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Road vehicles — Test scenarios for automated driving systems — Scenario based safety evaluation framework

Véhicules routiers — Scénarios d'essai pour les systèmes de conduite automatisée — Cadre d'évaluation de la sécurité basé sur des scénarios

Reference number
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Foreword

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This document was prepared by Technical Committee ISO/TC 22, *Road Vehicles*, Subcommittee SC 33, *Vehicle dynamics and chassis components.*

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Introduction

In order to safely introduce automated driving systems (ADS) into the market, socially acceptable and technically sound scenario-based safety evaluation methodologies need to be developed. A number of national and international governmental institutions are gradually releasing technical safety guidelines[7][8][9] to support the development of these methodologies, as well as associated regulations and standards.

In order to evaluate whether ADSs are free from unreasonable risks, it is beneficial to develop safety evaluation methodologies. Considering emphasis on limited access highways, scenario-based safety evaluation methodologies are suitable for assessing safety in a repeatable, objective and evidence-based manner and that is compatible with existing standards.

Functional safety is defined as the absence of unreasonable risks that arise from malfunctions of an electric/electronic (E/E) system. The ISO 26262 series specifies a hazard analysis and risk assessment to determine vehicle level hazards. This evaluates the potential risks due to malfunctioning behaviour of the system and enables the definition of top-level safety requirements, i.e. the safety goals, necessary to mitigate the risks.

For some E/E systems, which rely on sensing the external or internal environment to build situational awareness, there can be potentially hazardous behaviour caused by or within the intended functionality. Examples of the causes of such potentially hazardous behaviour include the inability of the function to correctly comprehend the situation and operate safely or insufficient robustness of the function, system, or algorithm. The absence of unreasonable risk resulting from hazardous behaviours related to functional insufficiencies is defined as the safety of the intended functionality (SOTIF).

Functional safety (the ISO 26262 series) and SOTIF (ISO 21448) are distinct, necessary, and complementary aspects of safety. This document is conformant with SOTIF and adds specificity to its content, by incorporating a scenario-based safety evaluation process that identifies risk factors and related critical scenarios that affect the intended functionality, and apply them to evaluate whether the ADS is free from unreasonable risks.

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Road vehicles — Test scenarios for automated driving systems — Scenario based safety evaluation framework

1 Scope

This document provides guidance for a scenario-based safety evaluation framework for automated driving systems (ADSs). The framework elaborates a scenario-based safety evaluation process that is applied during product development. The guidance for the framework is intended to be applied to ADS defined in ISO/SAE PAS 22736 and to vehicle categories 1 and 2 according to Reference [10]. This scenario-based safety evaluation framework for ADS is applicable for limited access highways.

This document does not address safety-related issues involving misuse, human machine interface and cybersecurity.

This document does not address non-safety related issues involving comfort, energy efficiency or traffic flow efficiency.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 34501, *Road vehicles — Test scenarios for automated driving systems — Vocabulary*

ISO 21448, *Road vehicles — Safety of the intended functionality*

ISO 26262-3, *Road vehicles — Functional safety — Part 3: Concept phase*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 34501 and the following apply.

ISO and IEC maintain terminology databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at https://www.electropedia.org/

3.1
critical scenario
scenario including one or more *risk factors* (3.3)

3.2
hazardous scenario
scenario in which harm occurs unless prevented by an entity other than the ADS

3.3
risk factor
factor or condition of a scenario that, if present, increases either the probability of the occurrence of harm, or the severity of harm, or both

3.4
safety test objective
safety property of the ADS to be shown via a set of tests

Note 1 to entry: The safety test objectives can be derived from the validation targets or the acceptance criteria of ISO 21448.

Note 2 to entry: The safety test objectives also include the aspect of the test end criteria.

Note 3 to entry: Depending on the kind of the safety test objectives the pass/fail-criteria of a concrete test scenario can be included within the safety test objectives.

4 Test scenario-based safety evaluation process

4.1 Integration into the overall development process

4.1.1 Objectives

The objectives of this clause are:

a) to provide an overview of the overall safety tasks and content of this document;

b) to provide an overview of the scenario-based safety evaluation process;

c) to explain the relationship between this framework and other standards and legislation.

4.1.2 General

4.1.2.1 Overall safety tasks and content of this document

Figure 1 presents the overall safety task "Identification and risk evaluation of the hazardous scenarios of the ADS" and its derived subtasks.

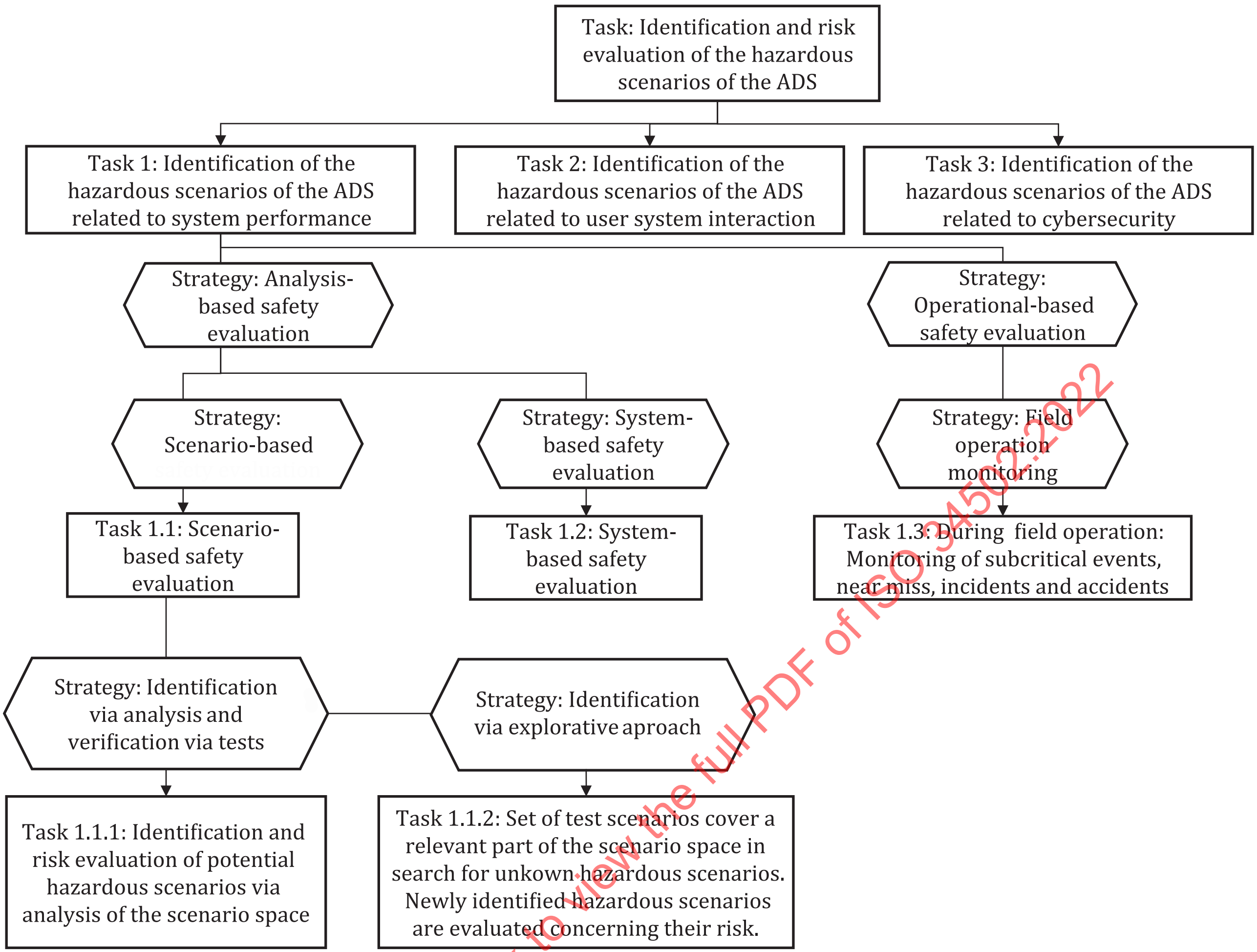


Figure 1 — Overview of the different safety tasks to identify hazardous scenarios for the ADS

This document proposes to address the identification of potential hazardous scenarios via analysis from two different starting points:

1. the relevant scenario space (task 1.1);
2. the system (task 1.2).

This approach is similar to the approach found in functional safety where the safety analysis is executed from two different and complementary perspectives: The deductive approach (e.g. Fault Tree Analysis, FTA) and the inductive approach (e.g. Failure Modes and Effects Analysis, FMEA).

In system-based approaches (task 1.2), the starting point of the analysis is the system itself. In scenario-based approaches (task 1.1), which are the focus of this document, the starting point is the analysis of the scenarios belonging to the relevant scenario space. For this approach the relevant scenario space is analysed to identify risk factors. Only general physical limitations of the systems are considered, for example, a sensor has a field of view based on the physics of its detection system, but other implementation specific issues, e.g. the limitations of a machine learning algorithm to classify a detected object correctly or sensor failures due to random hardware faults, are neglected. These system specific aspects can be better analysed with system-based approaches. One advantage of the scenario-based approach is that it can be applied with minimal dependency on the implementation of the system itself (e.g. for regulatory use). As such, the results of a given analysis can be reused for different systems as long as the relevant scenario space is the same, considering that the concrete parameters maximizing the risk factor for a given scenario still have system dependencies (e.g. exact number and positions of sensors).

NOTE 1 Knowledge gained during the execution of one approach (e.g. the system-based approach) can be used to support the analysis by another approach (e.g. the scenario-based approach).

NOTE 2 The results of the system-based safety analysis can also be test scenarios to be executed.

Not all the relevant tasks for ADS safety evaluation are addressed by this document. This document predominantly focuses on:

— task 1.1.1: identification and risk evaluation of potential hazardous scenarios via analysis of the relevant scenario space (see 4.3); and

— task 1.1.2: derivation of a representative set of test scenarios to argue a sufficient coverage of the relevant scenario space in search for unknown hazardous scenarios (see Annex K).

Guidelines for the execution of the remaining safety tasks can be found in other standards, e.g.

— task 2: ISO 21448;

— task 3: ISO/SAE 21434;

— task 1.2 and task 1.3: ISO 21448, the ISO 26262 series.

NOTE 3 Some safety issues can be assigned to multiple tasks.

EXAMPLE An adversarial attack, also known as "physical hack", for example, in which sensors are spoofed with the help of stickers on traffic signs, can be assigned to task 3 and task 1. Within task 3, the relevant attack scenarios are identified. Within task 1.1 and task 1.2, it is evaluated whether the system is sufficiently robust against the identified relevant attack scenarios.

NOTE 4 The result of task 1.2, the system based analysis, can also be scenarios that need to be tested in order to evaluate the safety of the system.

NOTE 5 Overall guidance concerning safety for ADS considering SOTIF, functional safety and security can be found in, e.g. ISO/TR 4804.

4.1.2.2 Overall flow of this document

Figure 2 shows the overall flow of this document within the scope of product development processes. Within the figure:

— the first column from the left represents the inputs to the scenario-based safety evaluation process elaborated within this document;

— the second column represents the preparation phase preceding the identification of critical scenarios phase in which safety test objectives are specified;

— the third column provides an overview of the specification of the relevant scenario space, and identification of risk factors and critical scenarios for safety evaluation according to the scenario-based safety evaluation framework;

— the fourth column shows the interconnections among the scenario-based safety testing and evaluation process (safety analysis phase) and the remaining product development phases;

— the fifth column represents how the output of the scenario-based safety evaluation framework fits into the overall vehicle safety approval process that includes other safety validation steps;

— lines indicate iteration loops and influence conditions; they can contain new findings and trigger necessary adaptations, when, for example, functional modifications are necessary due to safety reasons.

The subclauses in Clause 4 aim at addressing the following points to contribute to an overall scenario-based safety evaluation process.

— 4.1 **Integration into the overall development process:** How the framework integrates into existing product development processes.

— 4.2 **Safety test objectives:** Specification of safety test objectives that the system needs to fulfil.

— 4.3 **Specification of the relevant scenario space:** How the relevant scenario space is defined.

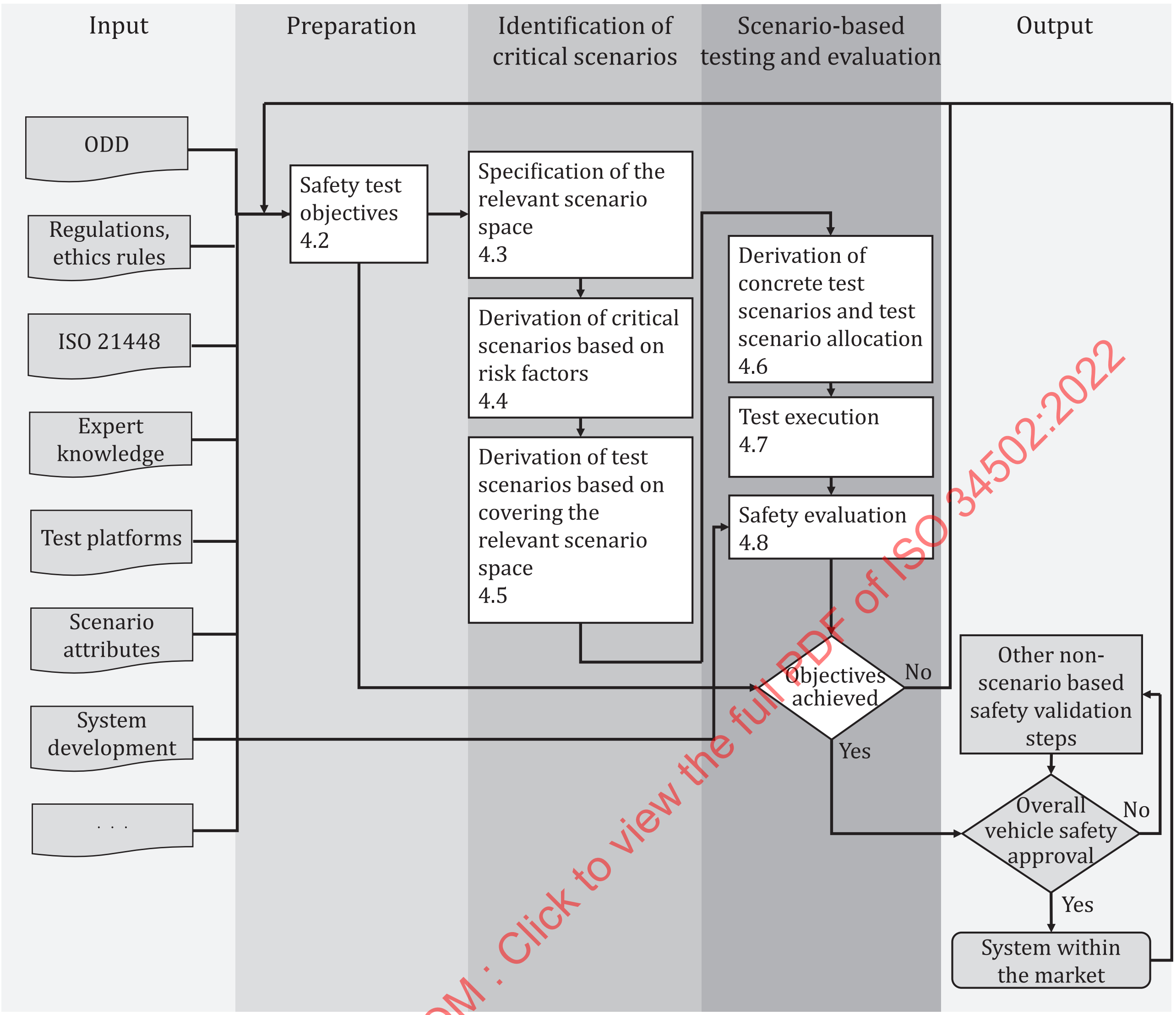
— 4.4 **Derivation of critical scenarios based on risk factors:** How to define a set of critical scenarios from which a set of test scenarios are derived.

— 4.5 **Derivation of test scenarios based on covering the relevant scenario space:** The identification of critical scenarios to potentially be tested.

— 4.6 **Derivation of concrete test scenarios and test scenario allocation:** How test scenarios are generated and allocated to different testing platforms.

— 4.7 **Test execution:** Requirements that need to be fulfilled while running test scenarios.

— 4.8 **Safety evaluation:** How the test results are evaluated to achieve an overall result.



Key

- input
- step in this document (clause number)
- decision in this document
- decision in this document
- external decision

Figure 2 — ISO 34502 flow

Figure 3 illustrates the relationship between ISO 21448 and this document.

4.3 adds specificity to ISO 21448:2022, Clause 7, by identifying reasonably foreseeable risk factors that may lead to hazardous scenarios. By structuring these risk factors, critical scenarios are generated and compiled into a scenario catalogue for testing purposes. Therefore, the approach to identifying and structuring risk factors in this document contributes to maximize the coverage of known hazardous scenarios in SOTIF.

4.5 contributes to address ISO 21448:2022, Clause 9, by defining the concrete scenarios that need to be tested and their corresponding platforms, which is an essential step to define the verification and validation strategy.

Finally, 4.3 to 4.8 contribute to address ISO 21448:2022, Clauses 10 and 11. By using the known hazardous scenario as additional input to the safety evaluation process, and varying some of the properties/attributes of these scenarios, unknown hazardous scenarios can also be explored, and the space and amount of unknown scenarios can be reduced.

NOTE The scenario-based safety evaluation process or parts of it can be applied to the system, subsystem or component level, in addition to the vehicle level. Accordingly, the process is adapted to the corresponding ADS under test.

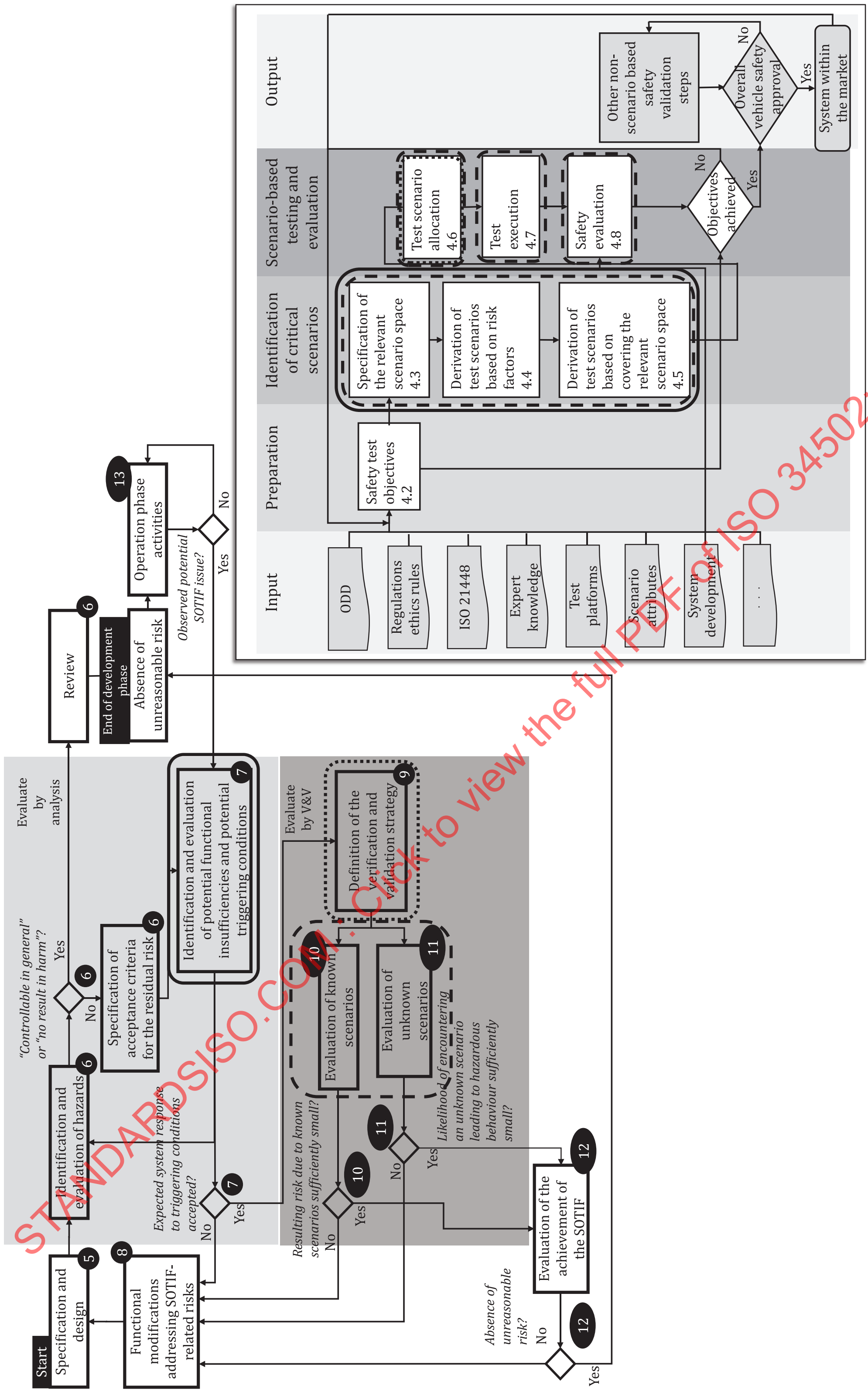


Figure 3 — Relationship between ISO 21448 (left) and ISO 34502 (right) flow charts

4.1.3 Requirements and recommendations

This document shall be applied in combination with:

— ISO 21448.

4.1.4 Requirements for conformity

When claiming conformance with this document, each requirement shall be met unless a rationale is provided, demonstrating that the non-conformity is deemed acceptable, i.e. the corresponding objectives are still achieved.

4.2 Safety test objectives

4.2.1 Objectives

The objective of 4.2 is to specify the relevant safety test objectives for the ADS safety evaluation.

4.2.2 General

The safety test objectives represent the safety properties of the ADS to be shown via a set of tests. The objectives are derived from general risk acceptance criteria like the principles of 'as low as reasonably practicable' (ALARP), of 'minimal endogenous mortality' (MEM), of 'positive risk balance' (PRB), and of applicable regulations. The safety test objectives are either derived from or provided by an external source like ISO 21448 or by a related regulation[11]. The safety test objectives are typically expressed by using, for example, one of the two following procedures.

a) Safety test objectives specified as a boundary value (upper, or depending on the formulation, lower boundary value) of the acceptable and demonstratable occurrence rate of a measurable safety-related behaviour of the ADS (or its elements) during operation within the operational domain.

   EXAMPLE 1 A hazardous behaviour of the system that is evaluated as critical, does not occur during x hours of test operation within the operational domain.

   EXAMPLE 2 The perception element forwards incorrectly perceived objects to the control element less than once per y hours during operation within the operational domain.

   EXAMPLE 3 The relative frequency of undesired behaviour in a given scenario is lower than x.

b) Safety test objectives specified as a performance reference model regarding the capability of the ADS to handle certain scenarios safely, based on minimum performance levels required for these scenarios.

   EXAMPLE 4 The ADS is capable of preventing any accident that would be preventable according to a reference performance model of a competent and careful human driver.

