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

Part 1: State-of-the-art and general method overview

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

Partie 1: Etat de l'art et aperçu des méthodes générales

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ISO copyright office
CP 401 • Ch. de Blandonnet 8
CH-1214 Vernier, Geneva
Phone: +41 22 749 01 11
Email: copyright@iso.org
Website: www.iso.org

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Foreword

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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

Different Active Safety and Advanced Driver Assistance Systems (ADAS), in the following both referred to as active safety technology, have been developed and introduced into the market. The question that goes along with the development and introduction is, what impact these technologies have on road traffic and more specifically, to what extent these technologies prevent crashes and injuries. Such questions are of relevance for different stakeholders, such as vehicle manufacturers and suppliers, road authorities, research organisations and academia, politics, insurance companies as well as consumer organisations.[1]

The answers to these questions are derived from assessment of such technologies in terms of road traffic safety. Different assessment methodologies have been developed in the past and are being used today.[2] In general, the utilized methodologies can be divided in two types of assessment. The first type determines the technology's safety effect after its market introduction. Typically, in this assessment type accident statistics are analysed in order to determine the difference between the accident situation with the technology compared to a control group without the technology.[1] These methods are called retrospective assessment methods. A precondition for these methods is that the technology under assessment has reached a sufficient penetration rate in the market and that sufficient accident cases with and without the technology are recorded for a comparison. The penetration rate does not necessarily need to be related to the whole vehicle fleet, but can also be related to a certain vehicle subgroup or class.[3]-[5] On the other hand, there are methods that predict the technology's effect on traffic in relation to traffic safety before its market introduction.[6][7] These methods are called prospective methods using different approaches and tools.

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 means of comparing data from the baseline and treatment simulations based on a certain metric. The baseline for the assessment is the situation without the vehicle-integrate technology under assessment present. The virtual simulation with the technology is called treatment simulation.

The described assessment 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. Although the main focus is often on passenger cars, the method is also applicable to motorised two-wheelers as well as heavy goods vehicles. Furthermore, the assessment approach discussed in this document focuses rather on accident avoidance and the technology's contribution to the mitigation of the consequences. Safety technologies that act in the in-crash 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. The extension of the method to technologies, such as automated driving and V2X based technologies, are discussed in the outlook at the end of this document.

In general, the assessment of active safety technologies requires the consideration of interaction with surrounding traffic as well as the host vehicle driver. These interactions increase the complexity of the assessment due to the high number of resulting variables. Consequently, for a comprehensive assessment, the technology's safety performance is analysed in a high number of test scenarios, in order to cover all relevant circumstances that affect the critical situation and crashes. The virtual simulation approach allows for running large numbers of test scenarios while offering a promising combination of safety performance, flexibility, reproducibility, and experimental control. The need for using virtual simulations in the prospective assessment of safety technologies is generally recognized. However, standardized terminology and processes of methodological aspects to perform such assessments are not available to date, which makes results hardly comparable.[1] For this reason, automotive industry,

research institutes, and academia joined in the P.E.A.R.S.[1)] (**P**rospective **E**ffectiveness **A**ssessment for **R**oad **S**afety) initiative with the objective to develop a comprehensible, reliable, transparent, and accepted methodology for quantitative assessment of crash avoidance technology by virtual simulation. [1]

This document aims to provide an overview on the state-of-the-art in the prospective assessment of road safety for vehicle-integrated (active) safety technologies by means of virtual simulation, see Figure 1.

After the introductive Clauses 1 to 4, the general method for a prospective assessment study is described in Clause 5, where special attention is given to the definition of the traffic safety evaluation scope and the establishment of the baseline. Clause 6 describes various data that can be used as input for different tasks within the assessment procedure. Then a general virtual simulation framework and various simulation models needed for conducting the simulation are presented in Clause 7, followed by a description of the approaches to quantify the derived safety effect in Clause 8. A description of validation and verification aspects as well as an overview on tools are given in Clause 9. Clause 10 of the document provides a practical example of a comparative study of different simulation tools and discusses the lessons learned. Clause 11 provides conclusions as well as describes limitations for the state-of-the-art methods. Clause 12 provides an outlook towards the prospective safety performance assessment for automated driving as well as the follow up to the current document.

