



Technical Specification

ISO/TS 21934-2

Road vehicles — Prospective safety performance assessment of pre-crash technology by virtual simulation —

Part 2: Guidelines and requirements for application

*Véhicules routiers — Évaluation prospective de la performance
sécuritaire des systèmes de pré-accident par simulation
numérique —*

Partie 2: Lignes directrices et exigences pour la mise en œuvre

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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

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This document was prepared by Technical Committee ISO/TC 22, *Road vehicles*, Subcommittee SC 36, *Safety and impact testing*.

A list of all parts in the ISO 21934 series can be found on the ISO website.

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

Active safety and advanced driver assistance systems (ADAS), collectively referred to in this document as active safety technologies, as well as automated driving technology have recently been introduced into the market. Their development raises questions about the extent to which these technologies prevent crashes and their ensuing injuries. These questions are of relevance to stakeholders such as vehicle manufacturers and suppliers, road authorities, research organisations and academia, politicians, insurance companies as well as consumer organisations.

The answers to these questions are derived from assessing the technology in terms of road traffic safety. There is a number of assessment methodologies in use (see ISO/TR 12353-4). In general, the current methodologies are divided into two types: retrospective assessments and prospective assessments. Retrospective methods determine the technology's safety effect after its market introduction based on accident data. A precondition for these methods is that sufficient accident cases with and without the technology have been recorded for a comparison in a certain vehicle subgroup or class. Prospective methods, on the other hand, predict the technology's safety effect before its market introduction.

This document focuses on the prospective assessment of traffic safety for vehicle-integrated technologies acting in the pre-crash phase by means of virtual simulation.

The safety performance of a technology is determined by comparing data from the baseline and treatment simulations. The baseline for the assessment is the simulation without the vehicle-integrated technology while the treatment is the simulation with the technology.

The assessment method that is described in this document is limited to vehicle-integrated technology and does not consider technologies operating off-board. The virtual simulation method per se is not limited to a certain vehicle type. Furthermore, the assessment approach discussed in this document focuses on crash avoidance and the technology's contribution to the mitigation of the consequences. Safety technologies that act in the in-crash phase or the post-crash phase are not explicitly addressed by the method, although the output from prospective assessments of crash avoidance technologies can be considered as an important input to determine the consequences of these technologies.

In general, the assessment of active safety technologies requires consideration of the interaction with surrounding traffic as well as the driver of the vehicle under test. Consequently, for a comprehensive assessment, the technology's safety performance must be analysed in a multitude of scenarios to cover all relevant circumstances that affect the critical situation. The virtual simulation approach allows for running large numbers of cases and offers a promising combination of flexibility, reproducibility and experimental control in the assessment of safety performance. The need for virtual simulations in the prospective assessment of safety technologies is generally recognized. This will have a positive impact on the comparability of results by virtual assessment.

The state of the art with respect to prospective safety performance assessment is described in ISO/TR 21934-1, which builds the foundation of this document.

Road vehicles — Prospective safety performance assessment of pre-crash technology by virtual simulation —

Part 2: Guidelines and requirements for application

1 Scope

This document specifies methods, guidelines and their application for prospective safety performance assessment of pre-crash technologies in road vehicles by virtual simulation. The purpose of the document is to provide prerequisites for the procedures to achieve comparable results among different safety performance assessments and tools.

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 8855, *Road vehicles — Vehicle dynamics and road-holding ability — Vocabulary*

ISO 12353-1, *Road vehicles — Traffic accident analysis — Part 1: Vocabulary*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 12353-1 and the following apply.

ISO and IEC maintain terminological 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 baseline

set of data to which the performance of the technology under study is compared when performing prospective assessments of performance of technologies

3.2 simulation block

grouping of at least two simulation models that are related to each other in terms of topic

3.3 collision

road vehicle accident event in which a vehicle strikes, or is struck by, another vehicle, road user or obstacle (on or off the road), with ensuing damage and/or injury

Note 1 to entry: In simulation, a collision is typically detected once the volumes of two objects overlap in an infinitely small manner.

[SOURCE: ISO 6813:1998, 3.3, modified — Note 1 to entry added.]

3.4

conflict

situation in which at least two road users are involved and which leads to a collision in the near future if no actions is taken

Note 1 to entry: The definition of conflict is based on Reference [8].

3.5

data point

set of one or more discrete measurements on a single member of a unit of interest

EXAMPLE Vehicle mass and velocity.

3.6

data series

description of multiple data points that are linked via another type of information

EXAMPLE The velocity over time measured during the simulation for the centre of gravity of the vehicle under test.

Note 1 to entry: Typically, the type of information that links the data points is time.

3.7

deterministic simulation model

model that produces the same result when simulated twice with the same inputs and parameter values

3.8

distribution-based pre-simulation model

model that includes a distribution for at least one of the simulation parameters defined by the pre-simulation model

Note 1 to entry: Most pre-simulation models are distribution-based. The following are examples of distribution-based simulation models:

EXAMPLE 1 A simulation parameter (e.g. the road friction coefficient or a system parameter such as maximum intervention deceleration) is sampled at specific values within a range and a simulation is run for each of these parameter values.

EXAMPLE 2 Like EXAMPLE 1, but with a nonuniform distribution for the simulation parameter (e.g. driver brake reaction time). A simulation parameter, such as Monte Carlo, is sampled for each simulation run from a probability distribution (either defined on a closed mathematical form, such as a lognormal distribution, or defined as an empirical, numerical distribution).

EXAMPLE 3 Like EXAMPLE 2, but instead of a Monte Carlo-style draw, only one simulation is carried out per simulation parameter's bin in an empirical distribution. The simulation results are weighted accordingly in a post-processing step.

Note 2 to entry: If a pre-simulation model is not distribution-based, it transforms parameters provided by the simulation framework user to other parameters needed by the simulation model (e.g., simple unit conversions or calculating model update matrices for a linear vehicle model from parameters specifying vehicle mass, tire stiffnesses, etc).

3.9

driver

vehicle occupant in actual control of a vehicle, or who was in control before that control was lost or taken over by a technology

3.10

event

state change at a certain point in time

3.11

injury risk function

description of the probability of an injury or fatality in relation to collision attributes

Note 1 to entry: The most frequently used injury risk functions describe the probability of an injury of a specific severity in relation to collision severity, for example impact velocity or change of velocity during collision.

