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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

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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
$I_{Baseline,i}$	severity of (injury) type i in the baseline simulation
$I_{Treatment,i}$	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)
$f_{Baseline,i}$	occurrence frequency of a scenario with injury level i in the baseline
$f_{Treatment,i}$	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
$t_{collision}$	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.

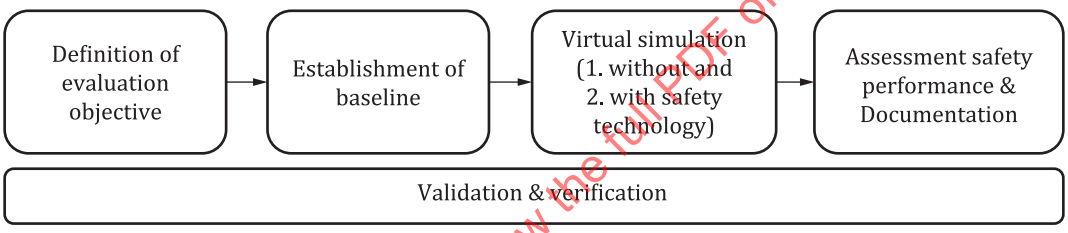


Figure 1 — Overview of the prospective assessment of traffic safety process for vehicle-integrated technology by means of virtual simulation

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

	Simulation control	Vehicle surrounding			Vehicle under test			Collision
		Infrastructure	Environmental conditions	Traffic	Vehicle	Technology	Driver	
Definition of evaluation 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 performance		(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) — Develop sim. models — V&V	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

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 milage 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 milage 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

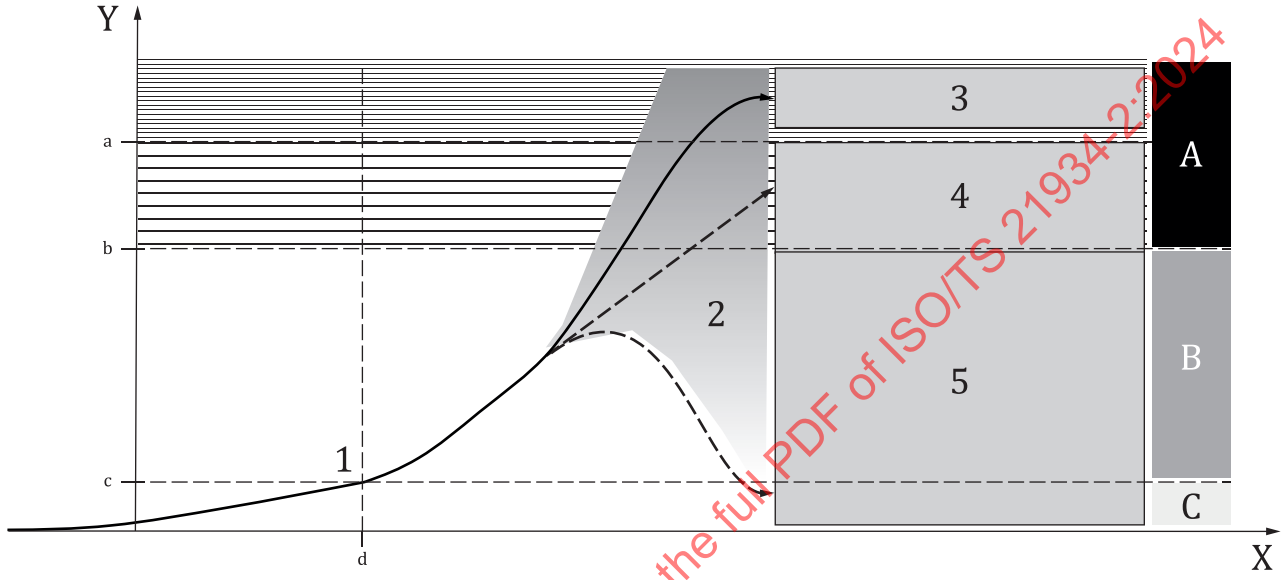
6.4.1 Introduction to metrics

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):

$$t_{\mathrm{TTC}} = \frac{d_{\mathrm{VUT}}}{v_{\mathrm{VUT}}} \tag{1}$$

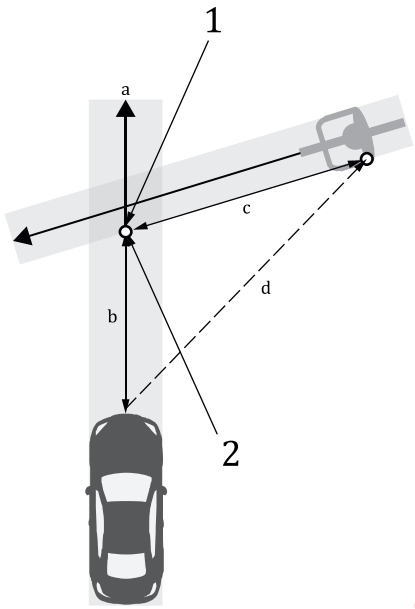
$$t_{\mathrm{TTC}} = \frac{d_{\mathrm{rel}}}{v_{\mathrm{rel}}} \tag{2}$$

The definitions of the used variables are available in Figure 3.

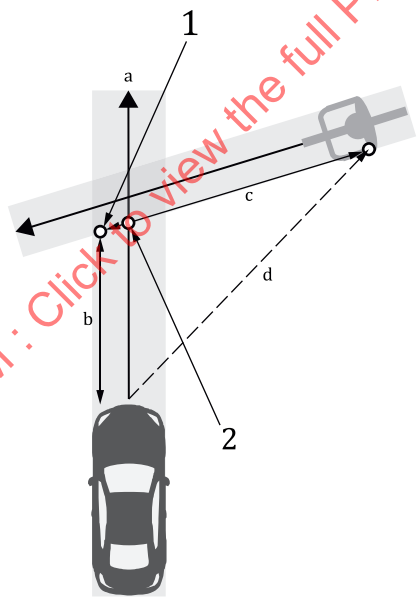
Formula (1) takes only the longitudinal distance of the VuT to the hit point into account. Therefore, this method delivers correct results for any lateral offset of the hit point. Since the longitudinal distance to the hit point is not directly measured by a sensor, additional calculation is required 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_{cylist}.

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).

$$t_{THW} = \frac{d_{VUT}}{v_{VUT}} \tag{3}$$

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:

$$t_{TLC} = \frac{d_{DLC}}{v_{VUT}} \tag{4}$$

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):

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

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):

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

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):

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

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):

$$E_{\mathrm{EES}} = \sqrt{\frac{2 \cdot E_{\mathrm{def}}}{m}}\,[\mathrm{m/s}] \tag{8}$$

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, it the difference between the velocity shortly before the collision ($t_{\mathrm{collision}} - \Delta t$; Δt: simulation step size) and the velocity shortly after the collision ($t_{\mathrm{collision}} + \Delta t_{\mathrm{collision}}$). $\Delta t_{\mathrm{collision}}$ 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):

$$\Delta v_{\mathrm{i}} = v_{\mathrm{i}}\left(t_{\mathrm{collision}} - \Delta t\right) - v_{\mathrm{i}}\left(t_{\mathrm{collision}} + \Delta t_{\mathrm{collision}}\right)[\mathrm{m/s}] \tag{9}$$

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;

— using additional in-simulation models (e.g. driver models (see 8.2.5.3) or technology such as ABS) on the original scenario and thus creating a modified scenario.

Like approach A, this baseline approach focuses on individual real-world scenarios. The number of treatment simulations results from the number of variations of the individual scenarios in the baseline.

— Baseline approach C, "baseline consisting of synthetic cases": General crash mechanisms, determined from traffic and accident research, result in parameter distributions that can be used to generate synthetic cases, which aim to represent scenarios that could occur in the real world. The key aspect in this approach is to create trajectories of the involved traffic participants, since in contrast to the other approaches, there are no pre-determined trajectories available from accident data.

Here, two different sub-approaches shall be distinguished for baseline approach C (see Figure 4):

— Baseline approach C1, "analysis driven with pre-defined trajectory";

— Baseline approach C2, "sampling driven with trajectory derived by means of in simulation models".

The C1 approach is used where fewer cases are required to allow a direct comparison between different implementations of technology. The trajectories of the involved traffic participant are (manually) pre-defined. In contrast, the C2 approach is typically used where a technology is assessed with a large sample of cases. Here, the trajectories are computed by using models that describe human behaviour, such as a driver model or a pedestrian behaviour model. The initial parameters of each simulation case are statistically sampled from available parameter distributions. Consequently, the use of in-simulation models is a prerequisite of this baseline approach C2.

Given the stochastic approach, the quantity and the similarity of scenarios in baseline and treatment does not have to be the same.

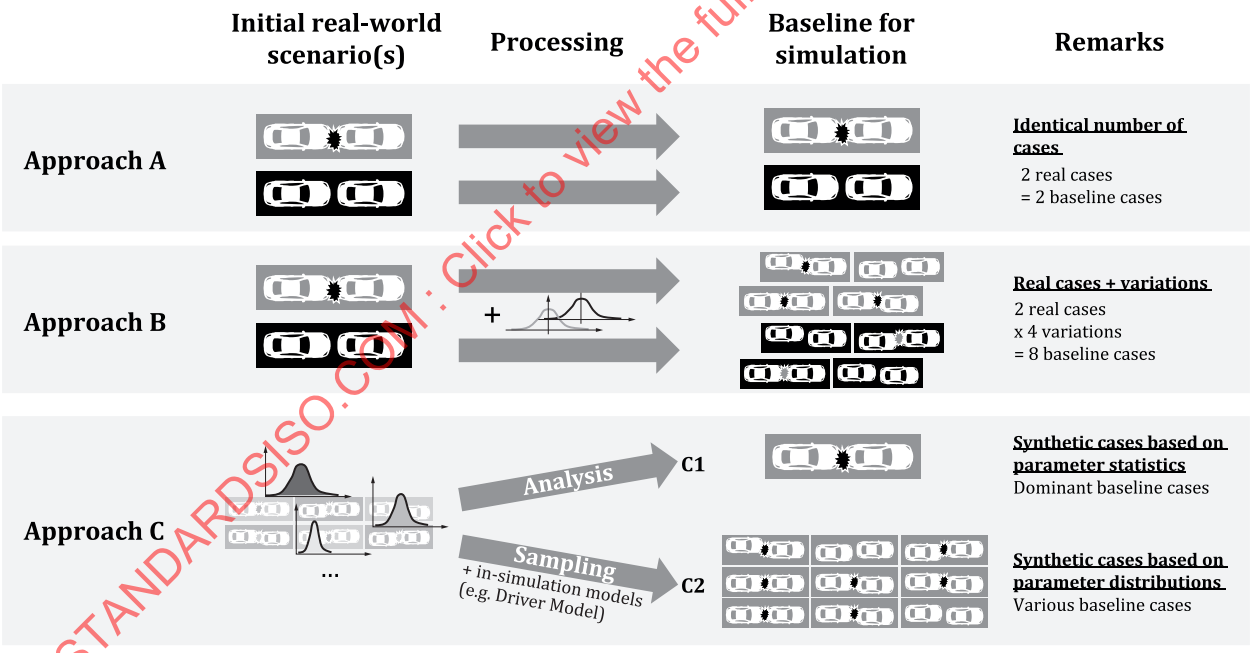


Figure 4 — Overview on baseline approaches for the prospective safety performance assessment by virtual simulation

The baseline shall be transferred to a format specific to the simulation tool. Depending on the simulation tool used and the models that are available in the simulation tool, the level of detail at which the baseline is described may vary. In 7.2, minimum requirements for the baseline definition are presented.

The choice of a baseline approach strongly depends on the evaluation objective.

7.1.2 Approach A

The following considerations are presented for baseline approach A:

1. This approach should be considered if real-world scenarios are used as the baseline.
2. Cases shall be used directly as they are and without further processing.
3. The duration of the baseline is limited to the duration of the original real-world scenario.
4. If the research question asks for statistically meaningful results, the number of suitable real-world scenarios may be too low for such results. This would lead to approach B or C.
5. For non-recorded events (e.g. in-depth accident data), the farther the assumptions on the numerical time-series go back in time, the higher the uncertainties. For recorded events (e.g. FOT and EDR data), this is not the case. A data grading method can help in documenting the uncertainty.
6. The possibility of including or excluding certain technologies and changing their penetration rate is limited. This may lead to approach B.
7. Driver behaviour in a scenario shall not be changed from the original real-world case. A behaviour change would lead to approach B. For recorded events, driver behaviour is covered implicitly. For non-recorded events, it is based on assumptions. These assumptions are given for the scenario.

7.1.3 Approach B

The following considerations are presented for baseline approach B:

1. All considerations mentioned in approach A apply to here as well, unless otherwise stated.
2. By using approach B, there is a risk that the number of suitable real-world scenarios is very low and may not be enough if statistically meaningful results are desired. However, the variations added may help to overcome this risk.
3. Other than as stated in approach A, point 6, the influence of parameters not included in the used real-world data on the performance of the technology of interest is studied.
4. Other than as stated in approach A, point 7, the driver response to a critical situation is considered and varied.
5. The created cases and driver response shall be plausible and representative.

