations, the combination of assumptions should still reflect reasonably foreseeable behavior from other road users.

Subclauses 4.2.1 and 4.2.2 give supporting information regarding the selection of scenarios considered in this standard as well as the reference coordinate system. Subclause 4.2.3 presents the definition of the scenarios summarized in Table 3 and expands on the minimum set of assumptions about reasonably foreseeable behaviors of other road users that shall be considered by safety-related models, if applicable for intended use-case.

Table 3—Summary list of scenarios

Subclause number	Scenario name	Scenario ID
4.2.3.1	Ego vehicle driving next to other road users	V1-S1
4.2.3.2	Ego vehicle driving longitudinally behind another road user	V1-S2
4.2.3.3	Ego vehicle driving in between leading and trailing road users	V1-S3
4.2.3.4	Ego vehicle’s path intersecting with VRU crossing the road	V1-S4
4.2.3.5	Ego vehicle’s path intersecting with other road user’s path moving in opposite direction	V1-S5
4.2.3.6	Ego vehicle negotiating an intersection with nonoccluded road users	V1-S6
4.2.3.7	Ego vehicle negotiating an intersection with occluded road users	V1-S7

Table 4 summarizes the minimum set of assumptions about reasonably foreseeable behaviors of other road users to be considered in the scenarios listed in Table 3. While some scenarios may have requirements on the same minimum set of assumptions, the usage of the assumptions between scenarios can differ. For example, assumptions about reasonably foreseeable behaviors of other road users in scenario V1-S7 can be used to account for potentially occluded safety-relevant objects; whereas assumptions in scenario V1-S1 can be used to calculate appropriate distances along road users adjacent to the ego vehicle. Please refer to 4.2.3 for details on scenario descriptions.

Table 4—Summary of minimum set of assumptions to be considered by safety-related models in the driving scenarios

	Scenario V1-S1	Scenario V1-S2	Scenario V1-S3	Scenario V1-S4	Scenario V1-S5	Scenario V1-S6	Scenario V1-S7
$v^{lon}(t) \leq v^{lon}_{max}$				X	X	X	X
$v^{lat}(t) \leq v^{lat}_{max}$	X			X	X	X	X
$\alpha^{lon}(t) \leq \alpha^{lon}_{max}$			X	X	X	X	X
$\alpha^{lat}(t) \leq \alpha^{lat}_{max}$	X			X	X	X	X
$\beta^{lon}(t) \leq \beta^{lon}_{max}$		X	X	X		X	X
$\beta^{lon}(t) \geq \beta^{lon}_{min}$			X	X	X	X	X
$\beta^{lat}(t) \geq \beta^{lat}_{min}$	X			X	X	X	X
$\lvert h(t) \rvert \leq h_{max}$	X			X	X	X	X
$\lvert h'(t) \rvert \leq h'_{max}$				X		X	X
$\lvert \lambda(t) \rvert \leq \lambda_{max}$	X			X	X	X	X
$\rho \leq \rho_{max}$	X		X	X	X	X	X

NOTE—A combination of scenarios and their assumptions could allow for considerations in more complex scenarios.

4.2 Application of assumptions to scenarios

In this standard, an initial set of high-level scenarios was considered in order to derive a normative set of assumptions for consideration in safety-related models. This clause, thus, presents the derived minimum set of assumptions about reasonably foreseeable behaviors of other road users in relation to the kinematic properties of interest. Furthermore, it provides supporting information for their interpretation.

4.2.1 Rationale for example scenario selection

The rationale behind scenario differentiation and selection is based on the different and relevant assumptions to be made about other road users' behaviors and their applicability to safety-related models implemented by an ADS. Classification of the scenarios is not part of the standard, and the selection included in this standard is not meant to be interpreted as an exhaustive taxonomy.

The scenarios defined in 4.2.3 are high-level descriptions of common driving situations, including interactions with VRUs. The consideration of assumptions about reasonably foreseeable behaviors of other road users in these scenarios is intended to help the ADS-operated vehicle avoid overcautious behavior, while driving safely.

The scenarios in this standard are not meant to be detailed and prescriptive definitions of driving situations. Rather, the scenarios describe basic interactions between the ego vehicle and other road users, with the intent of providing building blocks for more complex scenarios. Therefore, the scenarios are not mutually exclusive. While scenarios can describe a particular driving situation, their high-level description allows for composability of scenarios. For example, scenario V1-S3 is built upon the driving situation and the assumptions about reasonably foreseeable behaviors of other road users described in scenario V1-S2. The high-level scenario description also allows for transitioning from one scenario to another. In this way, more-complex situations likely to be found in the real world can be constructed. For example, the ego vehicle driving next to a pedestrian walking on the sidewalk that later decides to cross the road at the crosswalk would be a transition from scenario V1-S1 to scenario V1-S4.

Furthermore, the scenarios are intended to be able to accommodate variations of the road users' attributes (e.g., speed), variations of road geometry, environmental conditions, and geographic locations. In this manner, the scenarios can be applicable to a broad number of ODD definitions in which an ADS-operated vehicle may operate, unless otherwise stated within the scenario description.

Throughout the development of this standard, a thorough review of documents about scenario selection, categorization, and definition was made with the goal to adopt previously defined methodology, scenario taxonomy, and/or examples that are applicable to the scope of this standard work (UNECE ECE/TRANS/WP.29/2020/81[B38], NHTSA [B22], NHTSA DOT HS [B23], CETRAN [B7], PEGASUS [B25], Catapult [B5]).

4.2.2 Coordinate system

The definition of kinematic assumptions about road users' behaviors requires the definition of a clear coordinate system for their interpretation. The coordinate system in this subclause is provided as an example and does not need to be used when showing compliance with this standard or to meet this standard's requirements. Users of this standard are responsible for performing the appropriate transformations of the assumptions from the reference coordinate systems of this standard to the reference coordinate system of choice used by the ADS. While it is always possible to employ appropriate mathematical transformations to make use of the proposed assumptions in a different reference frame, this standard leverages multiple coordinate systems that allow abstract and generalized road geometries, while at the same time simplifying how such kinematics assumptions are presented.

Specifically, this standard adopts the following two reference frames:

— A lane-based coordinate system: This reference system is used to verify that a relative placement of various road agents can be established. Such a general reference system allows to create a relative "ordering" of the agents (e.g., establishing who is in front and who is in the back—when applied to a longitudinal direction, or establishing who is to the left/right of whom—when applied to a lateral direction). For purposes of this standard, a lane-based coordinate system is considered to be aligned with the curvature of the road (i.e., defining the longitudinal axis of the coordinate system as tangential to the road curvature) in which longitudinal and lateral motion of road users are defined with respect to their lane of travel (see examples in Figure 3). Among other things, this allows the definition of a clear longitudinal and lateral ordering, even when the road presents a curvature (e.g., in a turn), abstracting road users' actions that follow the lane curvature (e.g., steering) as not performing a lateral maneuver (see examples in Figure 4).

  In the case of vulnerable road users, such as pedestrians or cyclists, the concept of a lane is equivalent to (but not restricted to) a sidewalk, a crosswalk, or a bike lane. In the case of unstructured scenes—namely, a scene in which no lanes are clearly defined, e.g., open parking lots—the lane-based coordinate system assumes that there exists a partition of the drivable surface into "virtual lanes," which considers road users' position and direction of travel to derive road user's behavior. Furthermore, occluded areas of the world can be transformed into and represented in this coordinate system as well as right-of-way and traffic rules.

— A road user-based coordinate system: This reference system is used to define the longitudinal and lateral axes for each road user present in a given scenario. For the case of a vehicle, such as the one presented in Figure 1, this reference system is based in the center of gravity of the road user and presents a longitudinal coordinate (X in Figure 1) along the direction of travel and a lateral coordinate perpendicular to it (Y in Figure 1).

This standard refers to a simplified 2-D representation of the world. However, the lane-based coordinate system uses the definition of a longitudinal lane axis tangential to the road curvature and slope to handle traditional z-axis variations.

In each driving situation described in this standard (see 4.2.3), each participating agent presents its own reference system, so that the two types of reference systems result in a total of 1+M+N sets of axes: one vehicle-based system for the ego vehicle, M lane-based systems for the M lanes relevant to the scenario, and N systems for the N participating agents other than the ego vehicle. An example of how the reference frames get applied to different agents is presented in Figure 3.

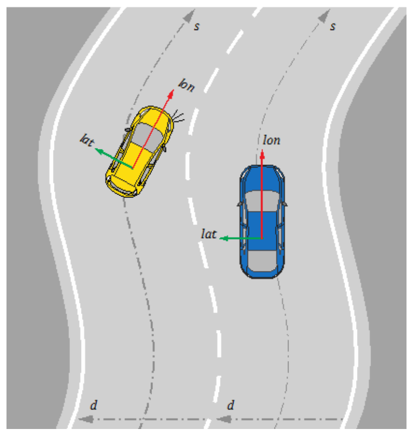
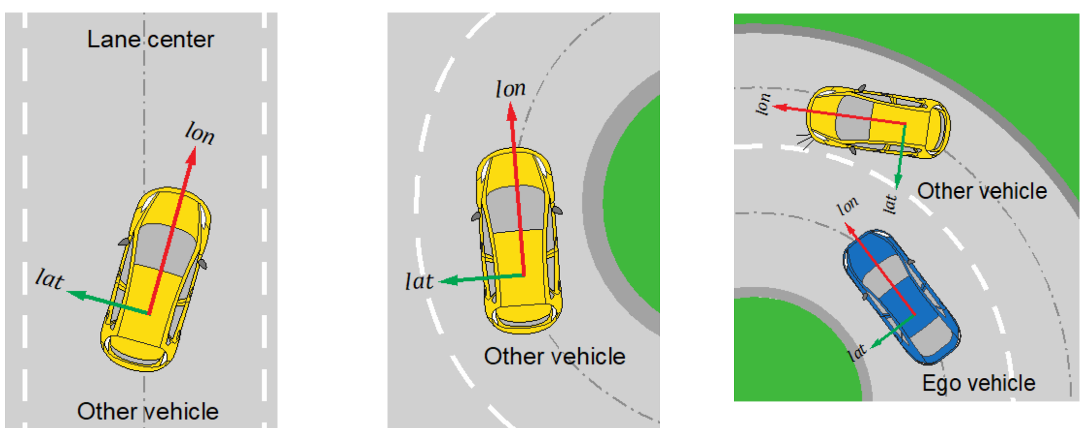


Figure 3—Example diagrams of lane-based and agent-based reference systems



(a) Other vehicle with $|v^{lat}(t)| > 0$

(b) Other vehicle with $v^{lat}(t) = 0$

(c) Ego vehicle with $v^{lat}(t) = 0$, other vehicle with $v^{lat}(t) > 0$

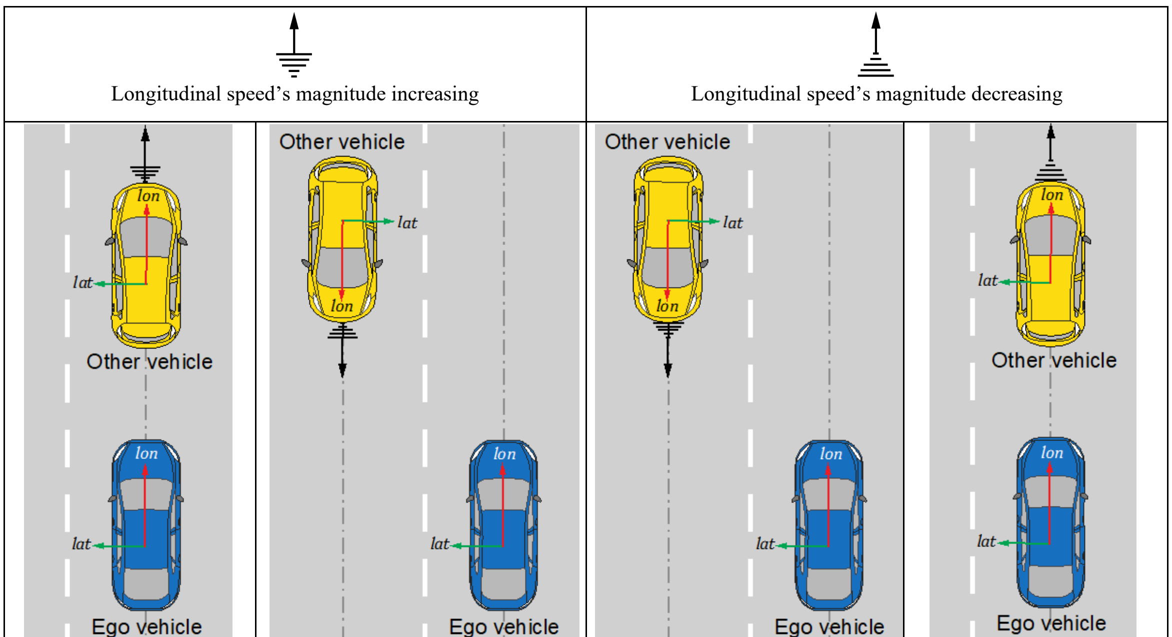
Figure 4—Examples of lateral vehicle control in straight and curved roads and its effect on the transformed lateral velocity component

For the vectorial kinematics assumptions, the signs and naming conventions are specified at a longitudinal and lateral component level. Therefore, to simplify the presentation of the assumptions related to the reasonably foreseeable kinematics of the road users, this standard adopted the following sign and naming conventions, unless otherwise specified.