3.12

in-simulation model

model that is part of the simulation framework and is updated for each time-step in the simulation

3.13

model

covers at least one (physical) domain (e.g. mechanical or electronic) and can consist of different process steps and calculations

Note 1 to entry: A simulation model can also be a container to a collection of simulation models.

3.14

non-deterministic simulation model

model that can produce different results between simulations even when inputs and parameters are constant

Note 1 to entry: Non-deterministic simulation models are often probabilistic, including some form of random draw occurring during the simulation. A probabilistic model becomes deterministic if the random seeds are assigned fixed values.

3.15

penetration rate

number of vehicles of a certain type equipped with the technology under assessment compared to the total number of vehicles of that type in a certain geographic area

3.16

probability distribution

function that describes the probabilities of outcomes of a random event

Note 1 to entry: A probability distribution of a sufficiently large sample size can be used to make inferences about the distribution of a population.

3.17

pre-crash phase

time phase immediately prior to the crash

Note 1 to entry: This phase ends with the contact between participants or objects involved in the crash.

Note 2 to entry: In this document, the pre-crash phase covers normal driving and critical situations up to the point of contact.

3.18

pre-simulation model

model that is part of the simulation framework outside of the simulation over time

Note 1 to entry: Such models are used to determine and set parameters for the in-simulation models.

3.19

projection

estimation of time or space changes for a population or target area based on the results of a smaller sample of input data

Note 1 to entry: A projection can be conducted either in time or space or in both dimensions. The time projection is an estimation of (future) changes for a population based on the results of a reference period. The space projection is an estimation of changes for a target area based on the results of a smaller sample/subset of input data.

3.20

prospective assessment

predictive assessment of the future performance of given technologies before their deployment into a vehicle population

3.21

real-world data

data collected in a non-virtual situation and environment

3.22

representative

sample that is an available subset of a population

Note 1 to entry: The sample is representative of the population for a set of features if their statistical characteristics (e.g. proportion, distribution) match those of the entire population.

3.23

research question

question that a research project is designed to answer

Note 1 to entry: A research question defines the scope of a prospective safety performance assessment by simulation.

3.24

retrospective assessment

assessment of the past performance of given technologies after their deployment into a vehicle population

3.25

safety critical event

SCE

conflict or series of related conflicts that involves the subject vehicle either alone or in combination with another vehicle, pedal cyclist, pedestrian, object or road edge

Note 1 to entry: This document describes the range of conflict types that may comprise an SCE and an SCE may be composed of a single conflict type or multiple simultaneous or sequential conflict types. Conflicts should be non-intentional and non-premeditated (unplanned) by at least one conflict partner.

[SOURCE: ISO/TR 21974-1:2018, 3.13]

3.26

safety performance

quantified capability of a technology to achieve an improvement in road traffic safety

3.27

scenario

description of the traffic, infrastructure and environmental conditions (e.g. weather and lighting conditions) for the simulation that consists of a time sequence of scenes

Note 1 to entry: A scenario is limited in terms of time and space.

Note 2 to entry: A scene describes a snapshot that encompasses the mobile and immobile elements of the traffic, infrastructure and environmental conditions, the self-representation of all actors and observers and the relations between these elements.

3.28

scenario category

selection of scenarios that share one or more characteristics

3.29

severity

estimate of the extent of harm to one or more individuals or of property damage that can occur in a potential collision

3.30

simulation

enactment of a situation with artificial conditions, typically performed by updating models over discrete time steps

3.31

simulation framework

aggregate of all components in a simulation including all simulation blocks and models

Note 1 to entry: Process steps outside the simulation (e.g. post processing) are not part of the simulation framework.

3.32

traffic agent

anyone who uses a road including sidewalk and other adjacent spaces

3.33

technology

collection of vehicle-implemented techniques, processes and systems capable of temporarily or permanently taking control of the vehicle and from which the expected safety benefit is predicted in the prospective assessment

3.34

test

use of quantitative measures to evaluate technology under a set of specified conditions, with reference to values that represent an acceptable outcome

3.35

treatment

use of a specific technology to affect the course of events in a scenario to avoid or mitigate crashes when performing prospective assessments of performance of technologies

Note 1 to entry: Treatment simulations provide data on the performance of the technology under assessment to compare with baseline data.

Note 2 to entry: See [3.1](#).

3.36

validation

confirmation, through the provision of objective evidence, that the requirements for a specific intended use or application have been fulfilled

Note 1 to entry: For the prospective safety performance assessment, it is important that the results of the virtual assessment are reliable (i.e. the results are reproducible under the same conditions) and trustable (i.e. the results are consistent with the real-world safety performance of the technology).

3.37

vehicle under test

VuT

vehicle that is focused on in the safety performance assessment

Note 1 to entry: In the treatment, this vehicle is equipped with the technology under assessment.

3.38

verification

confirmation through the provision of objective evidence that (internal) requirements of the safety performance assessment process and tool (including methods and models) have been fulfilled

4 Symbols and abbreviated terms

4.1 Symbols

E_{EES}	energy equivalent speed
E_{def}	kinetic energy dissipated by the vehicle during the contact phase by deformation
$I_{\text{Baseline},i}$	severity of (injury) type i in the baseline simulation
$I_{\text{Treatment},i}$	severity of (injury) type i in the treatment simulation
P_{CR}	crash rate
P_{K}	probability of being killed in a crash
P_{KSI}	probability of being killed or severely injured in a crash
P_{VR}	victim rate
S	safety performance
S_i	safety performance of the injury severity, i
d_{Cyclist}	distance of a cyclist to a reference point (position or another vehicle)
d_{DLC}	distance to the lane
d_{Rel}	relative distance between two objects
d_{VUT}	distance of the VuT to a reference point (position or another vehicle)
$f_{\text{Baseline},i}$	occurrence frequency of a scenario with injury level i in the baseline
$f_{\text{Treatment},i}$	occurrence frequency of a scenario with injury level i in the treatment
m	mass
n_{coll}	number of collisions either in the baseline or treatment simulation
n_{vict}	number of victims either in the baseline or treatment simulation
N_{sim}	number of simulations either in the baseline or treatment simulation
t	time
$t_{\text{collision}}$	time of the collision
t_{THW}	time headway
t_{TLC}	time to line crossing
t_{TTC}	time to collision
Δt	time step
x	longitudinal position
y	lateral position
v	velocity

v_{Rel}	relative velocity between two objects
v_{VUT}	velocity of the vehicle under test