7.1.4 Approach C

The following considerations are presented for baseline approach C:

1. Since this approach relies only on distributions sampled from real-world data and not the concrete real-world data time series, the number of baseline cases can be chosen arbitrarily. In approach C2, this ensures that a statistically sufficient number of cases is investigated. For C1, finding a higher number of cases is more challenging due to the required effort of pre-defining the trajectories.
2. Inclusion or exclusion of any technology with arbitrary penetration rate is possible.
3. The duration of the baseline may be extended arbitrarily.
4. Surrounding traffic participants are considered and varied. For approach C1, it is relevant that the effort and complexity of defining trajectories increases with each participant. This results in an implicit limitation in terms of the number of participants and complexity.
5. Approach C2 relies on modelling the behaviour of all involved traffic participants. It is therefore also possible to generate a large amount of non-critical driving trajectories via simulation. This makes it possible to study the effects of false-positive system actions in everyday driving efficiently and with the necessary statistical power. Furthermore, full knowledge of the underlying parameters and their

distribution (e.g. age) eases the subsequent statistical analysis because, for example, individual effect sizes for different driver age groups may be weighted accordingly.

6. Variation by means of pre-simulation models (applicable in C1 and C2) and during the simulation by means of in-simulation models (applicable only in C2) allows coverage of a large scenario space. A suitably large number of cases then enables an assessment of the technology's ability to minimise the effects of confounding factors in its safety performance.

7. Since there is no direct link to a specific real-world scenario, the relevance of the created scenarios shall be ensured.

8. Requirements (in terms of modelling and validation) for in-simulation models are higher than for the other approaches, particularly for the driver behaviour model (applicable only in C2).

9. There must be enough data to derive the input distributions and crash mechanisms.

10. In contrast to the other approaches that usually do not include uncritical everyday driving, C2 includes uncritical everyday driving. It therefore requires higher simulation efforts in terms of simulated time (and/or distance) to generate safety critical events (crashes and near-crashes). It also provides more information as it can generate relevant situations (e.g. false-positive studies) that are not considered when using other approaches.

7.1.5 Requirements

Other criteria influence the choice of a baseline approach, for example the available input data, the available driver behaviour model or the specific technology to be assessed. Each baseline approach requires certain data and model types to be available. The respective baseline approach shall only be used if these minimum requirements are met.

Table 4 provides the minimum requirements for the different baseline approaches. Table 4 specifically refers to the dynamic part of the baseline, which is the part of the traffic and the environmental conditions (see 8.2.3.3 and 8.2.3.2) that changes during the course of the scenario for which the baseline is described.

Table 4 — Minimum requirements for the dynamic part of the different baseline approaches

Baseline approach	Data	Models
A	Time-series data on real-world scenarios providing the movement of all relevant traffic participants	Trajectory-following model (see 8.2.5.3) (if simulation is used for generating the baseline)
B	Time-series data on real-world scenarios providing the movement of all relevant traffic participants Distributions of parameters that are to be added/modified to existing scenarios	Trajectory-following model (see 8.2.5.3) An adequate driver model for the modified scenario (if the driver's behaviour is modified)
C1	Distributions of parameters describing everyday driving Distributions of parameters describing the drivers' response to critical events Distributions of parameters describing representative scenarios	Trajectory-following model (see 8.2.5.3)
C2	Distributions of parameters describing everyday driving Distributions of parameters describing the drivers' response to critical events Distributions of parameters describing representative scenarios	Everyday driving model (see 8.2.5.3) Critical event response model (see 8.2.5.3)

7.1.6 Example research questions

The choice of the baseline approach strongly depends on the evaluation objective, specifically the research question (see 6.2). In Table 5, the example research question is varied to differentiate when a certain baseline approach should be used.

Table 5 — Example research questions for the different baseline approaches

Baseline approach	Possible research question	Remarks
A	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 Germany in 2017 as represented in GIDAS PCM?	Approach A should be used due to the specific choice of the country and time series in-depth dataset as well as the performance metric (alteration of MAIS2+ injuries)
B	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 Germany in 2017 as represented in GIDAS PCM while considering only ESC-equipped vehicles?	Approach B should be used since a direct link to certain crash data is desired (GIDAS-PCM). Furthermore, the baseline should consider only cases in which the vehicle is equipped with ESC. Since not every vehicle in every GIDAS PCM crash is equipped with ESC, there are two options: 1. If sufficient ESC cases are available, approach A can be applied as well. 2. If there are not enough ESC cases, approach B shall be applied, to correct the baseline in the identified cases to the extent that the movement of the VuT considers an ESC system.
C1	What is the safety performance of a VRU AEB (warning + autonomous intervention) in car to cyclist crashes as defined in the Euro NCAP protocol?	
C2	What is the safety performance of a VRU AEB (warning + autonomous intervention) at a penetration rate of 100 % in car to cyclist crashes at non-signalized intersections on urban roads in terms of avoided crashes related to the situation in Europe in 2017?	Approach C2 should be used as insufficient numbers of real-world accidents for this research question exist and therefore only distributions describing general traffic behaviour can be used in such a case.

The baseline approach shall be transferred to a technical format to be simulated. Different formats are available. One example is the OpenX standards of ASAM (OpenDrive, OpenScenario).[9],[10] Independent of the format used, the format shall be capable of providing the minimum required information (see 7.2) for the baseline. The interfaces for the used simulation tool shall also be available.

7.2 Example for minimum required information for establishing a baseline

The minimum required information for establishing the baseline in the example of a VRU AEB is given in Table 6. See Clause 5 for the limitations of the example.

Table 6 — Minimum required information for the three baseline approaches in the given example: data point (DP), data series (DS) and probability distribution (PD)

Information type	Baseline approach A	Baseline approach B	Baseline approach C1 and C2
Simulation control	Scenario time (DS), collision detection (DP)	Scenario time (DS), collision detection (DP), number of cases (DP)	Scenario time (DS), collision detection (DP), number of cases (DP)
Vehicle surroundings — infrastructure	x-/y-position of visual obstructions (DP), dimension of visual obstructions (DP)	x-/y-position of visual obstructions (PD), dimension of visual obstructions (PD)	x-/y-position of visual obstructions (PD), dimension of visual obstructions (PD)
Vehicle surroundings — environmental conditions	N/A	If the environmental conditions are modified: Parameters of environmental conditions model (PD)	Parameters of environmental conditions model (PD)
Vehicle surroundings — traffic	Time (DS), x-/y-position VRU (DS), VRU dimensions (DP)	Time (DS), x-/y-position VRU (DS), dimension of VRU (DP), variation of x-/y-position (DS), variation of VRU dimension (DS)	x-/y-position VRU @ start (PD), velocity VRU @ start, yaw angle VRU @ start (PD), VRU dimension (DP), VRU model parameters (PD)
Vehicle under test — vehicle	Time (DS), x-/y-position (DS), vehicle dimension (DP)	Time (DS), x-/y-position (DS), vehicle dimension (DP), variation of the kinematic parameters (PD)	x-position @ start (PD), y-position @ start (PD), velocity @ start (PD), yaw angle @start (PD), vehicle dimension (PD)
Vehicle under test — technology	N/A	N/A	N/A
Vehicle under test — driver	N/A Driver reaction is implicitly covered by the vehicle position data	If the driver's behaviour is modified: driver reaction (DS), variation of driver reaction (DS)	Parameters for everyday driving model (PD) and critical event response model (PD)
Collision	Injury severity of original collision (DP/DS)	Collision status per run (DP) injury severity per run (DP/DS)	Collision status per run (DP), injury severity per run (DP/DS)

8 Virtual simulation

8.1 Framework

The simulation framework covers the relevant aspects to the assessment. A generic framework containing all in-simulation models and blocks for simulation for the prospective assessment of safety technologies is shown in Figure 5.

NOTE The implementation of simulation can be adapted in certain assessments up to the needs of this assessment i.e. the implementation can deviate from the one in Figure 5.

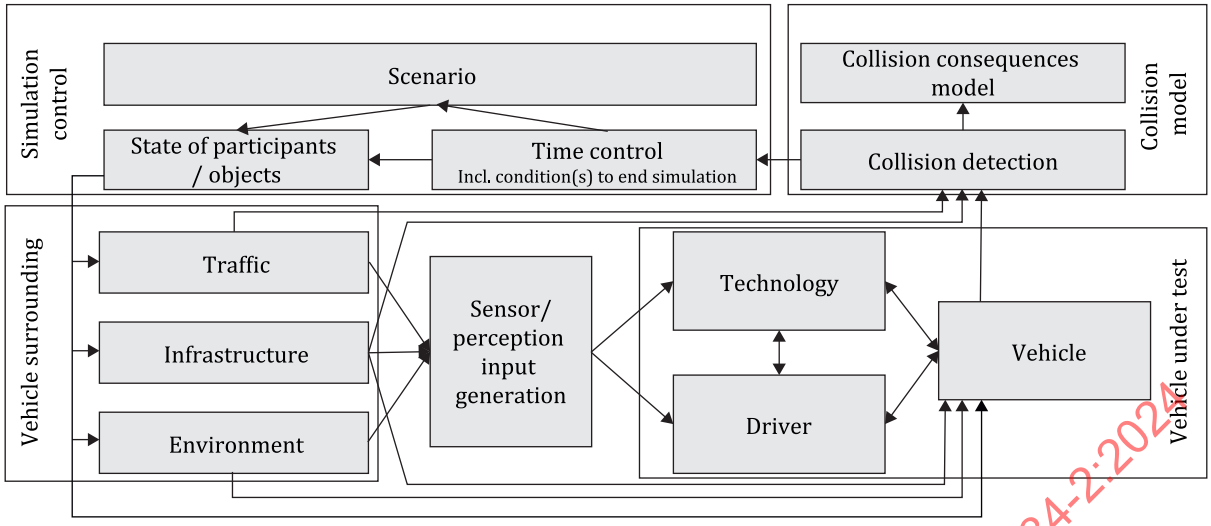


Figure 5 — Generic simulation framework architecture

The flow in this framework is organized in a logical way for a simulation in the time domain. It involves inputs/outputs and simulation control blocks.

Assembling the models into a global framework requires at least two essential features:

— Models shall be clearly identified. Their purpose, limitations and versions shall be accessible to their authorized users and stored in a standardized format. The following features should be made available: purpose and software (e.g. name and version), solver (e.g. name and version), timestep requirements (e.g. fixed value, limits, capacity to handle variable timestep), limitations (e.g. restriction to intervals of the inputs, and model limitations and constraints) and quality of validation (e.g. list of reference documents).

— Model inputs and outputs shall be clearly identified in nature (e.g. control, parameter), size (e.g. scalar, vector, matrix), type (e.g. Boolean, integer, real, double), maximum size(s) (e.g. for vectors and matrices), units and physical domain (e.g. inputs, solid or fluid mechanics, electromagnetics) to make their connectivity valid.

To ensure traceability within the simulation tool as well as for the entire safety performance assessment, meta information for each piece of information is required. This meta information shall at least contain the information outlined in Clauses 5 and 10. SI units should be applied for the information whenever possible to ensure the exchange of information within as well as outside the simulation framework.

8.2 Models

8.2.1 Scope of section

This subclause aims at describing the following items for each simulation block and model: purpose/ description, example model parameters, inputs/outputs and requirements.

To check whether the model fulfils the requirements, see Clause 11.

8.2.2 Simulation control block

This simulation block includes the time control (initial, final, timestep) and processing of the scenario description, which includes for example the initial states of relevant traffic participants – including the VuT – as well as of the vehicle surroundings. Furthermore, the scenario description can define actions or events to be triggered during the simulation. Depending on the baseline approach and the chosen simulation approach, the block should also be able to process trajectories for one or more traffic participants defined in the scenario description.

The simulation control should be able to process all the information that is required by the simulation tool internally to run the simulation. The information can be time dependent as well as time independent. The most important information handled in this simulation block is the simulation time.

Example parameters, inputs, and outputs are the following:

— parameters: scenario, output time step size, duration, end conditions;

— input during runtime: vehicle, traffic, environmental conditions and collision states at current timestep;

— output during runtime: VuT, traffic and environmental conditions initial states at beginning of scenario (initial velocity, position, etc.).

8.2.3 Vehicle surroundings block

8.2.3.1 Infrastructure model

This model contains the relevant elements that follow the rules for the design and operation of road infrastructure (e.g. horizontal or vertical information, lane configuration and pavement) related to the technology in the VuT.

The state of infrastructure elements does not change during the simulation of the scenario under study. The infrastructure consists of the description of the simulated road(s) (number of lanes, lane markings, road friction and special objects), applying restrictions for the road(s) (speed limit, overtaking prohibitions etc.), and, if considered and present, visual obstructions.

For the road, general information on the geometry and position related to the simulation coordinate system is required. Furthermore, the road attributes, such as information on the number of lanes, the type of road markings, and the applicable speed limit, shall be defined. Typically, the information is constant over time during one simulation run. However, road attributes can change along the road geometry.

The second information type of this category is the static object. A static object is any physical object that does not change its position before a collision in the simulation coordinate system during a simulation run. Besides the position of the object (e.g. the centre of the object or COG), the attributes of the object, such as the dimensions and type of object, shall be defined. If the static object is also relevant for collision and detection, further attributes, like the mass, material, and reflection properties, are relevant. Table 7 shows examples of infrastructure models.