The safety test objectives are chosen in such a way that their fulfilment supports the overall safety argument of the ADS. They represent a measurable or observable property of the ADS.

NOTE Additional safety arguments (e.g. safety analysis) can be a necessary part the fulfilment of the safety test objectives to demonstrate that the overall safety argument is valid.

4.2.3 Input to this clause

4.2.3.1 Prerequisites

The following information shall be considered if available:

— industry standards (e.g. ISO 21448, the ISO 26262 series);

— operational design domain (ODD);

— design and functionality of the ADS, including the intended behaviour;

— other safety-relevant scenario catalogues (e.g. NCAP).

4.2.3.2 Further supporting information

The following information can be considered:

— traffic rules and regulations (e.g. Reference [11]);

— government guidelines (e.g. References [7][8][9]);

— regional specific social norms (e.g. Reference [12]).

4.2.4 Requirements and recommendations

The safety test objectives derived from external sources shall be specified.

NOTE Multiple safety test objectives can be specified to reflect the requirements from different external sources or for different levels of abstraction.

4.2.5 Work products

Safety test objective(s) resulting from requirement 4.2.4.

4.3 Specification of the relevant scenario space

4.3.1 Objectives

The objective of 4.3 is to define and specify the relevant scenario space.

4.3.2 General

The relevant scenario space describes the possible scenarios that the ADS can encounter, in consideration of the ODD and the possible manoeuvres of the ADS.

4.3.3 Input to this clause

4.3.3.1 Prerequisites

The following information shall be available:

— safety test objectives in accordance with 4.2;

— item definition in accordance with ISO 26262-3;

— specification of the functionality in accordance with ISO 21448;

— capabilities of the ADS (e.g. according to ISO/TR 4804);

— ODD;

— description of the design and the functionality of the ADS, including the intended behaviour;

— other safety-relevant scenario catalogues (e.g. NCAP);

— sources of information based on which parameter ranges can be defined (e.g. traffic monitoring data, accident data, field operational test, naturalistic driving data, insurance data, map and road data, expert knowledge, coverage requirements).

4.3.3.2 Further supporting information

The following information can be considered:

— regulations (e.g. Reference [11]);

— government guidelines (e.g. References [7][8][9]);

— regional specific social norms (e.g. Reference [12]);

— scenario attributes.

4.3.4 Requirements and recommendations

4.3.4.1 The relevant scenario space shall be specified.

NOTE 1 Functional, abstract, logical and concrete scenario definitions can be used to support the specification of the relevant scenario space.

NOTE 2 The technical representation can be the ASAM OpenSCENARIO format[13].

NOTE 3 The specification of the relevant scenario space can include parameter ranges and statistical distributions.

4.3.5 Work products

Specification of the relevant scenario space resulting from 4.3.4.

4.4 Derivation of critical scenarios based on risk factors

4.4.1 Objectives

The objectives of 4.4 are:

a) to analyse the relevant scenario space to identify risk factors;

b) to determine critical scenarios with the help of risk factors.

4.4.2 General

There are different possible approaches to identify safety critical scenarios via analysis (see Figure 1, ISO 21448 and the ISO 26262 series). This document focuses on the scenario-based approach to identify critical scenarios with the help of risk factors.

4.4.3 Input to this clause

4.4.3.1 Prerequisites

The following information shall be available:

— the information listed in 4.3.3.1;

— relevant scenario space in accordance with 4.3.5.

4.4.3.2 Further supporting information

The following information can be considered:

— test results from previously tested scenarios.

4.4.4 Requirements and recommendations

4.4.4.1 Identification of risk factors

4.4.4.1.1 The relevant scenario space shall be analysed to identify risk factors.

NOTE 1 The physics principles approach can be used to identify the risk factors relevant to the ADS. See Annexes A, B, C and D for detailed examples.

NOTE 2 The criticality analysis approach can be used to identify risk factors relevant to the ADS. See Annex E for a detailed example.

4.4.4.2 Derivation of critical scenarios based on the analysis of the risk factors

4.4.4.2.1 The critical scenarios shall be identified under consideration of the identified risk factors.

NOTE 1 A structured approach can be used to fulfil this requirement. See Annexes A, B, C and D for detailed examples.

NOTE 2 For this analysis, specific system issues resulting from, for example, machine learning algorithms, are not considered. System restrictions are considered as far as physics principle aspects are concerned, e.g. the field of view of a sensor or the limited ability to decelerate in case of low friction coefficient between the tyres and the road surface. As such they reflect the general technical and physical limitations of the system.

NOTE 3 The critical scenarios can be described as functional, abstract, logical or concrete scenarios.

4.4.4.2.2 For the critical scenarios identified in 4.4.4.2.1 a representative set of scenarios shall be specified.

NOTE 1 A methodology for the determination of parameter ranges from real traffic data can be found in Reference [14].

NOTE 2 A methodology for the determination of traffic data sufficiency, by establishing a relationship between the amount of data collected and the accuracy of the parameter ranges defined from the data can be found in Annex L.

NOTE 3 Regional, national and international ordinance, guidelines and regulations can be used to determine parameter ranges and statistical distributions.

NOTE 4 A set of logical scenarios can be used to derive a set of concrete test scenarios.

4.4.5 Work products

Set of critical scenarios resulting from requirements in 4.4.4.

4.5 Derivation of test scenarios based on covering the relevant scenario space

4.5.1 Objectives

The objective of this clause is to derive a set of test scenarios. The set of test scenarios is chosen in such a way that the relevant scenario space is sufficiently covered.

4.5.2 General

This approach addresses the task 1.1.2 mentioned in Figure 1.

4.5.3 Input to this clause

4.5.3.1 Prerequisites

The following information shall be available:

— the information listed in 4.3.3.1;

— relevant scenario space in accordance with 4.3.5.

4.5.3.2 Further supporting information

The following information can be considered:

— set of critical scenarios based on risk factors in accordance with 4.4.5;

— test results from previously tested scenarios.

4.5.4 Requirements and recommendations

4.5.4.1 In case of safety test objectives based on a performance reference model, a set of test scenarios shall be specified under the consideration of the performance reference model (see 4.2.2).

NOTE The definition of test scenarios can be supported by a scenario database (see Annex G).

4.5.4.2 A set of test scenarios shall be specified to ensure a sufficient coverage of the relevant scenario space (see 4.2.2).

4.5.5 Work products

Set of test scenarios resulting from requirements in 4.5.4.

4.6 Derivation of concrete test scenarios and test scenario allocation

4.6.1 Objectives

The objectives of 4.6 are:

a) to define general requirements for testing concrete scenarios;

b) to provide guidance for the allocation of test scenarios to different testing platforms;

c) to define general capability requirements for tools used for verification and validation.

4.6.2 General

In general, different platforms, including simulation/virtual test platforms (VTP), track-test platforms, and real-world test platforms, can be used individually or in combination for scenario-based safety evaluation. While using them, each platform fulfils different requirements relating to accuracy, repeatability and traceability (see 4.6.4.3).

4.6.3 Input to this clause

4.6.3.1 Prerequisites

The following information shall be available:

— the information listed in 4.3.3.1;

— relevant scenario space in accordance with 4.3.5;

— information about the capability of the testing platforms to be used (see Annex F).

4.6.3.2 Further supporting information

The following information can be considered:

— set of test scenarios in accordance with 4.5.5;

— results from previously tested scenarios;

— exposure data (e.g. based on recorded data, statistics, etc.).

4.6.4 Requirements and recommendations

4.6.4.1 Derivation of a set of concrete scenarios to be tested

4.6.4.1.1 To achieve a test coverage of the scenario space sufficient for the required safety argument, parameter ranges and their combinations shall be defined for testing.

NOTE 1 An approach to segment the scenario space and to define relevant representative scenarios can be found in Annex E.

NOTE 2 If the databases of the parameter distribution are insufficient, parameter variation methods can be used (see Annex G), e.g. Monte Carlo methods, methods considering parameter dependencies[15] or risk-based model methods[16].

NOTE 3 When selecting representative test scenarios, scenarios involving multiple risk factors can be given special consideration. The combination of multiple mild factors can potentially lead to a severe case. For example, for snowy weather, non-favourable light conditions, and an aggressive cut-in by a surrounding vehicle, the combined scenario considering all these factors can potentially be very dangerous.

4.6.4.1.2 The definition of concrete parameter values and their combinations shall be based on the relevant safety test objectives provided in 4.2.

NOTE 1 Using randomly selected concrete test scenarios can support the safety argument against unknown hazardous scenarios. See Annex K for more details.

NOTE 2 Parameter variation methods can also help to identify new risk factors or the worst case conditions for these risk factors. See Annex G for more details.

NOTE 3 In the case of logical scenario, adaptive generation of concrete scenarios can be done for each logical scenario, dynamically, based on results from previous tests.

4.6.4.1.3 All test scenarios that have been identified from 4.3 to 4.5 as relevant with respect to the safety test objectives defined in 4.2, shall be tested.

4.6.4.2 Allocation of tests to different test platforms

4.6.4.2.1 Relevant test scenarios shall be allocated to at least one test platform.

4.6.4.2.2 The selected test platform shall be suitable for the assigned test scenarios.

NOTE 1 The allocation of tests to VTP can consider large number of scenarios. These platforms are particularly suitable to execute tests that would be too dangerous or too complicated to execute in real life.

NOTE 2 The allocation of tests to track-test platforms can be based on pre-selected tests, e.g. certification tests, test with a high relevance regarding drive dynamics and real sensor performance, rare events which can hardly be seen in real-world tests or events on public road with less repeatability.

NOTE 3 The allocation of tests to real-world platforms can consider public road safety and can be based on high relevance regarding real system performance. Depending on the possibility to control each single parameter the surrounding conditions can vary more or less randomly.

4.6.4.3 Capability requirements for qualification of the used platforms (including models)

4.6.4.3.1 VTP and track-test platforms shall deliver the same repeatable and reproducible results, within reasonable tolerances.

4.6.4.3.2 VTP track-test platforms and real-world platforms shall deliver traceable results.

NOTE Traceable refers to the relation between safety test objectives, test scenarios and test results.

4.6.4.3.3 Platforms shall be suitable to perform their allocated tests.

4.6.4.3.4 Platforms shall provide all necessary functionalities in sufficient quality. The result of an ADS test can contribute to the validation of the test result itself, as well to the validation of the tool.

NOTE Depending on its architecture, a VTP can contain several systems (e.g. scenario generation system, test management system, data management system, simulation system, evaluation system). Whether the quality of the functionalities of those systems is sufficient for the purpose of virtual testing of ADS can be checked. This is also applicable to other test-platforms.

4.6.4.3.5 To ensure that the used platforms are working correctly, the test results can be validated by comparison with the test results of a more realistic platform (e.g. vehicle) or of another platform previously validated (e.g. concrete test scenarios run on track tests to validate the virtual test results and the functionality of the tools).

4.6.4.3.6 The result of an ADS test can contribute to the validation of the ADS behaviour itself, as well as to the validation of the tool.

NOTE 1 The validation of the platform is done by using a representative subset of the concrete test scenarios.

NOTE 2 One possible way for the qualification of the VTP using statistical methods can be found in Annex F. Additional metrics can also be considered for, e.g. state changes, integration errors.

NOTE 3 ISO 26262-8:2018, Clause 11 provides additional information regarding tool qualification.

EXAMPLE One example is to qualify the hardware-in-the-loop (HiL) by comparison of HiL tests to vehicle-in-the-loop-tests (ViL) and then qualify the software-in-the-loop (SiL) by comparison with the HiL.

4.6.5 Work products

4.6.5.1 A set of concrete test scenarios in accordance with requirements 4.6.4.1.

4.6.5.2 Test allocation report in accordance with requirements 4.6.4.2.

4.6.5.3 Report of the fulfilment of the capability requirements for qualification of the used platforms in accordance with 4.6.4.3.

4.7 Test execution

4.7.1 Objectives

The objectives of 4.7 are:

a) to provide relevant information for test execution;

b) to provide information for efficient testing.

4.7.2 Input to this clause

4.7.2.1 Prerequisites

The following information shall be available:

— the information listed in 4.3.3.1;

— relevant scenario space in accordance with 4.3.5;

— test end criteria (e.g. x % logical or concrete scenario or y % confidence to achieve positive risk balance);

— set of scenarios to be tested, including test allocation from 4.6.5.

4.7.3 Requirements and recommendations

4.7.3.1 General requirements

4.7.3.1.1 All defined test scenarios from 4.5 shall be executed.

4.7.3.1.2 If complete coverage does not exist within the data, at least one variation method shall be used until a sufficient coverage according to the safety test objectives defined in 4.2.5 is achieved.

4.7.3.2 Simulation/virtual tests

VTP tools shall fulfil the capability requirement (see 4.6.4.3).

4.7.3.3 Track tests

4.7.3.3.1 For test execution in track tests, the test scenarios shall be replicated with sufficient accuracy.

4.7.3.3.2 Track-test tools shall fulfil the capability requirement (see 4.6.4.3).

4.7.3.3.3 Real-world tools shall fulfil the capability requirement (see 4.6.4.3).

4.7.3.3.4 The vehicles used for track tests shall be equipped with qualified measurement equipment.

4.7.3.3.5 The behaviour of all relevant dynamic entities shall be documented for the evaluation.

4.7.3.4 Real-world tests

4.7.3.4.1 Guidelines and limits regarding route selection, weather, surrounding conditions, etc. can be considered to support the execution of real-world tests.

4.5.3.4.2 The test vehicles used for real-world testing shall be equipped with qualified measurement equipment.

4.7.3.5 Test coverage of the provided test scenarios and the relevant scenario space

4.7.3.5.1 All relevant scenarios provided by 4.6.5 shall be executed within at least one of the platforms.

4.7.3.5.2 A sufficient test scenario coverage of the relevant scenario space shall be fulfilled before ending the test execution.

NOTE The achieved test coverage of the ODD is part of this evaluation.

4.7.3.5.3 Single representative test scenarios may cover a dedicated set of scenarios.

NOTE It is ensured that the most critical scenarios from the dedicated set are still considered.

4.7.4 Work products

4.7.4.1 Results report for each test scenario in accordance with requirements in 4.2.5, 4.4.5, and 4.6.5.

4.7.4.2 Overall test report summary.

4.8 Safety evaluation

4.8.1 Objectives

The objectives of this clause are:

a) to define general requirements for the evaluation of each test scenario;

b) to define general requirements for overall risk evaluation.

4.8.2 General

In general, different approaches can be used to enable a safety evaluation and to evaluate that the test objectives are fulfilled.

4.8.3 Input to this clause

4.8.3.1 Prerequisites

The following information shall be available:

— the information listed in 4.3.3.1;

— relevant scenario space in accordance with 4.3.5;

— stochastic information (optional regional specific);

— results from the test execution 4.7.4.

4.8.3.2 Further supporting information

The following information can be considered:

— safety evaluation method as described in ISO/TR 21934-1.

4.8.4 Requirements and recommendations

4.8.4.1 A safety evaluation shall be done for each test scenario.

4.8.4.2 Pass/fail criteria for the evaluation of each test scenario shall be adopted from the corresponding safety test objective.

4.8.4.3 The selection of the safety evaluation approach for each individual test scenario shall be in accordance with the relevant safety test objective.

NOTE 1 An approach for each test scenario evaluation based on a multistage approach can be found in Annex H.

NOTE 2 Probability distributions can be used to support the safety argumentation.

4.8.4.4 An evaluation regarding the fulfilment of all safety test objectives based on the executed test scenarios shall be done.

NOTE 1 One approach for the evaluation based on the physics principle approach can be found in Annex A.

NOTE 2 One approach for the evaluation based on positive risk balance can be found in Annex J.

4.8.5 Work products

Safety evaluation report in accordance with requirements in 4.8.4.

Annex A
(informative)

Physics principles scenario-based approach

The objective of this annex is to outline a physics principles scenario-based approach for ADS safety evaluation.

The number of possible safety-relevant risk factors that an ADS may be confronted with in real traffic is commonly deemed infinite. When a scenario-based safety evaluation approach is adopted, logically structured scenarios become necessary to facilitate the handling of a large number of variables and to enable testing of these scenarios. This structuring of scenarios can be achieved following a number of approaches, including but not limited to descriptions from the outside of the ADS (e.g. PEGASUS 6-layer), from the inside the ADS (e.g. SAKURA 3-categories), or by establishing a relationship between the scenario structures and corresponding patterns reported in accident databases. Independent of the inside and outside view, the resulting scenarios can be implemented by technical formats such as ASAM OpenSCENARIO. In this methodology, focus is put on a structuring of scenarios based on a description from the inside of the ADS.

In contrast with the infinite number of safety-relevant scenarios that an ADS may be confronted with in real traffic, the number of physics principles that an ADS can rely on for the safe handling of such scenarios is limited. One approach to ADS design is to decompose the dynamic driving task (DDT) into perception, judgement and control subtasks, and each of these subtasks is associated with one or several specific physics principles. For example, perception subtasks are addressed by camera-, radar- and lidar-based systems that rely on physics principles that govern light ray-, radio wave-, and laser propagation, respectively. V2X and digital maps, regarded as special perception sensor, are also included. Similarly, judgement subtasks are addressed by path and speed planning based on traffic actors' relative kinematics, which is the branch of physics that describes the motion of points, objects and systems of groups of objects, without reference to the causes of motion. Finally, control subtasks are addressed by actuation commands so the vehicle can achieve the targeted path, speed and stability through vehicle dynamics, which is the branch of physics concerned with the study of forces and their effects on motion.

It is therefore hypothesized that, if risk factors and their corresponding critical scenarios (scenarios including one or more risk factors) are decomposed and logically structured in accordance with the physics of the ADS, then it is possible to provide a holistic coverage of all the reasonably foreseeable safety-relevant root causes for a given DDT (Figure A.1). This motivates the specific recommendations for perception-, traffic-, and vehicle control-related risk factors, and the corresponding scenario structures elaborated in detail in Annex B, Annex C and Annex D, respectively.

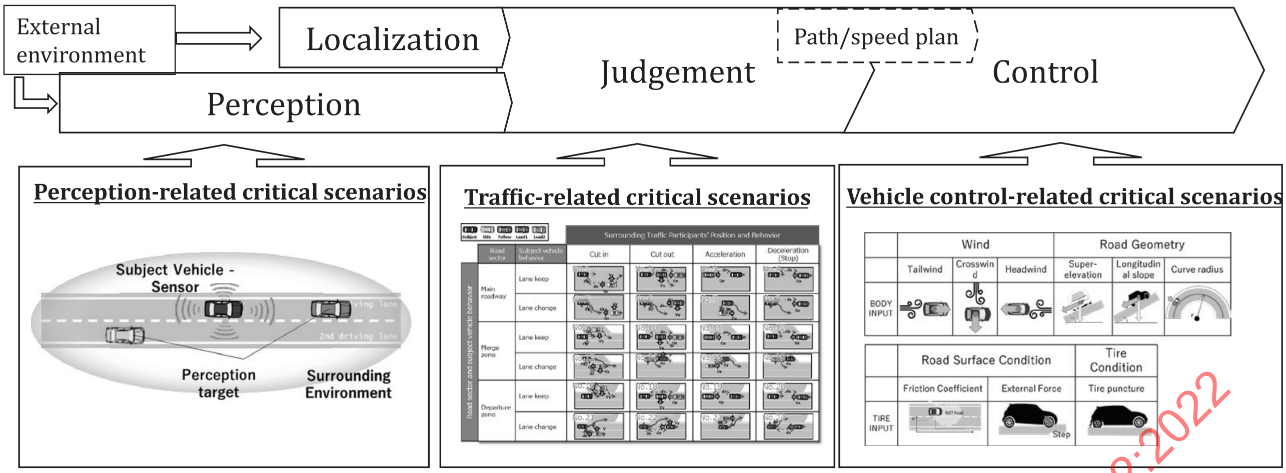


Figure A.1 — Outline of the physics principles scenario-based approach for ADS safety evaluation

In this context, perception-related risk factors refer to conditions under which the ADS of the subject vehicle may fail to correctly perceive the situation, possibly leading to a critical scenario (scenario that includes one or more perception-related risk factors). Perception-related critical scenarios may be resultant of a combination of conditions that are intrinsic or extrinsic to the sensor or vehicle. Examples of intrinsic reasons include part mounting (e.g. unsteadiness related to sensor mounting or manufacturing variability), or vehicle conditions (e.g. vehicle inclination due to uneven loading that modifies sensor orientation, or sensor shielding with external attachments such as bicycle racks). External reasons include environmental conditions (e.g. sensor cloudiness, dirt, light) or blind spots induced by surrounding vehicles.

Traffic-related risk factors refer to conditions under which the ADS of the subject vehicle may fail to correctly judge the situation, possibly leading to a traffic-related critical scenario (scenario that includes one or more traffic-related risk factors). Traffic-related critical scenarios may be resultant of a combination of the following factors: road sector (e.g. main roadway, merging zone), subject-vehicle behaviour (e.g. lane change manoeuvre), and surrounding vehicle location and motion (e.g. cut-in from a near side vehicle).

Vehicle control-related risk factors refer to conditions under which perception and judgement work correctly but the ADS may fail to control the subject vehicle, possibly leading to a vehicle control-related critical scenario (scenario that includes one or more vehicle control-related risk factors). Vehicle control-related critical scenarios may be resultant of a combination of conditions that are due to intrinsic vehicle factors (e.g. total weight, weight distribution) or extrinsic vehicle factors (e.g. pot holes, wind).

The methodology proposed in this annex can be linked to different approaches to parameterise the structured critical scenarios based on traffic situation-, perception- and vehicle control-related risk factors, and the relevant safety test objectives based on performance reference models, such as UN/WP29/R157 regulation (Figure A.2). By systematising and defining reasonably foreseeable and preventable ranges for each of the traffic-related critical scenarios, whenever quantitative criteria are established by the regulations, these criteria can be incorporated into the testing. When combining different factors and variables to develop the scenarios and defining the corresponding parameter ranges, observed real-world data may be used to prevent the generation of scenarios that cannot exist in reality. Based on these traffic-related critical scenarios, it is then possible to expand the evaluation to incorporate perception- and vehicle control-related critical scenarios into the assessment.