4.2 Abbreviations

AIS	abbreviated injury scale
ADAS	advanced driver assistance system
AEB	autonomous emergency braking
COG	centre of gravity
CSV	comma-separated values
CVNB	car-to-vulnerable road user near-side bicycle
DLC	distance to line crossing
DP	data point
DS	data series
EDR	event data recorder
EES	energy equivalent speed
FCW	forward collision warning
FE	finite element
FoV	field of view
FOT	field operational test
HIL	hardware in the loop
I2V	infrastructure to vehicle
IRF	injury risk function
KSI	killed or severely injured
MAIS	maximum abbreviated injury scale
NCAP	new car assessment program
ND	normal driving (not safety critical)
NDS	naturalistic driving study
PD	probability distribution
PET	post encroachment time
THW	time headway
TLC	time to line crossing
TTC	time to collision

V2X	vehicle to x (vehicle, pedestrian, cyclist and/or infrastructure) communication
VR	victim rate
VRU	vulnerable road user
V&V	validation and verification
VuT	vehicle under test
V2V	vehicle to vehicle
XML	extensible markup language

5 Overview: A general description of the process for prospective safety performance assessment of pre-crash technology by virtual simulation

5.1 General approach and structure

To estimate the performance of technologies designed to avoid or mitigate crashes, the analysis of a high number of scenarios is needed. The general process for prospective safety performance assessment of pre-crash technology by virtual simulation is described in [Figure 1](#) and builds up on ISO/TR 21934-1.

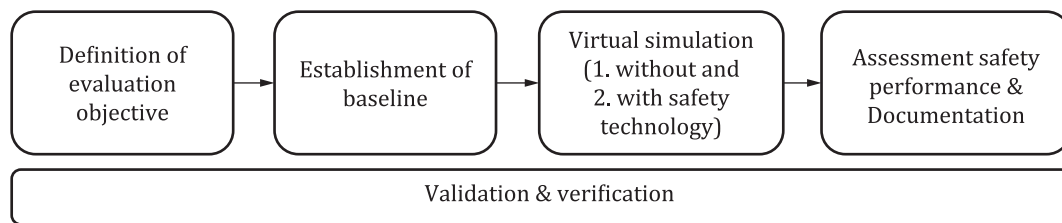


Figure 1 — Overview of the prospective assessment of traffic safety process for vehicle-integrated technology by means of virtual simulation

The process does not provide any development guidelines or assessment results in terms of functional safety (the ISO 26262 series) or safety of the intended functionality (ISO 21448). These topics are covered by other ISO documents. Furthermore, no recommendations are given with respect to the usage of certain input data sources or simulation tools. No methodology advises are given for the scaling up and projection of the simulation results which is often conducted in conjunction with this type of assessment.

5.2 Input data

Input data are required in all parts of the prospective safety performance assessment by simulation. An overview of the information type that is required for the simulation models and process steps and their relevance is given in [Table 1](#). Information about possible data sources is given in ISO/TR 21934-1. The technical format and the type of the input, as well as the definition of minimum required information is crucial for safety performance assessments.

Table 1 — Overview on relevance of information for the stages of the prospective safety performance assessment

	Simu- lation con- trol	Vehicle surrounding			Vehicle under test			Collision
		Infra- structure	Environ- mental conditions	Traffic	Vehicle	Technol- ogy	Driver	
Definition of eval- uation objective		(X)	(X)	X	(X)	X		X
Establishing the baseline		X	X	(X)	X		X	X
Virtual simulation with and without technology	X	(X)	(X)	X	X	X	X	(X)
Estimation of the safety perfor- mance		(X)	(X)	X	X		X	X
V&V	X	X	X		X	X	X	X
NOTE "X" means the information is always relevant; "(X)" means the relevance of the information depends on the research question.								

A combination of different information and/or different information sources can be applied to derive the required input information. Input data can serve four main purposes:

- generate (in the sense of digitizing, replicating, reconstructing or sampling) baseline scenarios (either completely or in part);
- development and parameterisation of simulation models (e.g. driver, vehicle, technology);
- V&V of the prospective safety performance study as a whole, of models or created crashes (and other created traffic situations);
- scaling up and projection.

The input type is either a single DP, a series of DPs or a PD (see [3.5](#) and [3.16](#)). Independent of the input type, the quality shall be ensured by checking the validity of the data as well as its source. The assessment result is sensitive to the complex interplay of input data and its usage along the process chain. The following three aspects shall be considered:

- 1) Ensure data quality and representativeness for prospective safety performance assessment.

The simulations consist of models that intend to replicate and predict relationships between variables of interest of a real-world system as accurately as possible. However, these mathematical models are not real-world systems and are therefore inherently subject to uncertainties. Biases of the input data influence the descriptive and predictive power of the models. To assure an unconfounded and valid safety performance assessment, input data are checked for their validity and, if possible, quantified by confidence intervals. The generalizability of the estimated safety performance depends on the representativity of the simulation and its models. Specifically, since the models rely on the input data, the representativity of input data for the defined evaluation objective shall be checked and reported.

- 2) Guidelines for checking data quality criteria.

Due to the complexity and diversity of traffic, it is not possible to provide a universal and generally accepted method to quantify the above-mentioned quality criteria (including representativity) for input data to the assessment process. A qualitative decision process for the grading of used input sources should be applied in the assessment when available.

- 3) Transparent communication of the used input data sources.

For a transparent assessment, the used data source shall be reported in the documentation (see [Clause 10](#)). This includes results of the data quality assessment according to item 2) of this subclause.