Table 7 — Example infrastructure models and their properties

Model	Purpose	Model prerequisites	Recommended area of application	Limitations
Horizontal plane with defined friction	Minimal model	Road-tire friction shall be defined	Research question asks for a proving ground like infrastructure	Only usable if: — no infrastructure input (including visual obstructions) to sensor/perception required — vertical vehicle dynamics is not relevant — no effects of sensor view limitations due to road unevenness considered
2D road (e.g. centreline, edges, road markings, 2D contour of visual obstacles) without intersection	Provide a road the VuT should follow	Additional to above: defined centreline, position and type of road markings	Research questions ask for single roads without intersections	Only usable if: — vertical vehicle dynamics is not relevant — no effects of sensor view limitations due to road unevenness and/or other visual obstruction considered
3D road (e.g. centreline, edges, road markings, contour of visual obstacles) without intersection	Provide a road the VuT should follow	Additional to above: road elevation, banking etc.	Research question asks for the influence of vertical dynamics induced by the road	
Full 3D (e.g. 3D roads, lanes, lane markings, location dependent friction, traffic signs, intersections, buildings)	Most complex model. Provide a full 3D description of all relevant infrastructure elements including material/reflection properties	Data from e.g. ultra-high definition maps	Research question asks for a detailed description of the infrastructure or at least consideration of visual obstructions	Only usable if: — corresponding model for environment exist (e.g. reflection properties of objects) — sufficient calculation power for the simulation is available

Example parameters, inputs, and outputs are the following:

— parameters: at minimum, parameters describing the road as well as static objects;

— input during runtime: none;

— output during runtime: position and attributes of relevant infrastructural elements.

8.2.3.2 Environmental conditions model

This model contains all elements with time-dependent behaviour that are not part of the traffic (e.g. lighting, weather conditions, traffic lights, I2V communication from the infrastructure to the VuT). Taking changes in environmental conditions into account, such as weather and lighting conditions, requires sufficiently accurate models, capable of taking their effects into account. Changing conditions of lighting may influence the sensors' and driver's perception.

If the research question asks for the influence of environmental conditions on the safety system's performance, other models should be able to consider weather conditions (e.g. driver reducing vehicle speed and modifying reaction time accordingly or the road friction influence on longitudinal and lateral vehicle dynamics).

Depending on the area of application, the minimum required level of detail of the environmental conditions model is given by the following:

— Constant environmental conditions can be satisfactorily modelled with a model that provides global and static environmental conditions information.

— If the environmental conditions are not the same everywhere, a model that provides information on environmental conditions depending on location can be used.

— If temporal changes of the global environmental conditions are required, a dynamic (time-dependent) model can be used.

— If both local and temporal changes should be considered, a local and dynamic (time-dependent) model can be used.

More details on these environmental condition models are given in Table 8.

Table 8 — Example environmental conditions models and their properties

Model	Purpose	Model prerequisites	Recommended area of application	Limitations
Global and static	Minimal model. Suitable for studies where environmental conditions are the same everywhere and do not change over time	Definitions of constant environmental conditions relevant for the study (e.g. visibility) shall be defined	Research question and/or scenario does not require time nor location-dependent changes of environmental conditions	Not suitable for assessments requiring change of environmental conditions (time or location)
Local and static	Studying effects of local changes of environmental conditions, e.g. wet road areas and their influence on braking and vehicle stability	Changes of environmental conditions relevant for the study depending on location shall be defined and provided to all models requiring this information depending on their reported position	Research question and/or scenario asks for some or all environmental conditions to change depending on location, e.g. parts of the road having limited friction due to rain, change of lighting conditions when entering or exiting a tunnel	Not suitable for assessments requiring time-dependent changes of environmental conditions
Global and dynamic	Studying effects of temporal changes in environmental conditions, e.g. the influence of different lighting and visibility conditions at a certain junction and their influence on sensor detection performance	Changes of environmental conditions relevant for the study over time shall be defined and provided to all models requiring this information depending on the current simulation time	Research question and/or scenario asks for some or all environmental conditions to change depending on time, e.g. change of lighting conditions due to sunset/sunrise, change from natural light to artificial light	Not suitable for assessments requiring change of environmental conditions depending on location
Local and dynamic	Most complex model. Suitable for studying local temporal changes of environmental conditions e.g. the influence on pedestrian detection at night with road lighting and oncoming vehicles	Changes of environmental conditions relevant for the study over time and location shall be defined and provided to all models requiring this information depending on the current simulation time and on their reported position	Research question and/or scenario asks for changes of environmental conditions depending on time and location, e.g. start of a local rain shower at a certain time resulting in locally reduced friction and visibility	None

Example parameters, inputs, and outputs are the following:

— parameters: points in time (and location) where environmental conditions changes take place, including the quality and quantity of the environmental conditions change;

— input during runtime: simulation timestep and location where environmental conditions information is required;

— output during runtime: timestep and location dependent environmental conditions states.

8.2.3.3 Traffic model

This model contains all mobile entities (e.g. pedestrians, powered two-wheelers and cars) moving within the infrastructure other than the VuT. In simulation, traffic may be represented simply by a predefined number of vehicles and VRUs (e.g. when real crashes are under study and traffic participants are known) with pre-defined trajectories. Other baseline approaches (typically C2) use more sophisticated traffic generation models, such as stochastic traffic generation models or third-party traffic flow simulation software.

The traffic participants, independent of whether they are vehicles or VRU, can be modelled at different levels of details. Here, the same mechanisms apply as for the VuT. With respect to the behaviour of the traffic participants, the model approaches range from pre-defined trajectories up to complex models, which determine for each traffic participant its reaction based on the given state of other road users, infrastructure and environmental conditions.

The level of information can differ among traffic participants for two reasons. First, different types of dynamic objects require different information (e.g. vehicle vs. pedestrian). Second, some dynamic objects are solely used to establish a realistic scenario. These objects are not directly involved in the actual traffic conflict but can influence the behaviour of the relevant traffic participants indirectly (e.g. an evasive manoeuvre is not the appropriate manoeuvre if another traffic participant is in the adjacent lane; the manoeuvre would be possible without traffic). In this case, these objects can be simulated with less detailed information compared to the dynamic objects which are directly involved in the actual traffic conflict.

The description of traffic participants shall at least cover the type of traffic participant (pedestrian, cyclist etc.) and the geometry of the traffic participants (similar level of detail as the vehicle). Additional parameters for the traffic participant (size, weight, age, etc.) can be added if relevant to the simulated crash or as a variation in traffic conditions.

If the traffic participant is also relevant for detection, further attributes like material and reflection properties should be considered. State of mind and influences (e.g. drugs, alcohol, or drowsiness) can, as in the driver perception model, also be attributed to traffic participants. If at least one vehicle in traffic has V2X capabilities, and the technology in the VuT makes use of such communication technology, then the V2X-communication should also be covered for that vehicle in the traffic model.

This category includes also mobile but temporarily not moving objects that are relevant for the simulation but not covered by the infrastructure, e.g. parked cars or broken-down trucks on the shoulder. During the simulation, the position of the objects remains constant. Hence, these static objects require only static information about their attributes (e.g. geometrical shape, weight and type) and information on the position within the global coordinate system. Table 9 shows examples of traffic models.

Table 9 — Example traffic models and their properties

Model	Purpose	Model prerequisites	Recommended area of application	Limitations
One other road user with predefined trajectory	Minimal model. Open-loop model to generate the movement of an external road user to which the technology should react	Time-dependent trajectory shall be defined	Research question asks for the technology's reaction to one other road user is in focus like in NCAP tests	As the trajectory is predefined, reaction to VuT and other road user behaviour is impossible
Multiple other road users with predefined trajectory	Open-loop model to generate the movement of multiple external road users to which the technology should react	Time-dependent trajectories shall be defined	Additional to above: Research question asks for the technology's capability to determine the most critical road user among several is relevant	As the trajectory is predefined, reaction to VuT and other road user behaviour is impossible
One or multiple other interactive, deterministic road users	Closed-loop (traffic agent based) model to generate movements of other road users that also can react to their surrounding	Predefined route(s); desired deterministic behaviour to avoid conflicts	To be used if the research question includes the reaction of other road users to the VuT action, e.g. VuT performs AEB braking and following car has to brake as well to avoid collision; as the model is deterministic, the reaction (when and how) is always the same	Model for traffic participants that handles everyday driving and critical event response model shall be available
One or multiple other interactive, stochastic road users	Most complex model. Closed-loop (traffic agent based) model to generate movements of other road users that also can react to their surroundings	Predefined route(s); desired behaviour to avoid conflicts; distributions of all relevant random elements	To be used if the research question includes the reaction of other road users to the VuT action, e.g. VuT performs AEB braking and following car has brake as well to avoid collision	Model for traffic participants that handles everyday driving and critical event response model for all shall be available, including stochastic behaviour

Example parameters, inputs, and outputs are the following:

— parameters: open-loop models: pre-defined trajectories; closed-loop (traffic agent based) models: probabilistic distributions for driver behaviour, vehicle types, vehicles per hour as boundary conditions on the investigated areas, light signal logic, driver characteristics, public transport schedules, etc.;

— input during runtime**:** VuT positions, velocity, orientation, heading;

— output during runtime: traffic positions, velocities, orientations, accelerations.

8.2.4 Sensor/perception input generation

8.2.4.1 Scope of sensor/perception input generation

The perception input generation model connects the technology and driver model with the vehicle's surroundings. It generates appropriate information from the surroundings and provides it directly to the vehicle driver and sensor module.

NOTE This model does not represent a physical system like the other models do. This model is often required to represent the "world" in the virtual simulation. All processes happening in a real sensor are put in the sensor model. Everything else that cannot be processed in a real sensor (like deciding which objects are visible or visually obstructed by others) is put in the sensor/perception input generation model.

8.2.4.2 Input generation for the driver model

The sensor and perception generator for the driver model should provide information continuously about the VuT surroundings in the model. These consist mainly of the kinematics of other road users, information from infrastructure (e.g. lane markings, traffic light status) as well as the general environmental conditions (e.g. view obstructions, weather). This information is thereby transformed from a global point of view into the driver's point of view.

Therefore, the input generator for the driver model is highly dependent on the chosen driver model in the simulation and should be adapted accordingly.

Parameters: The parameters are dependent on the used driver model. The values (e.g. position and intention of other road users, FoV for view obstructions) used from other simulation modules to create the needed input for the driver model shall be mentioned.

Input during runtime: The input is gathering information from other simulation modules as needed. This can include information about the current VuT kinematics, positions of other road users including their classification, and other information from the vehicle surroundings (e.g. intentions of other road users as defined in the simulation).

Output during runtime: The input generator shall generate the output depending on the used driver model. Therefore, information from the input may need to be transformed (e.g. the information about other road users shall be processed with a delay to simulate view obstructions).

8.2.4.3 Input generation for the sensor model

When delivering input to sensors, the information format highly depends on the interfaces and requirements defined by the sensor model, which are described in 8.2.4.3. Possible outputs are generated lidar point-cloud data, radar detection lists, camera images or object lists with different fidelities, depending on the type of sensor model used.

The delivered information should map the relevant details of the surroundings and consider influences of traffic, infrastructure and environmental conditions on the sensor perception (e.g. view obstructions).

Parameters: The parameters are dependent on the sensor model used and may vary from positions of other road users and environmental objects in cartesian coordinates or even information about material properties for more sophisticated models.

Input during runtime: Same as for the driver model. Additionally, input for materials used within the simulation environment may be needed to simulate the corresponding sensor responses.

Output during runtime: Depending on the sensor model used, raw sensor information can be generated which may vary between basic detection information (object lists) and sensor responses generated based on materials or colours of other road users (images, radar detections, point clouds).

8.2.5 Vehicle under test block

8.2.5.1 Vehicle model

This model represents the physical effects of the VuT during the driving process. The vehicle type considered by the vehicle model can be the passenger car, motorcycle, truck or bus. The different modelling approaches (see Table 10) are limited by the vehicle type to be modelled, e.g. a two-track model is not applicable to a motorcycle.

NOTE Although often only one vehicle is under test, it is also possible to have multiple vehicles under test.

Depending on the area of application, the vehicle model can have different levels of detail. The following are recommendations and requirements for vehicle models related to certain areas of application:

— Longitudinal only manoeuvres (e.g. braking) can be satisfactorily modelled with a simplified dynamic model, such as point-mass.

— For combined manoeuvres (longitudinal and/or lateral) under ND conditions, a linear bicycle model can be used.

— For combined manoeuvres up to the friction limit, a non-linear bicycle model can be used, but only if the lateral and longitudinal load transfer is not relevant.

— If the effect of the load transfer and brake or propulsion torque to individual wheels is being considered, a two-track model should be used.

— The influence of chassis kinematics and elastokinematics on tire forces can be considered using a multi-body-system model.

More details on these vehicle models are given in Table 10.