Specifically:

— A road user that is increasing the absolute value of his/her longitudinal speed is considered to have a longitudinal acceleration (i.e., α^{lon}) in its own reference frame. See Figure 5(a) and (b). If the road user is reducing the absolute value of his/her longitudinal speed, they are considered to have a longitudinal deceleration (i.e., β^{lon}) in its own reference frame. See Figure 5(c) and (d).

— A road user that is increasing the absolute value of his/her lateral speed is considered to have a lateral acceleration (i.e., α^{lat}) in their own reference frame. See Figure 6(a). In case the road user is decreasing the absolute value of his/her lateral speed, they are considered to have a lateral deceleration (i.e., β^{lat}) in their own reference frame. See Figure 6(b).



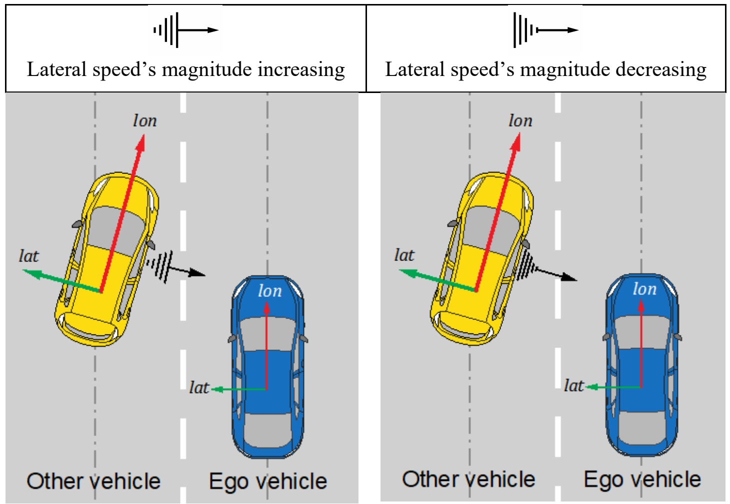
(a) Other vehicle driving in same direction accelerating with $\alpha^{lon}(t) > 0$

(b) Other vehicle driving in opposite direction accelerating with $\alpha^{lon}(t) > 0$

(c) Other vehicle driving in opposite direction decelerating with $\beta^{lon}(t) > 0$

(d) Other vehicle driving in same direction decelerating with $\beta^{lon}(t) > 0$

Figure 5—Examples of longitudinal movement of road users in the reference coordinate system



(a) Other vehicle with $\alpha^{lat}(t) > 0$

(b) Other vehicle with $\beta^{lat}(t) > 0$

Figure 6—Examples of lateral movement of road users in the reference coordinate system

4.2.3 Scenario definitions

This subclause contains the definitions of the scenarios considered by this standard. A scenario taxonomy is described next, outlining the following list of main elements that constitute a scenario:

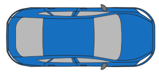
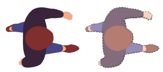
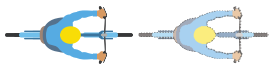
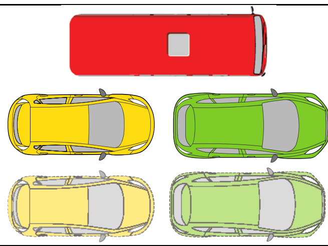
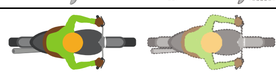
- Scenario description
  1) Dynamic elements
  2) Scenery
  3) Representation of road users
- Scenario schematic examples
- Minimum set of assumptions

First, each scenario comprises the description of a high-level driving situation in which the ego vehicle may have to interact with other safety-relevant objects. Within the scenario description, the dynamic elements section describes particular properties of the behavior of other road users considered in the scenario, such as pedestrians on the sidewalk. The different elements of the scenery relevant to the scenario, as well as the representation of road users, are outlined in the scenario description.

Second, visual schematics for each scenario are provided for illustration purposes only to graphically portray the driving situation in a high-level manner. Users of this standard are not restricted to the scenarios' schematic examples illustrated in this standard. The variables d^{lon} and d^{lat} present in the scenarios' schematic examples represent the relative distance between the ego vehicle and other safety-relevant objects decomposed in longitudinal and lateral components, respectively, following the ego vehicle's lane-based coordinate system (as defined in 4.2.2). The longitudinal and lateral distances are shown only for illustrative purpose. Road users are represented in the scenario schematic examples using the symbols as shown in Table 5.

Finally, the scenario's minimum set of assumptions about the behaviors of other road users that the safety-related model shall consider are defined for each road user category unless otherwise stated. The minimum set of assumptions is applicable to all scenario variations that fall under the same scenario description.

Table 5—Explanation of the different symbols used for road users in the scenario schematic examples

Image(s)	Description
	Ego vehicle
	Pedestrian, occluded pedestrian
	Cyclist, occluded cyclist
	Bus, other vehicle(s), occluded other vehicle(s)
	Other VRUs, occluded other VRUs
	Road user's path
	Ego vehicle's line of sight

4.2.3.1 V1-S1: Ego vehicle driving next to other road users

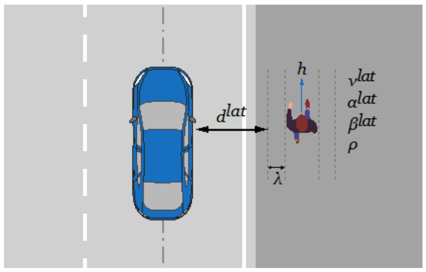
Scenario description
This scenario includes common driving situations, such as driving next to another vehicle on a multi-lane road or driving next to a pedestrian on a sidewalk. The ego vehicle is traveling along a road next to other road users. The other road user stays in its path, which does not intersect with the ego vehicle's path. The lateral separation between the other road user and the ego vehicle could be small. The ego vehicle and the other road user could be traveling in opposite directions. **Dynamic elements:** • **Pedestrians** on the sidewalk or on the road (e.g., due to lack of sidewalk), stopped or in motion, laterally to the left or right of the ego vehicle • **Cyclists** on the road, whether or not there is a bike lane or designated area for cyclists, stopped or in motion, laterally to the left or right of the ego vehicle • **Other VRUs** on the road, a sidewalk, or specific designated area such as a bike/electric scooter lane, stopped or in motion, laterally to the left or right of the ego vehicle • **Vehicles** on the road or adjacent open space (e.g., parking lot), whether or not there are clearly defined lane markings, stopped or in motion, laterally to the left or right of the ego vehicle **Scenery:** • No crosswalks • Posted speed limit

Scenario description

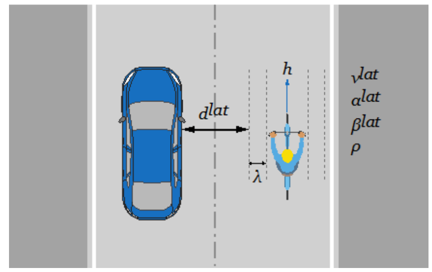
Representation of road users:

- No occlusions between ego vehicle and other road users

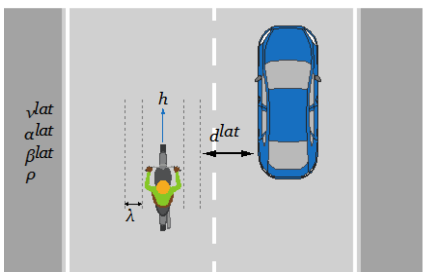
Scenario schematic examples



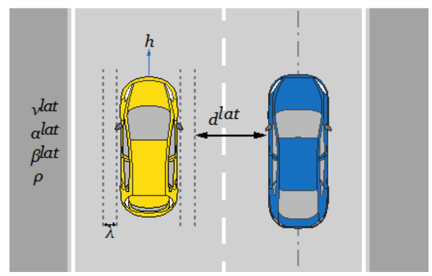
A pedestrian walking on a sidewalk laterally to the right of the ego vehicle



A cyclist riding laterally to the right of the ego vehicle



Other VRU driving laterally to the left of the ego vehicle



Other vehicle driving laterally to the left of the ego vehicle

Minimum set of assumptions

Pedestrians	Cyclists	Other VRUs	Vehicles
$v^{lat}(t) \leq v^{lat}_{max}$	$v^{lat}(t) \leq v^{lat}_{max}$	$v^{lat}(t) \leq v^{lat}_{max}$	$v^{lat}(t) \leq v^{lat}_{max}$
$\alpha^{lat}(t) \leq \alpha^{lat}_{max}$	$\alpha^{lat}(t) \leq \alpha^{lat}_{max}$	$\alpha^{lat}(t) \leq \alpha^{lat}_{max}$	$\alpha^{lat}(t) \leq \alpha^{lat}_{max}$
$\beta^{lat}(t) \geq \beta^{lat}_{min}$	$\beta^{lat}(t) \geq \beta^{lat}_{min}$	$\beta^{lat}(t) \geq \beta^{lat}_{min}$	$\beta^{lat}(t) \geq \beta^{lat}_{min}$
$\lvert h(t)\rvert \leq h_{max}$	$\lvert h(t)\rvert \leq h_{max}$	$\lvert h(t)\rvert \leq h_{max}$	$\lvert h(t)\rvert \leq h_{max}$
$\lvert \lambda(t)\rvert \leq \lambda_{max}$	$\lvert \lambda(t)\rvert \leq \lambda_{max}$	$\lvert \lambda(t)\rvert \leq \lambda_{max}$	$\lvert \lambda(t)\rvert \leq \lambda_{max}$
$\rho \leq \rho_{max}$	$\rho \leq \rho_{max}$	$\rho \leq \rho_{max}$	$\rho \leq \rho_{max}$

NOTE 1—Bounds on v^{lat}, α^{lat}, and β^{lat} are safety-relevant in this scenario for lateral motion in the direction toward the ego vehicle.

NOTE 2—The value for h_{max} is assumed to be very small (~ 0°) because of the conditions defined in the scenario description (i.e., road users' paths do not intersect).

4.2.3.2 V1-S2: Ego vehicle driving longitudinally behind another road user

Scenario description

The ego vehicle is traveling along a road longitudinally behind other road users moving in the same direction. There is no road user following behind the ego vehicle. A potential frontal collision is assessed as avoidable and no emergency maneuver is required.

Dynamic elements:

- **Pedestrians** on the road (e.g., due to lack of sidewalk), in motion longitudinally in front of the ego vehicle
- **Cyclists** on the road, whether or not there is a bike lane or designated area for cyclists, in motion longitudinally in front of the ego vehicle
- **Other VRUs** on the road or specific designated area such as a bike/electric scooter lane, in motion longitudinally in front of the ego vehicle
- **Vehicles** on the road, whether or not there are clearly defined lane markings, in motion longitudinally in front of the ego vehicle

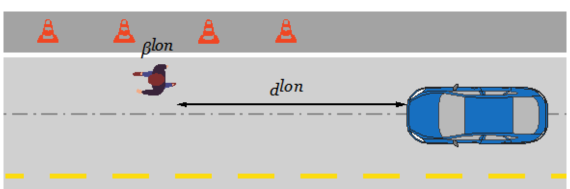
Scenery:

- Posted speed limit
- No crosswalks

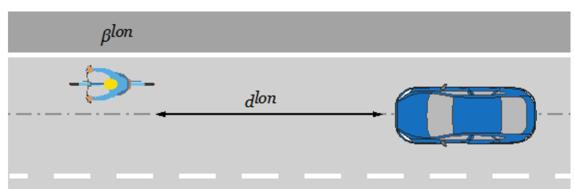
Representation of road users:

- No occlusions between ego vehicle and other road users

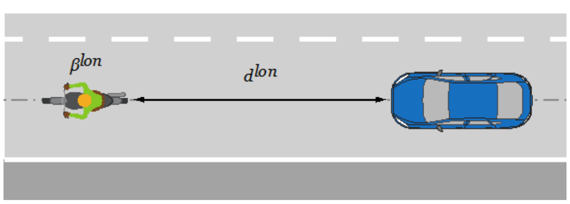
Scenario schematic examples



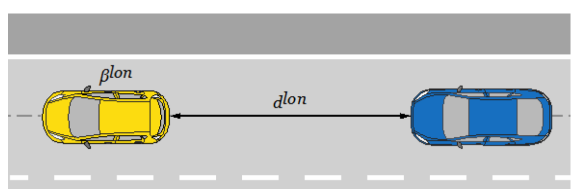
A pedestrian walking on the road longitudinally in front of the ego vehicle in a construction zone



A cyclist traveling longitudinally in front of the ego vehicle



Other VRU traveling longitudinally in front of the ego vehicle



Other vehicle traveling longitudinally in front of the ego vehicle

Minimum set of assumptions

Pedestrians	Cyclists	Other VRUs	Vehicles
$\beta^{lon}(t) \leq \beta^{lon}_{max}$	$\beta^{lon}(t) \leq \beta^{lon}_{max}$	$\beta^{lon}(t) \leq \beta^{lon}_{max}$	$\beta^{lon}(t) \leq \beta^{lon}_{max}$

4.2.3.3 V1-S3: Ego vehicle driving in between leading and trailing road users

Scenario description

The ego vehicle is traveling along a road longitudinally behind another road user (leading road user) and longitudinally in front of another road user (trailing road user). All road users are moving in the same direction. A potential frontal collision is assessed as avoidable, and no emergency maneuver is required.