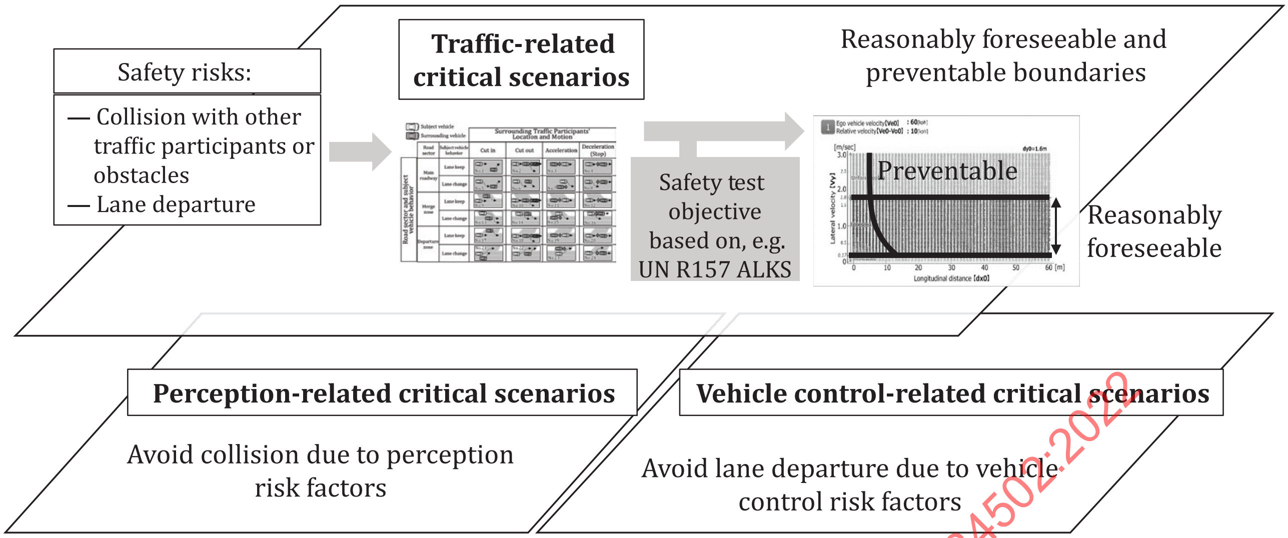


Figure A.2 — Determination of a set of structured scenarios to potentially be tested based on the recommended scenario structure and safety objectives

As ADSs are released into the market, evidence can be gathered to strengthen the hypothesis presented in this subclause. In general, it will be possible to revisit the proposed scenarios and, if necessary, update them accordingly, e.g. due to observed incidents/accidents and newly identified risk factors.

Annex B
(informative)

Traffic-related critical scenarios

B.1 General

The objective of this annex is to define specific traffic-related risk factors and their corresponding structured critical scenarios in relation to the physics principles approach outlined in Annex A. The output of this annex is a set of structured functional traffic-related critical scenarios. Guidance on the definition of parameter ranges for logical scenarios can be found in Reference [14].

Traffic-related critical scenarios are classified into general vehicle specific (including vehicle categories M, N and L), motorcycle-specific (vehicle categories L), and other traffic participants or obstructions-specific scenarios (Figure B.1).

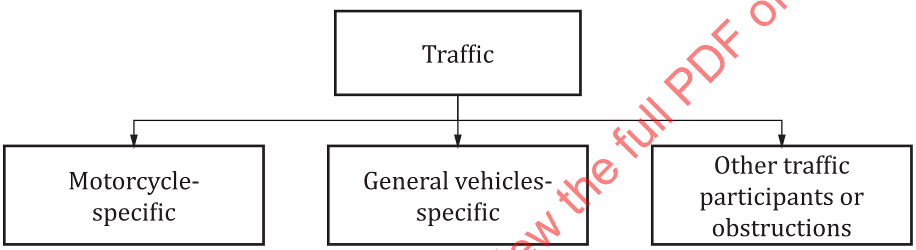


Figure B.1 — Traffic-related critical scenario classification

B.2 General vehicle specific traffic-related critical scenarios

B.2.1 General

General vehicle specific traffic-related critical scenarios are developed by systematically analysing and classifying different combinations of road sector, subject-vehicle behaviour, as well as surrounding vehicle location and motion (Figure B.2).

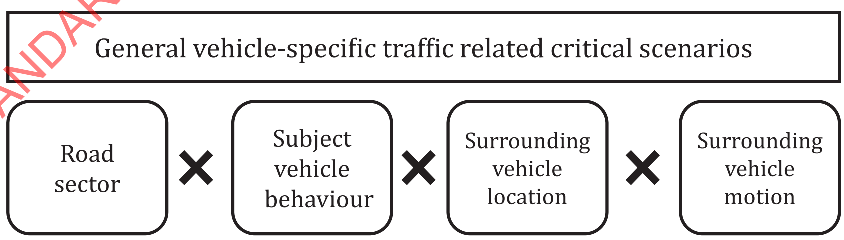


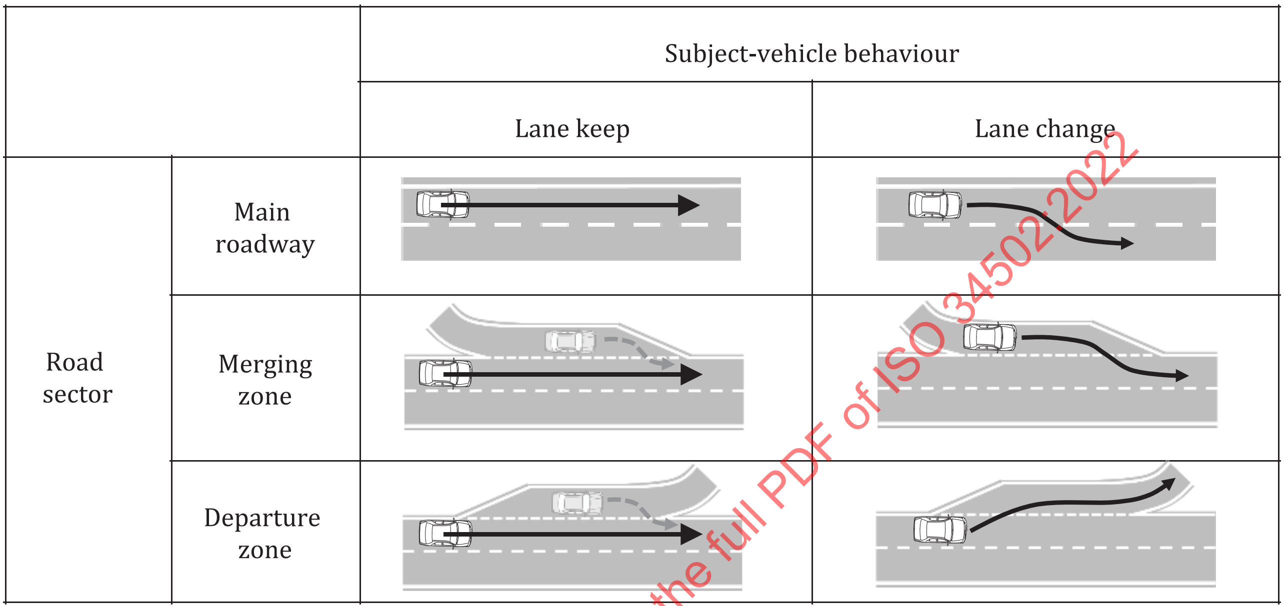
Figure B.2 — General vehicle specific traffic-related critical scenario structure schematic

B.2.2 Road-sector classification

In order to develop 'general vehicle' specific traffic-related critical scenarios, as the document focuses on highways, road sector is classified into three categories: main roadway, merge zone, and departure zone. This road-sector classification for scenario development has been deliberately simplified so it can be applied to motorways internationally.

B.2.3 Subject-vehicle behaviour classification

A lane change manoeuvre from a contiguous lane or from a merging lane may differ in road-sector category, but share the subject-vehicle behaviour. The same holds for lane-keeping manoeuvres. Therefore, possible subject-vehicle behaviours are categorised into lane keep and lane change. This simple categorization of vehicle behaviours, in combination with the road sector information provided previously, leads to six combinations (Figure B.3).

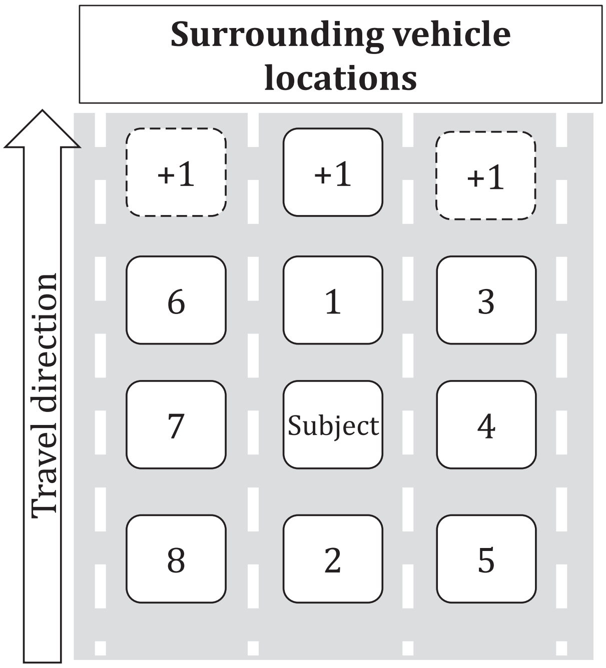


NOTE This figure explains the left-hand driving traffic situations. Right-hand driving situations are horizontal mirrored.

Figure B.3 — Road sector and subject vehicle behaviour parameters surrounding vehicle locations and motions classification

The location of surrounding vehicles to be considered in the scenario structure is defined as the adjacent locations in eight directions around the subject vehicle, since these vehicles may invade the subject vehicle's trajectory. In addition, when there is a large speed difference between the lead vehicle and the vehicle ahead of the lead vehicle, the former may cut out to avoid a collision. If this cut out occurs suddenly, the oncoming subject vehicle may also need to intervene for crash avoidance. To account for this possible scenario, the location of the vehicles ahead of the lead vehicle is also considered and is noted as '+1' (Figure B.4, left).

Possible motions of the surrounding vehicles are categorised into four groups: cut-in, cut-out, acceleration and deceleration. It is noted that this categorization refers to conditions relative to the subject vehicle, therefore acceleration or deceleration categories actually imply relative velocity differences with respect to the subject vehicle. From the perspective of safety evaluation, it is possible to minimize the number of evaluation tests by focusing on the motion of the target participants that may obstruct the subject vehicle's trajectory (Figure B.4, right chart). For example, deceleration of vehicles in locations 5, 2 and 8 does not become obstructive to the subject vehicle, and therefore can be excluded from the safety analysis. The circles in the chart indicate the cases in which the corresponding combination of surrounding vehicle locations and motions may become obstructive to the subject vehicle, and therefore can be considered in the safety analysis.



Surrounding vehicle locations and motions

Surrounding vehicle location	Cut in	Cut out	Accel.	Decel.
1. Lead		○		○
2. Follow			○	
3. Parallel	○			○
4. Parallel	○			
5. Parallel	○		○	
6. Parallel	○			○
7. Parallel	○			
8. Parallel	○		○	

Figure B.4 — Surrounding-vehicle locations (left) and combination of surrounding-vehicle locations and motions that may obstruct to the subject vehicle (right)

Surrounding-vehicle location and surrounding-vehicle motion risk factors can be structured in accordance with Figure B.5.

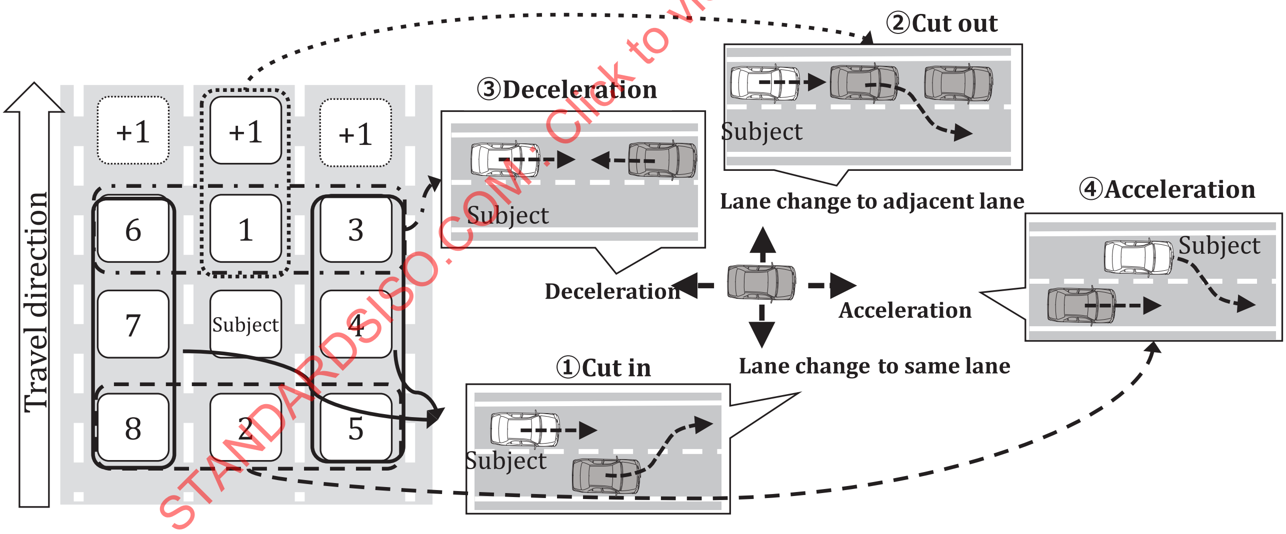
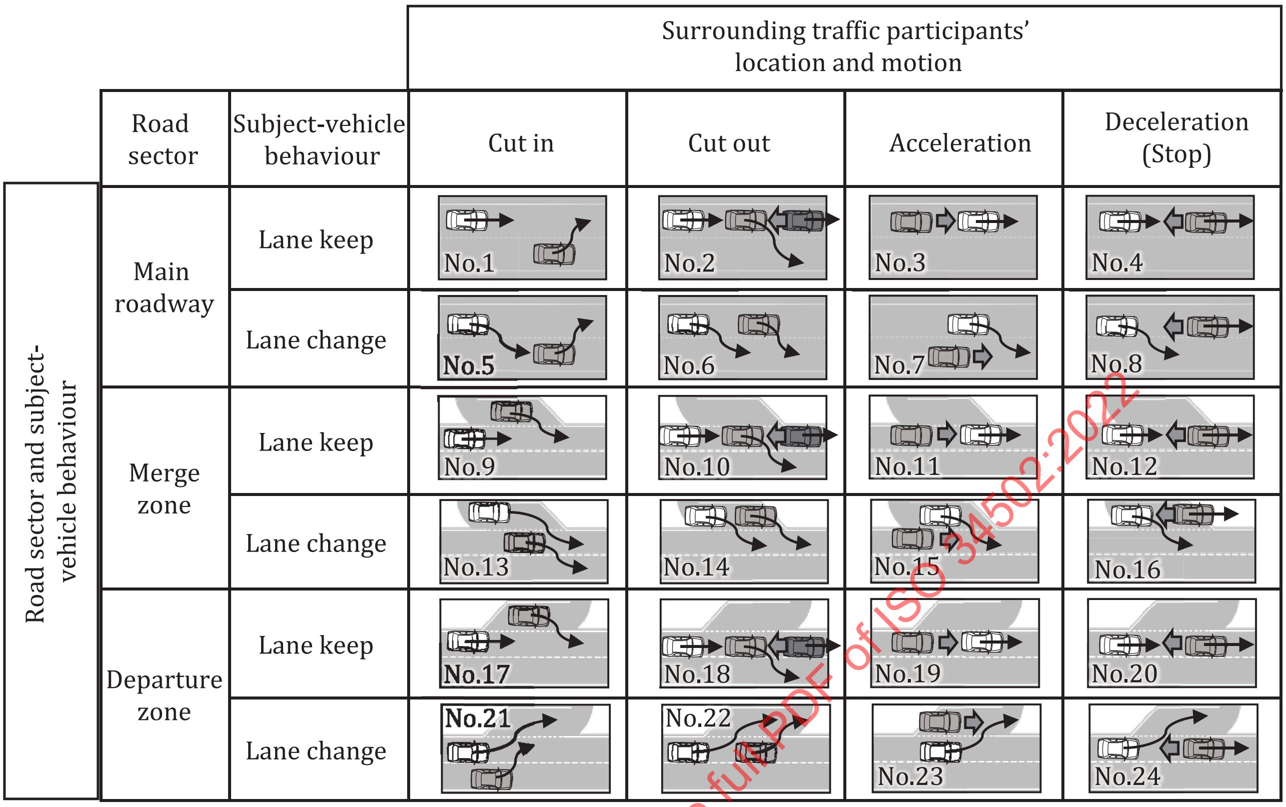


Figure B.5 — Structuring of surrounding-vehicle location and motion risk factors

B.2.4 Resulting general vehicle specific traffic-related critical scenarios

As a result of the systematic process described, a methodology to structure scenarios as a combination of road sector, subject-vehicle behaviour, surrounding-vehicles location and motion is proposed. The structure consists of a matrix containing a total of 24 possible combinations that are feasible in real traffic (Figure B.6).



Key

subject vehicle

surrounding vehicle

Figure B.6 — General vehicle specific traffic-related critical scenarios

B.3 Motorcycle-specific traffic-related critical scenarios

B.3.1 General

In general, the classification of surrounding-vehicle locations and motions described previously (Figure B.6) applies to four-wheelers and motorcycles. However, in some cases, motorcycles may travel through reduced spaces within the same lane as the subject vehicle, incurring additional safety relevant scenarios.

Analogously to the systematised process described for general vehicle specific traffic-related critical scenarios, a methodology is proposed to structure motorcycle-specific traffic-related critical scenarios as a combination of road sector, subject-vehicle behaviour, and surrounding-motorcycle position and motion (Figure B.7).

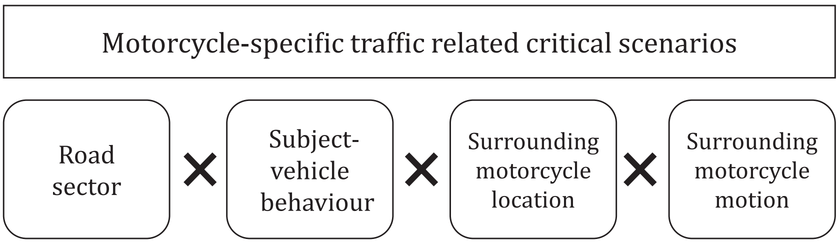
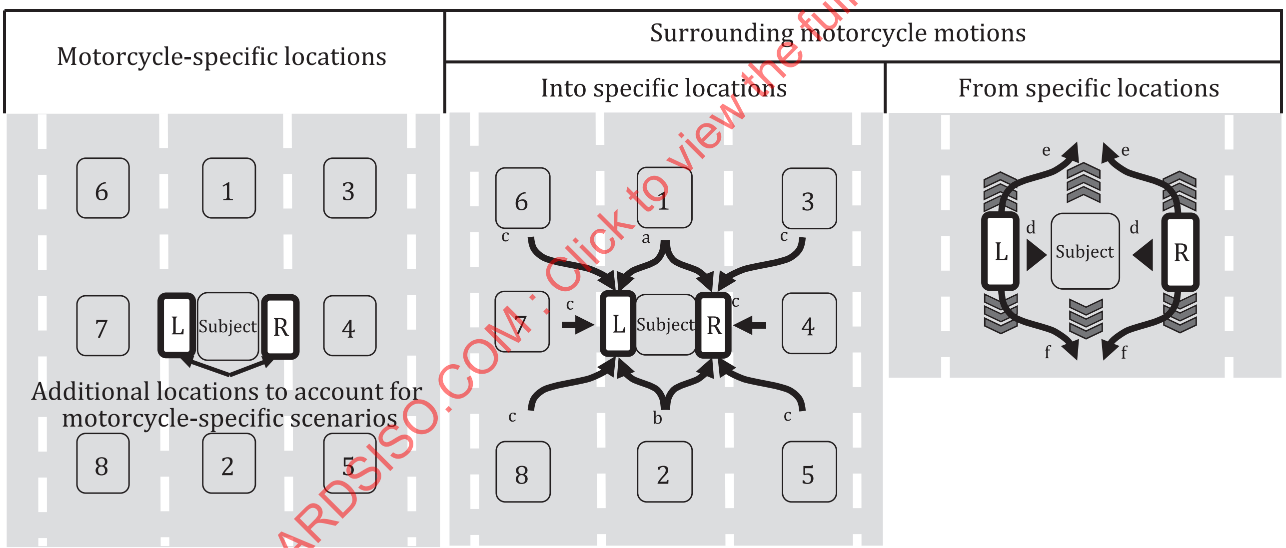


Figure B.7 — Motorcycle-specific traffic-related critical scenario structure schematic

B.3.2 Surrounding motorcycle-specific location and motion classification

Two additional location definitions (left and right) are added and applied to define a series of possible scenarios that could potentially affect the eight surrounding vehicles.

As illustrated in the left side of Figure B.8, motorcycle-specific locations [L] and [R] are positioned on either side of the subject vehicle and within the same lane. Motorcycles may move into these locations (as illustrated in the middle section of Figure B.8) by decelerating (a) from lead position 1, by accelerating (b) from rear location 2, or by changing lanes (c) from surrounding locations 3, 4, 5, 6, 7 or 8. As shown in the right side of Figure B.8, motorcycles may also move out of locations [L] and [R]. They can do so by leaning towards and approaching the subject vehicle laterally (d), by advancing (e) to a lead position, by retreating (f) to a rear position.



a Deceleration.

b Acceleration.

c Lane change.

d Lean.

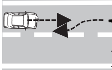
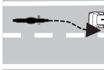
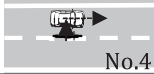
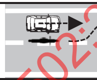
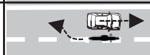
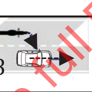
e Advance.

f Retreat.

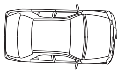
Figure B.8 — Surrounding motorcycle-specific locations that may obstruct the subject vehicle (left) and surrounding-motorcycle motions into (middle) and from (right) them

B.3.3 Resulting motorcycle-specific traffic-related critical scenarios

The structure is represented by a matrix containing a total of 36 possible combinations. From these, all the combinations involving subject-vehicle lane change are excluded because it is not feasible for the subject vehicle or because as soon as the subject-vehicle lane change manoeuvre is initiated, the motorcycle does not have the option to execute any of the pre-defined motorcycle manoeuvres. This leaves a total of eight scenarios that are feasible in real traffic and therefore are incorporated into the safety evaluation (Figure B.9).

		Surrounding motorcycle location and motion					
		Into specific location			From specific location		
Road sector	Subject-vehicle behaviour	Deceleration to side	Acceleration to side	Lane change to side	Lateral approach	Advance	Retreat
Main roadway	Lane keep	 No.1	 No.2	 No.3	 No.4	 No.5	 No.6
	Lane change	—	—	—	—	—	—
Merging zone	Lane keep	—	—	 No.7	—	—	—
	Lane change	—	—	—	—	—	—
Departure zone	Lane keep	—	—	 No.8	—	—	—
	Lane change	—	—	—	—	—	—

Key

 subject

 motorcycle

NOTE This figure explains the left-hand driving traffic situations. Right-hand driving situations are horizontal mirrored.

Figure B.9 — Motorcycle-specific traffic-related critical scenarios

B.4 Critical scenarios for other traffic participants or obstructions

The remaining critical scenarios for other traffic participants (e.g. pedestrian or cyclists) or obstructions on the lane (e.g. fallen objects, animals, temporal installations) can be defined as generic scenarios by adding simplifications to the general vehicle scenarios (e.g. number four and eight in Figure B.6, or number six in Figure B.9) and substituting the surrounding vehicle by the corresponding traffic participant or obstruction. The premise for these scenarios is that they have been properly perceived by the system (see Annex C for perception targets).