Table 10 — State of the art vehicle models and their properties

Model	Degrees of freedom	Purpose	Recommended area of application	Limitations
Point mass model	Longitudinal motion	Studying longitudinal dynamics	Longitudinal manoeuvres (e.g. braking)	Longitudinal dynamics only, only one overall brake/acceleration force
Linear bicycle model	Longitudinal, lateral, yaw motion	Studying longitudinal dynamics up to friction limits and lateral dynamics up to 0,4 g	In case lateral load transfer can be neglected and braking and propulsion torque to individual wheels can be neglected, but only for quasi steady state analysis	Only applicable for ND (lateral accelerations up to 0,4 g) COG assumed to be at ground level, therefore no lateral or longitudinal load transfer and its consequences on tire forces considered Influence of chassis kinematics and elastokinematics on tire forces not considered
Non-linear bicycle model	Longitudinal, lateral, yaw motion	Studying longitudinal and lateral dynamics up to friction limits	In case lateral load transfer can be neglected and braking and propulsion torque to individual wheels can be neglected	COG assumed to be at ground level, therefore no lateral or longitudinal load transfer and its consequences on tire forces considered Influence of chassis kinematics and elastokinematics on tire forces not considered
Two-track model	Longitudinal, lateral, vertical, yaw, roll, pitch motion	Studying motion control systems and vehicle handling	In case the effect of load transfer and brake or propulsion torque to individual wheels shall be considered	Influence of chassis kinematics and elastokinematics on tire forces not considered
Multi-body-system model	High degree-of-freedom	Development and validation of chassis structure	In case a very high resolution/specification is required, and design has to be validated against real-world behaviour	None

By this category, information is covered that is static (does not change during the simulation run) as well as dynamic (changes over time during one simulation run). The static information includes the dimensions, the linked driver (if there is a driver), engine or brake parameters, as well as limitations in the movement. For crashes, an analysis of the weight or material and construction of the vehicle can be necessary.

The dynamic information covers, for example, the position in the global coordinate system of the simulation, the velocity and accelerations in a vehicle-fixed coordinate system, the rotation angles as well as the rotation velocity. For the object, a fixed coordinate system according to ISO 8855, such as a vehicle coordinate system, shall be used. Next to the kinematic information, state information (e.g. turn indicator) and internal information (e.g. engine speed) can be part of the dynamic information for the movable object. The dynamic information can also cover information about the (on-board) technology (sensors, function, etc.).

Example parameters, inputs, and outputs are the following:

— parameters: parameters describing the physical driving behaviour of the VuT: mass, suspension characteristic, geometric model (a 2/3D contour model or simply a box);

— input during runtime: actuator inputs from the driver or the technology, road geometry from infrastructure, road friction modifying conditions (e.g. rain) from environmental conditions;

— output during runtime: vehicle state for the next simulation time step as a response to driver or actuator input.

8.2.5.2 Technology model

The technology model covers the information related to the simulated vehicle technologies. Within this category, information is required for the sensor, logic and control and the actuator models. The technology does not necessarily only cover the technology under assessment. It can also cover additional technologies that are considered in the assessment. This model covers static and dynamic information. Moreover, the

level at which a technology is modelled can vary depending on the evaluation objective. This aspect shall be considered for the subcategories individually, meaning that, for example, the logic and control step is modelled in a high level of detail, whereas the actuators are only modelled in a rather straightforward way.

The static information describes the technical attributes of the technology (FoV, object detection conditions, activation conditions, max. force of an actuator etc.), whereas the dynamic information is the internal and external output of the model (status of activation, applied force etc.).

The technology model can also be a container to different models, an example of which is shown in Figure 6.

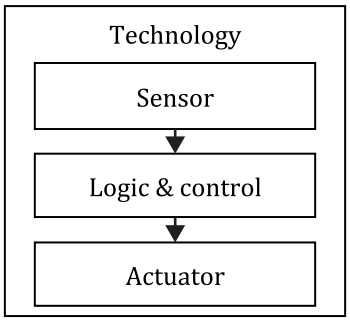


Figure 6 — Technology details

The sensor model represents the perception mechanisms of the sensors that are used by the active safety technologies to gather information from the vehicle surroundings. This can also include information from V2X technology[1)] or digital maps. In case environmental or infrastructure factors (e.g. weather conditions, glaring due to the sun) are of relevance to the research question, the effects of these factors on the perception should be modelled. Depending on the research question, the sensor model can have different levels of abstraction (e.g. ideal, phenomenological). A possible classification and brief overview of characteristics of different sensor models is given in Table 11.

NOTE Table 11 represents one possible classification. Intermediate solutions between these categories are also feasible.

Table 11 — Overview of modelling approaches for the technology's sensor model part for virtual assessments (modified version of Reference [12])

	Ground truth model	Idealized model	Phenomenological model	
			Stochastic model	Physical model
Principle	Transformation of global ground truth in sensor perspective ground truth	Perfect measurement range (the sensor only measures values)	Stochastic (probabilistic and statistic) for modelling observable effects	Modelling of signal propagation, reflection, diffraction, refraction, absorption, transmission, reception, etc.
Possible specifications	None (only transformation)	Position, orientation, ideal measurement range	False detections (FP/FN), noise, atmosphere, dirt, manipulation, etc.	Wave lengths, material properties, surfaces, signal processing.
Sensor accuracy	Perfect	Perfect	Realistic overall stochastic	Realistic single measurements
Complexity	Very small	Very small	Small	Very high to infinite
Level of abstraction	Very abstract	High abstraction	Middle abstraction	Almost no (known) abstraction

1) When the technology that is being assessed includes V2X communication technology, the sensor model includes a model to describe the receiving and interpretation of communication messages. At the sensor side of the technology block, only the reception of messages is considered, hence only the V2X component. The V2X communication receives information from the infrastructure (I2V) or from other vehicles directly (V2V).

Input for the sensor model is given by sensor/perception input generation model (see 8.2.4). All processes happening in a real sensor should be put in the sensor model, everything else that could not be processed in a real sensor (like deciding which objects are visible or visually obstructed by others) should be put in the sensor input generation model.

Example inputs, outputs and parameters are:

— sensor model parameters: at least parameters describing how object detection and classification works (e.g. FoV, initial detection latency, object classification logic, tracking latency);

— sensor model input during runtime: information on geometrical models of traffic participants and infrastructure (static 3D objects) including position and orientation in space as well as colour and transparency information (cameras) or texture and reflectance (radar), environmental conditions;

— sensor model output/logic and control model input during runtime: an object list is generated, which can include detected objects, geometry of the detected objects (e.g. points on the detected objects), detected (estimated) velocities and positions relative to vehicle, detected (estimated) object types, object state (e.g. standstill or moving); driver state (safety logic may not override driver reaction).

The logic and control model describes the part of the technology that responds to the input provided by the sensor models. For technology's safety performance, the technology 's logic and control shall be represented at an accuracy that is sufficient for the assessment. There are different ways the logic and control part of technology can be modelled. Table 12 provides an overview of the basic approaches.

Table 12 — Overview of modelling approaches for the technology's logic and control part for virtual assessments

Model	Description	Recommended area of application	Limitations
Model in the loop	A model of the technology (logic and control part) is defined and implemented. This model is used for assessment. For the implementation different approaches are feasible, for example: — implementation from function description — implementation of simplified version of the original software — implementation based on test data (i.e. re-engineering).	This approach can be used to check the model against requirements, obtain reference signals and verify algorithms. It can be applied in the development from the early concept phase onwards since it allows for quick adaptation of the logic and control model. For the later development phases, the appropriate representation of reality becomes more relevant for this type of model.	In the V&V, it shall be proven that the model represents the actual technology in a sufficient way. If the model covers only parts of the technology's logic or is only built up for certain scenarios, this limitation shall be documented.
Software in the loop	The same software code of the technology's logic and control is simulated as is running in the real version of technology	This approach can theoretically be applied during the entire development process. Considering the assessment purpose, it is more likely that the approach is used in the final stages of development or after the technology's market introduction.	Although the same software is used, it shall be proven that it represents the actual technology. The approach requires the actual software code to be available. The simulation software shall provide an interface to run the actual software.
Hardware in the loop	The actual control unit of the technology is linked to the simulation.	This approach can only be applied in the late stages of the development since it requires the actual hardware to be in place. This is typically not the case in the early development phases.	Although the actual hardware is used, it shall be proven that it represents the actual technology. The approach requires the hardware (control unit) to be available. The hardware (control unit) shall be linked to simulation software. The simulation can only run at real time.

Example inputs, outputs and parameters are:

— logic and control model parameters: at least parameters describing when the counter measures are triggered (e.g. below a certain TTC value) and how the counter measures commands are performed (e.g. braking slope and maximal intensity, response and actuation delays).

— logic and control model output/actuator model input during runtime: necessary warnings to driver or commands to actuators.

The actuator model transfers the commands of the logic and control model into actions that can result in a changed movement of the VuT. Theoretically, the same modelling approaches as for the logic and control part (see Table 12) – including the limitations – apply also for the actuator. Practically, the model in the loop and the software in the loop are used, since the hardware in the loop approach requires a specific test bench. For the model and software in loop approaches, the physical limitations of an actuator in the actuator model shall be considered. These limitations are typically maximal ranges, delays in the implementation as well as build-up of the calculated actions (i.e. forces, torques or displacements).

Example outputs and parameters are:

— actuator model parameters: delays; limitation in the build-up of forces, torques or displacements; max. range of applied forces, torques or displacements;

— actuator model output during runtime**:** commands made to the vehicle model (e.g. accelerate, brake, steer) or warnings made to the driver.

8.2.5.3 Driver model

Human behaviour is tremendously complex and is not easily described in mathematical models. For this reason, human driver modelling is a more immature field of knowledge than, for example, vehicle dynamics modelling. The driver model component of a safety performance assessment is likely to be the component with which most uncertainty is associated.

The following are general guidelines for the use of driver models in safety performance assessment, which are further expanded in 8.2.5.3.1 to 8.2.5.3.3:

— It should be carefully considered, and clearly stated, to what extent the adopted driver model can be considered valid for the purposes of the safety performance assessment:

  — Whenever possible, references should be made to publicly available technical reports or scientific publications describing the models and for what driving situations model validity is demonstrated. References to internal company documents can be added, but that does not help users to assess model validity.

  — Specific guidelines apply regarding model capabilities for capturing driver behaviour variability (between-driver and within-driver) and factors that may affect driver behaviour (traffic scenario, safety system design, driver traits/states, etc.). See 8.2.5.3.2 and 8.2.5.3.3.

— Different baseline approaches require different types of driver models. See 8.2.5.3.1.

— Since some uncertainty about driver model validity will persist (due to the complexity of human behaviour), it is recommended to conduct and present sensitivity analyses with respect to the adopted model and parameterisation. In other words, how are the safety performance assessment results affected by choosing a different model and by varying the model's parameters? For example:

  — Sensitivity analyses are more important the more uncertainty there is about the model's validity.

  — Sensitivity analyses are also particularly important if simplified models are chosen over more advanced state-of-the-art models, e.g. for reasons of computational complexity and simulation execution time. In these situations, it is recommended to demonstrate that the model simplification does not substantially alter safety assessment conclusions (at least for some subset of simulations).

— If the technology under assessment is operating in a completely automated way (never requiring human action) no driver model is needed in the treatment simulations (although driver models may still be part of the baseline creation in baseline approaches B or C; if so, the same guidelines as above apply to these models).

8.2.5.3.1 Types of driver models

A variety of driver models may be used in virtual assessment. Here, they are divided into three types. First, trajectory following models, which are models that simply follow a predefined trajectory. These are models that are not designed to be human-like in inputs or model mechanisms, but instead use a controller to follow a given trajectory, which may or may not have been recorded while a human was driving. Second, critical event response models, which model the driver's response process to critical events, such as imminent collisions or safety critical events. Third, everyday driving models, which model how a driver controls the vehicle under non-critical situations, including lane keeping, distance keeping, overtaking and curve negotiation. The main reason for differentiating between the two latter models is that driver behaviours often differ substantially between everyday driving and critical events. However, note that in a simulation

a combination of these model types may be used (e.g. trajectory following and critical response models). A single model may be capable of capturing both everyday driving and critical event responses.

The following are guidelines regarding which model types are suitable for safety assessment adopting the respective three different baseline approaches:

— For baseline approach A and C1, trajectory-following and critical event response models are typically suitable. However, every-day driving models are by definition inappropriate, since in baseline approach A the non-critical driver behaviour before the critical event should remain the same as in the original event.

— For baseline approach B, all three model types can be used, both in baseline creation and in treatment simulations.

— Baseline approach C2 requires a model of both everyday driving and critical event response (as a single model or as separate models).

8.2.5.3.2 Capturing driver variability

In many contexts, behavioural variability is an important aspect of the driver model. There are two main types of driver variability: between-driver variability and within-driver variability.

— Between-driver variability is when two different drivers behave differently in a fixed scenario. For example, some drivers have faster reactions than others, some drivers brake harder than others, and drivers often have different visual scanning strategies. This can be related to driver traits, such as age, gender, driving experience, driving style, general trust in technology, etc. These factors can influence the differences in behaviour and how they should be captured in the driver model and in simulations.

— Within-driver variability, when there is variability in how a single driver behaves in a fixed scenario. This can be related to well-defined high-level driver states which change on a slow time scale (but not as slowly as driver traits), such as drowsiness or trust in or reliance on a specific safety system. These driver states can be either static during simulation (e.g. set as fixed parameters via pre-simulation models) or dynamic during simulation (e.g. if the simulation model describes how drowsiness or system trust changes during a drive). However, within-driver variability can also be lower-level in nature, not arising from any identifiable higher-level driver state. One example is within-individual variability in decisions and reaction times even when all else is kept as constant as possible.

From a concrete implementation perspective, variability in the driver model is typically captured in the simulations in one of two ways (or both). First, one may use a probabilistic driver simulation model.

EXAMPLE 1 A random process for determining where a driver is looking at any one time.