To allow external stakeholders to generally understand the assessment and decide whether the assessment is reasonable, the following approach should be used:

First, information shall be provided on the input data for establishing the baseline (see [Clause 7](#)), which can either be one single source or a combination of multiple sources. The following aspect shall be stated:

- characteristics of the data source(s) used for establishing the baseline scenarios:
 - data on crashes
 - data on critical events (i.e. near-crash data)
 - data without crashes (i.e. non-critical driving data)

In addition to describing the used database(s), any selection process (inclusion and exclusion criteria) for the study shall be described as well. If the scenarios have been provided by a third party, a reference to the project/report that provides information about the origin of scenarios shall be mentioned.

The following are examples for this first step in documenting the source of data (for baseline approaches, see [Clause 7](#)):

- using baseline approach A, digitized crashes from crash database “nn1” of the time frame 2010 to 2017 were used;
- using baseline approach C2, crash database “nn1” was used for input when designing driver model “x”. FOT dataset “nn2” was used to design the traffic model “y”. Then, these models were used to create crashes for the baseline in a setup where the digitized maps in “nn3” was used to represent the streets.

Additional information about the used data source can be added optionally, but this is not required for the first item.

Secondly, information that is relevant for understanding the complete simulation process shall be provided. This concerns all data that have been used within the process. To provide a comprehensive overview, a description of the data collection method, their representativeness with respect to the evaluation objective, and if different datasets are used, how well they match each other should be presented. In general, references should be used wherever possible to facilitate documentation. These references shall be accessible to any organization or person that has an interest in the results of the assessment from a professional point of view. The interest is driven by the needs of a person or organization to assess the correctness of the assessment result(s).

For the development and/or parameterization of models and scenarios, different data should be used than the data used for the V&V. If the same data has been used in development and/or parameterization, it should be made clear why the data can also be applied to the V&V.

[Table 2](#) should be filled for documentation.

Table 2 — Information on input data for documentation

Input data are used for...	If input data are used for development or V&V of simulation models:		Type of input data (indicating purpose)	Details on the input data (collection and processing)	Details on the input data (representativity)
	Model	Parameter of the model			
— Baseline (digitization of traffic situations or traffic specific layers)	Model name (see Clause 8)	Depends on the model	List with type of data: see Table 3	Depending on input data, see Table 3	Depending on input data, see Table 3
— Develop sim. models					
— V&V					

Information should be provided in a table that informs (per aspect of the model) which data sources have been used, how the data collection and processing was done and how representative the data are. Examples for reporting on used data sources are given in [Annex A](#).

For different types of input data, different aspects are relevant to document. An overview of the items that shall be reported at least per input type is given in [Table 3](#).

Table 3 — Items to be reported for different types of input data

Type of input data	Details on the input data (collection and processing)	Details on the input data (representativity)
Experiment data (FOT/NDS/static FOT, driving simulator or study in controlled field)	— Data collection method (used tools, vehicles data logging equipment etc.) — Data analysis/aggregation processes — Considered filter criteria in the study (e.g. for specific events like near-crashes incl. trigger conditions)	— Amount of logged data (km driven and/or driven time) — Region and time of data collection — Primary purpose of the study — Number of involved vehicles and test persons (+ demographics) — Limitations in the access to the data
Crash data (reconstructed, digitized accident data as provided in detail crash databases)	— Data recording process — Digitizing process (tools, assumptions for non-measurable indicators) — Applied weighting procedures (if applicable) — Considered filter criteria in the data collection (e.g. certain accident types)	— Number of accident cases — Overall mileage of the considered population (if it can be determined) — Covered types of accidents — Region and time of data collection — Primary purpose of database and its operator — Limitations in the access to the data
Aggregated crash data (i.e. crashes are not reported individually as in e.g. national accident statistics)	— Data recording process (police report, insurance data, on-spot analysis incl. sketch, post-crash measurement, EDR etc.) — Applied weighting procedures (if applicable) — Considered filter criteria in the data collection (e.g. just personal injury)	— Number of accident cases — Overall mileage of the considered population (if it can be determined) — Covered types of accidents — Region and time of data collection — Primary purpose of database and its operator — Limitations in the access to the data
Environment(al) data (infrastructure data, traffic flow data, weather data)	— Data collection method — Conducted analysis/aggregation steps — Considered filter criteria in the database	— Amount of data — Region and time of data collection — Primary purpose of the database and its operator — Reference if available — Limitations in the access to the data
Other (literature review, scientific article, reports, studies etc.)	— Data collection method — Data analysis/aggregation processes — Description which and where information of the document has been used — Description of the conducted study/analysis — Considered filter criteria in the study (if applicable)	— Type of publication — Information about the publication (author, year, location, publisher etc.) — Primary purpose of study and its operator — Limitations in the access to the data — In case of study, number of persons included and randomization procedure

Any information that is required to do the assessment since it has a quantifiable impact on the traffic safety indicators builds the minimum required information. This minimum required information strongly depends on the assessment scope. If the required minimum information is not available and cannot be derived from alternative information, the assessment cannot be conducted.

As an approach for deriving the minimum required information, the following steps should be considered:

- identify all potential inputs that can influence the results of the virtual simulation and evaluate them regarding their relevance for the given evaluation aspect (e.g. information about road friction becomes relevant once a technology intervenes in the vehicle dynamics and different weather conditions should be considered);
- identify systematically the required input information for the models that are applied in the simulation (e.g. road friction for the vehicle model). A list of models with example input information is given in [8.2](#);
- check the derived minimum required information set for plausibility based on the available input data. Critical aspects are:
 - No information is available for a required input. In this case, it should be checked in the following order: whether the input can be substituted or derived by other input(s) for which information is available; whether another model with similar output is available that does not require the information; whether the input can be described based on expert opinion.
 - Two information sources provide a similar input (e.g. distribution of road friction and weather). It should be checked whether the information can be merged into a larger information source.
 - Two information sources contradict each other (e.g. weather is sunny at 30 °C and the road is icy). In this case, it needs to be decided which information source is more trustworthy. This information source should be used.

Independent of the critical aspect and the steps taken, the aspect itself as well as the related decision and conducted steps shall be reported in the documentation of the study under the data section.

Input data for the steps in the safety performance assessment process are presented in the following clauses. Only the minimum required information is presented for the chosen example (see [6.2](#)). The minimum required information for the baseline approaches is given in [7.2](#), for the virtual simulation in [8.3](#) and for the assessment of the safety performance in [9.2](#).