Dynamic elements:

- **Pedestrians** on the sidewalk or on the road (e.g., due to lack of sidewalk), in motion longitudinally in front of the ego vehicle and/or behind
- **Cyclists** on the road, whether or not there is a bike lane or designated area for cyclists, in motion longitudinally in front of the ego vehicle and/or behind
- **Other VRUs** on the road or specific designated area such as a bike/electric scooter lane, in motion longitudinally in front of the ego vehicle and/or behind
- **Vehicles** on the road, whether or not there are clearly defined lane markings, in motion longitudinally in front of the ego vehicle and/or behind

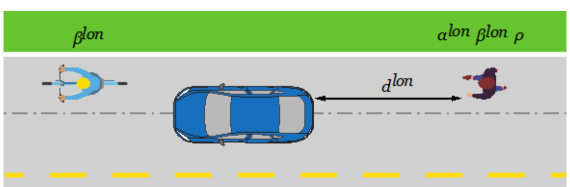
Scenery:

- Posted speed limit
- No crosswalks

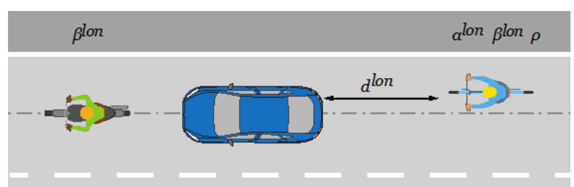
Representation of road users:

- No occlusions between ego vehicle and other road users

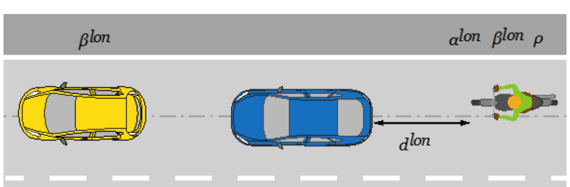
Scenario schematic examples



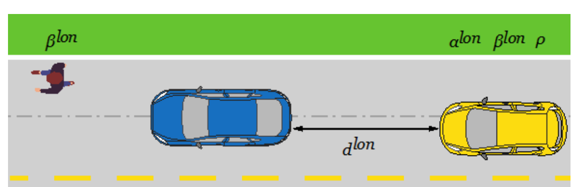
A cyclist traveling longitudinally in front of the ego vehicle and a pedestrian moving behind the ego vehicle



A VRU traveling longitudinally in front of the ego vehicle and a following cyclist behind the ego vehicle



Other vehicle traveling longitudinally in front of the ego vehicle and a following VRU behind the ego vehicle



A pedestrian walking on the road longitudinally in front of the ego vehicle in a residential zone and a following vehicle behind the ego vehicle

Minimum set of assumptions for following road user

Pedestrians	Cyclists	Other VRUs	Vehicles
$\alpha^{lon}(t) \leq \alpha^{lon}_{max}$	$\alpha^{lon}(t) \leq \alpha^{lon}_{max}$	$\alpha^{lon}(t) \leq \alpha^{lon}_{max}$	$\alpha^{lon}(t) \leq \alpha^{lon}_{max}$
$\beta^{lon}(t) \geq \beta^{lon}_{min}$	$\beta^{lon}(t) \geq \beta^{lon}_{min}$	$\beta^{lon}(t) \geq \beta^{lon}_{min}$	$\beta^{lon}(t) \geq \beta^{lon}_{min}$
$\rho \leq \rho_{max}$	$\rho \leq \rho_{max}$	$\rho \leq \rho_{max}$	$\rho \leq \rho_{max}$
Additional assumptions on β^{lon} for preceding road user are defined in V1-S2.			

4.2.3.4 V1-S4: Ego vehicle's path intersecting with VRU crossing the road

Scenario description

The ego vehicle is traveling along a road in which other vulnerable road users, such as pedestrians, are already on the road in or near the crosswalk zone or entering a crosswalk to cross the road. If traffic signals are present in the scene, it could be that the vulnerable road user is crossing against the controlling signal (e.g., a pedestrian crossing against the pedestrian crossing signal).

Dynamic elements:

- **Pedestrians** stopped or in motion about to cross the road, in or near the crosswalk zone, whether or not there is a clearly marked/designated crosswalk
- **Cyclists** stopped or in motion about to cross the road, in or near the crosswalk zone, whether or not there is a clearly marked/designated crosswalk
- **Other VRUs** stopped or in motion about to cross the road, in or near the crosswalk zone, whether or not there is a clearly marked/designated crosswalk
- **Vehicles** do not apply in this scenario

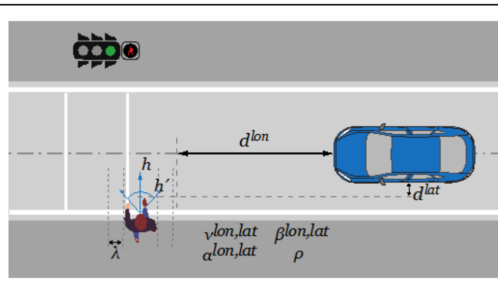
Scenery:

- Posted speed limit
- Traffic signals for pedestrian crossing may or may not be present

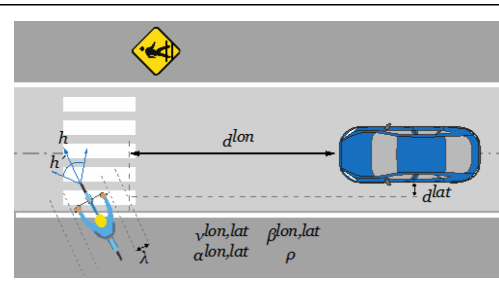
Representation of road users:

- No occlusions between ego vehicle and other road users

Scenario schematic examples



Pedestrian crossing the road near a marked/designated crosswalk against a red light



Cyclist crossing the road near a marked/designated crosswalk

Minimum set of assumptions			
Pedestrians	**Cyclists**	**Other VRUs**	**Vehicles**
$v^{lon}(t) \leq v_{max}^{lon}$	$v^{lon}(t) \leq v_{max}^{lon}$	$v^{lon}(t) \leq v_{max}^{lon}$	*N/A*
$v^{lat}(t) \leq v_{max}^{lat}$	$v^{lat}(t) \leq v_{max}^{lat}$	$v^{lat}(t) \leq v_{max}^{lat}$	*N/A*
$\alpha^{lon}(t) \leq \alpha_{max}^{lon}$	$\alpha^{lon}(t) \leq \alpha_{max}^{lon}$	$\alpha^{lon}(t) \leq \alpha_{max}^{lon}$	*N/A*
$\alpha^{lat}(t) \leq \alpha_{max}^{lat}$	$\alpha^{lat}(t) \leq \alpha_{max}^{lat}$	$\alpha^{lat}(t) \leq \alpha_{max}^{lat}$	*N/A*
$\beta^{lat}(t) \geq \beta_{min}^{lat}$	$\beta^{lat}(t) \geq \beta_{min}^{lat}$	$\beta^{lat}(t) \geq \beta_{min}^{lat}$	*N/A*
$\beta^{lon}(t) \leq \beta_{max}^{lon}$	$\beta^{lon}(t) \leq \beta_{max}^{lon}$	$\beta^{lon}(t) \leq \beta_{max}^{lon}$	*N/A*
$\beta^{lon}(t) \geq \beta_{min}^{lon}$	$\beta^{lon}(t) \geq \beta_{min}^{lon}$	$\beta^{lon}(t) \geq \beta_{min}^{lon}$	*N/A*
$\|h'(t)\| \leq h'_{max}$	$\|h'(t)\| \leq h'_{max}$	$\|h'(t)\| \leq h'_{max}$	*N/A*
$\|\lambda(t)\| \leq \lambda_{max}$	$\|\lambda(t)\| \leq \lambda_{max}$	$\|\lambda(t)\| \leq \lambda_{max}$	*N/A*
$\rho \leq \rho_{max}$	$\rho \leq \rho_{max}$	$\rho \leq \rho_{max}$	*N/A*

NOTE 1—Bounds on v^{lon}, v^{lat} are safety-relevant in this scenario for longitudinal and lateral motion in the direction toward the ego vehicle.

NOTE 2—A minimum bound on β^{lon} is safety-relevant in this scenario when the other road user is moving in the opposite direction as the ego vehicle (see scenario V1-S5 for reference). A maximum bound on β^{lon} is safety-relevant in this scenario when the other road user is moving in the same direction as the ego vehicle (see scenario V1-S2 for reference).

4.2.3.5 V1-S5: Ego vehicle's path intersecting with other road user's path moving in opposite direction

Scenario description

The ego vehicle is traveling along a road with other road users moving in the opposite direction at a non-junction. The ego vehicle's path may temporarily intersect with the other road user's path (e.g., while performing a legal passing maneuver). A potential front collision is assessed as avoidable; therefore, no emergency maneuver is required.

Dynamic elements:

- **Pedestrians** in motion longitudinally in front of the ego vehicle on the sidewalk or on the road (e.g., due to lack of sidewalk)
- **Cyclists** in motion longitudinally in front of the ego vehicle on the road whether or not there is a bike lane or designated area for cyclists
- **Other VRUs** in motion longitudinally in front of the ego vehicle on the road or on specific designated area such as a bike/electric scooter lane
- **Vehicles** in motion longitudinally in front of the ego vehicle on the road, whether or not there are clearly defined lane markings

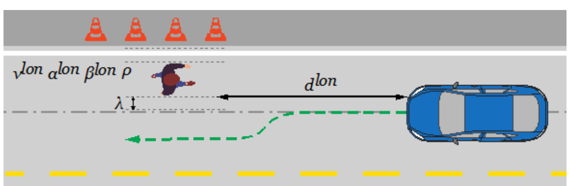
Scenery:

- Posted speed limit
- No crosswalks

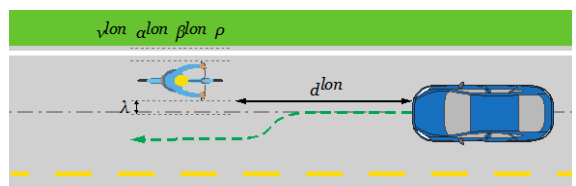
Representation of road users:

- No occlusions between ego vehicle and other road users

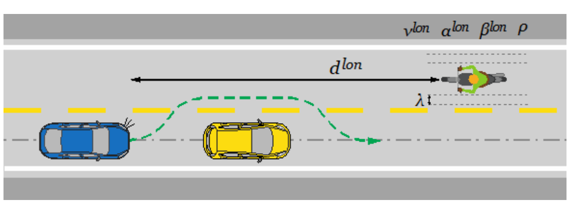
Scenario schematic examples



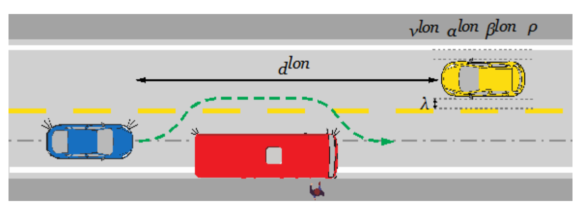
A pedestrian walking on the road longitudinally in front of the ego vehicle traveling in the opposite direction



A cyclist moving longitudinally in front of the ego vehicle traveling in the opposite direction in residential area



A motorcycle traveling longitudinally in front of the ego vehicle, in the opposite direction, while ego vehicle performs legal overtaking maneuver