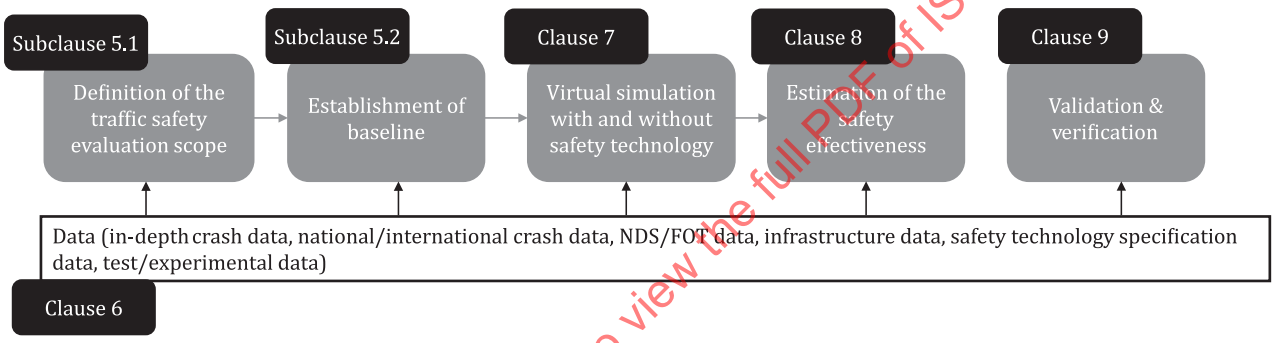


Figure 1 — Overview of the process of prospective assessment of traffic safety for vehicle-integrated safety technologies by means of virtual simulation and the structure of this document

1) P.E.A.R.S. is an open consortium (established in 2012) in which engineers and researchers from the automotive industry, research institutes and academia join with the objective to develop a comprehensible, reliable, transparent and accepted methodology for quantitative assessment of crash avoidance technology by virtual simulation. Partners of P.E.A.R.S. are (status Sep. 2020): Automotive Safety Technologies, AZT Automotive, BMW Group, Federal Highway Research Institute (BASt), Chalmers University of Technology, Continental, Denso, Fraunhofer IVI, Generali, RWTH Aachen University (ika), LAB, Swiss Re, TH Ingolstadt, Technical University Dresden, Technical University Graz, TNO, Toyota, Technical University Dresden, TÜV Süd, University Leeds, UTAC CERAM, Virtual Vehicle, Volkswagen, Volvo Cars, VUFO, ZF. More information at https://pearsinitiative.com/.

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

Part 1: State-of-the-art and general method overview

1 Scope

This document describes the state-of-the-art of prospective methods for assessing the safety performance of vehicle-integrated active safety technologies by virtual simulation. The document describes how prospective assessment of vehicle-integrated technologies provides a prediction on how advanced vehicle safety technology will perform on the roads in real traffic. The focus is on the assessment of the technology as whole and not of single components of the technology (e.g. sensors).

The described assessment approach 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. The assessment approach discussed in this document focuses accident avoidance and the technology's contribution to the mitigation of the consequences. Safety technologies that act in the in-crash 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 overall consequences of a crash.

The method is intended as an overall reference for safety performance assessment studies of pre-crash technologies by virtual simulation. The method can be applied at all stages of technology development and in assessment after the market introduction, in which a wide range of stakeholders (manufactures, insurer, governmental organisation, consumer rating organisation) could apply the method.

2 Normative references

The following documents, in whole or in part, are normatively referenced in this document and are indispensable for its application. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

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
levels of automation
levels that primarily identify how the "dynamic driving task" is divided between human and machine

Note 1 to entry: See Reference [8].

3.2
baseline
initial set of data to which the performance of the technology under study is compared when performing *prospective assessments* (3.7) of the technologies' performance

Note 1 to entry: This concept also complements *treatment* (3.13).

3.3
cooperative
applications based on vehicle-to-vehicle, vehicle-to-VRU and vehicle-to-infrastructure communication

3.4
host vehicle
vehicle, which is subject for assessment, i.e. is equipped with the technology in the treatment simulation

3.5
injury risk function
description of the probability of an injury in relation to crash attributes

Note 1 to entry: The most frequently used injury risk functions describe the probability of an injury occurrence in relation to crash severity, e.g. impact speed or change of velocity.

3.6
projection
indicates what the future changes in a population would be if the assumptions (often based on patterns of change which have previously occurred) about future trends actually occur

Note 1 to entry: Population projections – in the sense of Reference [9] - are estimates of total size or composition of populations in the future, see Reference [10].

3.7
prospective assessment
assessment of the performance of technologies in a predictive way

Note 1 to entry: The assessment can be done, for example, before their deployment into a vehicle population.

3.8
target population
all situations or accidents that are addressed by the function under assessment

3.9
real-world data
data collected in a non-experimental, non-virtual situation

3.10
retrospective assessment
assessment of the performance of technologies after their deployment into a vehicle population

3.11
time series
series of data points indexed (or listed or graphed) in time order

3.12
traffic situation
crash-, near-crash or normal driving situation whose description can be considered for the establishment of the *baseline* (3.2)

3.13
treatment
use of a specific technology to affect the course of an event in a *traffic situation* (3.12) in order to avoid or mitigate crashes

Note 1 to entry: Treatment simulations provide data on the performance of the technology under assessment to compare with the *baseline* (3.2) data when performing *prospective assessments* (3.7) of performance of technologies.