NOTE Only the simplest form of a model that is required to answer the research question is used. For example, the vehicle model considers a simple point mass model that represents only the longitudinal behaviour.

6 Evaluation objective

6.1 Process for identification of the evaluation objective

This clause gives guidelines for the definition of a valid research question and the target of a prospective safety performance assessment study, including the identification of relevant scenarios and appropriate metrics. The target of such studies is formulated by two types of processes:

- A technology-driven process, in which a request is put forward to estimate the safety benefit of a technology. This technology is defined at the time of the study; it could be an idea, a concept, a product under development (bottom-up approach).
- A traffic safety-driven process, in which existing or expected safety problems are identified as well as categories of scenarios that should be addressed. In this context, the safety problems are defined by common relevant attributes of scenarios (e.g. weather, type of traffic participant, accident type). In this case, the target for the study is not linked to a particular technology but to an area with a lack of traffic safety that should be addressed (top-down approach).

An evaluation objective for a study of a prospective safety performance assessment consists of three elements:

1. definition of a precise research question;
2. identification of relevant scenario categories;
3. definition of evaluation metrics to be applied, for example “percentage of avoided crashes” or “fatal injury reduction for involved traffic participants”.

These three elements should be defined as a first step in such a study.

6.2 Definition of a precise research question

The research questions shall be precisely formulated and accessible such that the results of different studies can be compared. The research questions shall define what will be assessed and why. The research questions should address each of the following categories:

- the metric to be used;
- the technology under study, including the type of technology and penetration rate;
- the scenario or scenario categories;
- the limitations (environmental conditions, infrastructure etc.);
- the region and time horizon of the projection;
- the level of confidence envisioned in relation to the objective of the research question;

By combining these categories, various but harmonized research questions can be generated.

One example research question that is used in this document (see [7.2](#), [8.3](#), [9.2](#)) is:

What is the safety performance of a VRU AEB (warning + autonomous intervention) at a penetration rate of 100 % in car-to-cyclist crashes on urban roads in terms of MAIS 2+ injuries related to the situation in Europe in 2017?

6.3 Identification of relevant scenario categories

Relevant scenario categories should be identified by analysing retrospective accident data, naturalistic driving data, data from field-operational tests, knowledge gathered during technology development (including potential benefits or disbenefits) or a combination thereof.

For the specific technology under assessment, the relevance of a scenario and scenario category depends on whether it is influenced by the technology either positively or negatively.

6.4 Metrics in prospective safety performance assessment by simulation

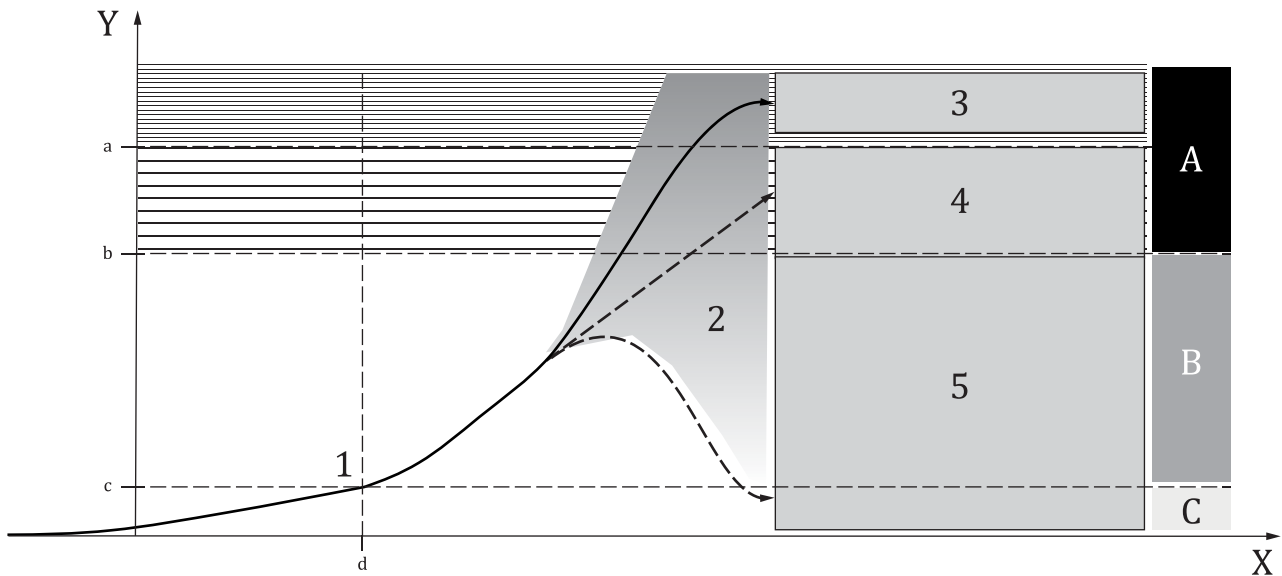
6.4.1 Introduction to metrics

A variety of factors contribute to the causation of crashes, such as the environmental conditions (e.g. weather), the vehicle (e.g. sensor or actuator problems) and the driver. However, it is not enough to identify and model crash causation mechanisms to perform a safety benefit assessment. It is also necessary to identify metrics that quantify the impact of these mechanisms, and the countermeasures addressing them. The metrics used for evaluation shall be able to quantify the safety performance of a technology. The evaluation metric should be technology independent, such that the impacts of distinct types of technologies addressing the same research question can be compared.

As scenarios range from normal, uncritical driving to scenarios including crashes, various metrics for the assessment of a technology are defined. The relationship between the metrics and risk is then typically

expressed as risks of the respective outcomes (see [Figure 2](#)). The risk (of a conflict, injury or fatality) may be expressed as individual risk functions (e.g. based on individual metrics, such as TTC for conflict or impact speed for injuries or fatalities). However, risks may also be expressed as a single risk function that combines metrics across the types of risk (conflict, injury or fatality).