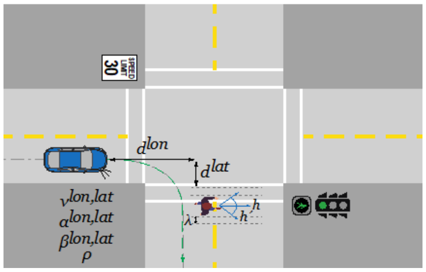
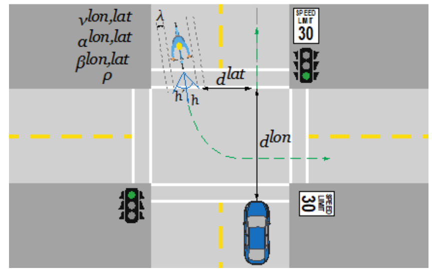
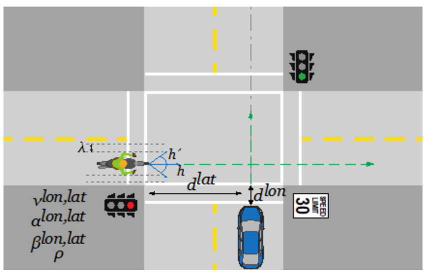
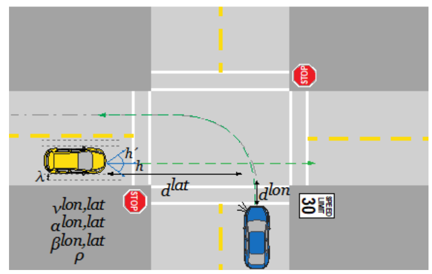


A vehicle traveling longitudinally in front of the ego vehicle, in the opposite direction, while ego vehicle performs legal overtaking maneuver

Minimum set of assumptions			
Pedestrians	**Cyclists**	**Other VRUs**	**Vehicles**
$v^{lon}(t) \leq v^{lon}_{max}$	$v^{lon}(t) \leq v^{lon}_{max}$	$v^{lon}(t) \leq v^{lon}_{max}$	$v^{lon}(t) \leq v^{lon}_{max}$
$\alpha^{lon}(t) \leq \alpha^{lon}_{max}$	$\alpha^{lon}(t) \leq \alpha^{lon}_{max}$	$\alpha^{lon}(t) \leq \alpha^{lon}_{max}$	$\alpha^{lon}(t) \leq \alpha^{lon}_{max}$
$\beta^{lon}(t) \geq \beta^{lon}_{min}$	$\beta^{lon}(t) \geq \beta^{lon}_{min}$	$\beta^{lon}(t) \geq \beta^{lon}_{min}$	$\beta^{lon}(t) \geq \beta^{lon}_{min}$
$\lvert\lambda(t)\rvert \leq \lambda_{max}$	$\lvert\lambda(t)\rvert \leq \lambda_{max}$	$\lvert\lambda(t)\rvert \leq \lambda_{max}$	$\lvert\lambda(t)\rvert \leq \lambda_{max}$
$\rho \leq \rho_{max}$	$\rho \leq \rho_{max}$	$\rho \leq \rho_{max}$	$\rho \leq \rho_{max}$
Additional assumptions on v^{lat}, α^{lat}, β^{lat}, and h, for driving next to other road user whose path does not intersect with ego vehicle's path are defined in V1-S1			
NOTE—Bound on v^{lon} is safety-relevant in this scenario for longitudinal motion in the direction toward the ego vehicle.			

4.2.3.6 V1-S6: Ego vehicle negotiating an intersection with nonoccluded road users

Scenario description
The ego vehicle is approaching an intersection. The right of way of the ego vehicle and other road users is directed by the traffic laws of the particular scene (e.g., stop signs). Other road users may violate or give up the right of way (e.g., another vehicle going against the controlling signal). **Dynamic elements:** • **Pedestrians'** interactions with section of the crosswalk are specified in scenario V1-S4 • **Cyclists** stopped or in motion on the road, about to go through the intersection, whether or not there is a bike lane or designated area for cyclists • **Other VRUs** stopped or in motion on the road, about to go through the intersection, whether or not there is a bike lane or designated area for cyclists, e-scooters, etc. • **Vehicles** stopped or in motion on the road, about to go through the intersection **Scenery:** • Posted speed limit • Traffic signals, stop signs, etc. may or may not be present at the intersection **Representation of road users:** • No occlusions between ego vehicle and other road users

Scenario schematic examples	
 Ego vehicle turning right at intersection. Pedestrian crossing at intersection with priority.	 Ego vehicle driving straight at intersection with priority. Cyclist turning left at intersection.
 Ego vehicle driving straight at intersection with priority. Other motorcycle at intersection going against the controlling signal.	 Ego vehicle turning left at intersection with priority. Other vehicle at intersection driving straight.

Minimum set of assumptions

Pedestrians	Cyclists	Other VRUs	Vehicles
$v^{lon}(t) \le v^{lon}_{max}$	$v^{lon}(t) \le v^{lon}_{max}$	$v^{lon}(t) \le v^{lon}_{max}$	$v^{lon}(t) \le v^{lon}_{max}$
$v^{lat}(t) \le v^{lat}_{max}$	$v^{lat}(t) \le v^{lat}_{max}$	$v^{lat}(t) \le v^{lat}_{max}$	$v^{lat}(t) \le v^{lat}_{max}$
$\alpha^{lon}(t) \le \alpha^{lon}_{max}$	$\alpha^{lon}(t) \le \alpha^{lon}_{max}$	$\alpha^{lon}(t) \le \alpha^{lon}_{max}$	$\alpha^{lon}(t) \le \alpha^{lon}_{max}$
$\alpha^{lat}(t) \le \alpha^{lat}_{max}$	$\alpha^{lat}(t) \le \alpha^{lat}_{max}$	$\alpha^{lat}(t) \le \alpha^{lat}_{max}$	$\alpha^{lat}(t) \le \alpha^{lat}_{max}$
$\beta^{lat}(t) \ge \beta^{lat}_{min}$	$\beta^{lat}(t) \ge \beta^{lat}_{min}$	$\beta^{lat}(t) \ge \beta^{lat}_{min}$	$\beta^{lat}(t) \ge \beta^{lat}_{min}$
$\beta^{lon}(t) \le \beta^{lon}_{max}$	$\beta^{lon}(t) \le \beta^{lon}_{max}$	$\beta^{lon}(t) \le \beta^{lon}_{max}$	$\beta^{lon}(t) \le \beta^{lon}_{max}$
$\beta^{lon}(t) \ge \beta^{lon}_{min}$	$\beta^{lon}(t) \ge \beta^{lon}_{min}$	$\beta^{lon}(t) \ge \beta^{lon}_{min}$	$\beta^{lon}(t) \ge \beta^{lon}_{min}$
$\lvert h(t)\rvert \le h_{max}$	$\lvert h(t)\rvert \le h_{max}$	$\lvert h(t)\rvert \le h_{max}$	$\lvert h(t)\rvert \le h_{max}$
$\lvert h'(t)\rvert \le h'_{max}$	$\lvert h'(t)\rvert \le h'_{max}$	$\lvert h'(t)\rvert \le h'_{max}$	$\lvert h'(t)\rvert \le h'_{max}$
$\lvert \lambda(t)\rvert \le \lambda_{max}$	$\lvert \lambda(t)\rvert \le \lambda_{max}$	$\lvert \lambda(t)\rvert \le \lambda_{max}$	$\lvert \lambda(t)\rvert \le \lambda_{max}$
$\rho \le \rho_{max}$	$\rho \le \rho_{max}$	$\rho \le \rho_{max}$	$\rho \le \rho_{max}$

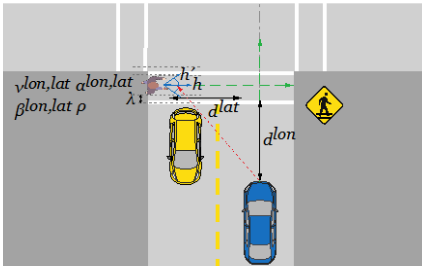
NOTE 1—Bounds on $v^{lon,lat}$, $\alpha^{lon,lat}$, and $\beta^{lon,lat}$ are safety-relevant in this scenario for longitudinal and lateral motion in the direction towards the ego vehicle.

NOTE 2— A minimum bound on β^{lon} is safety-relevant in this scenario when the other road user is moving in the opposite direction as the ego vehicle (see scenario V1-S5 for reference). A maximum bound on β^{lon} is safety-relevant in this scenario when the other road user is moving in the same direction as the ego vehicle (see scenario V1-S2 for reference).

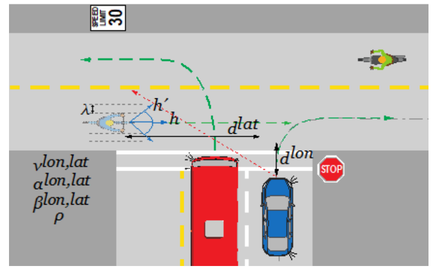
4.2.3.7 V1-S7: Ego vehicle negotiating an intersection with occluded road users

Scenario description
The ego vehicle is approaching an intersection. The right of way of the ego vehicle and other road users is defined by the traffic laws of the particular scene (e.g., stop signs). Visibility of other safety-relevant objects is temporarily blocked due to static objects (e.g., a tree, a building, a sharp curve, or a hill) or dynamic objects (e.g., a bus, a vehicle) in the scene. **Dynamic elements:** In the case of limited visibility, other safety-relevant objects could appear from the occluded area based on the following (but not limited to) context: • **Pedestrians** in motion at a crosswalk, about to go through the intersection, whether or not there is a clearly delimited area for pedestrian crossing, such as crosswalk markings • **Cyclists** in motion on the road or at a crosswalk, about to go through the intersection, whether or not there is a bike lane or designated area for cyclists • **Other VRUs** in motion on the road or at a crosswalk, about to go through the intersection, whether or not there is a bike lane or designated area for VRUs • **Vehicles** in motion on the road, about to go through the intersection **Scenery:** • Posted speed limit • Traffic signals, stop signs, etc. may or may not be present at the intersection • Static or dynamic objects occluding safety-relevant objects **Representation of road users:** • Occluded safety-relevant objects

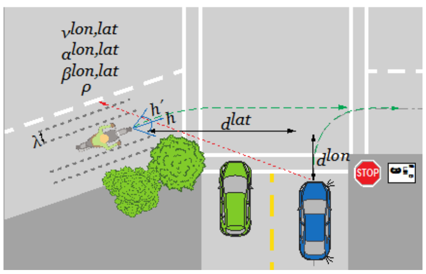
Scenario schematic examples



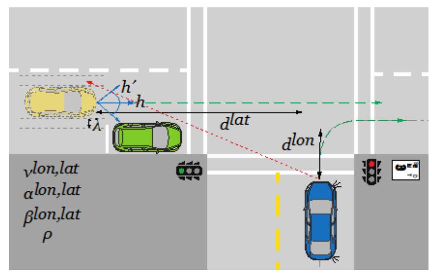
Ego vehicle continuing straight at intersection and another road user is blocking visibility of potential incoming pedestrians at crosswalk area



Ego vehicle turning right at intersection and another road user is blocking visibility of potential incoming traffic



Ego vehicle turning right at intersection with limited visibility due to static and dynamic objects



Ego vehicle turning right at intersection with limited visibility due to a parked vehicle

Minimum set of assumptions

Pedestrians	Cyclists	Other VRUs	Vehicles
$v^{lon}(t) \leq v^{lon}_{max}$	$v^{lon}(t) \leq v^{lon}_{max}$	$v^{lon}(t) \leq v^{lon}_{max}$	$v^{lon}(t) \leq v^{lon}_{max}$
$v^{lat}(t) \leq v^{lat}_{max}$	$v^{lat}(t) \leq v^{lat}_{max}$	$v^{lat}(t) \leq v^{lat}_{max}$	$v^{lat}(t) \leq v^{lat}_{max}$
$\alpha^{lon}(t) \leq \alpha^{lon}_{max}$	$\alpha^{lon}(t) \leq \alpha^{lon}_{max}$	$\alpha^{lon}(t) \leq \alpha^{lon}_{max}$	$\alpha^{lon}(t) \leq \alpha^{lon}_{max}$
$\alpha^{lat}(t) \leq \alpha^{lat}_{max}$	$\alpha^{lat}(t) \leq \alpha^{lat}_{max}$	$\alpha^{lat}(t) \leq \alpha^{lat}_{max}$	$\alpha^{lat}(t) \leq \alpha^{lat}_{max}$
$\beta^{lat}(t) \geq \beta^{lat}_{min}$	$\beta^{lat}(t) \geq \beta^{lat}_{min}$	$\beta^{lat}(t) \geq \beta^{lat}_{min}$	$\beta^{lat}(t) \geq \beta^{lat}_{min}$
$\beta^{lon}(t) \leq \beta^{lon}_{max}$	$\beta^{lon}(t) \leq \beta^{lon}_{max}$	$\beta^{lon}(t) \leq \beta^{lon}_{max}$	$\beta^{lon}(t) \leq \beta^{lon}_{max}$
$\beta^{lon}(t) \geq \beta^{lon}_{min}$	$\beta^{lon}(t) \geq \beta^{lon}_{min}$	$\beta^{lon}(t) \geq \beta^{lon}_{min}$	$\beta^{lon}(t) \geq \beta^{lon}_{min}$
$\lvert h(t)\rvert \leq h_{max}$	$\lvert h(t)\rvert \leq h_{max}$	$\lvert h(t)\rvert \leq h_{max}$	$\lvert h(t)\rvert \leq h_{max}$
$\lvert h'(t)\rvert \leq h'_{max}$	$\lvert h'(t)\rvert \leq h'_{max}$	$\lvert h'(t)\rvert \leq h'_{max}$	$\lvert h'(t)\rvert \leq h'_{max}$
$\lvert\lambda(t)\rvert \leq \lambda_{max}$	$\lvert\lambda(t)\rvert \leq \lambda_{max}$	$\lvert\lambda(t)\rvert \leq \lambda_{max}$	$\lvert\lambda(t)\rvert \leq \lambda_{max}$
$\rho \leq \rho_{max}$	$\rho \leq \rho_{max}$	$\rho \leq \rho_{max}$	$\rho \leq \rho_{max}$

NOTE 1—Bounds on v^{lon}, v^{lat}, $\alpha^{lon}, \alpha^{lat}$, $\beta^{lon}, and\ \beta^{lat}$ are safety-relevant in this scenario for longitudinal and lateral motion in the direction toward the ego vehicle.