EXAMPLE 2 The inclusion of stochastic noise (with some underlying distribution) that vary over time (for each sample) in the execution of the simulation-model, e.g. to determine driver brake response time.

EXAMPLE 3 Decision-making in the driver model that has different probabilities for different decision alternatives. This can be some stochastic decision-making process related to whether the driver should overtake (e.g. part of an everyday driving model component) or whether the driver should brake or not, given external stimuli (e.g. part of the critical response model component).

Second, distribution-based pre-simulation models may be used to set the parameters of the driver simulation model. An example of this type of model for handling driver variability is sampling from pre-simulation distributions of a driver age parameter, which the simulation model transforms into a fixed brake reaction time typical of that age.

It is common to combine a probabilistic driver simulation model and a distribution-based pre-simulation model. For example, rather than transforming the age parameter to a deterministic simulation model for the brake reaction time, it can instead affect a probabilistic decision-making process implemented in the simulation model.

The following are guidelines related to the capturing of driver variability in safety assessment simulations:

— It should be clearly stated to what extent the driver model that is used in a safety performance assessment accounts for between and/or within driver variability, and, if so, what type of variability is being modelled.

— If driver variability is not considered, the implications on the results of not considering it should be discussed when reporting the results.

8.2.5.3.3 Controlling for factors influencing driver behaviour

There are many factors that are known to influence driver behaviour, often in complex ways. These can be conceptualised as parameters of the driving situation, and include the following:

— scenario parameters that are known to affect driver behaviour, such as:

  — surrounding road user kinematics (distances, velocities, accelerations);

  — road/weather/lighting/visibility conditions;

  — behaviour of surrounding road users beyond their kinematics (e.g. communicative gestures to the driver or behaviours indicative of the road users state, such as a pedestrian looking down at a phone while walking);

  — the presence of multiple other road users, potentially forming more complex interaction scenarios.

— design parameters of the safety system, such as the exact design of system warnings or interventions;

— driver trait and state parameters, such as those mentioned in 8.2.5.3.2.

It is important to keep in mind that a driver model that has been validated for one or more specific situations with respect to these parameters may not be valid in other situations, with different scenarios, safety system designs or driver traits/states.

The following are guidelines relating to factors that influence driver behaviour:

— It should be clearly stated to what extent the driver model used in the safety performance assessment has been validated for the situation(s) being simulated, with respect to scenario, safety system design, driver trait/state parameters and any other relevant parameters. One important example: has the model been validated for unusual and/or safety-critical cases (“edge cases”)? That is, have the cases at the tails of the distribution of scenario parameters been covered in the safety performance assessment? (see Clause 11).

— If it is not known or modelled how driver behaviour may change with some of the situation parameters being varied, this should be stated as a limitation of the safety performance assessment.

8.2.5.3.4 Model inputs, outputs and parameters

The parameters, inputs and outputs to driver models vary greatly between model types and individual models and between different safety performance assessments.

Parameters: These can be anything from very low-level parameters directly describing behaviour (e.g. a deceleration magnitude) to very high-level parameters (e.g. driver drowsiness level) from which the model then generates driver behaviour.

Input during runtime: Examples of model inputs are VuT vehicle kinematics, surrounding road user kinematics, messages/interventions from the system, information from the infrastructure (e.g. traffic light status) and other (non-kinematic) state information about surrounding road users (e.g. communicative gestures or engagement in secondary tasks). Input to the driver simulation model can be different from the “sensory input” assumed by the driver model itself. For example, the inputs to the simulation model can be given in Cartesian coordinates, which are then transformed inside the simulation model to more

psychologically plausible inputs for the model, for example lead vehicle size, range and velocity transformed into visual looming of the lead vehicle on the driver's retina.

Output during runtime: All driver models include some form of output regarding the driver's control of the vehicle, either longitudinally, laterally or both. Depending on the safety performance assessment and the model, this may be in the form of pedal positions and/or steering wheel angles or directly in the form of, for example, vehicle accelerations and/or yaw rates. More advanced models may also include outputs describing the driver's attention/gaze allocation (e.g. where the driver looks, such as on the roadway ahead, on in-vehicle interfaces, on mobile phones or towards other road-users in an intersection) and/or interaction with in-vehicle systems (e.g. use of on-board navigation or radio tuning).

8.2.6 Collision block

The collision block includes a collision detection model using VuT, traffic, infrastructure and environmental conditions states as inputs to perform geometry checks of collision/no-collision.

In general, a collision is detected in the simulation once the volumes of two objects overlap in an infinitely small manner. Therefore, it shall be ensured that overlapping volumes are correctly detected and with a sufficiently fine time step to avoid differences between different simulation tools. Besides a collision between two objects, single vehicle crashes shall also be detected if the VuT leaves the road or other areas on which a vehicle can drive.

Collision consequence models describe collision mechanics, including occupant/VRU response, and yield the information necessary for the assessment of the severity of collisions. Collisions can be represented at various degrees of detail: injury risk curve-based models directly link impact velocities with injury probability, allowing to quickly assess large numbers of simulations. Another approach is to use additional finite element (co-)simulation to derive the injuries. These simulations are used to analyse in detail resulting loads on occupants/VRUs acceleration during the crash. Injury criteria-based metrics are calculated based on the loads. The finite element simulation requires longer computation times but provides results in high levels of detail.

The collision information is required to parametrize the applied models for deriving the consequences of a collision. Here, the applied model shall be acknowledged. Where approaches like injury-risk-functions are used, the required information for the parametrization is static (collision data linked to an injury severity). Since the collision consequences are calculated for each collision, the outcome (e.g. probability of certain MAIS injury) is often a static single value for each collision.

Where further simulations are applied to determine the consequences of a collision, the direct simulation output is not static but an output over time. Depending on further calculations, this result can be converted into a single value (e.g. likelihood of certain injury level or monetary cost).

Example inputs and outputs are:

— collision consequence model input at time of initial contact: driving state of colliding vehicles objects and parameters for collisions calculation (FE model, stiffness parameters, mass, inter-vehicle friction, etc.);

— collision consequence model output: depends on the level of detail of the model. Post-collision driving state for momentum-based impact model (infinitely small collision duration is assumed, thus no collision pulse as output) or full collision deformation (FE models or similar) and collision pulse;

— option: injury risk curves can enter the collision consequence model as parameters. They can in turn be combined with the output listed above to result into injury probability (which would be an additional output of the collision model).

8.3 Example for minimum required information for treatment simulation

The minimum required information for establishing the simulation in the given example of a VRU AEB is given in Table 13. Regarding limitations of the example please see Clause 6. The term "@ start" means in this context the first time point of the simulation.

Table 13 — Example minimum required information for the treatment simulations using different baseline approaches in the given example; data point (DP), data series (DS) and probability distribution (PD)

Information type	Baseline approach A and C1	Baseline approach B	Baseline approach C2
Simulation control	Scenario time (DS), collision detection (DP)	Scenario time (DS), collision detection (DP), number of simulation runs (DP)	Scenario time (DS), collision detection (DP), number of simulation runs (DP)
Vehicle surroundings – infrastructure	x-/y-position of visual obstructions (DP), dimension of visual obstructions (DP)	x-/y-position of visual obstructions (DP), dimension of visual obstructions (DP), variation of the obstruction (position, size) (PD)	x-/y-position of visual obstructions (PD), dimension of visual obstructions (PD)
Vehicle surroundings – environmental conditions	Limitation of the maximum possible de-/acceleration (DP)	Limitation of the maximum possible de-/acceleration (DP), variation of the maximum possible de-/acceleration (PD)	Limitation of the maximum possible de-/acceleration (PD)
Vehicle surroundings – traffic	Time (DS), x-/y-position VRU (DS), dimension of VRU (DP)	Time (DS), x-/y-position VRU (DS), dimension of VRU (DP), variation of the VRU movement (DS)	x-position VRU @ start (PD), y-position VRU @ start (PD), velocity VRU @ start, yaw angle VRU @ start (PD), dimension of VRU (DP), VRU model parameters (PD)
Vehicle under test – vehicle	x-position @ start (DP), y-position @ start (DP), velocity @ start (DP), yaw angle @start (DP), vehicle dimension (DP), longitudinal and lateral acceleration (DS)	x-position @ start (DP), y-position @ start (DP), velocity @ start (DP), yaw angle @start (DP), vehicle dimension (DP), longitudinal and lateral acceleration (DS), variation of the kinematic parameters (DS)	x-position @ start (PD), y-position @ start (PD), velocity @ start (PD), yaw angle @start (PD), vehicle dimension (PD)
Vehicle under test – technology	Sensor FoV (e.g. angle and range) (DP), sensor position at VuT (DP), activation criteria (e.g. TTC threshold) (DP), reaction in case of activation (e.g. type of warning, braking) (DP/DS)	Sensor FoV (e.g. angle and range) (DP), sensor position at VuT (DP), activation criteria (e.g. TTC threshold) (DP), reaction in case of activation (e.g. type of warning, braking) (DP/DS)	Sensor FoV (e.g. angle and range) (DP), sensor position at VuT (DP), activation criteria (e.g. TTC threshold) (DP), reaction in case of activation (e.g. type of warning, braking) (DP/DS)
Vehicle under test – driver	VuT x-/y-position (DS) as input to trajectory following model, critical event response model parameters (e.g. time, type and amplitude of response (DP/DS))	VuT x-/y-position (DS) as input to trajectory following model, critical event response model parameters (e.g. time, type and amplitude of response (DP/DS)), everyday driving model parameters (e.g. longitudinal and lateral control, (DP)), variation of each driver model parameter (PD)	Critical event response model parameters (e.g. time, type and amplitude of response (PD)), everyday driving model parameters (e.g. longitudinal and lateral control, (PD))
Collision	Dimensions VRU and VuT (DP)	Dimensions VRU and VuT (DP)	Dimensions VRU and VuT (PD)

9 Assessment of safety performance

9.1 Calculation of safety performance

The assessment results shall be presented with the applied metric and the evaluation objective (see 6.4).

The traffic safety performance of a technology is in general measured in the dimensions severity I_{Scenario} and frequency of occurrence (or exposure) of relevant scenarios f_{Scenario}. The safety performance in an individual scenario is calculated by Formula (10) as the difference between the treatment and the baseline.

$$S_{\text{i}} = I_{\text{Treatment,i}} \cdot f_{\text{Treatment,i}} - I_{\text{Baseline,i}} \cdot f_{\text{Baseline,i}} \tag{10}$$

The change in severity $\Delta I = I_{\text{Treatment}} / I_{\text{Baseline}}$ and the change in the frequency of occurrence, $\Delta f = f_{\text{Treatment}} / f_{\text{Baseline}}$, the performance P is derived for all scenarios n by Formula (11).

$$S = \sum_{i=1}^{n} I_{\text{Baseline,i}} \cdot f_{\text{Baseline,i}} \left(\Delta I_{\text{i}} \cdot \Delta f_{\text{i}} - 1\right) \tag{11}$$

For the baseline approaches A, B, and C1, a direct comparison between the baseline case and the treatment case is feasible. For baseline approach C2, this is not always a given due to the applied (stochastic) variations. If the same variations are applied, a direct comparison is feasible. Where the variations for both conditions are not identical due to a stochastic approach, the number of simulated cases shall be large enough so that the results of the baseline and treatment are stable following the law of large numbers.

9.2 Example for minimum required information for safety performance assessment

For the example study of a VRU AEB that is described in Clause 5, the minimum required information for estimation of the safety performance is given in Table 14.

Table 14 — Example minimum required information for the three baseline approaches in the given example; data point (DP), data series (DS) and probability distribution (PD)

Information type	Baseline approach A, B, C1 and C2
Vehicle under test — vehicle	Velocity @ end (DP), x-/y-position @ end (DP)
Vehicle under test — technology	Technology activation status (DS)
Vehicle under test — driver	N/A
Vehicle surroundings — infrastructure	N/A
Vehicle surroundings — environmental conditions	N/A
Vehicle surroundings — traffic	Velocity @ end (DP), x-/y-position @ end (DP), VRU parameters (DP)
Collision	Status collision (DP), IRF MAIS 2+ VRU (PD)
Simulation control	N/A

NOTE "@ end" means that the information is available at least for the time step in which the collision is detected as well as for the last time step prior to collision.

10 Documentation

Besides the documentation of applied simulation software and models, the documentation of results shall fulfil certain criteria to ensure the proper exchange of results between different entities and facilitate understanding of the results. This clause focuses on documentation for external publication of an assessment's results (i.e. outside the conducting organisation).

The documentation for company internal purposes is not discussed in detail. Nevertheless, it is recommended to use the same requirements for internal documentation. In addition, further requirements, for example

due to the application of virtual assessments in a third-party assessment, may exist and shall be considered for the internal documentation depending on the purpose of the assessment.

Different purposes are distinguished for external-oriented documentation, such as:

A) documentation of the results of a study with the intention to assess it in conjunction with the outcome with other similar assessments (i.e. same technology under similar conditions), e.g. an assessment of a technology's safety performance in a consumer assessment (such as NCAP assessments);

B) directly comparing results of different simulation studies investigating the same technology but performed with different simulation tools, i.e. a round-robin study (see Annex B);

C) documentation of the results of a standalone assessment, e.g. in a scientific paper. The aim is to achieve an understanding of what has been done. Comparability is not the primary focus.

NOTE Examples for the different types of reports can be found in Annex C.