Annex C
(informative)

Perception-related critical scenarios

C.1 General

The objective of this annex is to provide guidance on how to define specific perception-related risk factors and their corresponding structured perception-related critical scenarios in relation to the physics principles approach outlined in Annex A. The output of this annex is a set of structured functional perception-related critical scenarios, complemented with a few examples including the definition of parameter ranges for the corresponding logical scenarios.

Perception-related critical scenarios are categorised into perception limitation, blind spot and connectivity scenarios (Figure C.1).

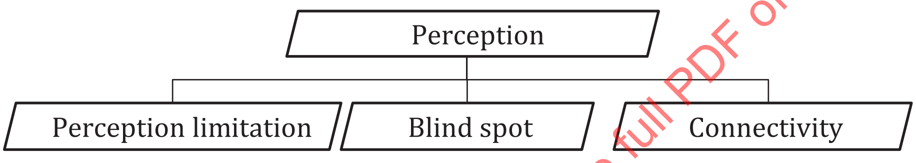


Figure C.1 — Perception-related critical scenario classification

C.2 Perception limitation related critical scenarios

C.2.1 General

Perception limitation related critical scenarios are defined as a combination of perception-related risk factors which are dependent on the physics of the system. Although numerous risk factors may cause perception-related critical scenarios, the number of factors that need to be considered in developing scenarios may be substantially reduced by cross checking causal factors with the sensor-related physics principles. Figure C.2 further illustrates this process. On the upper left part, a perception risk factor related causal factor classification is provided in the form of a tree. On the upper right, a classification of perception-related physics principles is provided by sensor type. Figure C.2 provides an illustrative image of this crosscheck. Please see Table C.1 for a detailed version. An example of physical principle is a “large difference of signals” power, like a reflection signal from truck and motorcycle”.

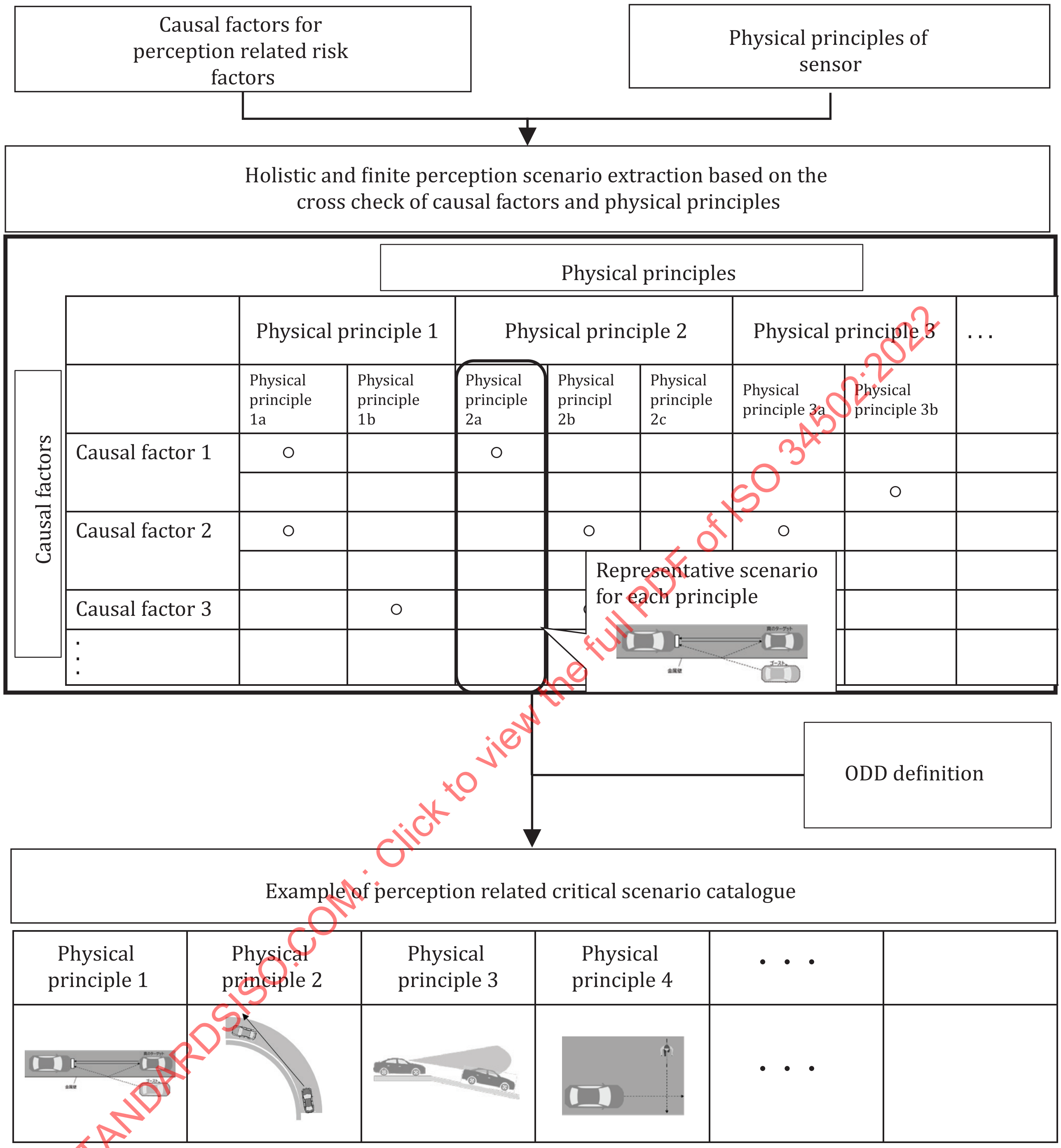


Figure C.2 — Process to develop holistic and finite critical scenarios based on the cross check of causal factors and physics principles

C.2.2 Perception-related causal factors

The causal factors for perception-related risk factors are defined in consideration of the characteristics inherent to sensor perception of different sensor technologies (e.g. radar, LiDAR, camera) according to three categories: subject vehicle-sensor, surrounding environment and perception target (Figure C.3), which allows for a categorization of related factors. Each of these categories is further decomposed as illustrated in Figure C.4.

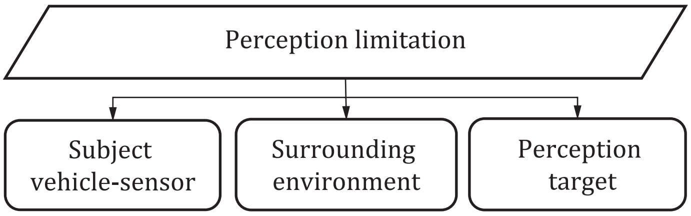


Figure C.3 — Perception limitation related risk factor classification

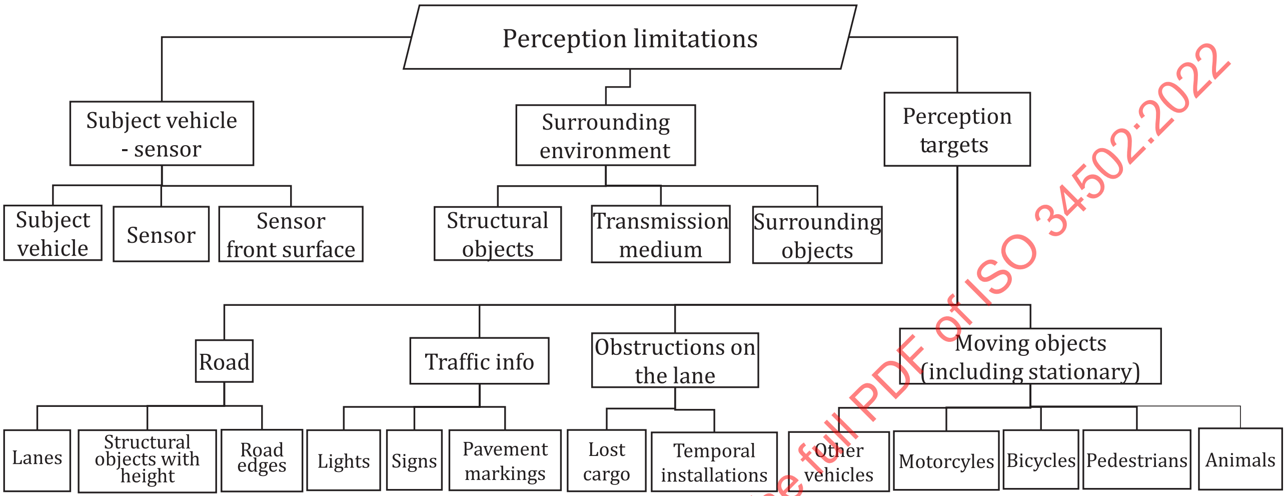


Figure C.4 — Perception limitation related risk factor detailed classification

Subject vehicle-sensor risk factors classification

Subject vehicle-sensor related perception risk factors are organized according to three categories: subject vehicle factors, sensor factors, and those due to the front surface of the sensor (Figure C.5).

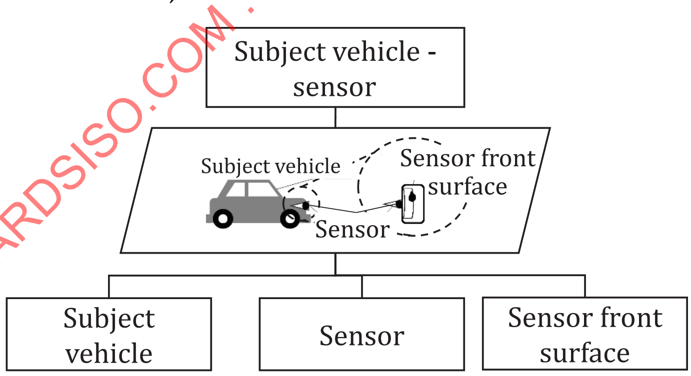


Figure C.5 — Subject vehicle-sensor perception limitation related risk factor classification

Subject vehicle-related risk factors are subcategorised according to vehicle conditions and posture. For example, permanent factors such as customised tyres or suspensions, motor vibration or suspension-induced vibration, or misalignments due to poor maintenance. Vehicle-posture factors include, for example, overload that induces vehicle pitching and alters the sensor orientation.

Sensor-risk factors are classified according to factors related to the sensor itself and those related to the sensor mounting. The former includes cases where the performance of the sensor is deteriorated, for example, due to power failure, heat, or lens wear. The latter includes installation position, mounting angle, axis misalignment, etc.

Sensor front surface factors are further classified into those that are time dependent (e.g. water drops or mud that vary with time when the vehicle is in motion) and those that are relatively independent from time (e.g. customized sensor mounting parts, or degradation due to temperature changes or sun wear).

Surrounding environment factors classification

The surrounding environment may inhibit recognition between the subject vehicle and the perception target. Surrounding environment related perception risk factors are classified into structural objects, transmission medium between the sensor and the target, and surrounding objects, as shown in Figure C.6.

Structural objects are classified into road surface, roadside objects, and overhead objects. Factors related to the transmission medium are classified into particles (e.g. rain, fog, mud), radio waves, and other sources (e.g. oncoming car lights). Surrounding objects involve factors related to the road surface (e.g. lane recognition), surrounding vehicles, roadside objects (e.g. guardrails or sound mitigating walls), and overhead objects (e.g. signboards or bridges).

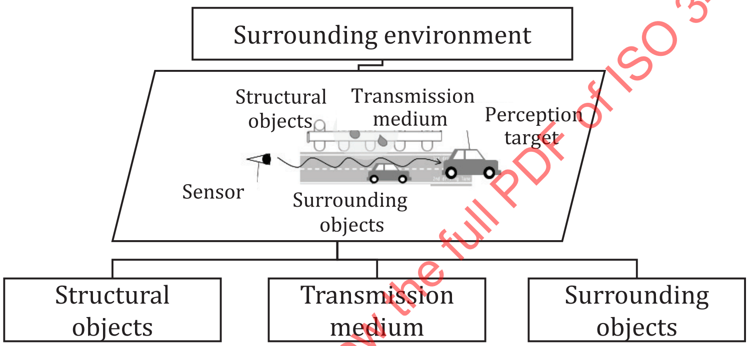


Figure C.6 — Surrounding environment related perception risk factor classification

Perception target factors classification

Perception target-related risk factors are classified into four layers: road, traffic information, obstructions on the lane, and moving objects (Figure C.7, including a mapping to the six PEGASUS layers). Road includes lanes, structural objects with certain height, and road edges. Traffic information comprise traffic lights, road signs and pavement markings. Obstructions on the road include lost cargo and temporal installations. Moving objects comprise other traffic participants including other vehicles, motorcycles, bicycles, pedestrians and animals.

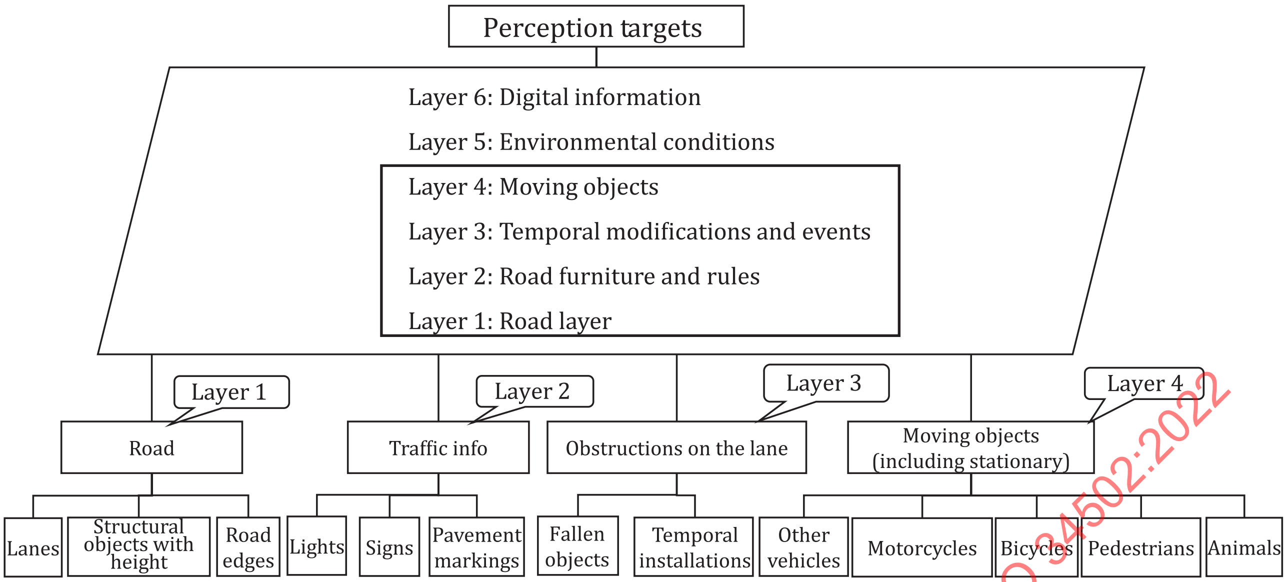


Figure C.7 — Perception targets related perception risk factor classification

C.2.3 Perception risk factor related physics principles

When a sensor detects a target object, a perception-related critical scenario may occur due to a number of factors. Although the fundamental principles for perception risk factors vary from sensor to sensor, it is possible to classify them under the following rationale:

— perception risk factors are classified as: “occurrences at perception processing”, “occurrences at recognition processing”, and “others”;

— risk factors derived from perceptual processing are classified into signal (S) from the targeted objects and conditions that alter the signal from the targeted object (noise N, unnecessary signal U);

— signals S and, N or U are to be listed as possible risk factors.

Figure C.8 shows an example of high-level perception risk factor physics principles for frontal millimetre-wave radar. Figure C.9 shows an example of detailed perception risk factors related to physics principles for the same type of sensor.

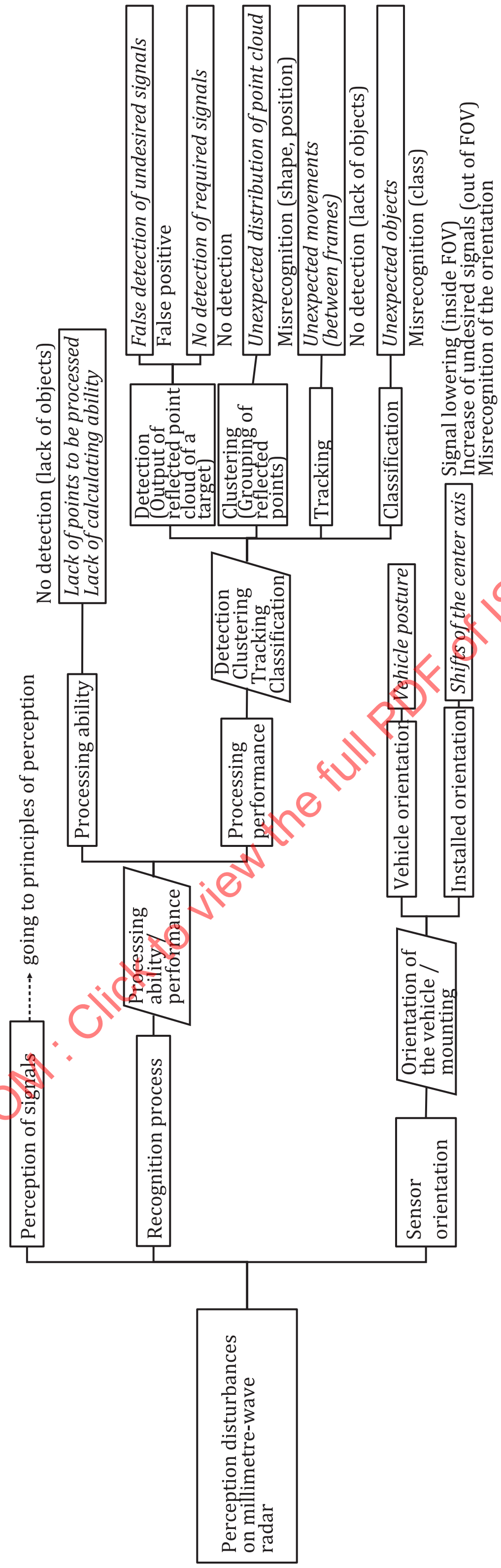


Figure C.8 — Physical principle structure of perception risk factors related to millimetre-wave radar

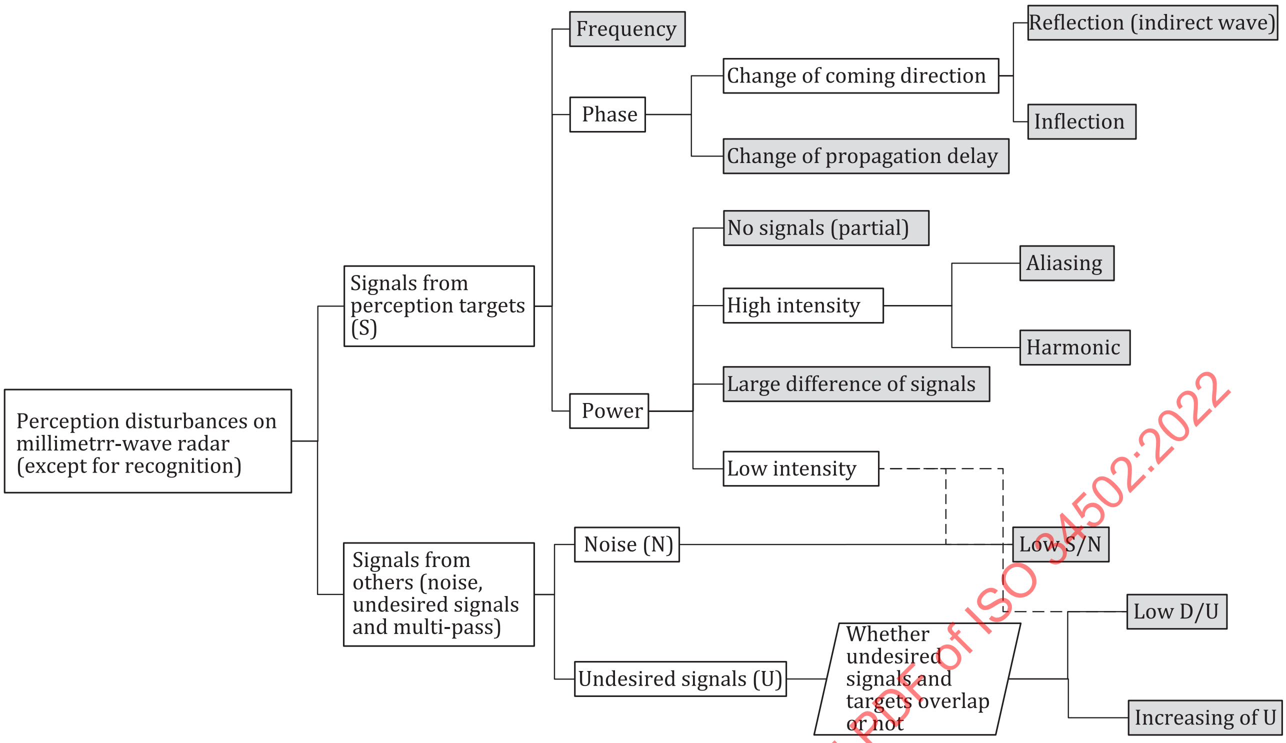


Figure C.9 — Detailed physics principle structure of perception risk factors related to millimetre-wave radar (excluding recognition process)

C.2.4 Scenario extraction by cross checking causal factors and physics principles

The perception-related critical scenarios generated from causal factors and physics principles (for sensor) based on millimetre-wave radar can be summarized by the following Table C.1. In this table, the perception-related causal factors are displayed in horizontal rows and the perception risk factor related physics principles related to the sensor are arranged in the vertical direction. For each principle, the factors that may cause a perception related critical scenario are displayed with a circle.

The group of factors circled in the same column indicate that the perception risk factors share the same sensor physical principle. For example, in a millimetre-wave radar there may be a perception risk factor that leads to the signal (S) intensity difference increasing due to two types of factors: the shape of the structure showing the roadway, and the shape and size of an object installed on the road. At this time, the evaluation of the perception risk factors of the large signal (S) intensity difference can be considered equivalent regardless of which of the above two factors causes the critical scenario. However, considering the magnitude of the influence on the sensor recognition performance, an evaluation scenario representative of this principle is selected based on the following concepts:

— among causal factors that belong to the same principle, the ones more severely affecting the perception performance are selected;

— if there are multiple items with equivalent effects on performance, those that are more frequently encountered in the market are prioritized.