Note 2 to entry: This concept also complements *baseline* (3.2).

3.14
test scenario
detailed description of trajectories, geometrical relations, speeds, etc. of a *traffic situation* (3.12)

Note 1 to entry: See References [11]–[13].

3.15
vehicle-integrated
technology under assessment operating on-board of the vehicle

4 Symbols and abbreviated terms

4.1 Symbols

E	Effectiveness / safety performance
N	Weighted frequency of the metric (e.g. percentage of crashes) in the simulation without the technology under assessment
N'	Weighted frequency of the metric (e.g. percentage of crashes) in the simulation with the technology under assessment
v	Velocity

4.2 Abbreviated terms

ACC	Adaptive Cruise Control
ADAS	Advance Driver Assistance Systems
AEB	Autonomous Emergency Braking
BAAC	Analysis report of road accidents involving physical injury (France)
BASt	Federal Highway Research Institute (Bundesanstalt für Straßenwesen)
CEDATU	Central Database for In-Depth Accident Studies (Austria)
CIDAS	China In-Depth Accident Study
EES	Energy Equivalent Speed
ETAC	European Truck Accident Causation
FESTA	Field opErational teSts supporT Action
FOT	Field Operation Test

GIDAS	German In-Depth Accident Study
HIL	Hardware-in-the-loop
IEC	International Electrotechnical Commission
IIHS	Insurance Institute for Highway Safety
IGLAD	Initiative of Global Harmonisation of Accident Databases
ISO	International Organization for Standardization
ITARDA	Institute for Traffic Accent Research and Data Analysis
J-TAD	Japan Traffic Accidents Databases
KBA	German Federal Motor Transport Authority (Kraftfahrtbundesamt)
LDW	Lane Departure Warning System
LIDAR	Light detection and ranging
MIL	Model-in-the-loop
NASS	National Automotive Sampling System
NDS	Naturalistic Driving Studies
RAIDS	Road Accident In Depth Studies
P.E.A.R.S.	Prospective Effectiveness Assessment for Road Safety
PTW	Powered Two Wheelers
RASSI	Road Accident Sampling System - India
SCP (cr/cl)	Straight Crossing Paths (cyclist from the right / cyclist from the left)
SIL	Software–in-the-loop
TTC	Time to collision
V2X	Vehicle to X (Vehicle and / or Infrastructure) Communication
VIN	Vehicle identification number
VRU	Vulnerable Road User
V&V	Validation and Verification

5 Evaluation objective and baseline of assessment

5.1 Definition of the evaluation objective

Since there are numerous objectives to conduct prospective safety performance assessments, it is important that a precise research question for the assessment is formulated. Then by identifying relevant traffic situations – the target population - to address the research question, a more precise specification and application for a virtual simulation study is provided.[14] Figure 2 shows the place in the process overview.

Figure 2 — Overview of the process — Definition of the evaluation objective

Various objectives to conduct safety performance assessments have been identified,[1] the main ones are:

— quantification of effects (positive and negative) of a certain technology in terms of traffic safety;

— prioritization and optimization of safety technologies during research and development;

— identification of business opportunities and anticipation of regulations and consumer testing.

Furthermore, two types of processes are used to formulate the target for this kind of studies.

— A technology-driven process in which a request is put forward to estimate the safety benefit of a safety technology. This technology can be more or less defined at the time of the study; it can be an idea, a concept, a product under development or a product that already has been implemented but not introduced into the market (also often called a bottom-up approach).

— A traffic safety-driven process in which existing or expected safety problems or certain relevant traffic situations are identified. In this case, the target for the study is not linked to a particular safety technology but to a targeted lack of safety (also often called top-down approach).

Hence, it is important to note that if results between different studies are compared the research question needs to be a) accessible and b) precisely formulated. This requires to rephrase the question asking additional information such as: “What type of safety technology will be evaluated?”, “What data segments will be addressed (pre-impact situation, traffic participants, type of road, etc.)?”, “What time horizon is being considered?”, “Should the installation rate of an optionally equipped safety technology in the vehicle fleet be considered?”, “What metric is suggested for the safety effect?”, “What is the expected accuracy of the result?”, “What could change the consequence on the road, if the cars were equipped with new safety technologies?”.

An adequate example of a properly formulated research question is: What is the relative change in car-to-cyclist crashes due to an autonomous emergency braking (AEB) system with 100 % penetration rate in a specific car in urban car-to-cyclist situations in Germany in two years from now?