In contrast to B) (focus is only on the simulation tool) and C) (no comparison intended), purpose A) (similar assessment) poses the biggest challenges in terms of the comparability of results. This is because the technology, simulation approach and tool influence the assessment results. Ideally, the assessment should show only differences due to the technology and not due to the simulation tool and approach. Conformity with this document should reduce the unintended effects of the simulation approach and tools. Nevertheless, V&V (see Clause 11) are the key aspects to prove the conformity of the simulations and their results with reality. Therefore, a detailed document of the V&V shall be part of the documentation.

Table 15 provides the minimum requirements for the documentation for the different purposes. Please note that Table 15 is only a general overview, more details are available in 8.2. Depending on the purpose of assessment, additional requirements for documentation can exist and need to be considered, for example see Reference [13].

Table 15 — Minimum requirements for the documentation for the different purposes

	A. Comparing technologies	B. Comparing simulation tools	C. Standalone assessment
Data (simulation output, if requested)			
Data format	Data shall be provided in a commonly readable data format which allows to review the data (e.g. CSV, XML)	Data shall be provided in a standardized data format, which allows for detailed investigations.	No requirements
Report			
Purpose	Comparison of safety technology performance	Comparison of simulation tools	Other motivations without main intention of comparison, e.g. scientific publication
Evaluation objective (see Clause 6)	Description of the evaluation objective including research question(s). Detailed description of metrics used.	Description of the evaluation objective including research question(s). Detailed description of metrics used.	Description of the evaluation objective including research question(s). Description of metrics used (a general outline is sufficient).
Metrics input data (see Clause 5)	Detailed description of parameters (if any) used to define the metrics, e.g. IRF. References to previous publications (if any) can be used to describe model details, are encouraged.	Detailed description of parameters (if any) used to define the metrics, e.g. IRF. References to previous publications (if any) can be used to describe model details, are encouraged.	General description of parameters (if any) used to define the metrics. References to previous publications (if any) can be used to describe model details, are encouraged.

Table 15 *(continued)*

	A. Comparing technologies	B. Comparing simulation tools	C. Standalone assessment
Applied baseline approach (see Clause 7)	Type of baseline approach according to Clause 7. Description of how baseline was set up including data sources; Description of baseline cases (trajectories of all participants, definition of visual obstructions (positions, sizes). If baseline definition is reused: Reference to the original definition.	Type of baseline approach according to Clause 7. If baseline definition is reused (default for such studies): Reference to the original definition. Otherwise: Description of how baseline was set up including data sources; Description of baseline cases (trajectories of all participants, definition of visual obstructions (positions, sizes).	Type of baseline approach according to Clause 7. Description of how baseline was set up including data sources; Description of baseline cases (trajectories of all participants, definition of visual obstructions (positions, sizes). If baseline definition is reused: Reference to the original definition.
Baseline input data (see Clause 5)	Detailed description on the input data regarding collection and processing and representativeness shall be included as a minimal information. References to previous works using the same baseline (if possible) are encouraged.	References to previous works using the same baseline (if possible). Only if a new baseline is created shall a general outline of the input data regarding collection and processing be included as a minimal information.	A general outline of the input data regarding collection and processing and representativeness shall be included as a minimal information. References to previous works using the same baseline (if possible) are encouraged.
Technology under assessment (see Clause 8)	Description of the technology (sensor, logic and control, actuator), its features and limitations. If technology definition is reused: Reference to the original definition.	Detailed description of the technology (sensor, logic and control, actuator), its features and limitations. If technology definition is reused: Reference to the original definition. Implementation of the technology (software, etc.).	General outline of the technology (sensor, logic and control, actuator), its features and limitations. If technology definition is reused: Reference to the original definition.
Simulation tool (see Clause 8)	General description, consisting of tool name and version, including an outline of adaptations (if any) made to run the study and a listing of simulation control parameter values (see 8.2.2).	General description, consisting of tool name and version, including a detailed description of adaptations (if any) made to run the study and a listing of simulation control parameter values (see 8.2.2).	General description, consisting of tool name, including an outline of adaptations (if any) made to run the study.
Applied simulation models (see Clause 8)	A general description of each model shall be given, including purpose and application area, principles, and limitations. References to previous works using the same models are encouraged.	Each model shall be described including purpose and application area, input and output types and units, detailed principles (including but not restricted to functional formulae), and limitations – especially those relevant to model integration into the simulation tool (including, but not restricted to, timestep and solver specifics). For each model (if any) which uses a different software than the simulation tool, name and version of software used shall be mentioned. References to previous publications, if any can be used to describe model details, are encouraged.	A general description of each model shall be given, including purpose and application area, principles and limitations. References to previous works using the same models are encouraged.

Table 15 *(continued)*

	A. Comparing technologies	B. Comparing simulation tools	C. Standalone assessment
Applied simulation models (including technology under assessment) input data (see Clause 5)	A detailed listing and description of the parameters used shall be given. References to previous works using the same models are encouraged.	A detailed listing and description of the parameters used shall be given. References to previous works using the same models are encouraged.	A generic listing and description of the parameters used shall be given. References to previous works using the same models are encouraged.
Results (see Clause 9)	Baseline and treatment simulation output (trajectories, crash configuration). Results in the specified metrics covering all cases: Depending on the number of cases, either all results in tabular form and/or statistical values (mean, median, min, max, range) in tabular form or in figures. Limitation of the assessment shall be named.	Units and coordinate systems used. The results documentation shall contain the metrics results for baseline and treatment simulations (all cases). Time-dependent values (positions, velocities, accelerations, technology data, simulation status flags (e.g. target detected, technology activated, collision) plus definition of measurement points relative to the participant's geometry for baseline and treatment. Baseline and treatment simulation output (trajectories, crash configuration). Results in the specified metrics covering all cases: Depending on the number of cases, either all results in tabular form and/or statistical values (mean, median, min, max, range) in tabular form or in figures. Limitation of the assessment shall be named.	Results in the selected metrics covering all cases: Depending on the number of cases, either all results in tabular form and/or statistical values (mean, median, min, max, range) in tabular form or in figures. Limitation of the assessment shall be named.
V&V (see Clause 11)	Description of the applied V&V process and its results on the overall as well as model level. It shall be named for which models V&V activities with respect to the models' usage in this study has been applied. Or, if that is not the case, a line of argumentation why the models' application in this study is still valid. Comparison of given baseline data to baseline simulation output (trajectories, crash configuration).	Description of the applied V&V process and its results on the overall as well as model level. It shall be named for which models V&V activities with respect to the models' usage in this study has been applied. Or, if that is not the case, a line of argumentation why the models' application in this study is still valid. Comparison of given baseline data to baseline simulation output (trajectories, crash configuration).	At least brief statement, whether V&V activities have taken place and if yes, which. It shall be named for which models V&V activities with respect to the models' usage in this study has been applied. Or, if that is not the case, a line of argumentation why the models' application in this study is still valid. Comparison of given baseline data to baseline simulation output (error in trajectories, crash configuration).
V&V input data	Detailed description of input data used to define the reference used in the V&V process (see Table 3 in Clause 5). References to previous publications, if any can be used to describe test details, are encouraged.	Detailed description of input data used to define the reference used in the V&V process (see Table 3 in Clause 5). References to previous publications, if any can be used to describe test details, are encouraged.	Brief outline of the type of input data used to define the reference used in the V&V process (if any). References to previous publications, if any can be used to describe model details, are encouraged.

Any exclusion criteria, filtering or weighting method that is applied shall be properly documented so that the V&V process can assess if such a processing is reasonable.

11 Validation and verification

To ensure that the prospective safety performance assessment process and its results sufficiently reflect the real world, a V&V process for the prospective safety assessment concerning its method and results shall be established and carried out. In addition, the V&V process should cover relevant (sub-) models and steps within the method. This clause addresses the execution of the V&V process while Clause 10 described the aspect to be documented.

The V&V process shall be conducted at least once and shall be repeated until the V&V criteria are met. In addition, the process shall be repeated depending on changes in the method and its steps, the simulation tool as well as used (sub-) models. A distinction is made between changes related to the evaluation objective (e.g. new technology, assessment of different environments) to input data or parameters and to technical updates. Technical updates of a tool are, for example, altering a model, fixing existing bugs, or the integration of new models in the tool.

Independent of the reason, change(s) in the simulation tool, methods or models shall be evaluated with respect to its impact on the outcome of the assessment and changes shall be classified into minor or major changes. In the case of major changes, the V&V shall be done for the affected parts of the process (models, simulation tool, method). For minor changes, no further V&V action is necessary. However, it shall be demonstrated that the criteria for a minor change are fulfilled.

The differentiation between minor and major shall be defined by the person(s) that conducts the simulation assessment. The person shall report on the differentiation criteria applied and the rationale for it. A general guideline for the differentiation is that major changes affect the principles of the conducted simulation and can lead to considerably different results, while minor changes may not affect the simulation considerably. A comparison between the old and the new implementation, like the back-to-back test, can provide supporting evidence for the decision on the type of change that was made based on expert knowledge.

Examples for potential major and minor changes are given in Table 16.

Table 16 — Examples of potential major and minor changes in the context of V&V

	Major change(s)	Minor change(s)
Method	— Change of the baseline type — Change to different input data, i.e. a database is used — Change of the scope of the study	— Add a new outcome or metric to the evaluation — New cases are added to the baseline data (e.g. due to a newer version of the previously used database) — Repeat the study with a different technology with the same evaluation objective
Simulation tool	— Use a different tool or a new version that includes substantial changes (new release) — A simulation tool that is not backwards compatible — A major release of the simulation tool (V1.x → V2.x)	— Use a new version that includes few changes — Change the simulation step size — A minor release of the simulation tool (V1.x → V1·(x+1)) — Changes to the tool that historically have not impacted the results
Model	— Use a different model (different sensor model, driver model, different vehicle dynamic model etc.) — Change of scenarios to which the assessment is applied, but where a sub-model (e.g. driver model) is substantially changed — Exchange the current model with a model that has not been validated beforehand — A model that is not backwards compatible	— Evaluation-specific modification of a model's parameter within the specified and validated parameter range (e.g. changing sensor position) — Exchange the current model with a model that has been validated beforehand — Change to scenarios for which a model (e.g. driver model) has previously been validated

The V&V process also becomes necessary when a model is applied outside its specification or in conditions for which it has not been validated in earlier assessments.

All aspects, including the overall method, baseline generation and the different models of the simulation, shall be covered by the V&V. Typically, the V&V requires a check of the simulation results in comparison to a reference. The reference is often defined by real world data from sources like real-world accident data, FOT data, NDS data or test track data etc. When comparing virtual and real-world data, it shall be identified which models have been tested and what their interactions is. For example, in a physical real-world test (e.g. a test track), the technology is always tested with a certain vehicle. If the interactions in the reference are not clear, there is the risk that the test result are falsely interpreted and a result that derives from the interaction of models (e.g. technology and vehicle model) is associated with one model (e.g. the vehicle). Therefore, the reference should also be analysed in detail.

All models and their application shall be checked during verification to ensure that they are applied in their defined scenarios and ranges, for which they are valid.

The following aspect should be considered within the V&V process with respect to the baseline generation:

— The V&V process should cover different crash severity levels.

— For relevant scenario parameters, the V&V process should be carried out at least once for each technology under assessment.

Table 17 presents approaches that should be considered for their V&V for the overall method for the baseline and the simulation models, as defined in 8.2.

Table 17 — Validation and verification approaches for the overall method, baseline and model

	Validation and verification approach	Example (VRU AEB, see 6.2)
Overall method/ result	— Comparison simulation results with a retrospective assessment for the same technology based on real-world data (e.g. crash statistics, insurance data). — Comparison simulation results with other prospective effectiveness assessment studies that are based on, e.g. test track testing, FOT data or other virtual simulation tools. NOTE 1 Comparison with a retrospective assessment is only feasible for technologies that have already reached a certain market penetration and enough accident data for such an analysis is available. For the comparison with other prospective effectiveness assessment studies, it shall be ensured that the results of these studies have been validated beforehand. When calculating the safety performance based on real-world data, interfering effects of other technologies shall be minimized. For example, if the safety performance of ACC is assessed, the AEB safety effect, which addresses rear-end conflicts as well, shall be calculated out.	The result of the VRU AEB "prospective" safety performance assessment is compared to retrospective assessment of the system effects based on insurance data. In this case, the assessment is only conducted for the purpose of the V&V. It is not really a prospective study since the system is already on the market. Another approach is to do the prospective study and wait until a retrospective assessment is available. However, this typically takes years.
Baseline (see Clause 5)		
Input data	The quality and representativity of the input data shall be ensured (see Clause 5). This can be done by: — inspection of the data (e.g. outlier detection); — quality checks (e.g. check that the data are within the physical limits); — statistical tests with the data (e.g. comparison distributions).	Check the data for baseline definition, e.g. for high velocities of cyclists (quality) and how many cases are represented in the data sample in relation to the overall amount of such crashes in a country per year (representativity).
Baseline approach A and B	The input that describes the real-world scenarios shall cover these scenarios correctly and shall not include systematic errors due to data generation. This includes a check whether the original scenario is replicated by the simulated baseline, i.e. the movement of the objects is identical for the relevant period of time in the scenario. The difference between the original trajectories of the involved traffic participant and the trajectories in the simulated baseline shall be calculated. For approach B, this applies only to cases without variations. For cases with variations, the average shall lead to the original case.	Calculate the error between the vehicle's and cyclist's states (e.g. trajectories and/or velocities and/or acceleration) in the described input data and the simulated baseline per time step.
Baseline approach C1	The key aspect here is to verify the determined baseline cases represent the relevant real-world scenario. — This can be done for example by calculating the proportion of the represented real-world cases. — The results of case clustering on relevant parameters (e.g. the resulting impact velocities, TTC, impact position and angle, velocity at collision) shall be representative of the most common cases of the real world.	Calculate the relevant parameters (e.g. impact velocity) the difference from the simulated cases towards the original cases. Check whether each real-world case falls at least once within a certain range of a simulated case (e.g. 5 km/h of the impact velocity).