Table C.1 — Example of matrix of causal factors and physical principles for millimetre-wave radar

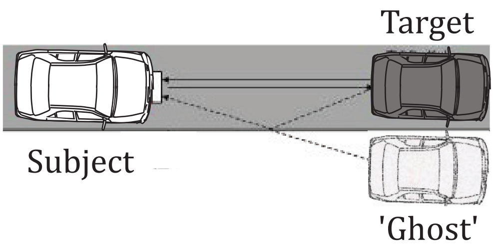
Millimetre-wave radar				Physical principles (Perception of signals / sensor orientation): Signals from perception targets (S): Frequency	Phase: Change of coming direction: Reflection (indirect wave)	Phase: Change of coming direction: Inflection	Phase: Change of propagation delay	No signals (partial)	Power: High intensity: Aliasing	Power: High intensity: Harmonic	Power: Large difference of signals	Signals from others: Noise (N): Low S/N	Signals from others: Undesired signals (U): Low D/U	Signals from others: Undesired signals (U): Increasing of U	Physical principles (recognition): Recognition process	Items
Causal factors for perception disturbances	Ego vehicle / sensor	Ego vehicle	Change of car posture									?	?	?		3
		Sensor	Variation in assembly			?	?					?	?	?		5
			Failure of sensor itself	?		?	?		?	?		?		?		7
		Front surface of sensor	Sticking objects			?	?					?				3
			Changes in characteristics			?	?					?				3
	Environment	Structural objects: Road surface	Shape									?	?	?		3
			Road condition										?	?		2
			Material										?	?		2
		Structural objects: Roadside objects	Reflection		?				?				?	?		4
			Screen					?				?				2
			Background													0
		Structural objects: Overhead objects	Reflection										?	?		2
			Screen					?								1
			Background													0
		Space	Spatial obstacles					?				?	?	?		4
			Radio wave and light in space										?	?		2
		Moving objects	Reflection		?				?	?			?	?		5
			Screen													0
			Background													0
	Perception targets: Lanes	Lines	Colour, material													0
			Shape													0
			Dirty / worn													0
			Relative position													0
		Structural objects with height	Colour, material									?				1
			Shape - Large reflection intensity						?	?	?					3
			Shape - Small reflection intensity									?				1
			Dirty									?				1
			Relative position									?				1
		Road edges: Road edges (flat)	Colour, material									?				1
			Shape									?				1
			Dirty									?				1
			Relative position									?				1
		Road edges: Road edges (uneven)	Colour, material									?				1
			Shape									?				1
			Dirty									?				1
			Relative position									?				1
	Perception targets: Traffic info.	Traffic lights	-													0
		Traffic signs	-													0
		Pavement markings	-													0
	Perception targets: Obstructions on the lane	Fallen objects	Colour, material									?				1
			Shape									?				1
			Relative position / movement									?				1
		Animals	Colour, material													0
			Shape									?				1
			Relative position / movement									?				1
		Temporal installations	Colour, material									?				1
			Shape - Large reflection intensity						?	?	?					3
			Shape - Small reflection intensity									?				1
			Dirty									?				1
			Relative position									?				1
	Perception targets: Moving objects	Other vehicles	Colour, material													0
			Shape - Large reflection intensity						?	?						2
			Shape - Small reflection intensity									?				1
			Dirty									?				1
			Relative position									?				1
		Motorbikes	Colour, material									?				1
			Shape, size									?				1
			Sticking objects									?				1
			Relative position									?				1
		Bicycles	Colour, material									?				1
			Shape, size									?				1
			Sticking objects									?				1
			Relative position									?				1
		Pedestrians	Colour, material									?				1
			Shape, size									?				1
			Relative position									?				1
Items				1	2	4	4	3	6	5	2	43	10	11		

C.2.5 Perception-related critical scenario examples

Figure C.10 and Figure C.11 show examples of a perception-related critical scenarios for millimetre-wave radar physics principles of “signal reflection” and of “no signal”, respectively.

Sensor： millimetre-wave radar
Physical principle：Reflection（indirect wave）

【Scenario for evaluation of 'Reflection'】



【Scenario description】
Multipath occurs from reflections on roadside structures such as metallic noise barriers, resulting in ghosts

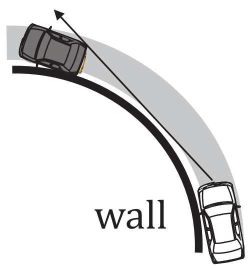
【Evaluation parameters】

Variable parameters	Types of road side structures	Guardrails, buildings, parapets of bridges, road signs, sound barriers, rubber poles, wire ropes, signs, etc.
	Lateral distance to road side structures (m)	0.5～3.5
	Road radius (m)	100, ∞
	Vehicle speed (kph)	10～ODD upper limit
Fixed parameters	–	–

Figure C.10 — Perception-related critical scenario example for signal reflection on millimetre-wave radar

Sensor: millimetre-wave radar
Physical principle: no signal (partial)

【Scenario for evaluation of 'no signal'】



【Scenario description】
A part of the object cannot be recognized because the path is blocked by a roadside structure such as a wall.

【Evaluation parameters】

Variable parameters	Types of road side structures	Guardrails, buildings, parapets of bridges, road signs, sound barriers, rubber poles, wire ropes, signs, etc.
	Perception targets	Other vehicles, motorbikes, bicycles, pedestrians.
Fixed parameters	Relative speed (kph)	ODD speed limit
	Distance to the perceived object (m)	
	Lateral distance to road side structures (m)	
	Road radius (m)	

Figure C.11 — Perception-related critical scenario example for “no signal” on millimetre-wave radar

In reality, multiple causal factors for perception-related risk factors may occur at once, e.g. camera perception limitations in snowy conditions with strong reflections of sun light from a snowy surface. A variety of tests should be done when causal factors would be considered to be validated. The physical principle based approach has the potential to combine multiple causal factors into one test scenario. The combination of multiple physical principles can also be considered.

C.3 Blind spot related critical scenarios

C.3.1 General

The traffic-related critical scenario structure described previously (Figure B.6) stands on the premise that the surrounding vehicles are detected by the system. However, in actual traffic environments, surrounding vehicles or road structure elements may obscure other vehicles in the periphery (hereafter, blind spot vehicles). Therefore, safety-relevant scenarios involving blind spot are conceivable and are incorporated into the safety analysis.

Blind spot-related critical scenarios are classified into three subcategories: blind spot vehicles, road structure and road shape (Figure C.12).

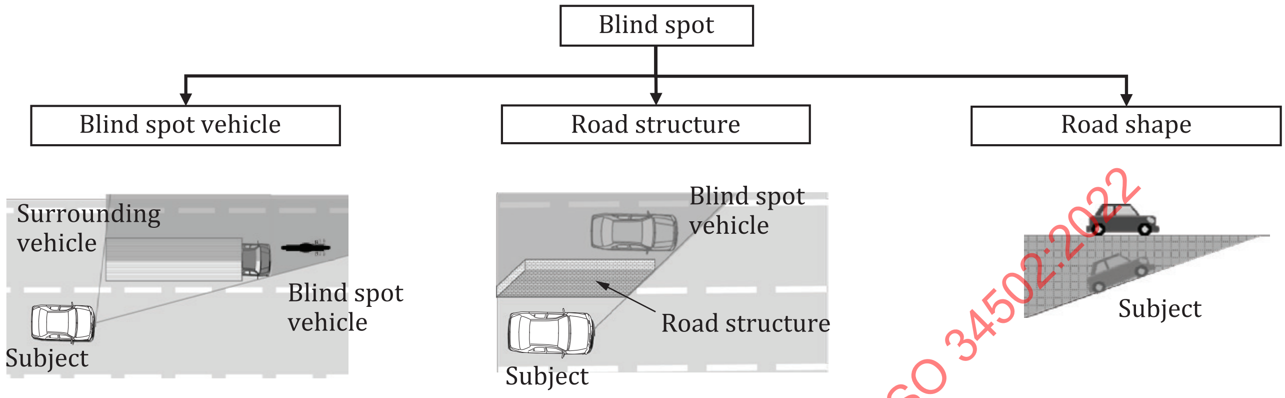


Figure C.12 — Blind spot related risk factor classification

C.3.2 Blind spot vehicle related critical scenarios

In order to structure blind spot vehicle scenarios, 16 new additional location definitions are added to the eight surrounding vehicle locations previously defined (Figure B.4, left), as shown in Figure C.13. It is noted that each surrounding vehicle may induce blind spots that affect not only the peripheral vehicle right behind the surrounding vehicle, but also other surrounding or peripheral vehicles. This is particularly the case in curves where, as the subject and the surrounding vehicles negotiate the curve, the blind spot area and the vehicle locations that fall within this area change.

To clarify this dynamic phenomenon, additional figures and descriptions follow. The process to account for blind spot vehicles, induced as a combination of road curvature and surrounding vehicles in the same lane as the subject vehicle is presented in Figure C.14. Analogously, blind spots related to surrounding vehicles in a lateral or a diagonal position with respect of the subject vehicle are presented in Figure C.15 and Figure C.16, respectively.

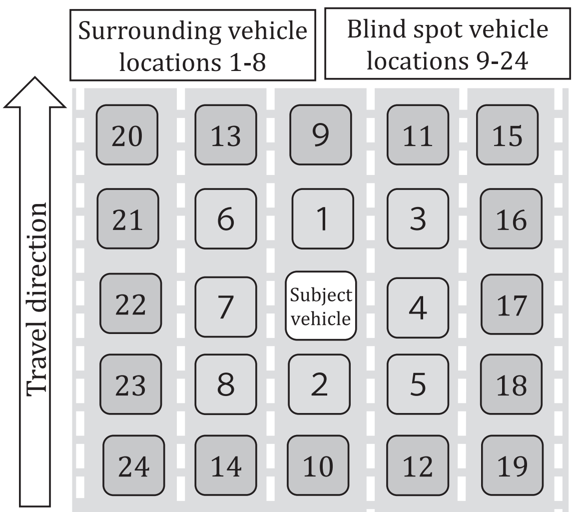


Figure C.13 — Subject, surrounding and blind spot vehicle locations applied to define blind spot vehicle related critical scenarios

The blind spot locations that may be induced by a surrounding vehicle in location 1 are shown in Figure C.14. In the figure, a truck is used as a surrounding vehicle for illustration purposes. The only safety-relevant blind spot location induced by the truck in a straight road is location 9. However, when both the subject vehicle and the truck negotiate a right curve, the orientation of the truck with respect to the subject vehicle changes, inducing blind spots in vehicle locations 6, 9, 13, 20 and 21. Analogously in left curves, vehicles in locations 3, 9, 11, 15 and 16 may be obscured by the truck. This adds up to a total of nine blind spot locations (3, 6, 9, 11, 13, 15, 16, 20 and 21) from which potentially risky manoeuvres can arise. Nevertheless, several of the risky manoeuvres that vehicles in these locations may take can be indirectly covered by more technically demanding safety scenarios. For example, in a right curve a lane change by a vehicle in blind spot location 20 will bring that vehicle to blind spot location 13. Therefore, if an ADS is evaluated in terms of its ability to safely handle the possible risky manoeuvres associated to blind spot 13 (closer distance to the subject, and therefore lower time to react), it can be assumed that the ADS can also handle the manoeuvre arising from location 20. Following a similar rationale, blind spot locations 15, 16 and 21, can also be excluded from the final list of blind spot locations. Therefore, the blind spot locations induced by a vehicle in location 1 that are considered in the final safety analysis are reduced to five locations (3, 6, 9, 11 and 13). These five locations are summarized in the simplified rectangular diagram on the right of Figure C.14.

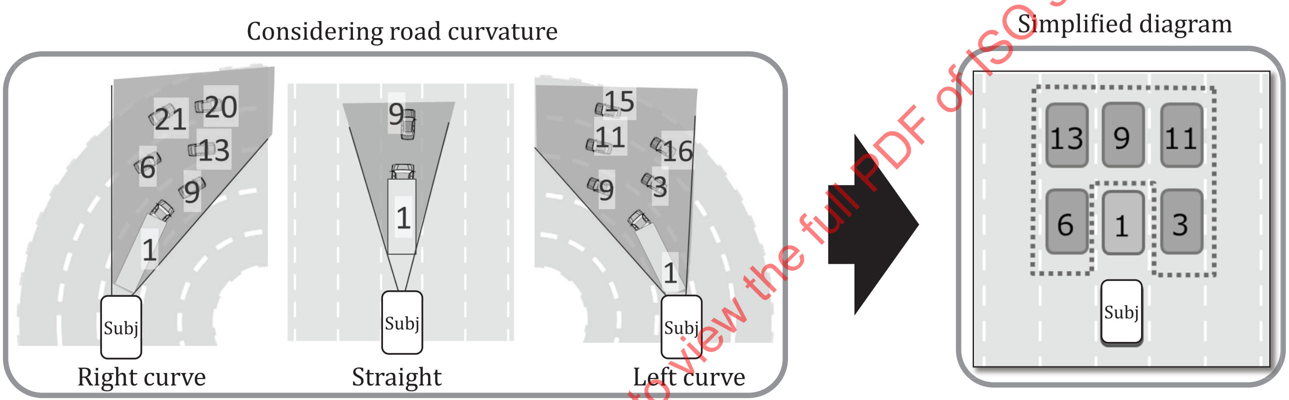


Figure C.14 — Blind spot locations due to a surrounding vehicle in longitudinal location 1 considering road curvature (left rectangle) and a simplified diagram (right rectangle)

Figure C.15 shows all possible blind spot locations induced by a truck in location 4, lateral to the subject vehicle. On a straight road, the truck may induce five blind spot locations (3, 5, 16, 17 and 18). When both the subject vehicle and the truck negotiate a right curve, the number of blind spots increases to 11 surrounding or blind spot vehicle locations (1, 2, 3, 5, 6, 8, 16, 17, 18, 21 and 23). In left curves, vehicles in three of these locations (16, 17 and 18) may be obscured. In this case, a reduction in the number of the blind spot locations considered in the safety analysis is also conducted. For example, a lane change by a vehicle in location 6 to the contiguous lane on its right side will bring it to a location similar to location 1. Therefore, if the safety analysis is conducted, for the vehicle in location 1 based on the most demanding scenario principle, the manoeuvres by the vehicle from location 6 may also be covered. A similar rationale applies for vehicles changing lanes from locations 21, 8 or 23 to the contiguous lane on their right. A deceleration of the vehicle in location 6 is less demanding than a simultaneous lane change to the contiguous left lane by the subject vehicle and the vehicle in location 1. Therefore, a vehicle in location 6 can be substituted by the vehicle in location 1. Similarly, acceleration manoeuvres by the vehicle in location 8 are less critical than simultaneous subject vehicle and vehicle 2 lane changes. Further, vehicle 16, 17 and 18 cut-in scenarios are excluded from the analysis since vehicle 4 is next to the subject vehicle, and the subject vehicle cannot execute lane changes. Therefore, the blind spots induced by a vehicle in location 4 that are considered in the final safety analysis are reduced to four locations (1, 2, 3, and 5), which are summarized in the simplified diagram on the right rectangle in Figure C.15.

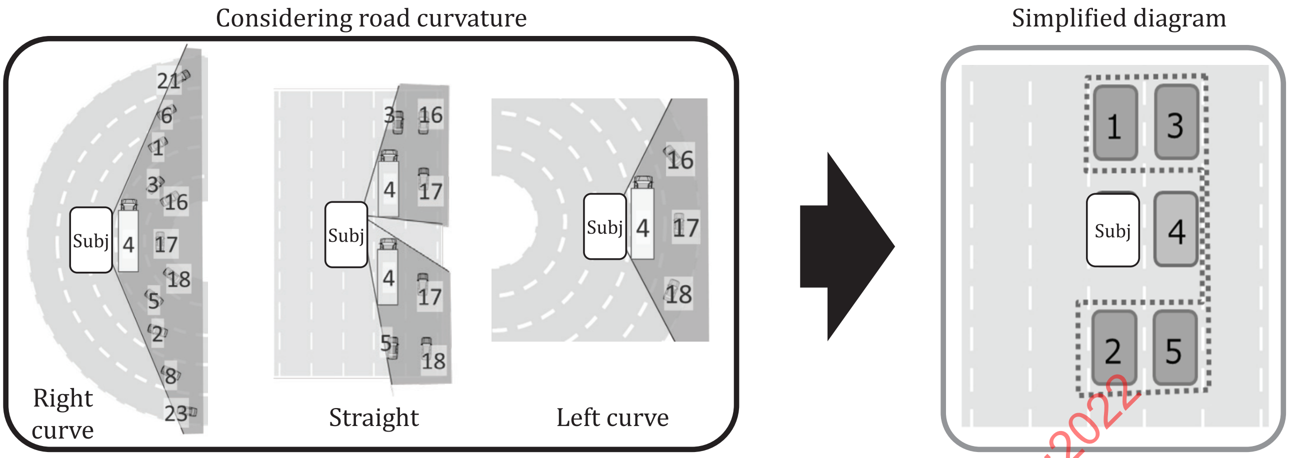


Figure C.15 — Blind spot locations due to a surrounding vehicle in lateral location 4 considering road curvature (left rectangle) and a simplified diagram (right rectangle)

Figure C.16 shows all possible blind spot locations induced by a truck in location 3, diagonal to the subject vehicle. On a straight road, the truck may induce three blind spot locations (11, 15, 16). When both the subject vehicle and the truck negotiate a right curve, the blind spots increase to nine surrounding or blind spot vehicle locations (1, 6, 9, 11, 13, 15, 16, 20 and 21). In left curves, vehicles in two of these locations (15 and 16) may be obscured. Similarly to the previous cases presented in Figure C.15, cut-in scenarios by vehicles in locations 6, 13, 20 and 21 are replaced by more challenging scenarios related to vehicles in location 9 and location 11. In addition, vehicle 6 and 13 deceleration scenarios are replaced by a simultaneous subject vehicle and vehicle 9 lane change to the left, as this is closer and more demanding to handle. Finally, the blind spot locations induced by a vehicle in diagonal location 3 that are considered in the final safety analysis are reduced to five locations (1, 9, 11, 15, and 16). These are summarized in the simplified rectangular diagram on the right side of Figure C.16.

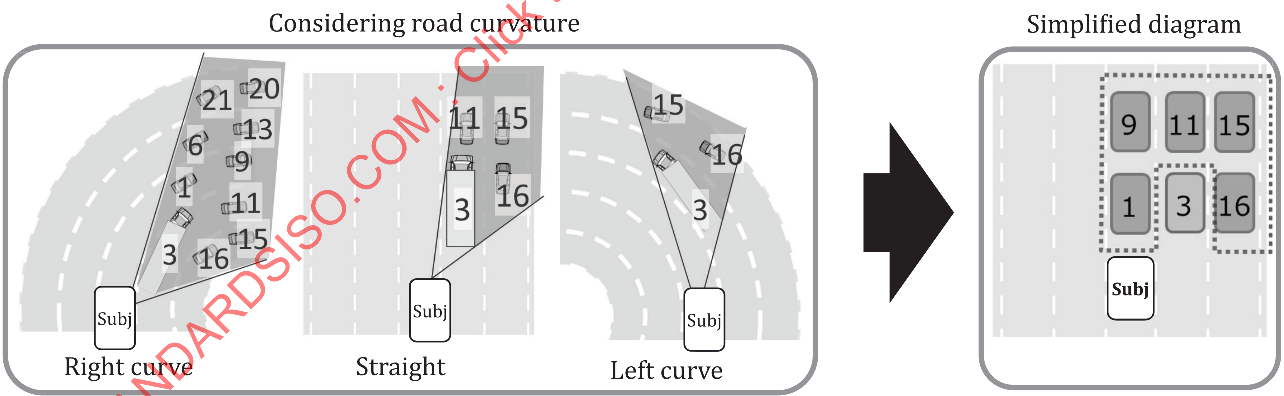
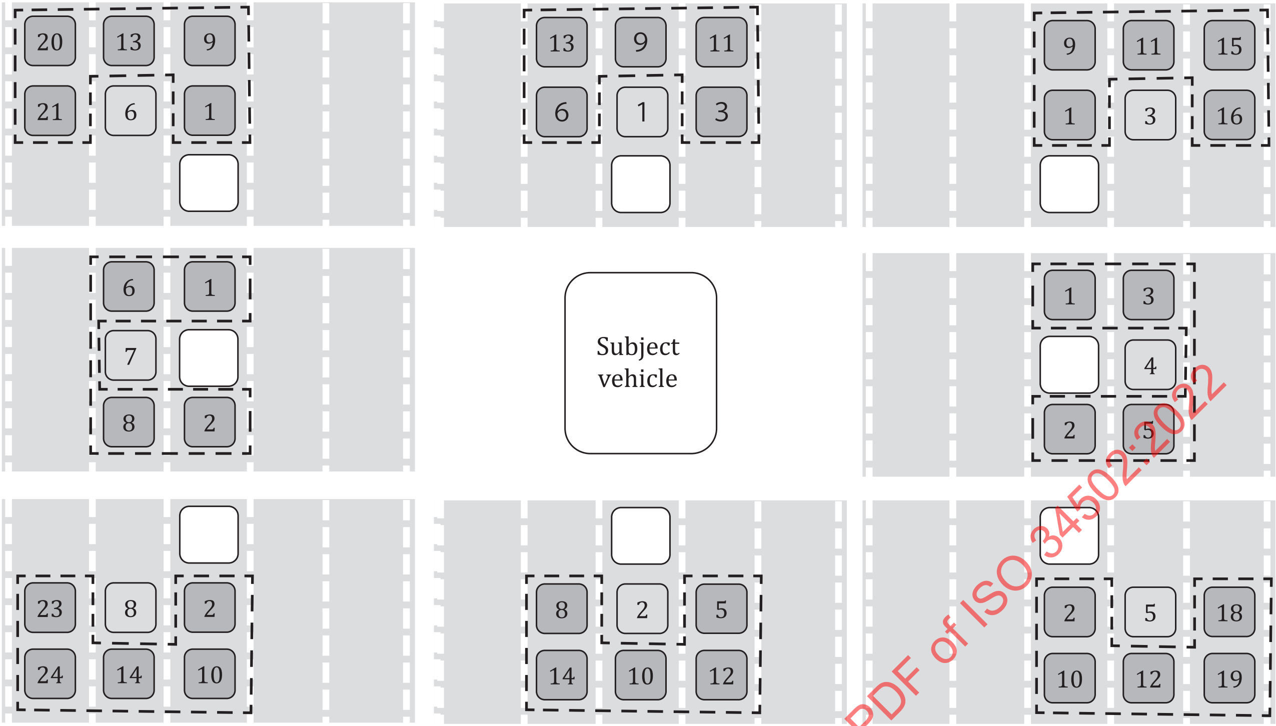


Figure C.16 — Blind spot locations due to a surrounding vehicle in diagonal location 3 considering road curvature (left rectangle) and a simplified diagram (right rectangle)

By applying analogy and symmetry principles to the three cases presented in Figure C.14 to Figure C.16, all the blind spot locations considered in the safety analysis are summarizes in a single diagram (Figure C.17).

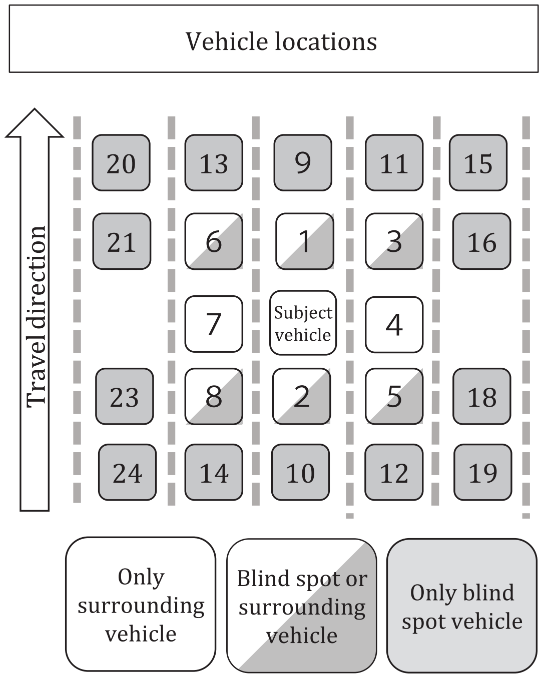


Key

- subject vehicle
- surrounding vehicle
- blind-spot vehicle
- blind-spot area

Figure C.17 — Diagram of all surrounding vehicle-induced blind spot locations that are considered in the safety analysis

Possible blind spot vehicle motions are categorized into cut-in, cut-out, acceleration, and deceleration. A reduction in the number of combinations that are considered in the safety analysis is made by focusing on the blind spot vehicle motions that may obstruct the subject vehicle (Figure C.18). For example, all deceleration of vehicles in blind spot locations behind the subject vehicle (2, 5, 8, 10, 12, 14, 18, 19, 23, 24) are discarded for not posing any risk to the subject vehicle. The circles in the chart indicate the cases in which the corresponding combination of blind spot vehicle locations and motions may become obstructive to the subject vehicle. They therefore are considered in the safety analysis.