NOTE 2—A minimum bound on β^{lon} is safety-relevant in this scenario when the other road user is moving in the opposite direction as the ego vehicle (see scenario V1-S5 for reference). A maximum bound on β^{lon} is safety-relevant in this scenario when the other road user is moving in the same direction as the ego vehicle (see scenario V1-S2 for reference).

5. Common attributes from contributed safety-related models

NOTE—The common attributes in this clause are provided as examples only and do not need to be used when showing compliance with this standard or to meet this standard's requirements.

A literature review of contributed safety-related models used in the DDT was performed in order to understand commonalities and differences. While additional research and publications may exist about this topic, for purposes of this analysis, the contributions included the following:

- A Novel Method to Evaluate the Safety of Highly Automated Vehicles (Every, et al. [B14])
- ISO/DIS 21448:2021, Road vehicles—Safety of the intended functionality, Annex D.1 Guidance for driving policy specification
- Model Predictive Instantaneous Safety Metric for Evaluation of Automated Driving Systems (Weng, Rao, Deosthale, Schnelle, & Barickman [B40])
- On a Formal Model of Safe and Scalable Self-driving Cars (Shalev-Schwartz, Shammah, & Shashua [B32])[4]
- Liability, Ethics, and Culture-Aware Behavior Specification using Rulebooks (Censi, et al. [B6])[4]
- An Introduction to the Safety Force Field (Nistér, Lee, Ng, & Wang [B24])[4]

Based on the review, a summary set of attributes for safety-related models used in the DDT has been compiled and documented. The demonstration that one or more of the following attributes applies to a particular safety-related model does not directly correspond to a measure of safety.

The attributes are divided into two categories: 1) attributes that can be demonstrated through inspection of the model and 2) attributes that can be demonstrated by verification and validation testing. The following subclauses list suitable attributes for safety-related models used in the DDT based on the aforementioned contributions and industry best practices.

5.1 Safety-related model attributes—verifiable or demonstratable via inspection

This subclause lists suitable attributes for safety-related models that can be verified or demonstrated by inspection of the model.

5.1.1 Incorporates the laws of physics

Safety-related models can incorporate the laws of physics and consider the impact that different attributes and assumptions about other road users can have on the possible motions of both the ADS-operated vehicle and other safety-relevant objects on a given roadway. It is also important to note that physics-based properties can be dynamic. For example, the coefficient of friction can change as road conditions change.

[4] At the time of this publication Responsibility Sensitive Safety (RSS), Rulebooks and Nvidia Safety Force Field (SFF) are examples of safety-related models. This information is given for the convenience of users of this standard and does not constitute an endorsement by the IEEE of these products. Equivalent products may be used if they can be shown to lead to the same results.

For example, a safety-related model that utilized the velocity of current safety-relevant objects, their assumed acceleration and deceleration capabilities, as well as the coefficient of friction of the roadway could be used to calculate a minimum following distance as an instantiation of this attribute.

5.1.2 Accommodates acceptable risk

Safety-related models can accommodate the concept of acceptable risk. If the ADS-operated vehicle were required to eliminate all risk, it would not be able to be used in an actual driving environment due to their uncertain nature. As this is not realistic, an acceptable level of risk is defined to facilitate real-world usage. Following this standard, the values for the kinematic assumptions can contribute to a level of acceptable risk.

Safety-related models can facilitate the setting and adjustment of varying risk levels that may be specified by government bodies or set by the ADS developer as the level of acceptable risk.

For example, a safety-related model that supports the ability to adjust the acceptable risk by utilizing different values for the parameters can represent a different desired balance between safety and usability.

5.1.3 Supports reasonably foreseeable scenarios

Safety-related models can provide coverage for reasonably foreseeable scenarios within the ODD. The ability to support reasonably foreseeable scenarios that the ADS-operated vehicle may encounter within the ODD, is an important quality to enable the scalability of ADS-operated vehicles within the ODD. Safety-related models that support general behavioral characteristics are more likely to support a wide variety of scenarios versus those that are hard-coded to a finite set of scenarios.

For example, if an ADS-operated vehicle with an ODD that includes dense urban environments uses a safety-related model that only supports interaction with other vehicles but not with vulnerable road users, this safety-related model would not instantiate this attribute.

5.1.4 Focuses on motion control

Safety-related models evaluated in this standard focus on behavior and motion control only. While the formulation of a safety-related model may still include uncertainty in the future behavior that other road users exhibit, the setting of reasonably foreseeable bounds allows the adoption of a deterministic approach for decision-making related to motion control.

For example, a safety-related model that evaluates proposed trajectories as part of a lateral and longitudinal motion control function is an instantiation of this attribute.

5.1.5 Incorporates assumptions

Safety-related models can incorporate assumptions about the behavior of other safety-relevant objects. Making assumptions about the reasonably foreseeable behavior of others is an important part of effective driving in the real world. The application of assumptions about reasonably foreseeable behaviors of other road users allows an ADS-operated vehicle to operate in everyday driving scenarios.

For example, a safety-related model that considers that a vehicle traveling in the adjacent lane is not expected to turn into the ego vehicle with a lateral velocity greater than the reasonably foreseeable assumption is an instantiation of this attribute.

5.1.6 Based on current position, heading and velocity of other safety-relevant objects

Safety-related models can be based on an understanding of the current position, heading, and velocity of other safety-relevant objects with assumptions about reasonably foreseeable behaviors of other road users. Measures of current position, heading, velocity, and assumptions about other safety-relevant objects can be made at periodic time intervals, taking into consideration the most current world model. Updated current position, heading, and velocity may impact reasonably foreseeable assumptions about other safety-relevant objects.

For example, a safety-related model that utilizes current position, heading, velocity, and assumptions about reasonably foreseeable behaviors of other road users to calculate a safety envelope around the ego vehicle would be an instantiation of this attribute.

5.1.7 Supports prioritization of safety objectives

The output of safety-related models may prioritize different safety objectives to maintain duty of care with respect to other road users.

For example, in an emergency situation the ADS-operated vehicle may perform a high-g maneuver to avoid a frontal collision, accepting the residual risk of a potential rear-end collision.

5.1.8 Is sensitive to adjustment in parameter values

The sensitivity of a safety-related model to different values/ranges of parameters can be tested and verified. In particular, safety-related models that allow the tracing of the effect of an adjustment in parameters values to their displayed behavior can provide valuable insights on how and why certain decisions were made toward validation of the model.

Note that some safety-related models used in the context of the DDT may include machine learning techniques that do not always lend themselves to supporting traceability. However, the overall system design and other functions within the DDT may combine to achieve this desirable attribute.

For example, a safety-related model in which a change in parameters results in an observable change in ADS-operated vehicle behavior is an instantiation of this attribute.

5.1.9 Supports diverse safety-relevant objects

Safety-related models can support multiple diverse safety-relevant objects. For example, a pedestrian and a passenger vehicle have different behaviors and hence assumptions being made upon them, so a suitable safety-related model is not only cognizant of the differences between diverse safety-relevant objects but also support a dynamic range of numbers and classes of objects. A safety-related model that may exclude multiple diverse safety-relevant objects and scenarios at the same time may not support common driving scenarios.

For example, a safety-related model that contains different assumptions about a variety of classes of safety-relevant objects (vehicles, pedestrian, bicyclist, etc.), and has the ability to simultaneously consider the different classes of safety-relevant objects in a given scenario, would be an instantiation of this attribute.

5.1.10 Supports emergency maneuvers

Safety-related models can support emergency maneuvers. Emergency maneuvers may be utilized when responding to a situation when a safety-relevant object is behaving outside of the boundaries of the assumptions about reasonably foreseeable behaviors of other road users as well as in situations within those boundaries where other types of responses to mitigate hazardous situations have failed.

For example, in a car following scenario, if the leading vehicle were to brake with greater force than was assumed to be reasonably foreseeable and the safety-related model were to perform an emergency maneuver to avoid the collision, that would be an instantiation of this attribute.

In another example, if a lead vehicle changes lanes revealing a previously occluded static object in the road, the safety-related model can determine that, based on the current trajectory, the ADS-operated vehicle does not have enough time to avoid colliding with the static object and then performs an emergency maneuver.

5.1.11 Defines a hazardous situation

Safety-related models can explicitly define what constitutes a hazardous situation. Typically, a hazardous situation is defined as an increased risk for potential violation of a safety envelope [attribute 5.1.16], which also represents a level of increased risk present in the DDT. A hazardous situation makes explicit when a proper response may be required in order to alleviate the hazardous situation.

5.1.12 Defines proper responses

Safety-related models can explicitly define what to do when a hazardous situation occurs. A hazardous situation might be the result of the actions of another safety-relevant object. A proper response is an action that is important to the avoidance and remediation of hazardous situations in reasonably foreseeable scenarios where other safety-relevant objects are operating within the bounds of the assumptions. If multiple ADS-operated vehicles implement the same safety-related model and simultaneously perform a proper response, the result can reduce the overall risk.

If, by performing a proper response, there is an insufficient reduction of risk, it may be necessary for the safety-related model to also trigger an emergency maneuver [attribute 5.1.10].

NOTE—It is also possible that the ADS-operated vehicle may initiate an emergency maneuver rather than performing a proper response first. For example, in a severe cut-in scenario the ADS-operated vehicle may be immediately exposed to an imminent collision and so perform an emergency maneuver.

5.1.13 Differentiates between initiator and responder

Safety-related models can differentiate between the initiator of a hazardous scenario and the responder to the hazardous scenario. Typically, the initiator causes a triggering event that requires action on behalf of the responder (e.g., the ego vehicle). Separation of initiator and responder is important for the ADS to clarify actions recommended for the initiator and the responder. This is useful not only for crash reconstruction but also to determine who should perform a proper response.

NOTE—There may be scenarios when the ADS-operated vehicle may be the initiator as well as the responder, and there may also be scenarios where both agents could contribute to the proper response.

For example, in a proper response definition, a safety-related model differentiates what actions the initiator and the responder should take, respectively, that would be an instantiation of this attribute.

5.1.14 Supports directional flexibility

If applicable, safety-related models can support the possibility that safety-relevant objects may move in a variety of directions and not always in a straight line. Some driving scenarios such as parking lots, residential areas, or special event modifications to traffic flow may result in the case where safety-relevant objects (including the ego vehicle) are operating in directions that may not necessarily conform to a lane. A similar situation occurs when in a shared middle lane where traffic from opposite directions may utilize the lane for the purpose of making unprotected left turns.

Note that omnidirectional movement may not be relevant in all scenarios. For example, an ADS-operated vehicle that operates on reserved roads on a fixed route would not, by definition, operate in a large unstructured parking lot. In this case, the safety-related model would not need to support omnidirectional travel.

5.1.15 Supports occlusion scenarios

Safety-related models can support scenarios relating to occlusion as an important safety-related situation for an ADS-operated vehicle to handle. Scenarios involving occluded safety-relevant objects provide unique challenges, such as when a pedestrian could be occluded behind a double-parked truck.

Safety-related models can utilize assumptions about possibly occluded safety-related objects to understand where and when occluded safety-related objects may appear and at what velocity in order to navigate safely in areas with occlusion.

For example, a safety-related model that accounts for the possibility of an occluded road user and provides constraints on speed or lane position would be an instantiation of this attribute.

5.1.16 Defines a safety envelope

Safety-related models can be consistent with the concept of a safety envelope for the AV, the violation of which can constitute a hazardous situation. Safety envelopes define a set of limits and conditions within which the ADS-operated vehicle should operate, typically combined with defined assumptions [attribute 5.1.5] about the reasonably foreseeable worst-case behavior of others, to provide a foundational building block of a safety-related model.

It is important to note that the boundaries of a safety envelope can be responsive to changes in context, changes in state and position of other safety-relevant objects, information available to the ADS, and other factors.