Table 17 *(continued)*

	Validation and verification approach	Example (VRU AEB, see 6.2)
Baseline approach C2	The key aspect here is to verify the determined baseline cases represent the relevant real-world scenario. — Comparisons of the (potentially joint) distributions of relevant parameters (e.g. the resulting impact velocities, TTC, impact position and impact angle and velocity at collision) between simulated baseline and the original database. — Sensitivity analysis of the simulations for which the impact of parameter changes in the model are compared to the real-world conflict configurations and outcome in terms of severity (e.g. impact velocities) should be conducted. A sensitivity analysis of the contribution to variance from the different models should be done (e.g. comparing the sensitivity to parameter variations in the vehicle-under-test model, the model of the technology under test and the driver model). In this context, statistical methods, for example calculating the effect size or, preferably, comparing outcome distributions with data from the real-world, can provide evidence for representativity. In addition, a combination of the different statistical approaches should be considered. And V&V should be made on (simulations compared with) real-world outcome severity data at the same severity level at which the model is used (e.g. if the assessment target is AIS2+, the comparison should not (only) be made on near-crashes or low severity crashes).	Calculate the distribution of the cyclist's and vehicle's impact velocity and location in the simulated baseline cases and comparing it by means of statistical tests (e.g. average, effect size, hypotheses testing, using Kullback–Leibler divergence, or Kolmogorov–Smirnov tests) with distribution of the original dataset. Run multiple tests with slightly changed distributions (e.g. ± 10 % of the reaction time of the vehicle driver) to determine how sensitive the baseline is towards certain parameters. This analysis should cover different injury levels (fatal, serious, slight).
Simulation model (see 8.2)		
Simulation control	System tests (test of simulation requirements, e.g. run time and verifying that a change in time step does not affect the outcome). Test that the scenario is correctly represented in the virtual environment.	Check the initial state and the state of the VUT and VRU at certain time point against the specification of the case.
Vehicle surroundings — infrastructure model	— Check that the infrastructure used in the simulated cases is in line with the corresponding real-world infrastructure with respect to its parameters/distributions. NOTE Here, "in line" means the model produces the desired effects. This means technical, rather than pure visual, representation. For example, an occlusion can limit the sensor view.	Check whether the road and obstructions have been implemented correctly according to the baseline definition.
Vehicle surroundings — environmental conditions model	— Check that relevant environment elements are correctly presented. — Check that relevant environment elements are presented stochastically correct by comparing distributions in real world and simulation. The chosen approach depends on the taken approach for the baseline simulation.	Not relevant for the example

Table 17 *(continued)*

	Validation and verification approach	Example (VRU AEB, see 6.2)
Vehicle surroundings — traffic model	— Check that the relevant variables (e.g. velocity, acceleration, relative longitudinal distance) are represented in the same way as in the baseline case. — Check that the distributions of driving parameters are the distributions of real-world data (e.g. measured in FOTs or NDS). — Check that the frequency of and the parameter distribution within the scenarios are like real world data (obtained for example by FOT or NDS data). NOTE 1 The chosen approach depends on the taken approach for the baseline simulation. NOTE 2 If the traffic surroundings and ego vehicle are "traffic agents" themselves, the verification includes comparisons of, at least, distributions of kinematics to real-world. If the models are used to create crashes, the full V&V is done for the outcome variables for all collisions.	Only relevant when surrounding traffic participants are considered; often relevant in approach C2. Check for the different types of traffic participants, whether the distribution of relevant kinematic parameters (velocity, accelerations) and the distance to other traffic participants (e.g. time gap between vehicles) is in line with the real-world distribution (e.g. from FOT, NDS, drone data). This should be checked by means of statistical tests (e.g. the effect size).
Vehicle under test — vehicle model	— Comparison of real-world test on a test track with output of simulation. Tested manoeuvres on the track should be open loop (not considering the driver, e.g. using a driving robot) manoeuvres. However, close loop manoeuvre can also be used. The rating approach described in ISO/TR 16250 and ISO/TS 18571 should be considered. — Sensitivity analysis to ensure a stable model. The variation of real-world tests shall be considered when defining the reference for the comparison. In general, vehicle model verification should follow a step-by-step process, starting from slow, longitudinal manoeuvres and increasing vehicle velocity and manoeuvre complexity (especially involving high speed lateral manoeuvres, e.g. evasive steering). In case a validated model is updated for a different vehicle model spot testing may be sufficient.	Compare deceleration behaviours of simulation model vs. real vehicle. For the comparison, the data for the real vehicle are derived from test track tests. For the simulation, the same initial conditions are set (e.g. apply the same brake pedal position and starting velocity). Then the relevant kinematic metrics (e.g. deceleration profile, the stopping distance) that are measured in both conditions are compared.
Vehicle under test — technology model (incl. sensor, logic and control and actuator)	— Review of implemented code versus specification. — Test of simulation output against the technology's specification (e.g. sensor range, internal delays). — Black-box test, where tests on a test track are performed and the same tests are conducted in the simulation considering the same initial conditions. NOTE 1 A combination of the different approaches can also be used. NOTE 2 The described approaches also apply to the components of the technology.	Comparison of the TTC of the warning and the TTC at the start of braking as well as the requested deceleration over time of the system for the simulated model as well as for the real function based on test on a test track. For a sensor, for example, the relative distance to object at the first detection can be compared. The comparison can be done based on the test track date (requires a reference measurement system) or the technology's specification can be made.

Table 17 *(continued)*

	Validation and verification approach	Example (VRU AEB, see 6.2)
Vehicle under test — driver model	— Comparison of driver model with literature references. — Comparison of driver model with results from tests in controlled environments (test track or driving simulator). — Comparison of driver model outputs with time series of driver actions in real-world crashes (considering different crash severity levels). — Comparison of driver model outputs with time series of driver actions from FOT or NDS studies. The driver reaction might depend on the scenario as well as on environmental conditions. Hence, the model shall be checked for all types of considered scenarios and environmental conditions, in which the driver model is applied. NOTE V&V of the model depends on the chosen model type (relation with evaluation objective need to be considered). A simple critical event response model requires less effort than a complex model or even everyday driving model, e.g. when the frequency of encountering a scenario and the driven velocity in different scenarios need to be checked. That is, if everyday driving models are used to generate crashes and the frequency of scenarios or of crash occurrence (per scenario type) is to be considered in the evaluation, the V&V compares the simulations outcome with real-world data on these metrics. The severity level of the evaluation objective and the validation shall be aligned. That is, if the evaluation objective is MAIS2+ crashes, it is not enough to only compare the simulations with real-world data on, for example, only TTC, near-crashes, or the lower tail of the severity distribution (e.g. impact velocities and resulting injury risks), but also with respect to impact positions, impact angles, relative and absolute velocities of involved conflict partners etc. Consequently, every-day driving models that are aimed at generating crashes shall be compared with real-world data on the level of crash severity of the evaluation objective.	Comparison of the applied reaction time and reaction strength (deceleration) with results (distributions) of driving simulator studies. Comparisons should be on distribution level and not only on the mean (and standard deviation), e.g. using different statistical methods. Comparison of the (multivariate) distributions of impact velocities, impact angles, impact positions, relative velocity of the involved conflict partners with crash data.
Collision	— Inspection, whether a collision is correctly detected. — Inspection, whether the collision's parameters in the simulation are in line with the original collision. Checking collision detection at the object's corners should be carefully considered in the V&V of the collision model. NOTE 1 Data for the comparison with real collisions can be derived from experiments in test facilities (crash lab, test track) or from real-world collisions that are provided by in-depth crash databases). NOTE 2 The chosen approach and effort depends at which level of detail the collision is considered in the simulation. Also, combinations of the above-mentioned approaches are feasible. NOTE 3 The inspection can be done manually or by an automatic software test (i.e. unit test).	Inspection, whether the crash configuration for the vehicle and VRU is correctly represented as specified (location, velocities and contact point etc.). Checking, whether the predefined collision point is close enough according to metrics and thresholds used (calculate deviation between simulation and defined target value). It should also be verified that the other variables (e.g. impact angle, speed) are as expected.

When developing models and simulation tools, further tests for the implementation of the software should be foreseen. Examples of these types of implementation tests are model-test (test to check e.g. whether an indicator is in a certain range), unit-tests (test of tool functionality) and integration test (review of the internal simulation processes and their communication).

Independent of the V&V approach for a model or the entire method, V&V shall be defined to decide whether the result of the entire method or a model is close enough to the reference. For the definition of the criteria, the

purpose of assessment as well as the quality of the reference data should be considered. If explicit thresholds (e.g. max. error) are available, it shall be demonstrated by the metric requested in the evaluation question that these thresholds are met by the simulation. The same applies where a certain target range is defined. Here, it may be required to break down this range into permitted inaccuracies per model. Where no explicit criteria are available, one of the following approaches should be used to quantify the quality of a model:

1) calculation of a quality indicator (e.g. max. error);

2) quantification of technical deviations between distributions (e.g. effect size);

3) sensitivity analysis;

4) explicit declaration of confidence intervals.

The quality of the entire virtual assessment should be quantified by means of a forward calculation of the single inaccuracies to determine the maximum expected error. The requested dispersion of simulations should consider the dispersion of similar real-world experiments. In addition, when describing the sensitivity of the simulation model, it should be made clear which parts (or which parameters) of the simulation have the largest impact on the outcomes and crash characteristics.

Annex A
(informative)

Example for documentation of input data

Using baseline approach B, data on digitized rear-end crashes on a motorway from 2010 to 2016 out of the "GIDAS PCM" crash database were used (see Reference [14]).

The variation within approach B covers the gaze direction and related reaction time of the driver as well as the weather conditions.

Table A.1 — Example documentation of input data for an assessment with baseline approach B with varied gaze direction and reaction time of the driver

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			
Development of simulation models	Driver model	Gaze control	Driving simulator study 1 NDS study 1	Driving simulator 1: — internal driving simulator study — simulator XYZ (dynamic, hexapod, 210° FoV) — all vehicle and driver input plus data from gaze monitoring system AAA were logged — only critical driving scenarios were considered for the analysis NDS 1: — vehicle model XXX that were equipped with data logger were driven on public roads — vehicle, sensor and driver input signals were logged — driver monitoring system BBB was used to log the gaze behaviour of the driver — data were filtered for traffic jams	Driving simulator 1: — 30 test participants (15 male and 15 female; 18-30: 5, 30-45: 10, 45-60: 13, >60: 2) — 3 000 km in 30 h of logged data — test drives on German motorway (artificial track) — primary purpose: collect data on the gaze behaviour in critical driving scenarios — internal study; no public access NDS 1: — test participants (6 male and 6 female; 18-30: 3, 30-45: 3, 45-60: 3, >60: 3) — 900 km in 24 h of logged data — test drives on German motorway (A7) — primary purpose: driver behaviour in traffic jams — internal study; no public access

Table A.1 *(continued)*

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			
Development of simulation models	Driver model	Reaction time after threat detection	Driving simulator study 1 Driving simulator study 2 Literature review	For driving simulator study 1 see previous item. Driving simulator 2: — internal driving simulator study — simulator XYZ (dynamic, hexapod, 210° FoV) — all vehicle and driver input plus data from gaze monitoring system AAA were logged — only rear-end conflict scenarios were considered for the analysis Literature review: — key word: reaction time driver — list of considered documents is provided and the relevant information (data collection and analysis, filter, context of study) can be found in section XYZ NOTE Since this is only an example, the list is not provided.	For driving simulator study 1 see previous item. Driving simulator 2: — 50 test participants (33 male and 17 female; 18-30: 15, 30-45: 15, 45-60: 15, >60: 5); driving experience (< 5 k km/a: 10, 5 k – 10 k km/a: 20, >10 k km/a: 20) — 2 700 km in 25 h of logged data — test drives on German motorway (artificial track) — primary purpose: measure drivers' reaction times — internal study; no public access Literature review: — EU deliverables, journals, conference papers — list of considered documents is provided and the relevant information (purpose, limitation, number of participants) can be found in section XYZ NOTE Since this is only an example, the list is not provided.