Blind spot vehicle locations and motions

Blind spot vehicle location	Blind spot vehicle motion			
	Cut-in	Cut-out	Acceleration	Deceleration
1		○		○
2		○	○	
3 (6)	○			○
5 (8)	○		○	
9		○		○
10		○	○	
11 (13)	○			○
12 (14)	○		○	
15 (20)	○			
16 (21)	○			
18 (23)	○			
19 (24)	○			

Figure C.18 — Blind spot vehicle locations (left) and of blind spot vehicle locations and motions (right)

As a result of the systematization process described, a structure containing all the surrounding vehicle related blind spot scenarios (as a combination of road sector, subject vehicle behaviour, blind spot vehicle motion and surrounding vehicle motion) is defined. The structure consists of a matrix containing a total of 48 possible combinations from which 31 correspond to scenarios that are feasible in real traffic (Figure C.19).

Road sector	Subject-vehicle behaviour	Blind spot vehicle motion							
		Cut-in		Cut-out		Acceleration		Deceleration	
		Surrounding -vehicle motion							
Main roadway	Lane keep	No.1	No.2	—	—	No.3	No.4	No.5	No.6
	Lane change	—	No.7	No.8	No.9	No.10	No.11	No.12	No.13
Merge zone	Lane keep	No.14	No.15	—	—	—	—	—	—
	Lane change	—	No.16	No.17	No.18	No.19	No.20	No.21	No.22
Departure zone	Lane keep	No.23	No.24	—	—	—	—	—	—
	Lane change	—	No.25	No.26	No.27	No.28	No.29	No.30	No.31

Key

subject vehicle

surrounding vehicle

 blind-spot vehicle

Figure C.19 — Blind spot vehicle related critical scenarios

C.3.3 Road structure element blind spot critical scenarios

Road structure element related blind spot scenarios are defined considering the location of an obscuring road structure element and the relative manoeuvres between the subject vehicle and the obscured vehicle. These obstructing elements may be inside the road structure. Therefore, depending of the type and location of the element, the scenarios are categorized into inner barrier and outer wall related scenarios (Figure C.20). The vehicle location definitions previously defined (Figure C.13) may be adapted and applied to structure these blind spot scenarios caused by road structure elements.

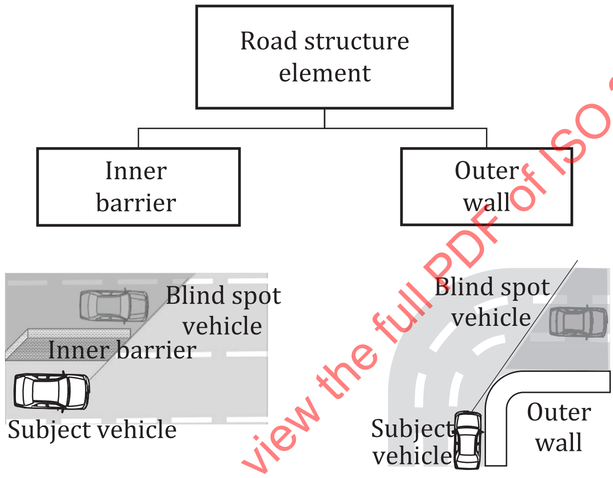


Figure C.20 — Road structure element blind spot related perception limitation classification

Inner barrier blind spot critical scenarios

In Figure C.21, when the subject vehicle is in front of the structure, the vehicle behind the structure, (vehicle 1), cannot be perceived and is therefore considered as a blind spot vehicle. The same situation is considered when the subject vehicle is in the middle of the structure. There is a blind spot behind (vehicle 3), in front (vehicle 4), and beside the structure (non-safety relevant vehicle). The vehicle located beside the structure in the middle is considered to not have an impact on safety. This is because the vehicle next to the blind spot cannot approach its own lane due to the position of the structure. However, it is a safety concern when the vehicle appears immediately after the structure, as the blind spot vehicle is located diagonally behind it (vehicle 2).

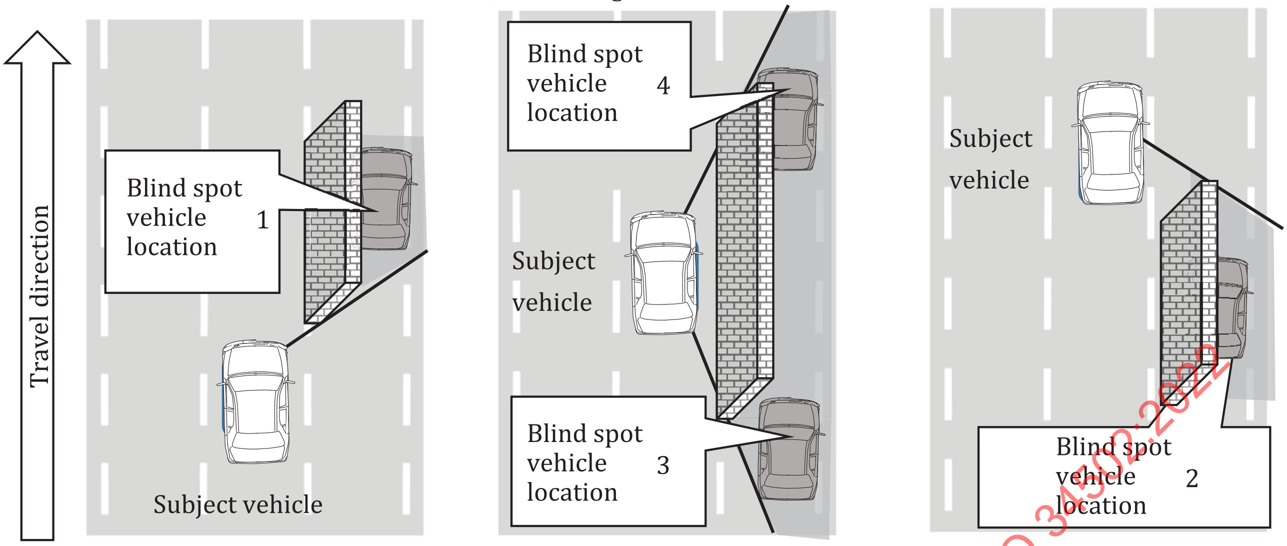


Figure C.21 — Location and inner barrier related blind spot definitions

The matrix presented in Figure C.22 summarizes the blind spot related perception limitation scenarios related to the inner barrier. In the matrix, the four blind spots previously defined (subject vehicle represented by the blue square and the blind spot vehicles are located in the darker grey areas) are combined with the five possible manoeuvres that vehicles in these spots may undertake (cut-in, cut-out, acceleration, and deceleration). This gives a matrix with 16 possible combinations from which not all of them are safety relevant. For example, in a scenario containing an inner wall, the subject vehicle and the blind spot vehicle would not be in the same lane and would therefore not cause any danger. In addition, when parallel driving with similar speeds occurs with an inner barrier in between, the subject vehicle and the blind spot vehicle cannot approach each other. Therefore, all cut-out scenarios are excluded. This leaves a total of five inner wall related blind spot scenarios (indicated with a circle in Figure C.22) that are incorporated in the safety analysis.

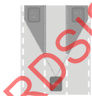
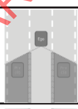
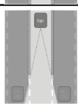
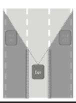
Inner barrier related blind spot pattern	Blind spot vehicle motion			
	Cut-in	Cut-out	Acceleration	Deceleration
1 	—	—	—	○
2 	○	—	○	—
3 	○	—	—	—
4 	○	—	—	—

Figure C.22 — Inner barrier blind spot related perception limitation scenarios

Outer wall blind spot scenarios

A road structure, such as an outer wall can induce blind spots in curves. As it is represented in Figure C.23, the outer wall's angle along with the curve, places the front and rear vehicles in a blind spot. For this reason, vehicles located either in the front lane of the subject vehicle or the lane behind it (1, 2, 3, 5, 6, 8) are considered to be blind spot vehicles.

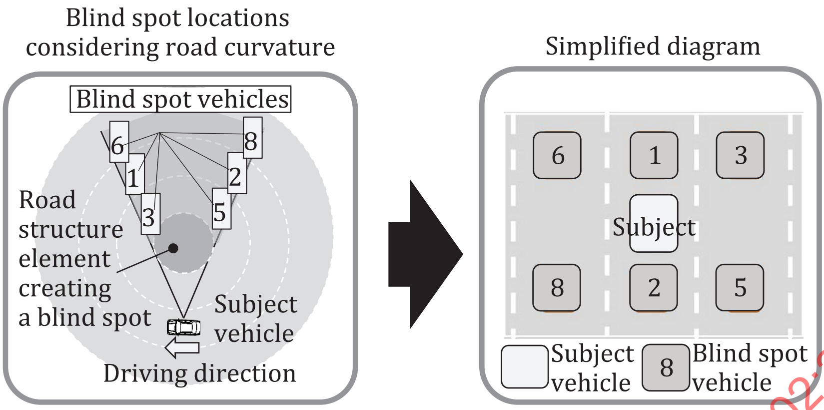


Figure C.23 — Location and outer wall related blind spot definitions

Figure C.24 represents the blind spot vehicles' movements that may obstruct the subject vehicle. To understand the movements, the blind spot vehicles' movements are listed as cut-in, cut-out, acceleration, and deceleration. Each time a blind spot vehicle enters the same lane as the subject vehicle, the motion is marked with a circle.

Outer wall related blind spot pattern	Blind-spot vehicle action			
	Cut-in	Cut-out	Accel.	Decel.
1		○		○
2		○	○	
3 (6)	○			○
5 (8)	○		○	

Figure C.24 — Outer wall blind spot related perception limitation scenarios

C.3.4 Road shape blind spot scenarios

Road shape related blind spot scenarios are defined according to road shape characteristics and subject vehicle-obscured-vehicle traffic patterns (Figure C.25). The blind spots that have been identified are created by a road geometry that causes a difference in height along the same road. These specific road shapes are characterized as vertical curves and parallel slopes. The vehicle location definitions previously defined (Figure C.13) may be adapted and applied to structure these blind spot scenarios caused by road shape.

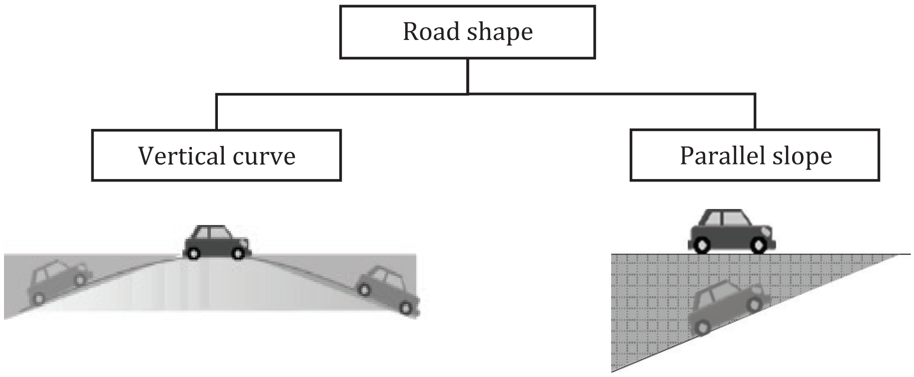


Figure C.25 — Road shape blind spot related perception risk factor classification

Vertical curve scenarios

A vertical curve (Figure C.26) is a road shape that creates two main blind spot areas (lead and rear). These blind spots limit the subject vehicle's perception of the vehicles within them (obscured vehicles). The positions and motions of the obscured vehicles (1, 2, 3, 5, 6, and 8) and the motion of the subject vehicle itself create potentially hazardous traffic patterns.

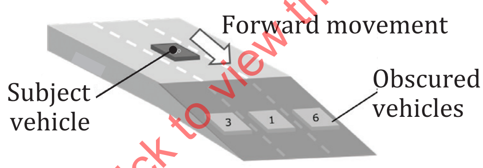
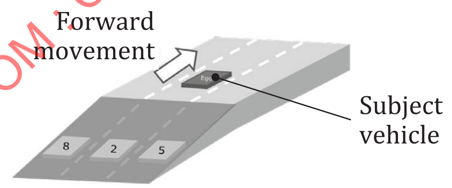
Blind spot area	Subject vehicle and obscured vehicle positions
Front	
Rear	

Figure C.26 — Vertical curve blind spot related critical scenarios

Parallel slope scenarios

A parallel slope is a merging or diverging roadway adjacent to the main road, yet parallel to it on a lower or a higher level. The difference in height between these two roads creates a blind spot that limits the subject vehicle's perception of the vehicles within it (obscured vehicles). A combination of this specific road shape, the behaviour of the subject vehicle, and the positions and motions of the obscured vehicle, create potentially hazardous traffic patterns. These patterns are categorised into four groups: obscured vehicle cut-in (1), cut-out (2), acceleration (3), and deceleration (4). This results in a matrix of 16 scenarios, 5 of which are incorporated into the safety analysis (see Figure C.27).

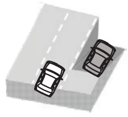
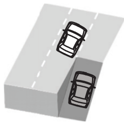
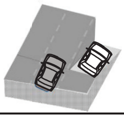
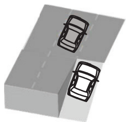
Ego-vehicle and obscured vehicle postions	Obscured vehicle motions			
	Cut-in	Cut-out	Acceleration	Deceleration
1 				○
2 	○		○	
3 	○			
4 	○			

Figure C.27 — Parallel slope blind spot related critical scenarios

C.4 Connectivity limitation scenarios

C.4.1 General

The connectivity limitation scenarios may be defined in consideration of the characteristics inherent to connectivity according to three categories: sensor, environment and transmitter (Figure C.28).

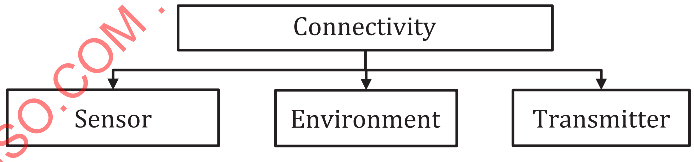


Figure C.28 — Connectivity limitation related risk factor classification

C.4.2 Sensor classification

Sensor-related connectivity limitations may be classified into the influence of digital map factors and V2X factors, as shown in Figure C.29.

Digital maps are used to support/implement ADS-required abilities, such as assisting vehicle's positioning and navigation. In addition, maps can be fused with perception sensors to increase the confidence of the perception system.

V2X (vehicle-to-everything) allows vehicles to communicate with other vehicles, road infrastructures, pedestrians and servers. V2X takes advantage in informing conditions surrounding the subject vehicle in advance, especially during severe weather conditions, and complex traffic environment.

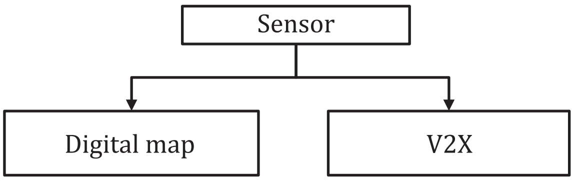


Figure C.29 — Sensor connectivity limitation related perception risk factor classification

Digital map related connectivity limitations mean map data being incorrectly collected due to an algorithm deficiency, or out-of-date due to untimely data collection (e.g. temporary lane closures, road curvature change). On the other hand, bad sensor fusion behaviour has an impact on both digital map and V2X, for example, when digital map, V2X and other sensors produce different information.

C.4.3 Environment classification

Environment-related connectivity limitations may be classified into static entities, space and dynamic entities (Figure C.30), which can disturb communication signals and positioning signals, thereby generating a blind spot or degrading the signal transmission for digital map and V2X.

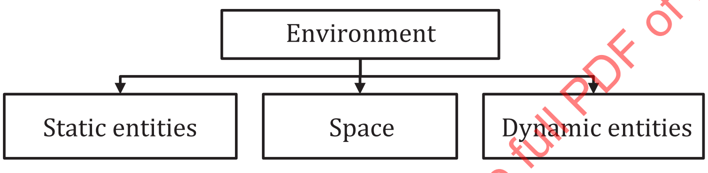


Figure C.30 — Environment connectivity limitation related perception risk factor classification

Static entities involve factors related to the roadside objects (e.g. buildings, trees, tunnels), overhead objects (e.g. overpass) and underground objects (e.g. parking lot). Risk factors related to space surrounding of vehicle can cause connectivity-related critical scenarios (e.g. signal interference, rain/fog attenuation). Dynamic entities involve factors such as surrounding vehicles, motorcycles, pedestrians.

C.4.4 Transmitter classification

Transmitter-related connectivity limitations may be classified into other vehicle, infrastructure, pedestrian, server, remote control and satellite, as shown in Figure C.31. V2X message may be unavailable or of low confidence due to transmitter errors, and GNSS signals may be lost or missed due to satellite error.

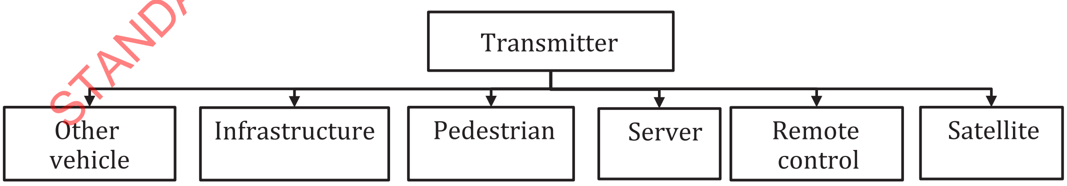


Figure C.31 — Transmitter connectivity limitation related perception risk factor classification

Annex D
(informative)

Vehicle control related critical scenarios

D.1 General

The objective of this annex is to define specific vehicle control related risk factors and their corresponding structured vehicle control related critical scenarios in relation to the physics principles approach outlined in Annex A. The output of this annex is a set of structured functional vehicle control related critical scenarios.

D.2 Vehicle control related critical scenarios

Vehicle control related critical scenarios are classified into body input and tyre input (Figure D.1)

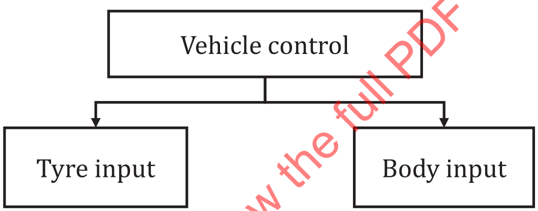


Figure D.1 — Vehicle control related critical scenario classification

D.2.1 Body input related critical scenarios

General body input force related vehicle risk factors are categorized into road geometry and natural phenomena (Figure D.2). Road geometry refers to curve radius, longitudinal gradients and transversal gradients. Natural phenomena refer to naturally occurring crosswind, tailwind and headwinds that exert forces on the body of the vehicle.

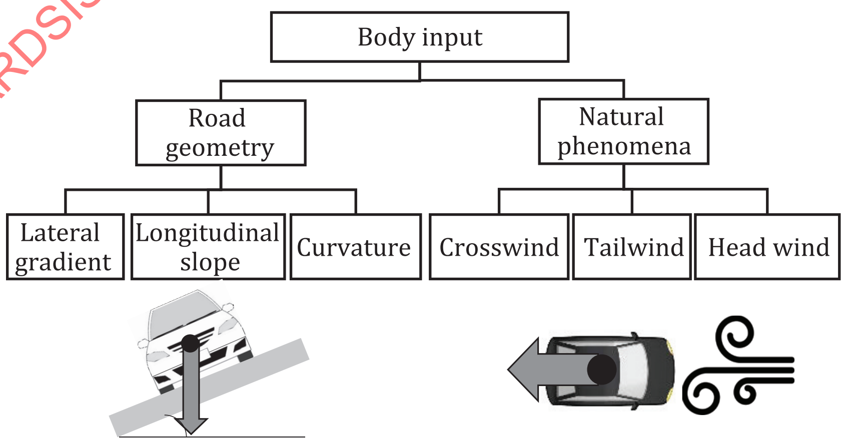
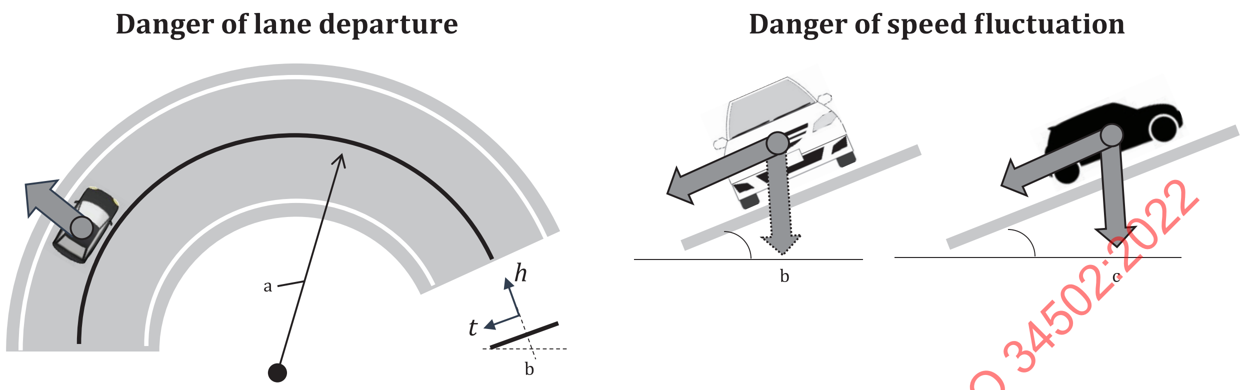


Figure D.2 — Body input related vehicle risk factors

Road geometry

The direction of the vehicle inertial and gravitational forces change depending on road geometry (e.g. curve) or shape (e.g. inclination). In the case of a curve, for example, a lateral inertial force is generated as the vehicle negotiates the curve, which may increase the risk of departure from the lane. In the case of a road superelevation or slopes, vehicle lateral and longitudinal forces are generated by gravity, which may induce lateral and longitudinal speed fluctuations that affect vehicle control (Figure D.3).



a Curve radius r(curvature).

b Superelevation.

c Longitudinal slope.

Figure D.3 — Classification of road geometry body input risk factors

Natural phenomena

Strong gusts of winds may generate lateral and longitudinal forces that affect the body of a vehicle. These forces may cause the vehicle to deviate from its lane or to collide with other vehicles due to fluctuations in its speed (Figure D.4).