For example, a safety-related model that defines safe longitudinal and lateral distances that vary based on the velocities of the safety-relevant objects is an instantiation of this attribute.

5.1.17 Considers reasonably foreseeable events regarding right of way

Safety-related models can incorporate a guideline: “right of way is given, not taken.” While the ADS-operated vehicle may have right of way, it may not necessarily insist on taking it. There are a variety of everyday traffic scenarios where the ADS-operated vehicle has the right of way due to explicit traffic markings or traffic signals; however, it may not always be able to take the right of way due to potential risk of collision. For example, if the ADS-operated vehicle receives a green traffic signal, and a vehicle is blocking the intersection, it would not take the right of way as this could otherwise result in a collision with the blocking vehicle. The safety-related model can ensure that despite having the right of way, the ADS-operated vehicle would not proceed into the intersection at the risk of a collision.

Additionally, there are scenarios where two roads meet at a non-perpendicular angle and with no traffic control device present to explicitly define who has right of way. The general principle of “right of way is given, not taken” can then help encourage taking appropriate precautions when the determination of a clear right of way is difficult and open to interpretation.

5.1.18 Supports a theoretical outcome of no collisions upon universal adoption

Safety-related models can support a theoretical outcome of no collisions within the bounds of the assumptions about reasonably foreseeable behaviors of other road users. This outcome can be proven if, for example, all road users were to implement the same safety-related model and operate within the defined assumptions, no collisions within the ODD could be achieved (assuming other aspects of the vehicle and infrastructure operate without failure). For this case, the guarantee could typically be proven inductively.

5.1.19 Supports formal verification

Safety-related models can be formally verified. Formal verification techniques provide greater confidence that the safety-related model correctly reflects the specified requirements. The correctness of the design of safety-related models that can be proven mathematically are a subset of formally verifiable models. If published, mathematical proofs also provide transparency and an opportunity for the proof to be checked by others.

5.1.20 Supports creation of performance indicators

Safety-related models can support use of quantitative performance indicators. Supporting performance measurement can be very useful to the assessment process by providing a quantifiable judgment that can be easily understood in assessing the safety case.

For example, if a quantitative performance metric were to be developed by summing violations of the safety envelopes of safety-relevant objects by the ADS-operated vehicle, that would be an instantiation of this attribute.

5.1.21 Can be expressed in formal notation

Safety-related models can be unambiguous and expressed in formal notation. Safety-related models expressed in formal notation allow for formal verification techniques that provide a stronger argument for the correctness of the safety-related model. Formal safety-related models also produce repeatable results for verification methods.

5.1.22 Is transparent

Safety-related models can be considered transparent when their definition is documented. This enables independent review and inspection of the safety-related models. Without documentation, safety-related models may provide equivalent results; however, transparency would help facilitate greater trust and alignment between industry, government, and the end users/public. Transparency also provides opportunities for independent review and inspection on the proposed behaviors defined in the safety-related model to improve alignment with public expectations.

For example, a safety-related model that has been published as part of a voluntary safety self-assessment report is an instantiation of this attribute.

5.1.23 Considers weather-related environmental conditions and road surface conditions

Safety-related models can take into consideration different road surface conditions and weather-related environmental conditions to be reasonably expected within the ODD. For example, dry asphalt has a very different coefficient of friction than loose gravel and icy asphalt will have a different coefficient of friction than wet asphalt. For these cases, a safety-related model that considers different coefficients of friction for different road surface types or conditions would be an instantiation of this attribute.

5.2 Safety-related model attributes demonstratable via validation

This subclause lists suitable attributes for safety-related models that can be demonstrated by validation testing of the model. Typically, this is done by tests using some combination of simulation, structured or track, and/or on-road testing.

5.2.1 Validated through empirical evidence and industry best practices

Safety-related models used to support the ADS's decision-making may be validated by demonstrating, based on empirical examination and tests, that their intended goals are met with a sufficient level of integrity. Furthermore, the validation of safety-related models considers the applicability of technical standards and industry best practices to inform such testing, where technical standards, industry best practices, or expert opinions can be used to assess the correctness and completeness of the requirements for the system.

5.2.2 Enables the ADS-operated vehicle to navigate safely

While a safety-related model can support the concept of acceptable risk, it may be useful to assess the performance of the safety-related model through demonstration or validation. The result verifies that the safety-related model can enable the ADS-operated vehicle to maintain acceptable risk within the bounds of the assumptions about reasonably foreseeable behaviors of other road users.

For example, a demonstration that the safety-related model does not initiate a hazardous situation for given scenarios within the bounds of the assumptions about reasonably foreseeable behaviors of other road users is an instantiation of this attribute.

5.2.3 Exhibits a reasonable level of caution

Safety-related models can help an ADS-operated vehicle exhibit a reasonable level of caution that is appropriate for the ODD while maintaining usability. Safety-related models that are overcautious may exhibit behaviors that pose additional risks, especially when the ADS-operated vehicle is operating in a mixed environment with human and machine drivers. This enables the ADS-operated vehicle to drive safely, consistently, and naturally with a reasonable level of caution, and makes it more likely to fit better with human drivers. Furthermore, overly conservative behaviors may prevent the ADS-operated vehicle from completing a requested trip within the ODD.

The use of assumptions about reasonably foreseeable behaviors of other road users can be helpful to understand what constitutes a reasonable level of caution.

For example, safety-related models that exhibit a reasonable level of caution by reducing their speed when traversing through areas with occlusions when pedestrians could be present would be an instantiation of this attribute.

5.2.4 Considers human violations of traffic rules

Safety-related models can take into consideration that sometimes human road users may intentionally or unintentionally violate traffic rules in specific scenarios. While there does not exist a universal and complete list of possible human violations of traffic rules, the safety-related model can consider those that are reasonably foreseeable in the ODD.

For example, in some ODDs a double-parked vehicle can result in other road users temporarily crossing a double yellow line into the ADS-operated vehicle’s lane of travel. For this case, the safety-related model can consider scenarios where there may be an opposite and technically unlawful direction of travel due to a reasonably foreseeable human violation of a traffic rule.

5.2.5 Supports regional differences in behavior

Safety-related models can take into consideration local traffic customs. For example, in some regions there may be commonly accepted human traffic behaviors that could be important for a safety-related model to incorporate. For example, in certain regions of the northeast in the United States, a maneuver known as the “Pittsburgh Left” (Broz, F, Nourbakhsh, I, Simmons, R. Planning for Human-Robot Interaction in Socially Situated Tasks, 2013 [B4]) results in the first left turning vehicle taking precedence over traffic that has the right-of- way to go straight. A safety-related model that is aware of such a maneuver may further reduce the chance of a collision in that specific region.

5.2.6 Incorporates empirical, evidence-based methods

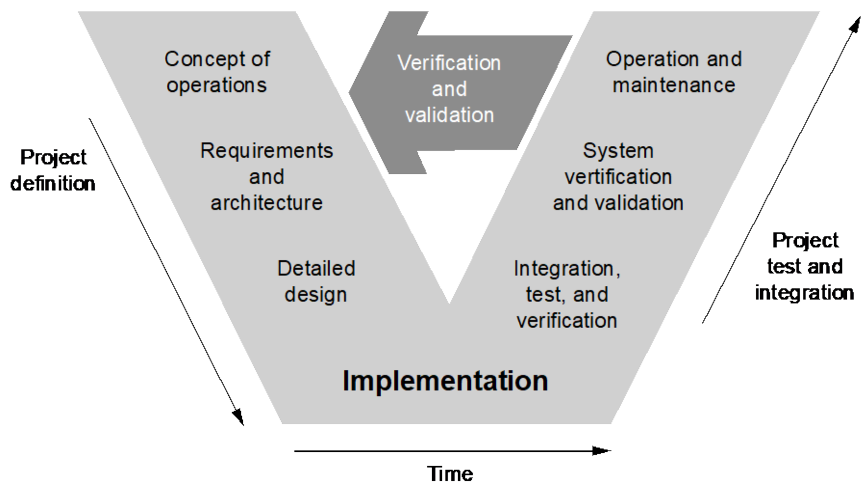
Safety-related models can support empirical evidence-based methods for the definition of reasonably foreseeable behaviors for other safety-relevant objects. Evidence-based methods derived from empirical driving analysis are more likely to produce natural driving behaviors and responses by the ADS.

6. Validation and Verification (V&V) methods for assumptions used in safety-related models

NOTE—The Validation and Verification methods in this clause are provided as examples only and do not need to be used when showing compliance with this standard or to meet this standard's requirements.

This clause describes methods that can be used to verify and validate the use of the minimum set of assumptions about reasonably foreseeable behaviors of other road users (defined in 4.2.3) in the safety-related model. This clause does not define an exhaustive set of methods for verification, nor does it define specific pass/fail criteria for a given scenario. The methodologies defined and described are intended to provide informative guidance on how certain methods can be used in different stages of ADS development.

When choosing a V&V method, it can be helpful to reference the well-established V-Model of product development, as shown in Figure 7. The V-Model is a structured process with stages in development along the lifetime of the product. Different V&V methods may be used in different stages of the V-Model, and the possible stages are listed for each of the included methods.



Source: Redesign of a public domain image from https://commons.wikimedia.org/wiki/File:Systems_Engineering_Process_II.svg

Figure 7—V-Model for product development

For all V&V methods included in this clause, the following elements are described:

- Description of the method
- How the method could be used to verify and/or validate the use of the assumptions
- Applicable standards/regulations/best practice documents related to the method
- A specific example of how the method could be applied to the scenario described in scenario V1-S2: Ego vehicle driving longitudinally behind another road user
- Within what stage(s) of the V-Model the method could be used

The following methodologies may also be included in an overall safety case argumentation. For example, following systematic process standards may lead to the definition of a safety-by-design architecture, which may then lead to the use of formal verification techniques with a formal model, which can be further analyzed using robustness techniques, which then can be tested within a simulator, on closed courses, and then on public roads.

6.1 Systematic process

Systematic process	
Method description (in general terms)	A product development process that follows best practices in how the product is defined, developed, verified and validated, deployed, and maintained.
How method can be applied for this standard	Use the minimum set of assumptions about reasonably foreseeable behaviors of other road users in systematic work products such as hazard analysis (e.g., Systems Theoretic Process Analysis (STPA), Fault Tree Analysis (FTA), Failure Mode and Effects Analysis (FMEA), etc.), safety requirements, scenario definitions, etc.
Regulations/standards/ best practices example(s)	ISO 26262, ISO 21448.
Example of use based on scenario of 4.2.3.2	The development of an ADS feature that controls longitudinal deceleration follows a systematic process as specified in ISO 26262 or ISO 21448, and documentation includes the use of assumption values for the maximum longitudinal deceleration (β_{max}^{lon}) to inform the safey envelope determination.
V-Model stages	Concept of Operations; Requirements and Architecture.

6.2 Safety-By-Design architectures

Safety-By-Design architectures	
Method description (in general terms)	A product design method that is compliant with accepted reference architectures.
How method can be applied for this standard	Demonstrate the use of the minimum set of required reasonably foreseeable assumptions in the design of the reference architecture.
Regulations/standards/ best practices example(s)	SAE J3131 ISO/TR 4804 [B17].
Example of use based on scenario of 4.2.3.2	The ADS architecture contains a trajectory planner as well as a trajectory monitoring system: The trajectory monitoring system evaluates the output of the trajectory planner in the ADS to confirm that the assumptions specified in the safety-related model are considered in the planned trajectory(-ies).
V-Model stages	Requirements and Architecture; Detailed Design.

6.3 Formal methods

Formal methods	
Method description (in general terms)	A product design method that uses mathematically rigorous techniques to model complex systems, particularly safety-critical systems, in a precise and unambiguous manner.
How method can be applied for this standard	A form of formal language (usually a type of temporal logic) is firstly used to specify the system properties/assumptions in mathematical notations. Together with the system model, the specifications are verified by corresponding algorithms. In the verification case, the algorithm returns confirmation that the specifications are satisfied or not.
Regulations/standards/ best practices example(s)	None.

Example of use based on scenario of 4.2.3.2	Signal Temporal Logic (STL) can be used to specify one property of Scenario V1-S2 as: $\square \beta_{max}^{lon} \leq 10$ where the assumed maximum longitudinal deceleration of the lead vehicle should ***always*** ($\square$) be less than or equal to the pre-defined threshold. (NOTE—The value 10 is a hypothetical value and is not a recommendation from this standard.) The above formula can be sent to an algorithm as input (together with the system model) for verification purposes (or runtime verification).
V-Model stages	Detailed Design; Integration, Test, and Verification.