Functions can be developed for risks during ND (see [Figure 2](#)). That is, when safety systems, such as higher levels of automated driving, include precautionary/predictive functionalities that try to avoid high-risk situations (e.g. not driving too close to a lead vehicle or staying away from the blind-spot of a truck), there may also be risk functions quantifying the level of risk a vehicle is exposed to in ND. Safety assessment can use risk functions across the entire spectrum of criticality, depending on the target of a study and the technology under assessment.



Key

- X time
- Y risk
- 1 increase of risk
- 2 risk reducing reaction
- 3 assessable by e.g. injury risk function
- 4 assessable by e.g. impact speed, closing speed, energy equivalent speed, change in speed during collision
- 5 assessable by e.g. time to collision, time headway, time to line crossing, post encroachment time
- A crash
- B near crash
- C ND
- a Threshold for “injury”.
- b Threshold for “crash”.
- c Threshold for “criticality risk”.

Figure 2 — Example sequence of safety critical event including different outcomes ranging from crash avoidance to a crash with personal injury during normal driving (ND)

In [Figure 2](#), a risk-time curve with the objective development from a ND situation to crash with personal injury is shown. There is always a latent risk level above “zero” with the start of road traffic participation, which is determined by the sum of the individual risk levels depending on the following properties:

- driver risk level: attentiveness, constitution, etc.
- vehicle risk level: technical fitness, tires, etc.

- environment risk level: infrastructure, weather, etc.
- behaviour of other road participants.

If a safety critical event occurs, the safety critical event threshold is exceeded and the further development of the situation depends on the subsequent reactions. In this case the vehicle has left the ND operating range. Even “no intervention” can represent a risk reducing reaction depending on the situation. Examples for metrics for determining such safety critical events are described in [6.4.2](#). If the risk reducing reaction is not sufficient, the criticality can further rise. The maximum criticality is reached if the corresponding thresholds for collision with property damage or with personal injury are exceeded. Examples for collision related metrics for assessing the resulting injury severity are described in [6.4.3](#).

6.4.2 Selective compilation of metrics to determine safety critical events

6.4.2.1 General information about safety critical metrics

Safety critical events are typically non-crash conflicts (see [Figure 2](#)) and are often used as surrogates for or a complement to crashes in safety assessment. There are several definitions of safety critical events, and several algorithms for detecting such events in driving data. These algorithms target different types of criteria (driver risk level, vehicle risk level and/or environment risk level), different perspectives of criticality (subjective, objective or both). The algorithms may include a range of different metrics.

Metrics to identify safety critical events can be used during or after the simulations to also determine the criticality of a situation before a crash, or even if there is no crash. Some metrics used for this purpose are described below. More complex metrics exist, see for example Reference [\[11\]](#).

NOTE The list of metrics is not exhaustive as other metrics can also be applied to determine the criticality of an event.

There are no specific definitions/algorithms recommended to be used in the safety assessment. However, to make results comparable, the applied detection algorithms and selection criteria for a safety critical event should be identical or similar. Assessment documentation should at least include descriptions of the detection algorithms and metrics used. Depending on the research question, one single metric or a combination of different metrics can be used.

6.4.2.2 Time to collision

The TTC describes the remaining time until a collision is going to occur in case the movement (direction, velocity) of the involved road users does not change. It is typically calculated during the simulation. The focus of this metric lies in the determination of the current criticality of the situation. Many safety-related in-vehicle technologies are triggered based on such criticality assessments.

There are different ways to calculate the TTC. Two example approaches for calculating the TTC in a conflict situation are given in [Formulae \(1\)](#) and [\(2\)](#):

$$t_{\text{TTC}} = \frac{d_{\text{VUT}}}{v_{\text{VUT}}} \quad (1)$$

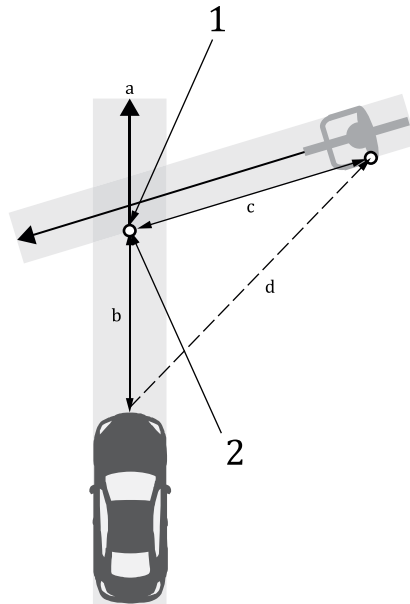
$$t_{\text{TTC}} = \frac{d_{\text{rel}}}{v_{\text{rel}}} \quad (2)$$

The definitions of the used variables are available in [Figure 3](#).

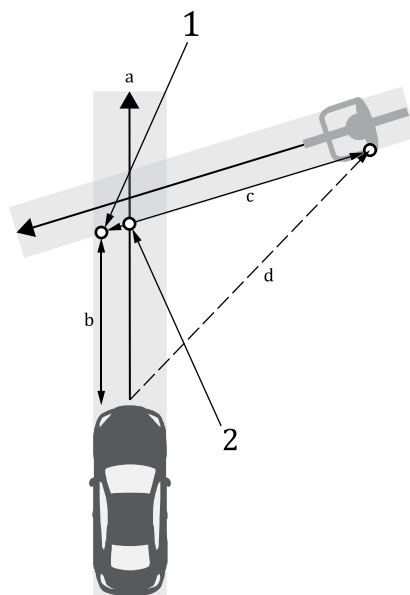
[Formula \(1\)](#) takes only the longitudinal distance of the VuT to the hit point into account. Therefore, this method delivers correct results for any lateral offset of the hit point. Since the longitudinal distance to the hit point is not directly measured by a sensor, additional calculation is required to estimate this value. The second input, VuT velocity, is measured directly.

[Formula \(2\)](#) does not require any assumptions on the hit point location. The relative distance and velocity are direct sensor outputs. However, if the lateral positions of the hit point and the sensor are not identical, this method does not predict the TTC value correctly.