NOTE For some vehicles other natural phenomena can become relevant.

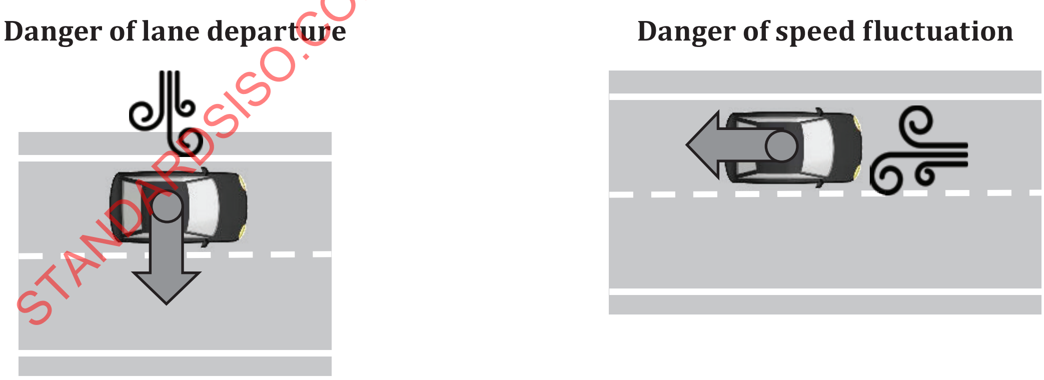


Figure D.4 — Natural phenomena (body input) vehicle-related risk factors

D.2.2 Tyre input related critical scenarios

Tyre input force related vehicle control related risk factors are divided into two subcategories related to road surface conditions and to tyre conditions. The road surface subcategory refers to changes in the road surface that affect the forces sustained by the tyres. For example, the coefficient of friction between the road surface and the tyre can change as a result of heterogeneous surface or rain, causing the tyre grip to decrease and possibly affecting vehicle control. The tyre subcategory refers to sudden or gradual changes in the state of the vehicle's tyres due to a tyre puncture or tyre wear (Figure D.5).

These tyre-related vehicle risk factors can cause instability and loss of control, resulting in critical scenarios.

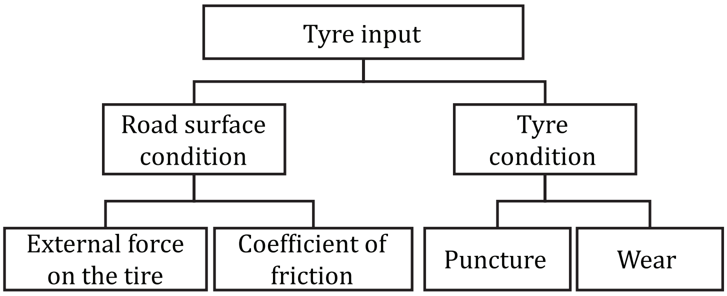


Figure D.5 — Tyre input related vehicle risk factors

Road surface condition

Tyre input vehicle control related critical scenarios may occur when forces are exerted onto the tyre as a result of a change in road surface conditions. This change may be due to either specific road surface changes that affect the friction coefficient between the tyre and the surface, or due to road surface conditions independent of the tyre itself, that induce a sudden external force on the tyre. The road surface risk factors are therefore classified into a friction coefficient and an external force (Figure D.6).

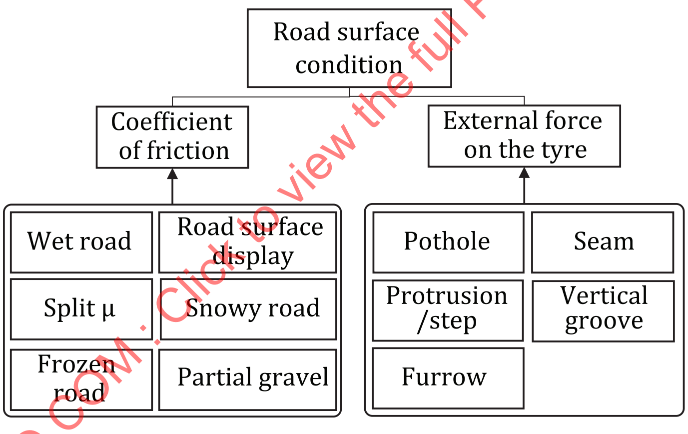
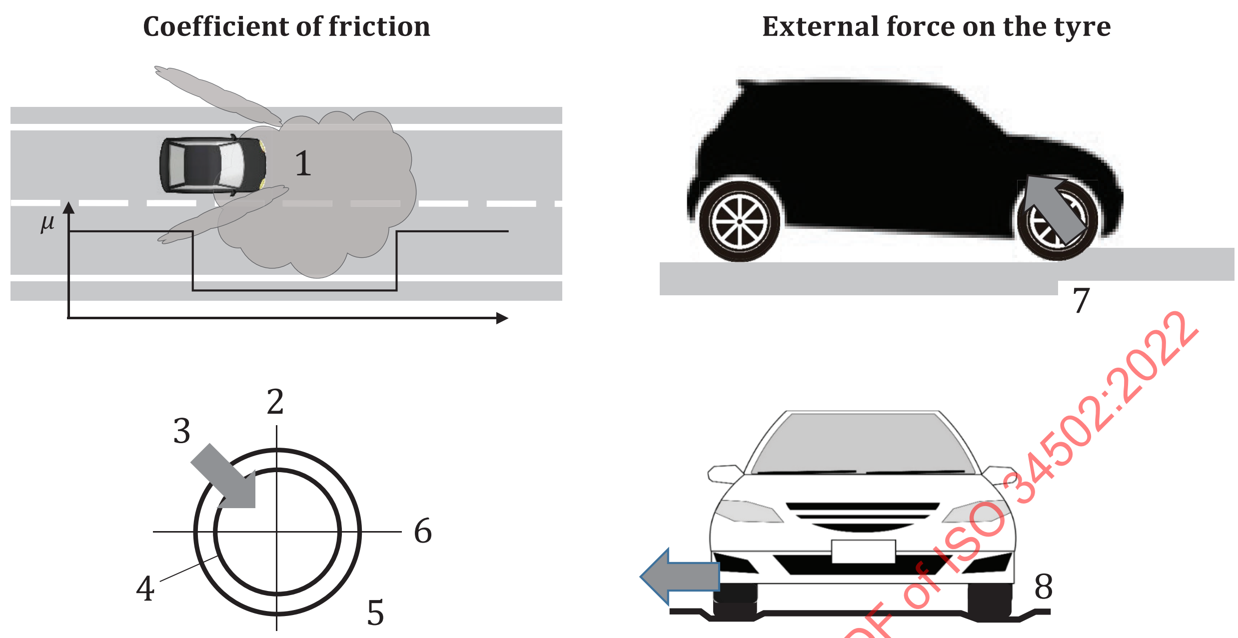


Figure D.6 — Road surface related vehicle risk factors

Road surface factors affecting the friction coefficient between the tyre and the road include: wet roads, frozen roads, snowy roads, partial gravel, etc. For example, when moving onto a wet area in the road from a dry one, a sudden drop in the friction coefficient may be induced (Figure D.7, left images). This drop may affect the vehicle's stability.

Road surface related external forces may be induced by potholes, protrusions, furrows, etc. For example, when a vehicle goes over a step or a protrusion on the road, a sudden force is applied to the tyre in an upward diagonal direction (upper right in Figure D.7) changing the direction of the vehicle. This change in movement could cause it to deviate from its planned trajectories, potentially resulting in a collision.



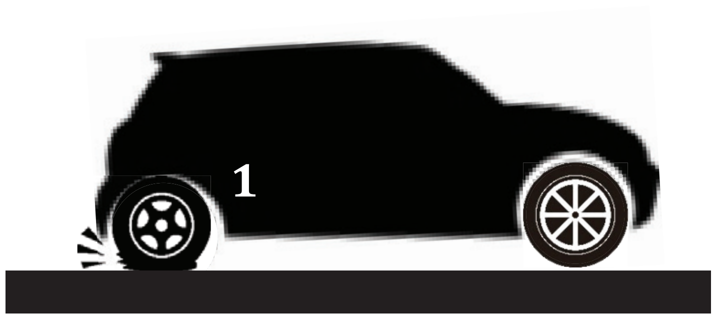
Key

1 WET road
2 front
3 friction circle
4 µSmall
5 µBig
6 side
7 step
8 rut/furrow

Figure D.7 — Road surface related vehicle risk factors

Tyre condition

A decrease in tyre condition can be sudden, such a puncture or burst (Figure D.8), or gradual, such as wear over time or a gradual loss of pressure. In either case, the tyre forces are altered which may result in a change in the vehicle's direction and risk of collision.



Key

1 burst

Figure D.8 — Illustration of tyre condition related vehicle risk factor due to burst

Annex E
(informative)

Derivation and structuring of scenarios using criticality analysis

E.1 General

The criticality analysis method[17][18] is designed to reveal the causes of criticality occurring in traffic situations, generally, and for automated vehicles in particular. To this end the traffic system itself is studied by identifying phenomena (e.g. observable concrete influence factors) related to an increase in criticality, when the traffic situation is continued. The criticality phenomena of the criticality analysis method correspond to the risk factors of this document. Criticality of a traffic situation denotes the combined risk of the involved actors to suffer any harm caused by the traffic. The criticality analysis aims to:

1) deliver **explanations** of the criticality phenomena by analysing the possible underlying causalities;

2) derive a **structuring** of the open context according to these causalities;

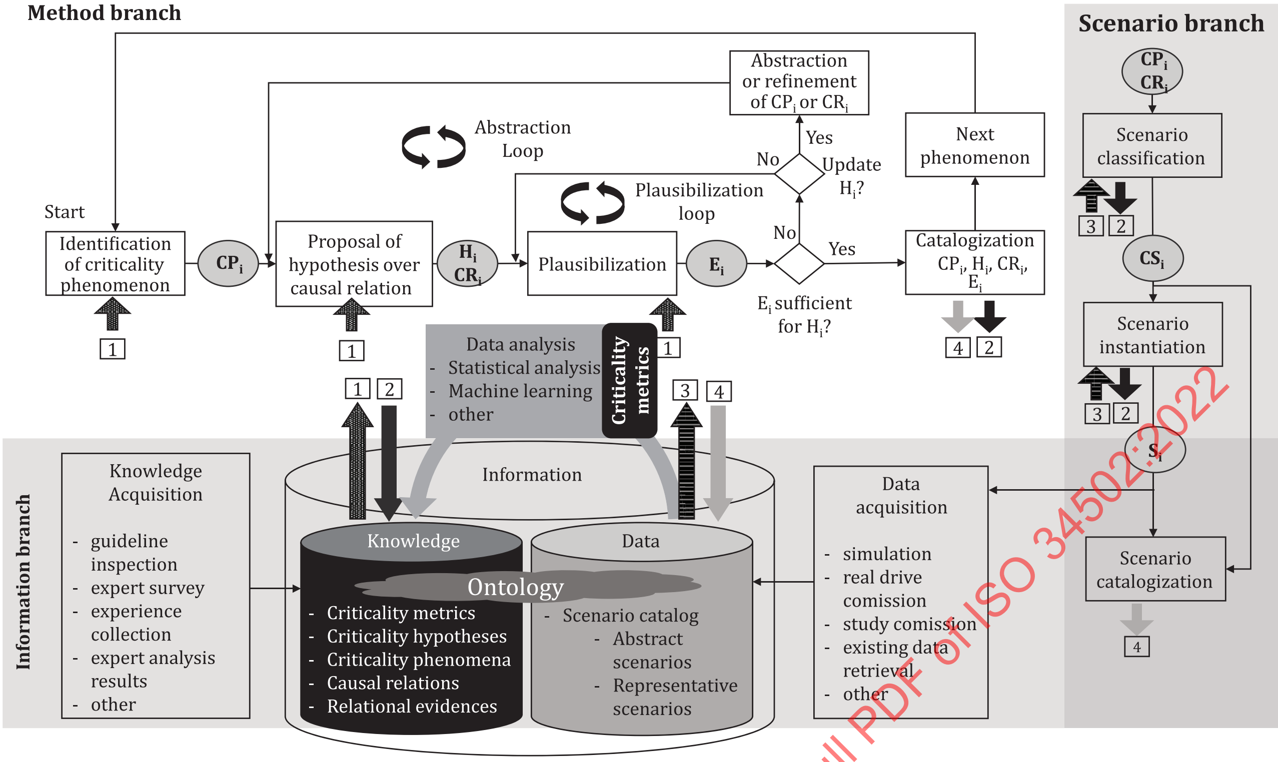
3) construct a **catalogue of abstract scenarios** based on the classification, including **representative instances**;

4) find an **adequate level of abstraction** for the criticality phenomena, explanations and scenarios;

5) achieve a **convergence** towards a manageable set of criticality phenomena.

The procedure of the criticality analysis is depicted in Figure E.1.

Figure E.1 consists of three branches interacting with each other: (1) the method branch explains the process of deriving causal relations within traffic and how to gather evidence for their plausibility, (2) the information branch covers the management of associated knowledge and data, (3) the scenario branch deals with the classification, abstraction and execution of scenarios.



Key

(ellipse)	artefact
(square)	connectivity point: arrow continues at number x
CP_i	i-th criticality phenomenon
CR_i	causal relation for CP_i
H_i	hypothesis for CR_i
H_i	hypothesis for CR_i
SC_i	scenario class for CP_i
S_i	scenario instance for SC_i

Figure E.1 — Overview of the criticality analysis

Criticality metrics play an important role within this framework. A criticality metric is a function, evaluated on a (discrete) set of measurements (in the case of real-world data) or values generated by a simulation engine (in the virtual case) with the goal to quantify the criticality of a traffic situation or scenario. It is used for checking the plausibility of causal relations, selection and filtering of data, data analysis, scenario classification, scenario instantiation, as well as for the refinement and abstraction steps.

E.2 Method branch

The basic concept of this step can be summarized as: pick a criticality phenomenon, improve understanding of phenomenon, and go to next phenomenon. To this end the workflow is as follows.

— Pick a criticality phenomenon.

The criticality analysis starts with extracting phenomena that are allegedly associated with increased criticality from available information about the domain of interest, e.g. expert-knowledge or related data.

— Improve understanding of phenomenon.

If a criticality phenomenon is deemed relevant, the goal is to derive an explanation for the underlying causal relation by means of an iterative process, establishing a hypothesis, evaluating the causal effects, and finally using a refinement and/or abstraction step to obtain a suitable hypothesis. If the evidence for the causal relation is statistically sufficient for the ensuing V&V process, it is accepted as a plausible explanation for the phenomenon.

— Go to next phenomenon - convergence.

For the criticality analysis to be effective in practice, it is necessary to establish the convergence of the number of identified criticality phenomena to the number of existing criticality phenomena.

Convergence follows from two fundamental assumptions:

a) the number of relevant criticality phenomena is limited and manageable;

b) the relevant criticality phenomena leave traces in a growing information basis.

Assumption a) is justified by the observation that an infinite number of criticality phenomena would already today hinder human drivers to operate reasonably safe in most situations. As the relevant criticality phenomena do exist in human consciousness on some level, it is likely that they can be identified using an ever-growing information basis comprised of all different kinds of data recorded with various sensor technologies. Even if relevant phenomena for the ADS are different than for humans, they will leave traces as data for automated driving accumulates, therefore justifying assumption b).

NOTE Scenarios can be classified according to manoeuvres, environmental conditions, presence of specific road users, etc.

E.3 Information branch

This branch contains the aspects of the method dealing with the management of information. Firstly, the foundations of the information branch approach are laid by introducing ontologies, a key enabler in formalizing and reasoning over the available information. The ontologies can cover, for example:

1) the automotive highway traffic domain, including concepts such as vehicles infrastructure and weather;

2) the criticality analysis domain, including artefacts like criticality phenomena, causal relations, etc.

The information branch also covers the issue of knowledge, information, and, data acquisition linking the derived criticality phenomena, causal relations, and scenario classes to the real world, e.g. using statistics.

E.4 Scenario branch

For various process steps of the method, it is required an adequate description of the interesting incidents and interactions within traffic. The point of view of a scenario is slightly different from a criticality phenomenon or a causal relation. The scenario is focused on describing the events in the surroundings of an ADS, e.g. the scenery and the actions of the involved actors. The criticality analysis uses scenario classification to complement the abstraction and refinement process described in step 2 of the method branch. Within this workflow, scenarios play various distinguished roles, they

— describe the happenings in traffic in a way that is comprehensible and can be interpreted for humans,

— enable the creation of a knowledge base, structured as a scenario database, and

— are also the glue connecting the workflow to simulation tools and real-world drives.

Scenario description

Four different qualification levels of scenario description can be used as shown in Figure E.2. In addition to the functional, logical and concrete scenarios, the criticality analysis additionally uses abstract scenarios, which are a formalized declarative description. This both human- and machine-readable description enables the expression of the derived causal relations as well as reaching the necessary degree of automation. Furthermore, the scenario description is the language used for the instrumentalization of the simulation engines.

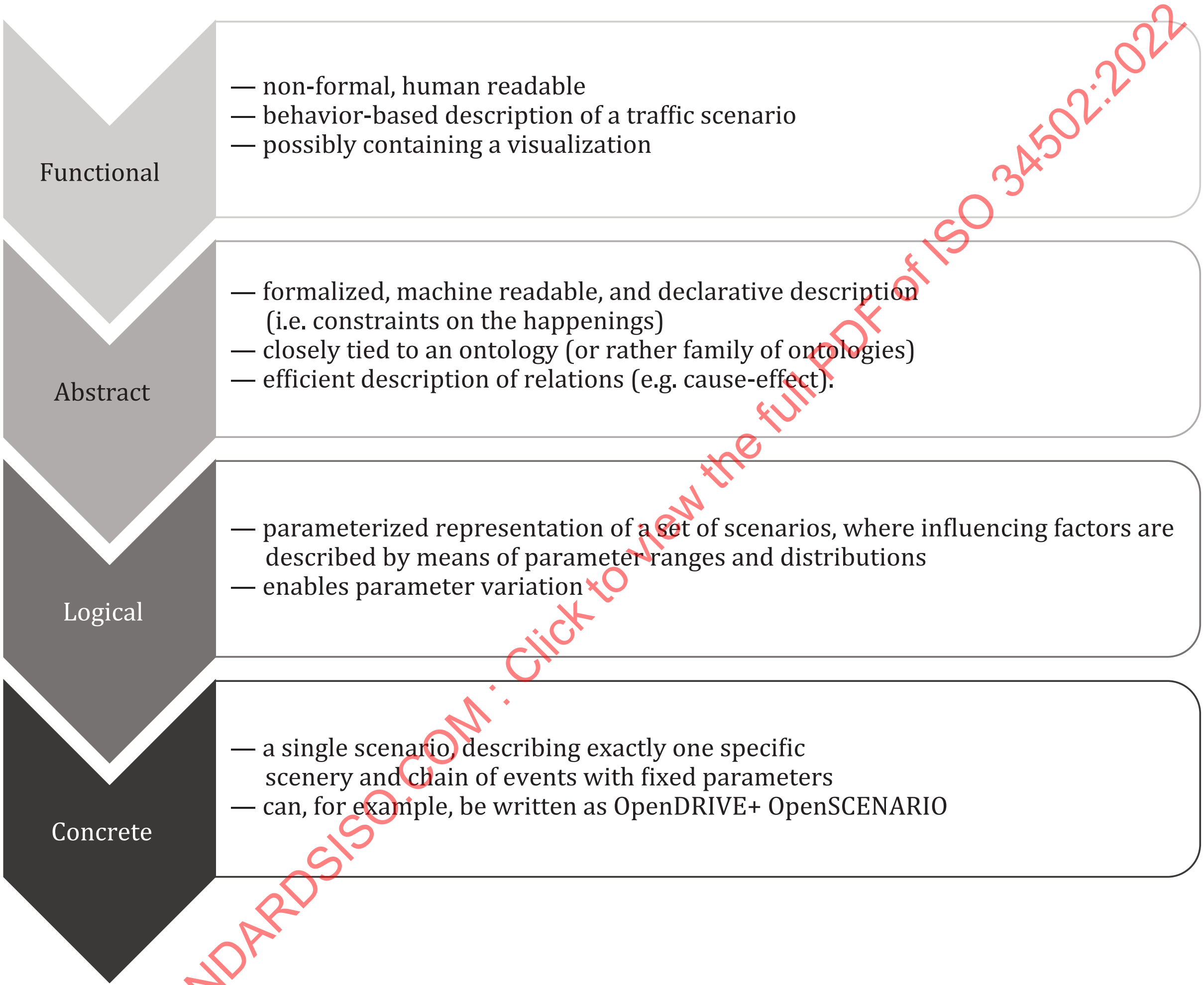


Figure E.2 — Qualification of scenario descriptions.

Scenario classification and structuring

The highly complex infinite scenario space requires the use of efficient structuring mechanisms. The SOCA method (System co-design for open context analysis)[19], patented by the Robert Bosch GmbH, laid out in a later section derives such a structure of equivalence classes based on the behaviour of the ADS and makes it possible to derive many scenarios in a structured way.

The analysis of the interaction of these decision models with the identified causal relations and the criticality phenomena enables the identification of a suitable abstraction level to aim for a manageable set of relevant causal relations. The scenario classes can then be used to obtain (i) a definition of done with respect to covering the scenario space and (ii) an input on where to look for new phenomena if the analysis is not yet done.

Scenario instantiation

The derivation of concrete instances of representatives of a scenario class is a necessary step to enable the execution of scenarios, e.g. in simulation, on the track test, or in real-world tests. Such a representative can be in form of a logical scenario as well as in the form of a single concrete scenario.

Scenario catalogue

The last step in the scenario branch consists of developing a catalogue with the emerging scenarios, as it is important to save and document scenarios that appeared in the criticality analysis. This catalogue of the created scenarios can be used to document the relations between the different levels of abstraction – abstract, logical and concrete scenarios. Furthermore, it is necessary to track the criticality phenomena or causal relations within the scenarios to allow for short iteration cycles when changes arise.

E.5 Structuring the scenario space with SOCA

SOCA has been developed with two main application areas in mind (Figure E.3). Firstly, SOCA is targeted towards analysing the externally observable behaviour of the system. On this level, SOCA does not make any assumptions on how the ADS is actually implemented or how it perceives the world around it. Secondly, SOCA can be used to specifically analyse the decision logic of a (rule-based) behaviour planner or the necessary abstract scenarios for testing (whatever kind of) a behaviour planner.

Since the real world offers a huge, if not infinite, variety of traffic situations that potentially need to be mastered by the ADS, suitable abstractions for handling traffic situations need to be introduced. To this end, SOCA uses two concepts: zone graphs for a geometric abstraction and a morphological behaviour analysis to derive equivalence classes based on the demanded behaviour of the ADS. This morphological analysis based on the SCODE method allows for a completeness check of the derived equivalence classes with respect to the used decision space in the analysis. These two components result in a model, which can provide a set of context-dependent system-level requirements. Furthermore, the model can be used to derive a suitable set of scenarios for testing.