6.4 Robustness analysis

Robustness analysis	
Method description (in general terms)	A product design technique that analyzes system sensitivity to variations in the inputs.
How method can be applied for this standard	The method could be used to investigate the robustness of the safety-related model to changes and variability within the assumptions' bounds. The analysis serves to verify consistency in, and sensitivity of, the behavior of the safety-related model to small changes in its assumptions.
Regulations/standards/ best practices example(s)	None
Example of use based on scenario of 4.2.3.2	Investigate the behaviors of the subject vehicle when the lead vehicle's assumed maximum longitudinal deceleration rate (β_{max}^{lon}) is subject to a specified variation range.
V-Model stages	Detailed Design; Integration, Test, and Verification.

6.5 Simulation testing

Simulation testing	
Method description (in general terms)	A product testing method that uses a simulation platform to support execution of a safety-related model, including the use of assumptions about reasonably foreseeable behaviors of other road users, in simulated scenarios in order to verify that the subject vehicle is operating appropriately to achieve an accepted level of safety performance.
How method can be applied for this standard	Simulating a set of scenarios with the applicable minimum set of assumptions about the reasonably foreseeable behavior of other road users. A coverage goal for different parameter value ranges could be set to verify that the safety-related model uses the assumptions correctly (see Annex A). This can be accomplished by comparing the actual outcome to an expected outcome (e.g., a collision vs. maintenance of a safety envelope around the ego vehicle).
Regulations/standards/ best practices example(s)	ASAM 2021 [B2] , ASAM 2021 [B3], ASAM 2020 [B1].
Example of use based on scenario of 4.2.3.2	Simulate variations of lead vehicle behavior, including behavior up to the assumed maximum longitudinal deceleration rate (β_{max}^{lon}). The testing objective is that the subject vehicle maintains the safety envelope. In this example, a reasonable set of parameters ranges (e.g., velocity, deceleration) should be determined, and coverage and other metrics could be measured.
V-Model stages	Detailed Design; Integration, Test, and Verification; System Verification and Validation.

6.6 Closed course testing

Closed course testing	
Method description (in general terms)	A product testing method that involves operation of the ADS-operated vehicle at a closed course test facility for the purpose of testing and validating its behavior (as well as the performance of the ADS sub-systems) in controlled scenarios by comparing the outcome to an expected outcome (e.g., a collision vs maintenance of a safety envelope around the ego vehicle).
How method can be applied for this standard	Testing of various scenarios within the ODD can be executed at a closed course test facility to continuously develop, refine, and validate assumptions about other road user behavior.
Regulations/standards/ best practices example(s)	NHTSA, 2018 [B22].
Example of use based on scenario of 4.2.3.2	Use a soft target vehicle as the lead vehicle, with the subject vehicle following under varying assumptions of the soft target deceleration rate up to the assumed maximum longitudinal deceleration rate (β_{max}^{lon}).
V-Model stages	System Verification and Validation; Operation and Maintenance.

6.7 Public road testing

Public road testing	
Method description (in general terms)	A product testing method that involves operation of the ADS-operated vehicle on public roads for the purpose of testing and validating its behavior (as well as the performance of the ADS sub-systems) in real-world (i.e., non-controlled) scenarios by comparing the outcome to an expected outcome (e.g., a collision vs maintenance of a safety envelope around the ego vehicle).
How method can be applied for this standard	Test runs of varying mileage can be executed within the ODD to continuously develop, refine, and validate assumptions about other road user behavior. A log of instances where surrounding vehicles did not behave within the assumptions could be kept.
Regulations/standards/ best practices example(s)	UNECE ECE/TRANS/WP.29/2020/81, 2020 [B38], SAE AVSC AVSC00001201911, 2019 [B31], SAE J3018, 2015 [B27].
Example of use based on scenario of 4.2.3.2	Use data collected on public roads to evaluate car-following behavior related to longitudinal separation and longitudinal acceleration and deceleration. Use collected data to refine and continuously verify the assumptions.
V-Model stages	System Verification and Validation; Operation and Maintenance.

Annex A

(informative)

Application area: Use of IEEE Std 2846 normative assumptions within scenario-based virtual testing

A.1 General

This annex considers the application of the minimum set of reasonably foreseeable assumptions proposed in Clause 4 within scenario-based testing. Specifically, this annex presents high-level considerations for the generation of relevant test-cases and introduces the notion of a bounded kinematic search space, established by the parameters of Table 1. The examples presented in this annex are not dependent on the specific implementation of a safety-related model.

A.2 Scenario-based testing (via simulation)

Scenario-based testing, as the name implies, is a methodology aimed at testing a system's capabilities in a number of different scenarios. This is done to verify that the system under investigation meets some pre-specified performance criteria of interest, and/or to validate that the safety-related model meets a level of acceptable risk. While scenario-based testing approaches can be adopted in both virtual environments and closed-track environments (where some refer to closed-track scenario-based testing using the term "structured tests"), this annex only covers simulated approaches.

Scenario-based testing (via simulation) has been employed by the automotive industry for a number of years. This is due to the necessity, recognized by many, to leverage virtual simulation environments in the assessment of the safety performance of an Automated Driving System (ADS), (Neurohr, et al. [B21], SAE IAMTS0001202104 [B30]). Simulation environments serve a key function in this process by providing a mechanism to efficiently address the likely infinite space of real-life scenarios that can prove safety-relevant for the ADS.

A.2.1 Toward the definition of a kinematic search space

At the heart of scenario-based testing is the definition of relevant test-cases. Relevant test-cases, in turn, can be derived in a number of ways, for example based on commonly observed situations encountered in a given operational design domain (ODD), or artificially constructed following given parameterizations of interest.

The examples provided in this annex focus on one parametrization of interest, as defined by the minimum set of assumptions from Clause 4, as explained next.

The high-level scenarios described in Clause 4 can be thought of as "seeds" that define an initial search-space (e.g., a car following scenario). For each seed, the desired number and type of road users are also to be specified. This level of abstraction is akin to that of functional scenarios within the Pegasus taxonomy (Menzel, Bagschik, & Maurer [B19], Neurohr, et al. [B21]). In order to generate actual test-cases from such high-level descriptions, it is necessary to:

1) Parametrize and formalize the search space of interest (i.e., define the variables of interest that fully describe the space that will be explored in the testing campaign—what Pegasus calls the abstract level [B25])
2) Define ranges of interest for the identified variables (what Pegasus calls the logical level [B25])
3) Select actual values of those parameters for the specific test-case (what Pegasus calls the concrete level [B25])

For the examples considered in this annex, the normative minimum set of assumptions from Clause 4 provides the desired parametrization for step 1). In so doing, Clause 4 thus informs the definition of a *kinematic search space*: a multi-dimensional testing space defined by the boundaries of other road users' reasonably foreseeable behaviors. Generated test-cases will then sample such kinematic search space and can thus be intended as an instantiation of the original seed scenario with a clearly defined and fixed set of parameters of interest. Following steps 1)–3), each seed scenario can generate multiple test-cases, since each seed can be instantiated across multiple combinations of parameters' values of interest for the relevant road users.

A.3 Role of assumptions for test-case generation

This subclause describes how the assumptions of Clause 4 can inform the generation of test-cases for scenario-based virtual testing. Figure A.1 depicts the example that will be leveraged in this annex, summarizing the minimum set of assumptions proposed in 4.2.3.1in the case of interaction with a cyclist.

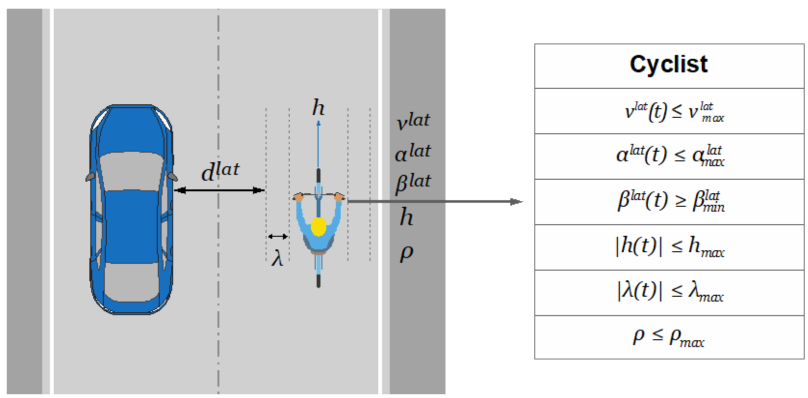


Figure A.1—Scenario V1-S1 and related assumptions for the cyclist case

For any desired key performance indicator (KPI) that defines the success criteria for the test-case (e.g., a "no collision" outcome, compliance with a pre-defined spatio-temporal margins of interest, agreement of the agent predicted path by the ego vehicle with the actual exhibited one, etc.), a user of this standard will need to verify that all the stated assumptions have been considered. It is not necessarily appropriate to consider all of the assumptions within a single test-case; furthermore, the assumptions considered within the test-case may be applicable at different points within the test. For example, in the case of Figure A.1, the cyclist cannot exhibit maximum lateral acceleration and minimum lateral deceleration simultaneously.

Furthermore, there are physical dependencies across the stated assumptions; in fact, the assumptions of Clause 4 were each derived independently, but are in reality coupled by physics. For example, the physical principle of conservation of angular momentum restricts the possible values that variables of lateral velocity, acceleration, and heading (and thus in-lane fluctuation) can take. In a similar way, in-lane fluctuation is constrained by the value of the longitudinal speed, which, in this case, would be an initial condition for the test to be iterated on.

The aforementioned examples are indicative of the existence of intra-assumptions dependencies, which are brought about when values for the specific parameters of interest are considered (i.e., at the test-case level).[5] Such dependencies lead to a constraint solving problem that affects the size and shape of the kinematic search

[5]Recommendations for deriving values for the kinematic parameters are outside the scope of this document. ADS developers can use existing literature and proprietary approaches for extracting relevant distributions and parametrizations (e.g., from naturalistic driving data and crash databases, and/or from logged data observed during on-road tests and operations, and/or from random sampling of reasonably foreseeable values Thal, et al. [B35], Junietz, et al. [B18], Webb, et al. [B39], Rodionova, et al. [B26]).

space that can be explored by a test-case, as notionally represented in Figure A.2 and Figure A.3 for the selected example.

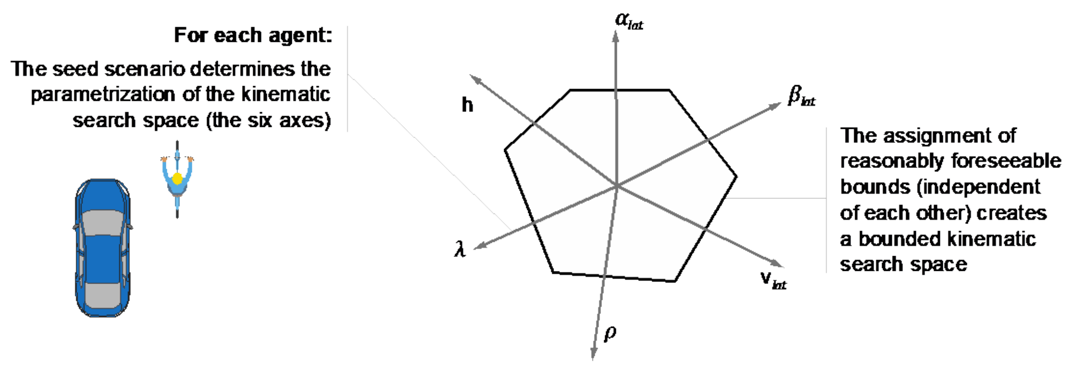


Figure A.2—Parametrization and bounds of the kinematic search space

The parametrization of the kinematic search space is dictated by the minimum set of assumptions (the axes of the spider plot of Figure A.2). Selected values then provide the bounds for the kinematic search space (the solid contour of Figure A.2). The axes of the spider plot can be calibrated to capture the range of interest (i.e., they can include both negative and positive values).

The bounds of the parameters shown in Figure A.2 are not static, but dynamically change in time according to a number of external factors (e.g., different bounds on reasonably foreseeable accelerations due to changing weather conditions during the test-case).[6]

Given the defined bounded space, users may test different combinations of assumptions through multiple test-cases, and need to verify that, at a minimum, all of the bounds listed in Clause 4 that apply to the case are exercised. The need for multiple test-cases happens, as mentioned before, because of intra-assumption dependencies. In fact, for each test-case, we talk about "valid" combinations of parameters exercised (for both assumptions and initial conditions for the test). This annex defines "valid" combinations of parameters as those that remain reasonably foreseeable and physically possible. Once values are associated with the parameters that make up the assumptions for the scenario depicted in Figure A.1, a user may need to filter out combinations that are not reasonably foreseeable and/or are physically impossible that can arise when more than one assumption is considered. Specifically:

— Physical dependencies across the assumptions limit how much space can be covered by one single test-case.