Formulae (1) and (2) therefore only deliver identical results if the lateral position of the hit point and the sensor are identical, see Figure 3 a). In any other case, the TTC is over- or underestimated by Formula (2), depending on the lateral offset of the actual hit point, see Figure 3 b). Further extension of the TTC by considering the acceleration of the road users is also feasible.



a) Collision configuration with the hit point in the middle of the car (the assumed sensor location)



b) Collision configuration with a lateral offset between hit point and the middle of the car^e

Key

- 1 actual hit point
- 2 assumed hit point by Formula (2)
- a v_{VUT}
- b d_{VUT}
- c $d_{cyclist}$
- d d_{rel}, v_{rel}
- e Formula (2) underestimates the TTC at this point.

Figure 3 — Variable definitions used for different TTC calculation methods

These methods of calculating the TTC demonstrate one possible source in differences between simulation results.

Therefore, in case such assessments are conducted to compare the safety performance of the technology, the calculation of the metric – in this case the TTC – shall be clearly defined before the assessment and the definition is followed by the different assessment partners. This also applies to the other metrics.

6.4.2.3 Time headway

The THW is defined as the time difference between two vehicles passing the same point where one vehicle follows the path of the second vehicle. Similar to the TTC, the THW is an in-simulation metric. The THW is calculated based on the intervehicle distance (d_{VUT}) and the current velocity of the VuT. See [Formula \(3\)](#).

$$t_{THW} = \frac{d_{VUT}}{v_{VUT}} \quad (3)$$

6.4.2.4 Time to line crossing

The TLC describes the remaining time before a road user crosses the adjacent lane marking. The TLC does not intend to describe criticality in relation to other road users, instead focusing entirely on the VuT's movement. Like the TTC and the THW, the TLC is an in-simulation metric that can be used by the technology under assessment as input to its decision logic. The definition in [Formula \(4\)](#) is applied:

$$t_{TLC} = \frac{d_{DLC}}{v_{VUT}} \quad (4)$$

where

d_{DLC} is the distance to line crossing along the vehicle's future path;

v_{VUT} is the vehicle velocity.

6.4.2.5 Post encroachment time

The PET describes the time between a first road user leaving the conflict zone and a second vehicle entering the conflict zone. The conflict zone is defined by the vehicles' dimensions and their trajectories. Typically, the PET is calculated after the simulation.

6.4.3 Selective compilation of collision related metrics

6.4.3.1 General information about collision related metrics

In [6.4.3.2](#) to [6.4.3.7](#), the most relevant metrics for presenting the crash avoidance/mitigation capabilities of the technology studied are defined in more detail. The list of metrics is not intended to be complete. In addition, other metrics can be applied for determining the safety performance of a technology. Depending on the research question, one single metric or a combination of different metrics should be used.

Some of the metrics below should be used on a case-by-case basis when calculating the safety performance of a technology (i.e. direct comparison of the outcome of a simulation run using the same initial and boundary conditions with and without analysed technology). Other metrics should only be used in an overall approach considering all simulation runs with the same technology configuration. For every metric below, there is a statement on its usability for case-by-case analysis or overall analysis.

If a metric based on accident samples is used to assess a technology (e.g. AEB pedestrian), these samples should be consistent with this technology (e.g. only car-pedestrian frontal impacts with no prior loss of control).

According to ISO 6813:1998, 3.1, road vehicle accidents are classified as collision or non-collision accidents. [Subclause 8.2.6](#) describes how a collision is detected in the simulation.

6.4.3.2 Number of collisions

The number of collisions (n_{coll}) counts the number of simulation runs where a collision between two traffic participants or between a traffic participant and a non-overrunable infrastructural element occurs. This metric is used to assess the technology under assessment's ability to avoid collisions. This is done in a relative way by comparing the number of collisions (n_{coll}) to the total number of simulation runs (N_{sim}) to obtain a collision rate (P_{CR}). See [Formula \(5\)](#):

$$P_{\text{CR}} = \frac{n_{\text{coll}}}{N_{\text{sim}}} [\%] \quad (5)$$

Depending on the research question, the analysis may be limited to certain road user groups or to collisions involving the VuT. This metric is only suitable for an overall analysis.

6.4.3.3 Number of victims

The number of victims (n_{vict}) counts the number of simulation runs where a collision between two traffic participants or between a traffic participant and a non-overrunable infrastructural element occurs and one of the involved traffic participants is injured in such a way that they are counted as victims.

The definition of victim shall be the same in the baseline and in the treatment. Common definitions of victim include the AIS-scale based injury level classifications or the "fatal vs not fatal" binary outcome of the collision.

IRFs allow derivation of the consequences of a collision from the collision setting or parameters (e.g. impact velocities, impact location, age or height of the VRUs involved, the EES of the vehicles involved or a change in velocity during collision). See [Formula \(6\)](#):

$$\text{IRF} = f(\text{collision parameters}) \quad (6)$$

IRFs quantify the consequences of collisions in terms of a probability of one or more injury levels, given a set of relevant collision parameters. To assess the number of victims with and without the technology present, the IRF are combined with the collision parameter distributions in both the simulation with the technology and the baseline simulation.

IRF are commonly derived from statistical models, such as regressions, over populations of collisions. For example, the Akaike information criterion or brain injury criteria can be used to check the validity of these models.

There are different IRFs available in the literature. IRFs differ in terms of the data source, the collision type addressed, the road user considered, the injury level predicted. Therefore, choosing an IRF depends on the research question. The consistency of this choice should be checked. An IRF used to assess a technology should be built on a population of collisions that is consistent with this technology (e.g. car-to-pedestrian frontal collisions used for AEB pedestrian assessment).

This metric can be used to assess the technology under assessment's ability to reduce the number of victims. This is done in a relative way by comparing the number of victims (n_{vict}) to the total number of simulation runs (N_{sim}) to obtain a VR (P_{VR}). See [Formula \(7\)](#):

$$P_{\text{VR}} = \frac{n_{\text{vict}}}{N_{\text{sim}}} [\%] \quad (7)$$

Depending on the research question, it might be necessary to limit the analysis to certain road user groups or just to collisions involving the VuT. This metric is only suitable for an overall analysis.