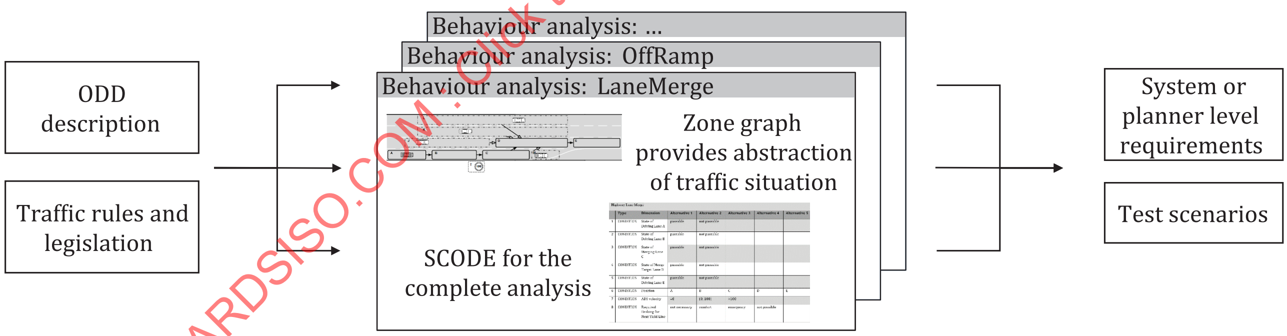


Figure E.3 — Structural overview of the SOCA approach

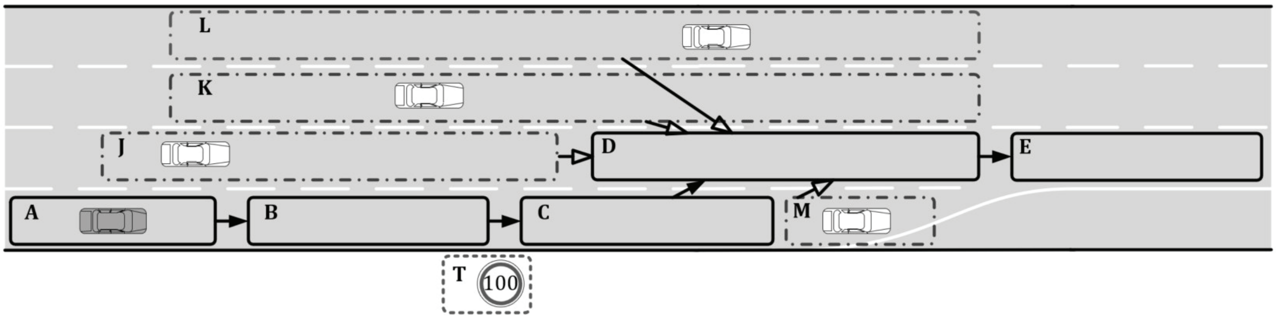
E.6 Using the zone-graph as abstraction mechanism

SOCA uses zone-graphs that abstract from concrete road geometries and concrete population with objects and other traffic participants. For each kind of scenery, for example, a 4-lane highway section, a single pedestrian crossing, or a multi-lane road, a zone graph is constructed for each ADS intention. Considering the 4-lane highway section depicted in Figure E.4, zone graphs are created. The zone graph is a topological abstraction of the actual layout (like road angle, curvature, lane width). There are three different kinds of zones used:

1) driving zones, where the ADS is passing through, connected by the (red) intention edges,

2) position zones, where other traffic participants may threaten the ADS on its path, and,

3) information zones, indicating areas with relevant information, e.g. a traffic light.



Key

- X — driving zone X
- intention edge
- Y — position zone Y
- threat edge
- T — information zone T

Figure E.4 — Exemplary zone-graph drawn on a schematic 4-lane highway for the vehicle on the right most lane

Driving zones and position zones can be populated individually with different traffic participants. The integration with an ontology is meaningful for automatic population of zones.

E.7 Structuring the decision space

Based on the illustration of the crossing, a Zwicky box is first created in order to apply SCODE for deriving the behaviour. A Zwicky box or morphological box is a representation of a discrete space given by the cartesian product of the dimensions. Each dimension represents an information aspect of the system's context that may be relevant for decisions and the behaviour of the corresponding system and is by a finite set of pairwise disjoint alternatives. Equivalence classes are defined by combinations of one or more alternatives for each dimension.

Table E.1 shows an exemplary Zwicky box for the merging manoeuvre shown. In the Zwicky box, one dimension was created for each of the areas of the intersection that the ADS needs to pass for performing the intended left turn. These areas are the two pedestrian crossings (F1 and F2), the intersection zone G, and the area H representing that the ADS may leave the intersection without coming to a permanent full-stop inside it. For the sake of brevity of this example, each of which only specifies two alternatives, namely "passable" and "not passable". Additionally, a dimension for the traffic light status was added with the different possible states, a dimension denoting the position of the AV inside the intersection referring to the aforementioned driving zones, a dimension for the velocity just distinguishing whether the vehicles moves or stands still, and finally a dimension that indicates how strong the vehicle needs to brake to stop at the next yield line.

Table E.1 — Zwicky box for a highway lane merge

Highway lane merge							
	Type	**Dimension**	**Alternative 1**	**Alternative 2**	**Alternative 3**	**Alternative 4**	**Alternative 5**
1	Condition	State of driving lane A	passable	not passable			
2	Condition	State of driving lane B	passable	not passable			
3	Condition	State of merging lane C	passable	not passable			
4	Condition	State of merge target lane D	passable	not passable			
5	Condition	State of driving lane E	passable	not passable			
6	Condition	Position	A	B	C	D	E
7	Condition	ADS velocity	= 0	(0, 100]	> 100		
8	Condition	Required braking for next yield line	not necessary	comfort	emergency	not possible	

Using this Zwicky box, the equivalence classes for the merge behaviour can now start being defined. The analysis is complete if the decision space is completely covered by the equivalence classes and if the equivalence classes are consistent, e.g. they have no overlaps. A bit more formally, completeness means that every combination that exists in the decision space has been added to at least one equivalence class. Consistency means that each combination from the decision space has been added to at most one equivalence class. In our example, a total of 11 equivalence classes was created, plus 1 non-system class that contains all combinations that cannot exist in the real world.

For this, the following, for example, is defined:

‘**Move at target velocity**’:

(State of driving lane A = “passable” and state of driving lane B = “passable” and position = “A”) or

(State of driving lane B = “passable” and state of driving lane C = “passable” and position = “B” and AV velocity = “(0, 100]”) or

…

‘**Adjust speed to find gap** ’:

(State of merging lane C = “passable” and state of merge target lane D = “not passable” and position = “C” and AV velocity = “(0, 100]” and required braking for next yield line = “not necessary”)

…

For each of the driving zone state dimensions, a separate additional analysis is carried out to derive the conditions on when it is ‘passable’ or ‘not passable’. Table E.2 shows the Zwicky box for merging zone D.

Table E.2 — Decision space for Merging Zone D

Merging zone D					
	Type	**Dimension**	**Alternative 1**	**Alternative 2**	**Alternative 3**
1	Condition	Merging zone D	occupied	free	
2	Condition	Upcoming traffic lane J	no threat	TP threatens D	
3	Condition	Merging traffic lane M	no threat	TP threatens D	TP waiting in M
4	Condition	Traffic lane K	no threat	TP threatens D	

Table E.2 *(continued)*

Merging zone D					
	Type	**Dimension**	**Alternative 1**	**Alternative 2**	**Alternative 3**
5	Condition	Traffic lane L	No threat	TP threatens D	

Two equivalence classes 'passable' and 'not passable' are defined here by the following rules:

'passable':

(Merging zone D = "free" and upcoming traffic lane J = "no threat" and merging traffic lane M = "no threat" and traffic lane K = "no threat" and traffic lane L = "no threat") or

...

'not passable':

(Merging zone D = "occupied") or

(Upcoming traffic lane J = "TP threatens D") or

...

E.8 Deriving scenarios based on the SOCA model

In summary, with the help of the zone graphs, a consistent decomposition into behavioural equivalence classes based on situations was developed through the modelling. Up to this point scenarios have not been in focus of the analysis. These describe processes in traffic and are used for simulations or tests. This clause shows how scenarios are derived from the previous models.

In contrast to a situation, a scenario describes a temporal sequence (of successive scenes). Here, scenarios mean abstract scenarios, for example, in the above highway section in Figure E.4, sequences are generated with different concrete states and predicted trajectories of road users, different populations of position zones, or different extents of the roadway itself. Concrete scenarios are then parameterized manifestations of these, which can be run in the simulation in this way. Furthermore, an expected correct behaviour of the ADS is assigned to a scenario.

Several different scenarios can be extracted from one situation. For this purpose, sequences of situations are extracted from the zone graph and the SCODE models based on a concrete intention of the ADS, e.g. merging on a lane on the highway, and (at least partial) specifications of the environment.

Such a sequence then describes an abstract scenario. Figure E.5 shows such a derivation. This approach then allows to generate individual sequences of conditions resulting in a specific sequence of ADS behaviour equivalence classes.

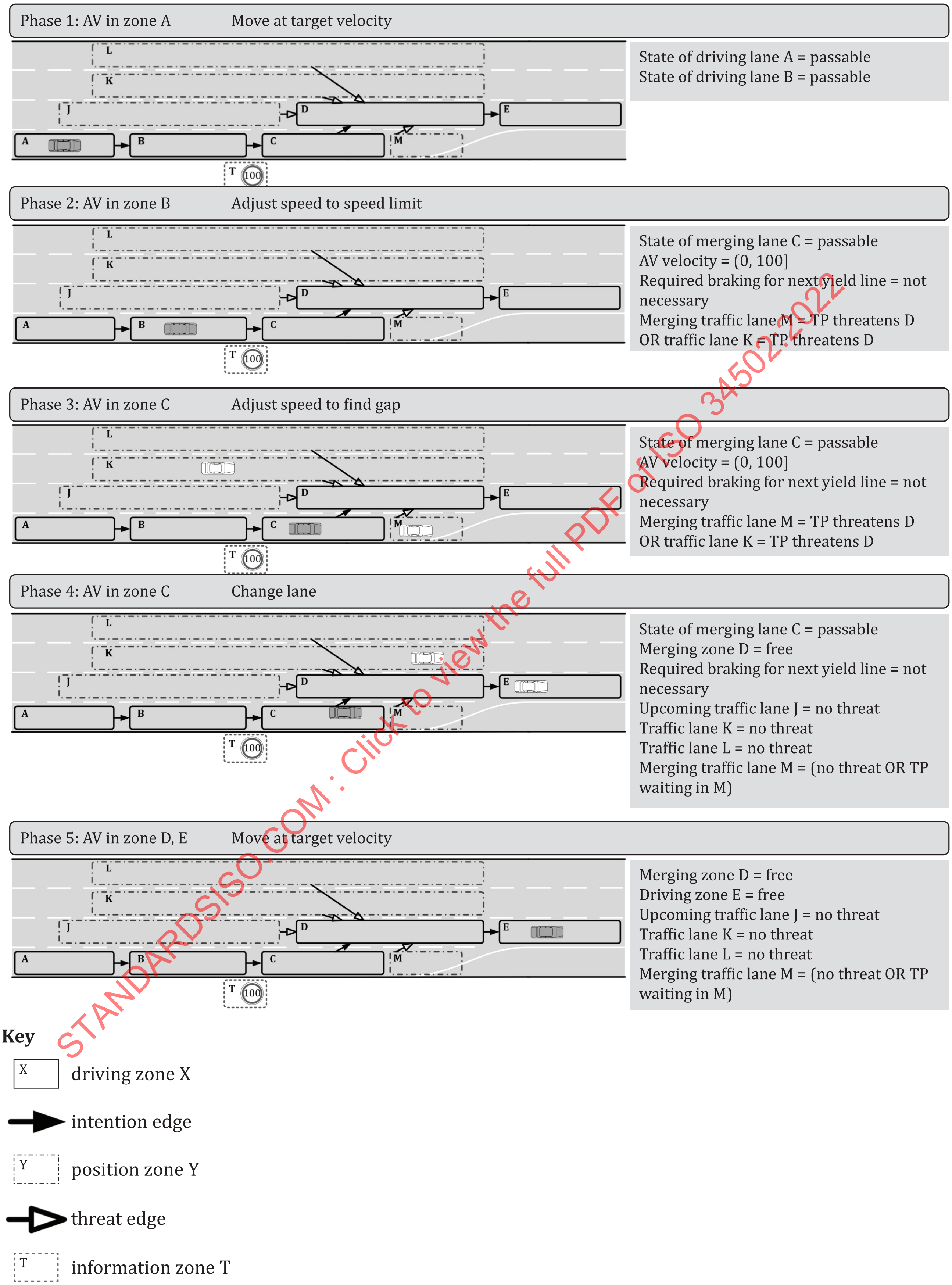


Figure E.5 — Derived formal abstract scenario for a highway merge example

Annex F
(informative)

Qualification of virtual test platforms

F.1 General

Simulation/virtual test platforms (VTPs) such as software-in-the-loop (SIL), hardware-in-the-loop (HIL), vehicle-in-the-loop (VIL), or model-in-the-loop (MIL) are typically used for test scenario evaluations that are not feasible on real-world test platforms (RWTPs), e.g. track testing and real-world testing, due to unacceptably high risks associated to the tests, and/or unreasonable amounts of data requirements and costs associated to the tests. Also, a much more detailed analysis of special scenarios is possible. The VTP includes the whole environment with all necessary tools and models (Figure F.1). The VTP has got a specific configuration, which is dependent on the use case. A VTP can be designed as open loop as well as closed loop and is a safety relevant element within the engineering framework for scenario-based testing of automated driving systems, in case of not purely using RWTPs. Different parameter variation, different scenarios as well as updates in components are extrapolations of the VTP and do not match with the validation points of the VTP, but are extrapolations of the validated area of the VTP.

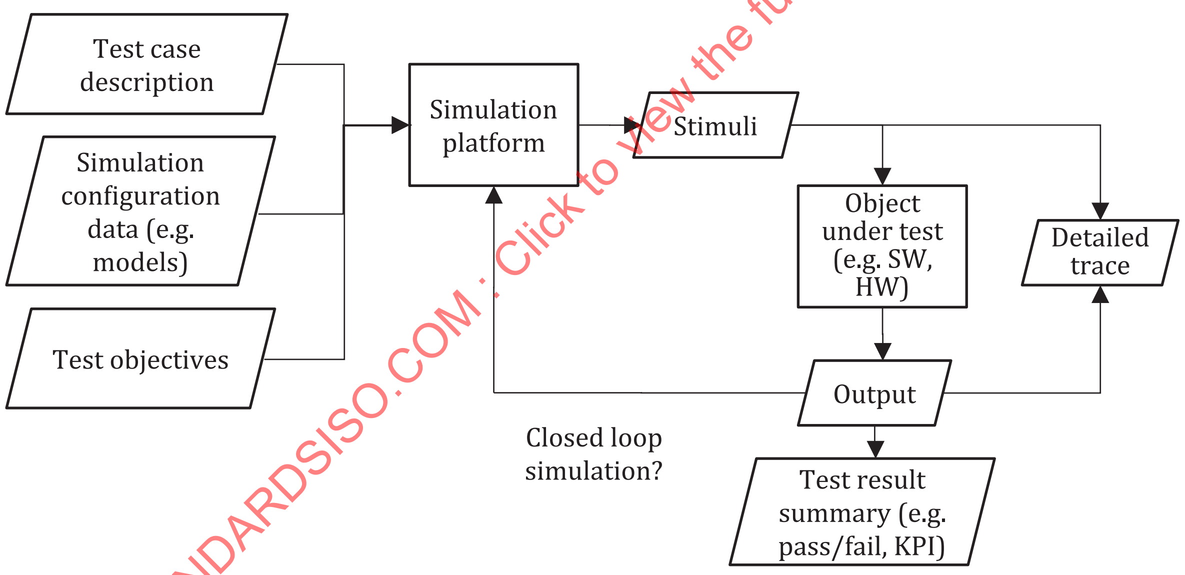


Figure F.1 — Generic VTP description

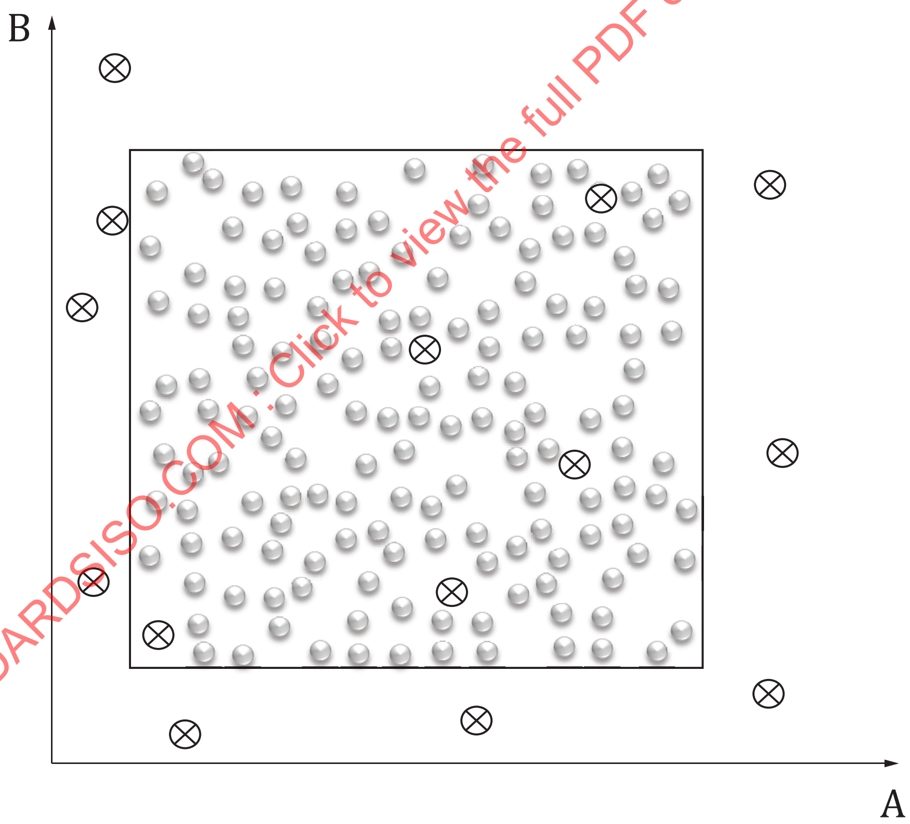
The validation of VTPs aims at showing that the evaluation result of a certain scenario is similar to that of a RWTP. The VTP is considered as valid for the evaluated scenarios only when the results deviation from RWTP is limited. This may be shown by verification of the validation process. One possibility is measuring the deviation between results of a certain scenario evaluated on a VTP and a reference from RWTPs. Thus, the error between a VTP compared to a reference can be statistically determined (=validation result).

The VTP validation can contribute to fulfil testing of the safety of the system (e.g. SOTIF safety requirements). The tools and models used for validation process are expected to be qualified based on state-of-the-art standards (e.g. functional safety according to the ISO 26262 series, vehicle model validation according to ISO 19364, simulation model taxonomy according to ISO 11010-1). Furthermore, VTPs are meant to produce repeatable and traceable results. The repeatability is allowed to vary within a predefined area, if non-deterministic models are integrated within VTP. The suitability of the VTP models also needs consideration. Finally, the models can be expected to be accompanied by documentation with regard to their capabilities, ODD, boundary conditions, assumptions and assignments.

After that the validity of the applied VTP (modelling and simulation tool) has been verified by means of comparisons with RWTP for certain concrete scenarios. The VTP can be utilized, for example, for the ranges of the corresponding logical scenarios, or for further vehicle variants fitted with the same ADS.

F.2 Extrapolation and validation of different components/subsystems

Intended operation of a VTP is typically the evaluation of scenarios for which no reference exists (e.g. extrapolation of the test space, interpolation in non-smoothness). Toolchain validation aims at increasing the trust on the results from the VTPs; it is considered as a necessary but not sufficient boundary condition for the use of VTPs. While the extrapolation accuracy of validation results can hardly be quantified for complex systems like AD, in addition to system validation, checks on components should be performed (e.g. test with complete ADS and separate sensor model) to increase the trustworthiness. Figure F.2 shows an extrapolation example including the relationship between RWTP measurements, a parameter range defined within the ranges defined by these measurements and a number of scenario variation for VTPs within the parameter range. The validation database is pictured in the background which covers typically a wider parameter range.



Key

A scenario parameter A

B scenario parameter B

⊗ measurement RWTP

(sphere) parameter range 1

(square) parameter range 2

Figure F.2 — Scenario variation example.

F.3 Criteria and natural metrics

Deviations of the VTP are quantified in terms of the intended test criteria, named key performance indicators (KPI). KPI with pass/fail criterion need to be well documented, together with clear statements that are considered for the evaluation of test results. KPI may be either macroscopic (e.g. accident avoidance capability for defined scenarios / manoeuvres, accidents per simulated kilometre calculated over several scenarios) or microscopic (e.g. minimum time to collision (TTC) calculated on one scenario). Final and intermediate signals may be evaluated with KPIs to increase trustworthiness. Since a KPI is usually a function of several VTP or RWTP output signals (e.g. relative object positions and velocities), additional use of metrics on the respective signals is recommended. One example of a metric for TTC is the root mean square error (RMSE) of the distance between the ego- and a surrounding vehicle.

F.4 Statistical evaluation

Toolchain validation aims for quantifying the expected deviation of a VTP with respect to a criterion by statistical means. The comparison of one scenario evaluated on the VTP and reference data are considered as one sample (Figure F.3). Several samples yield the test suite for a statistical evaluation (Figure F.4). This statistical evaluation is the baseline of the validation result.

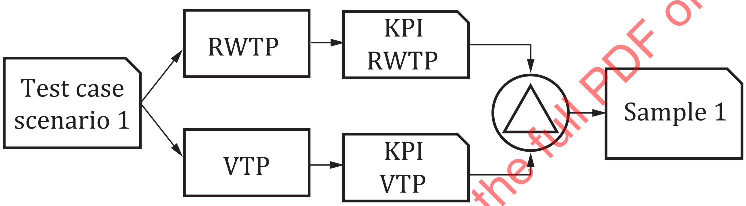


Figure F.3 — Sample calculated by comparing the result of a test scenario evaluated on a RWTP and a VTP

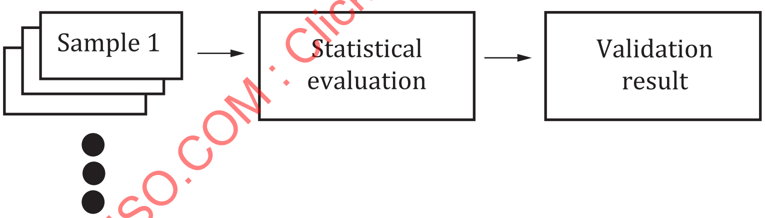


Figure F.4 — Test suite

F.5 Test suite

The test suite can be defined by a set of scenarios. Scenarios may be categorized by labels which determine the validity range of one specific validation result, which can be parameter ranges for logical scenario parameters. The labels are expected to be searchable in a larger data set in order to find the corresponding reference data (Figure F.5). One label may be associated to one parameter range. Test suite changes within the development process influences and therefore invalidates the validation result. Therefore ODD, boundary conditions, assumptions and assignment of the test suite should be well documented.