— Physical dependencies can also constrain and direct the scope of the search towards the inner regions of the kinematic search space (as opposed to sampling its boundary only). This happens because some of the actual values assigned to parameters of interest (e.g., α_{max}^{lat} and v_{max}^{lat}) may generate an invalid combination (for example, when maximum acceleration cannot be achieved during certain high-speed situations). In this case, consideration of one of the bounds as a starting point for the test-case generation leads to a new "conditional sub-bound" relevant for the test-case (e.g., a conditional maximum, lower than the original value) on some of the other variables. In Figure A.3, this is represented by having some of the dots (i.e., the sampled values) inside the space, rather than sitting on its boundary.

[6]The parametrization of the kinematic search space is constrained by which seed scenario applies, out of those proposed in Clause 4. Transitions from one scenario to another, where the other road user's behavior selected for the test-case implies a transition from one seed scenario to another, would impact the shape and size of the kinematic search space, following the new set of assumptions applicable to the road user.

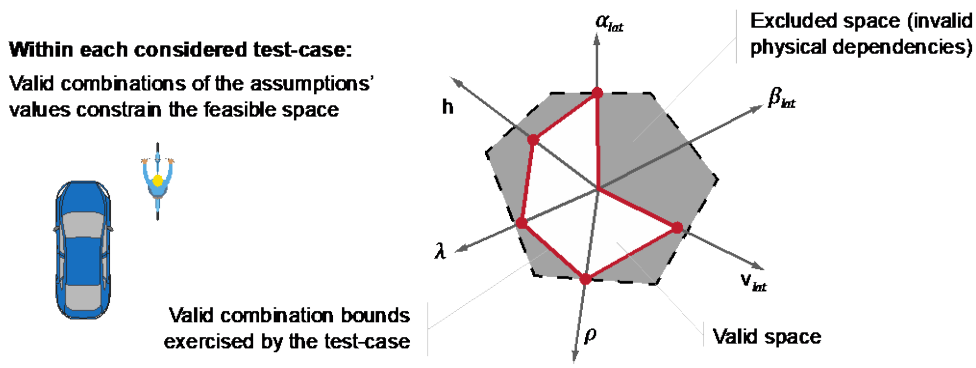


Figure A.3—A test-case exercises a portion of the search space, less than or equal to the original space

The ego vehicle behavior is then tested in concrete scenarios that execute valid combinations of the values considered for the bounds, and the initial conditions explored, which adhere to the intra-assumptions' constraints.

On a practical level, to test the scenario of Figure A.1 in a simulation environment, a user would need to set up initial conditions for the scenario, which, based on the description in 4.2.3.1, considers a cyclist traveling longitudinally and adjacent to the ego vehicle. The defined set of assumptions summarized in Figure A.1 provides bounds on the foreseeable change of behavior that the cyclist can execute at any point in time. If no change in behavior occurs, the cyclist will maintain their initial conditions. This concept, represented in Figure A.4, implies that two sets of information impact the decision-making process followed by the ego vehicle: 1) the initial conditions of the road agent (which, in on-road applications correspond to a measurement of the other road users condition); 2) bounds on the reasonably foreseeable behavior that the road user will exhibit. These two inputs help the ego vehicle plan its future actions by considering reasonably foreseeable changes in the behavior of the surrounding road users. For the example of Figure A.4, they would allow the ego vehicle to evaluate different options, such as deciding on whether to accelerate and overtake the cyclist or increase its lateral gap. To plan its next steps, the ego vehicle may leverage proprietary approaches that are not covered in this annex, and that may entail a computation of the risk associated with each of the options available to the ego vehicle.

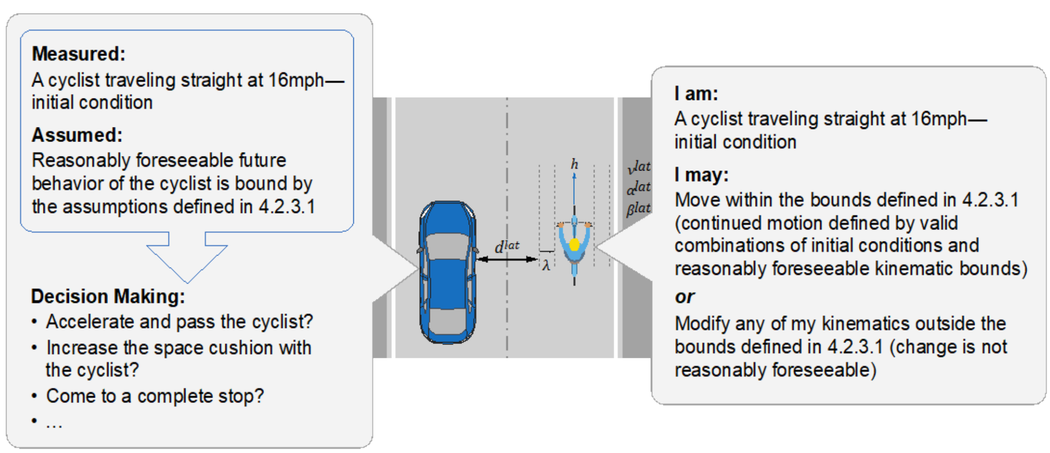


Figure A.4—Schematic representation of how the assumptions that bound the reasonably foreseeable behavior of the cyclist affect the set-up of test-cases of interest

The scenario-based testing campaign would thus analyze the behavior chosen by the ego vehicle considering the space of possible behaviors from the other road users. Such a space can be defined by the valid combinations of assumptions and initial conditions (for both the ego vehicle and the other road user), which need to be captured by the generated test-cases.

An example workflow is presented in Figure A.5, where a set of test-cases (1 through N) are generated from the seed scenario. Subsequently the output from the scenario-based testing process comprises both KPIs of interest and a check associated with the use of assumptions exercised through the various test-cases. The KPIs serve to determine the pass or fail criteria for the given test-case. Once a test-case has passed, analyzing which assumptions were considered within that test-case helps verify that all applicable assumptions for a given seed scenario were considered across the various test-cases generated. This is conveyed by the dashed arrow to the right of Figure A.5, connecting the "pass" rating to the assumption check.

While this annex does not deal with the selection of KPIs, it is important to understand that the adjudication of a "passing" score on a restricted set of scenarios only provides partial information about the performance of a safety-related model. In fact, such testing only considers behavior from the other road users within the agreed-upon reasonably foreseeable bounds. Furthermore, the consideration of the minimum set of assumptions is not an indication of the completeness of the set of test-cases considered in the testing campaign and/or to the overall safety of the system.

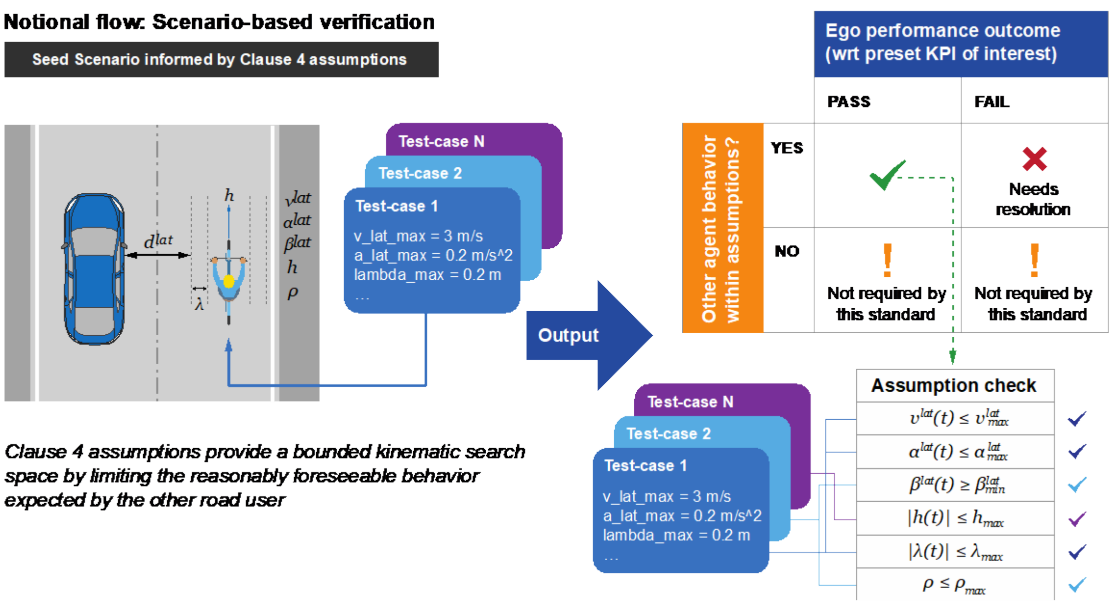


Figure A.5—Example workflow for a possible scenario-based testing approach, for a seed scenario of interest

This notional example was carried out for an interaction with a unique other road user and for a given seed scenario of interest. The process can be repeated considering valid combinations for all the agents involved in a scene, and for all the seed scenarios of interest.

A.4 Exploring the kinematic search space

Testing of the safety-related model through multiple test-cases leads to exercising and spanning the kinematic search space, as schematically presented in Figure A.6.

There exist multiple methodologies that can assist in ensuring a sufficient exploration of a given search space, each quantified in a different way. Some of those approaches can complement each other and are not exclusive in nature. This annex will provide two conceptual examples of such methodologies.

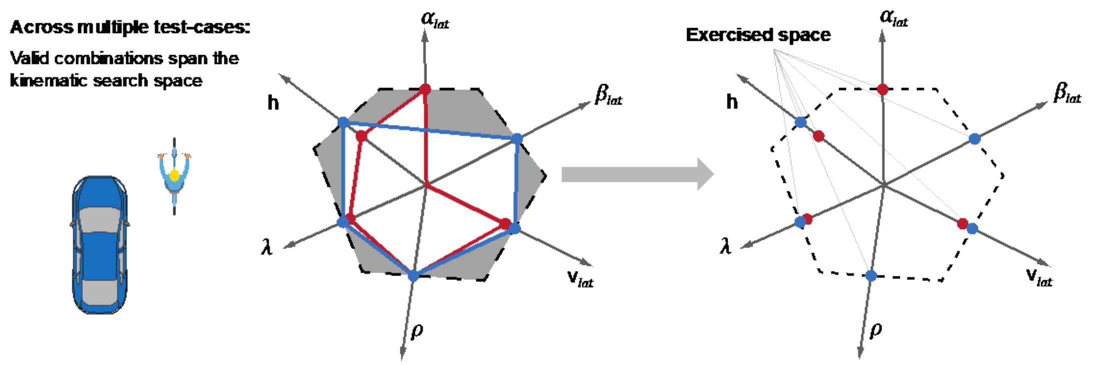


Figure A.6—Exploration of the kinematic search space through multiple test-cases

One example is guided testing methodologies, which typically aim at improving testing efficiency by reducing the overall number of tests while preserving statistical confidence in the evaluation of safety criteria or other KPIs (Collin, Bin-Nun, & Tebbens [B10]). One such methodology is an important sampling in De Gelder & Paardekooper [B12]. A possible metric employed in guided testing is “information gain,” which can be used to optimize a sampling strategy given some constraints and offers potential criteria for ultimately stopping the exploration within valid combinations of the assumptions (Hollander [B16]). Information gain, with respect to a specific KPI, such as the number of collisions or hard braking events, is defined as the reduction in uncertainty around that KPI. Observing the system in each new test-case reduces uncertainty around its general performance in scenarios related to the “seed” scenario. Search criteria for the kinematic space under this perspective could be set to reach a minimum level of information (threshold) on the KPI of interest for the specific seed scenario.

Another example is coverage driven testing, which typically partitions the kinematic search space according to parameters of interests and aims at maximizing testing across the partitions. Coverage driven testing (Claessen, Duregård, & Pałka [B8]) is a method that applies constrained random test generation, aimed at generating tests within the scenario space, with the goal of “covering” as much as possible of the partitioned search space. Coverage metrics can then provide an indication of what was tested out of the feasible testing space. In order to measure any such metric, a conversion from a continuous (and infinite) space to a discretized range would be needed (Claessen, Duregård, & Pałka [B8], Hollander [B16]). A simple way to achieve such a goal is to divide each range between minimum and maximum bounds into “buckets.” The granularity or resolution of the bucket can then serve as the denominator for a percentage measurement. When defining coverage goals, a user decides what are the coverage items (i.e., parameters), into which buckets (i.e., groups of values) to split each item, which items to cross (i.e., which parameters to combine together, and the associated values), and any relative weight to assign to each bucket. Coverage can then be measured in hits-per-bucket (e.g., defined by at least one test-case with a parameter value in a given bucket), as compared to the desired-hits-per-bucket. This metric is then aggregated bottom-up across all tests run to output a total coverage grade, normalized between the bounds of “no coverage of the feasible space” to “full coverage of the feasible space.” Defining coverage (and especially defining coverage buckets) involves engineering judgment, where one tries to maximize the coverage grade of the target testing space on which behavior of the safety-related model is verified. A possible application of this method would define coverage metrics based on the ranges of values adopted for each of the assumptions exercised in the testing campaign.

Annex B

(informative)

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