6.4.3.4 Impact velocity

The impact velocity describes the velocity of a road user, i , immediately prior to impact that is described by the time point of the collision ($t_{\text{collision}}$). In this case, "immediately prior to impact" means the last time step of

the simulation before the time point of collision. In a non-deterministic simulation model, the impact velocity can be calculated statistically considering all simulation runs with the same technology configuration. In other cases, this metric is also used in a case-by-case analysis.

6.4.3.5 Closing velocity

The closing velocity is defined as the vector difference between impact velocity and the velocity of the COG of a vehicle/object struck immediately prior to the contact. In a non-deterministic simulation model, the closing velocity can be calculated statistically considering all simulation runs with the same technology configuration. In other cases, this metric is used in a case-by-case analysis.

6.4.3.6 Energy equivalent speed

The EES is a measure for the kinetic energy dissipated by the vehicle during the contact phase by deformation and is defined in [Formula \(8\)](#):

$$E_{\text{EES}} = \sqrt{\frac{2 \cdot E_{\text{def}}}{m}} \text{ [m/s]} \quad (8)$$

EES can be interpreted as the impact speed on a non-deformable, immovable obstacle resulting in the same deformation as observed in a collision. In a non-deterministic (simulation) model, the EES can be calculated statistically considering all simulation runs with the same technology configuration. In other cases, this metric can also be used in a case-by-case analysis.

6.4.3.7 Change in velocity during collision

The change in velocity during collision, Δv_i , is calculated as the vector difference between impact velocity and separation velocity, which is the velocity of the COG of a crash-involved road user or roadside object immediately after the impact phase. For one road user, i , the difference between the velocity shortly before the collision ($t_{\text{collision}} - \Delta t$; Δt : simulation step size) and the velocity shortly after the collision ($t_{\text{collision}} + \Delta t_{\text{collision}}$). $\Delta t_{\text{collision}}$ is the timeframe between the first contact between two objects and the point of time at which the deformation energy is transferred between the objects. See [Formula \(9\)](#):

$$\Delta v_i = v_i(t_{\text{collision}} - \Delta t) - v_i(t_{\text{collision}} + \Delta t_{\text{collision}}) \text{ [m/s]} \quad (9)$$

The calculation can be conducted for each road user involved in a collision. In a non-deterministic simulation model, the change in velocity during collision can be calculated statistically considering all simulation runs with the same technology configuration. In other cases, this metric is also used in a case-by-case analysis.

6.5 Selection of metric

There are several metrics available for a safety performance assessment. The selection depends on the specific research question. The following statements provide guidance for selecting the appropriate metrics:

- If the research question requires a specific metric (e.g. number of crashes, injuries with MAIS2+, t_{TTC}), this metric can be used (see [6.4.3](#)).
- If the research question requires a quantification of avoided collisions as a result of the usage of the analysed technology, the number of collisions should be calculated (see [6.4.3.2](#)).
- If the research question requires the quantification of the mitigation of collision consequences without mentioning injury or property damage, it is recommended to use a metric such as impact velocity, closing velocity or change in velocity during collision (see [6.4.3.4](#) to [6.4.3.7](#)).
- If the research question includes mitigation of collision consequences in terms of injury (or property damage), the consequences should be calculated using a standard metric. These metrics require a two-step approach. First, a relevant set of collision parameters are calculated, e.g. impact velocity and collision position. Second, the injury risk or the property damage is calculated based on these parameters.

Relationships such as IRFs (see [6.4.3.3](#)) between the relevant (simulated) parameters of the collision and its injury outcomes should be used. A final step can be the determination of a VR.

- If the research question includes the change in the occurrence of certain scenarios before a crash (e.g. critical cases), in the first step, the scenarios are detected in the simulation data. For this purpose, the scenario shall be clearly defined. In case such definition is missing, stakeholders of the research question shall agree on which definition to be used. Typical examples for safety performance relevant scenarios are safety critical events.
- If the research question includes the change of a safety related measure prior to the crash, possible metrics are the TTC (t_{TTC}), THW (t_{THW}), time to line crossing (t_{TLC}) or the PET. The first three metrics can be calculated during the simulation, whereas the PET is typically calculated in the post-processing. The same definitions shall be used for these metrics, especially if the results of different simulations should be compared (see [6.4.2](#)).

If a projection of the results should be done, the following aspects should be considered:

- If the simulation results do not cover the entire time span (e.g. in the next 10 years) or region (e.g. EU-27) required by the research question, the results can be projected or extrapolated to the targeted time and/or location, respectively. In the simplest form, this is a comparison of the individual simulated results with the targeted time and/or location. In general, the projection/extrapolation shall be conducted in accordance with the available data sources (e.g. regional accident data).
- If the research question asks for the societal impact or a cost-benefit analysis of a technology, a general recommendation on the appropriate metrics is beyond the scope of this document, since the required metrics build upon the results derived by the simulations and the metrics applied to determine the safety performance.

7 Baseline

7.1 Baseline approaches

7.1.1 General

The baseline describes the scenarios to be analysed without the technology under assessment. The baseline is the basis for the simulation with the technology under assessment (treatment). The baseline shall be consistent with the evaluation objective. In general, the baseline description shall include all relevant traffic elements, infrastructure, environmental conditions as well as involved technologies not under assessment. These elements are represented in the simulation by models. The output of the models is either derived by means of pre-simulation calculations (pre-simulation models) or is calculated constantly during the simulation based on the previous time steps (in-simulation model). Depending on the chosen baseline approach, the two basic types of models are applied to a different extent.

The baseline description shall be derived from one of the following three approaches (see [Figure 4](#)):

- Baseline approach A, “baseline consisting of individual real-world scenarios”: Real-world scenarios (often crashes or near-crashes, but not necessarily) are represented in a numerical time-series description for the baseline. The real-world scenarios can then be used directly as a baseline or as input for a simulation (the latter to simulate both baseline and treatment in the same simulation tool). Since this baseline approach focuses on individual real-world scenarios, the approach can rely heavily on pre-simulation models. In-simulation models are not required for deriving the baseline.
- Baseline approach B, “baseline consisting of modified real-world scenarios”: To compensate for information with less validity in real-world scenarios (the numerical time-series description) or to update to a specific state of technology, parameters are added and/or modified. This is done by, for example:
 - adding variations around known parameters using sampling techniques, thus creating multiple variants of one scenario;