Table A.1 *(continued)*

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	N/A	N/A	GIDAS PCM	— GIDAS recording process, see Reference [15] — GIDAS PCM[14] data have been covered by means of tool CCC to the OpenDRIVE[9] and OpenScenario[10] — no weighing has been applied — only GIDAS PCM[14] cases with rear-end collisions on motorways with vehicles built after 2000 were considered	— 30 GIDAS PCM[14] cases — the identified accidents cover a time span of 6 years — rear-end collisions on German motorways — motorway collision in the regions of Dresden and Hannover — detailed accident — GIDAS PCM[14] is only available to limited number of partners
Baseline	N/A	N/A	Weather	Weather data: — data for the national weather service were analyse of one year — the weather per hour was analysis and divide into dry, rain and snow. The likelihood of each of the three conditions were calculated — the data have been filtered for location in south of country XY	Weather data: — the data covered 365 days with hourly measurement for 20 locations. — the data covered the year 2021 — primary purpose of the database is to record the weather conditions — no additional limitation to be reported

Table A.1 *(continued)*

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			
V&V	Vehicle model	Braking behaviour	Test track test 1	Test track: — test on DDD test track with the vehicle model YY1, YY2, YY3 and YY4 — vehicle has been equipped with a datalogger that records the vehicle's accelerations, speed and driven distance plus the driver input — the analysis has been limited to conducted braking manoeuvres	Test track: — overall, 800 braking manoeuvres have been performed. For each of the four vehicles, 200 braking manoeuvre have been performed covering different speeds (40, 80, 120, 160 km/h) and road friction conditions (1, 0,75, 0,5, 0,25) — test have been conducted on the test track DDD — investigate the braking behaviour of different vehicle at different speeds and road friction conditions — four different vehicles with two test drivers — internal study; no public access

Annex B
(informative)

Comparison of simulation tools

B.1 General

When the results of two or more simulation tools shall be compared to each other, certain aspects shall be considered. Otherwise, there is a risk that the results are misinterpreted.

B.2 Requirements

The following requirements shall be met if two simulation tools are compared:

1) The chosen baseline approach shall be the same. The chosen baselines shall be consistent with the evaluation objective.

2) The analysed scenario shall be the same.

3) The technology under study shall be implemented in identical ways.

4) The level of complexity of the models shall be the same and shall be consistent with the evaluation objective addressed.

5) The performance metrics used shall be the same.

B.3 Report

The results shall be reported in a harmonized way. To facilitate comparison, the reports shall contain the following elements:

1) description of software used (including version): if the model is an assembly of models built with different software, the description of software should be done for each of these models;

2) description of the baseline approach;

3) description of the sources (samples, databases) used to build the baseline;

4) detailed description of the analysed scenario(s) which entails:

   a. a description of the infrastructure model (if any) comprising road geometry (positions, shapes, markings and marking types, railings and fences), signal geometry (positions, type), building geometry (position, shape). Shapes and positions shall be given as software independent lists of 2D or 3D coordinates.

   b. a description of the traffic participants (number, type) along with their initial positions, speed, accelerations, and prescribed trajectories (if any) as a timeline of software independent lists of 2D or 3D coordinates. Traffic participants' shapes shall be given as software independent lists of 2D or 3D coordinates. The VuT shall be described using the same process.

   c. a description of the environmental conditions model (if any), comprising timelines of lighting, road surface conditions, signals' states (if time varying).

5) description of the simulation controls (initial conditions, update timesteps of models);

6) description of trajectories of traffic or VuT that are prescribed timelines of kinematic parameters;

7) description of the detection/action/driver interaction (if any) logics of the technology. If these involve "in-simulation" computed metrics (e.g. TTC) aimed at determining the current criticality of the situation, the logic used to compute these metrics shall be described;

8) description of Model types and inputs/outputs (model parameters can be subject to non-disclosure agreements);

9) description of the safety performance metric used. If IRF are involved, they shall be consistent with the evaluation objective and described in detail (sample used, independent variables used, type of regression used, prediction validity tests such as AIC/BIC performed along with their outcome) either in the report or in a publicly available reference paper.

Annex C
(informative)

Examples for documentation of a study

C.1 General

This Annex gives examples for all three types of reports. To make the differences between the types of reports more visible, the annex is organised in subclauses, each showing the different documentation depending on the report type presented. An overview of the subclauses and the related report types is presented in Table C.7.

There is not always content for all three report types required at each section of the report. Thus, cells with blank content in Table C.7 indicate that the respective information is not required for that type of report.

The three types of reports are:

— Type A report: comparing technologies;

— Type B report: comparing simulation tools;

— Type C report: standalone assessment.

C.2 Example assessment report

C.2.1 Clause “Evaluation objective”

C.2.1.1 Evaluation objective, report types A and C

The study is conducted to answer the following research question: “What is the safety performance of an AEB-Cyclist system in terms of collision avoidance and collision velocity reduction?” The metrics are defined in the following way (see Formulae (C.1) and (C.2)).

C.2.1.2 Evaluation objective, report type B

The study is conducted to answer the following research question: “When using the simulation tools X, Y, Z to simulate an AEB-cyclist system in the cyclist-AEB testing system (CATS) scenarios, what are the differences in the safety performance, based on each simulation tool, in terms of collision avoidance and collision velocity reduction?” The metrics to be compared are the following (see Formulae (C.1) and (C.2)).

C.2.1.3 Formulae for comparing metrics, report types A, B and C

$$\textit{Collision avoidance rate} = \frac{n_{\text{cases collision avoided}}}{n_{\text{all testcases}}} \tag{C.1}$$

$$\textit{Average velocity reduction} = \frac{1}{n_{\text{all testcases with collision}}} \sum_{i=1}^{n_{\text{all testcases with collision}}} \left(v_{\text{initial}} - v_{\text{collision}}\right) \tag{C.2}$$

C.2.1.4 Final statement for evaluation objective, report type A

The results are then discussed in comparison to other similar studies in the literature that investigate the performance of AEB-cyclist systems.

C.2.1.5 Final statement for evaluation objective, report type B

The results are then discussed and sources for possible deviations between the tools are analysed.

C.2.2 Clause "Baseline"

C.2.2.1 Approach, report types A, B and C

A baseline approach C1 as defined in this document was used when designing the test scenarios.

C.2.2.2 Detailed information, report types A and B

The test cases are taken from the Cyclist-AEB Testing System project (Reference [16]), which represents severe (in terms of resulting fatalities and injuries) passenger car-bicycle crash situations.

C.2.2.3 Detailed information, report type C

The test cases are reconstructed from real life accidents with cars impacting cyclists from six different countries with a focus on fatal and seriously injured outcomes as summarized in Table C.1. These accidents were categorized using a standardized accident layout. Furthermore, the accidents were analysed regarding their parameters including velocity, view blocking, lighting conditions, road layout, precipitation and location.

Table C.1 — Overview of the available accident databases to select relevant crash scenarios

#	Country	Source	Killed		Seriously injured		Period
			Definition	N	Definition	n	
1	France	LAB	Fatal	72	Severely injured	620	2011
2	Germany	GIDAS based PCM	Fatal	11	AIS2+	360	1999-2012
3	Italy	Fiat internal	Fatal	23	AIS2+	17	2003-2014
4	Netherlands	BRON	Fatal	902	Seriously injured	10 854	2000-2013
5	Sweden	STA/STRADA	Fatal	104	AIS2+	435	2005-2014 K 2010-2014 SI
6	UK	STATS19	Fatal	116	Seriously injured	2 699	2008-2010

A test matrix is constructed by focussing on the three main accident categories (cyclist coming from the left, cyclist coming from the right and cyclist in front) and considering all the different parameters.

C.2.2.4 Test matrix, report types A, B and C

The test matrix consists of four test cases. Values or ranges for the most relevant test parameters are provided in Figure C.1. In each test case, the car and cyclist are set to follow a straight line at constant speed, so that a collision at a prescribed location results if AEB does not react. This prescribed location is defined as follows:

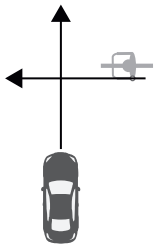
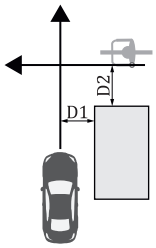
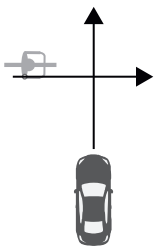
	CVNB	CVBO	CVFB	CVLB
Vehicle speed	20-60 km/h	10-40 km/h	20-60 km/h	20-60 km/h
Cyclist speed	15 km/h	10 km/h	20 km/h	15 km/h
Obstruction	without	with D1 = 3,55 m D2 = 4,8 m	without	without
Hitpoint	50 %	50 %	25 %	50 %
Layout sketch				

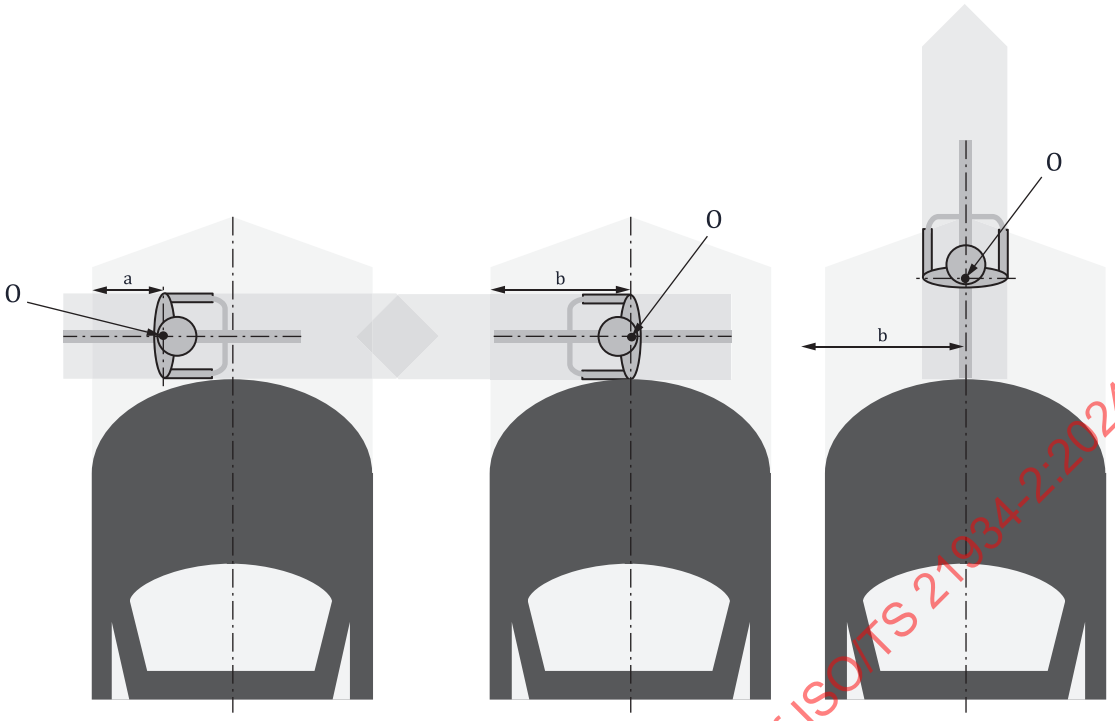
Figure C.1 — Cyclist-AEB test matrix used in the P.E.A.R.S. round-robin (see Reference [16])

When the collision occurs, the cyclist's reference point (the bottom bracket, "O" in Figure C.2) should be at a position where the absolute distance to the vehicle's left edge in the vehicle's lateral direction should be a given percentage ("hit point" value in Figure C.1) of the vehicle width.

The prescribed vehicle speed in each test is constant and chosen from the vehicle speed range. For each subsequent test, the speed is incrementally increased by 5 km/h starting from the minimum in the range until the maximum has been reached.

In the CVNB test case, the vehicle with AEB system travels forward in a straight line towards a cyclist crossing its path (in a straight path) from the near side. The relative positions of the vehicle and cyclist at the time of collision are depicted in Figure C.1. In this test case, no view-blocking obstruction is present and there is a direct line of sight between the vehicle and the cyclist for at least 4 s before the collision. During these 4 s, the cyclist speed and direction do not change. The direction and speed of the vehicle also do not change, apart from a possible AEB activation.

In the CVNBO test case, a view-blocking obstruction is located according to Figure C.1 (see D1, D2) from the left side of the cyclist. The obstruction completely blocks the view, so no single part of the cyclist can be seen from the perspective of the vehicle during the approach, until the cyclist appears from behind the obstruction. The relative positions of the vehicle and the cyclist at the time of collision are depicted in Figure C.2.



a 25 % of vehicle width

b 50 % of vehicle width

Figure C.2 — Vehicle and cyclist relative position at time of collision for the CVNB and CVNBO (left), CVFB (middle) and CVLB (right) test cases (without braking action)

CVFB describes a test case in which the cyclist approaches from the far side. In this test case, no view-blocking obstruction is present. The relative positions of the vehicle and the cyclist at the time of collision are depicted in Figure C.2.

CVLB, fourth test case, considers a sheer longitudinal configuration in which the vehicle travels forward towards a cyclist that is moving in the same direction in front of the vehicle. The relative positions of the vehicle and the cyclist at the time of collision are depicted in Figure C.2. This configuration is common when cyclists swerve in front of a car in the inner city.

C.2.3 Clause "Baseline"

C.2.3.1 Input data, report types A, B and C

Here the input data table shall be reported as described in 5.2 and analogous to Table A.1.

The table shall be included in all three types of report.

NOTE In the given example assessment, the table describes the input data for the baseline and IRF. The input for both were French police reported crashes from 2011. Overall, 850 crashes were used. The crashes covered car and cyclist crashes (except frontal collisions) with different levels of injuries. For the baseline, the crashes were reconstructed by a consortium of research institutes. For the IRF, the information was taken directly from the crash report.