Once the research question is set, relevant traffic situations for virtual simulation can be identified, for example the definition of a target population for the study. Relevant traffic situations can be derived by, e.g. analysis of retrospective crash data, naturalistic driving studies, and knowledge gathered during technology development. The outcome of the identification process is an overall description and quantification of the traffic situations and the involved traffic participants of the simulation. When it comes to analysis of real-world crash or near-crash data, various types of classification schemes can be used to set boundaries for the study. Especially important aspect is pre-impact relative movement of involved traffic participants before a crash or near-crash. One example is Straight Crossing Path scenarios (from right: SCPcr / from left: SCPcl), where the car was moving forward, and the cyclist was crossing the path either from left or right, see Figure 3. The pre-impact situation is often accompanied by pre-crash-factors that include parameters that may have influenced the course of events before the crash. Examples are speed-related measures, driver status, and traffic environment related factors such as light condition, road layout, and road status. In addition, the crash configuration can be of interest, e.g. the impact point and direction.

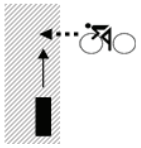
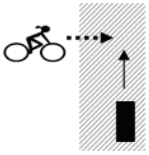
SCPcr	**S**traight **C**rossing **P**ath, **c**yclist from **r**ight	
SCPcl	**S**traight **C**rossing **P**ath, **c**yclist from **l**eft	

Figure 3 — Example from a pre-impact situation classification scheme [15][16]

To summarize, for a fictitious version of an AEB system addressing the example research question above, the target population could be expressed as; SCPcr and SCPcl situations during daylight on roads with lane markings and where the driver is visually distracted.

At this stage it important to mention that the metrics to be used for estimating technology's safety performance consider the potential impacts and the required input data. After establishing a baseline according to the target population (see 5.2), the outcome of simulations with and without the safety technology will be compared by this certain metric. Details with respect to the topic "metric" are presented in Clause 8.

5.2 Establishment of baseline

When target traffic situations are identified which address the research question, a detailed, measurable definition of these situations for the upcoming virtual simulations is provided, i.e. the baseline. In general, the prospective safety performance assessment conducts a comparison between traffic situations without and with the technology under assessment. Thus, the baseline refers to the situation without the technology under assessment present. This includes traffic situations that are needed to evaluate both positive and negative performance, according to the evaluation objective. The establishment of the baseline defines the reference to be used in the upcoming simulations and a real-world reference is essential. Figure 4 shows the place in the process overview.

Figure 4 — Overview of the process — Establishment of the baseline

Three main approaches are distinguished where the cases in the baseline are generated in different ways:

— baseline with original cases of real-world traffic situations,

— baseline with modified cases of real-world traffic situations,

— baseline with synthetic cases based on relevant characteristics of real-world traffic situations.

Below are explanation of each respective baseline.

— **Baseline with original cases of real-world traffic situations**

In a straightforward application, the baseline corresponds to real-world traffic situations that have been reconstructed from crash data or other sources such as NDS/FOT datasets. The cases are represented

according to parameters found in the corresponding database (e.g. collision speed and collision angle).[17]-[21]

Furthermore, the crash database parameters can be used in a model to perform a reconstruction of the cases, thus simulation is used to recreate real accidents in order to have a detailed, numerical time series description of the cases in the baseline. An example of this approach is the German In-Depth Accident Study (GIDAS) based Pre-Crash-Matrix (PCM).[22] Typical parameters needed in the PCM database are vehicle trajectories and speed related measures, crash configurations, sight obstructions, information on the traffic environment and driver behaviour.

— **Baseline with modified cases of real-world traffic situations**

As crashes reported in the database reflect the actual crash, with possibly rather old vehicles, replications of the traffic situations with a modern vehicle can be performed, i.e. a re-simulation to establish a baseline with more recent properties of the vehicles involved.[20][23][24]

Another challenge in crash databases is the limited information on pre-crash parameters, for example vehicle trajectories and driver behaviour such as inattention or drowsiness that can be influenced by a safety technology. The use of recorded crashes such as in naturalistic driving studies or usage of event data recorder data can enable more qualitative estimations when available.

If the crash sample does not provide a sufficient representation of the traffic situation identified based on the research question, sampling techniques can be used to create random, synthetic cases based on marginal distributions of event related variables.[25] However, in contrast to the next approach, presented below, the synthetic created cases still reflect the original traffic situation.

— **Baseline with synthetic cases based on relevant characteristics of real-world traffic situations**

Cases for a baseline can also be generated based on the understanding of contributing factors involved in the targeted traffic situations; the crash mechanisms.[26]–[28]

Once these mechanisms are revealed, the situation is modelled using distributions of selected parameters. Sampling methods, for example Monte Carlo simulations, can be used to vary the characteristics of the cases in the baseline, such as driver reaction/response as well as vehicle properties, vehicle trajectories, and traffic and environmental variables.[29] When the simulations for generating situations are performed, only a portion of the cases in the baseline might end up in a collision. The baseline then consists, besides cases where a collision occurs, also of cases without a collision or risk of a collision. These cases can be used to investigate situations, where an activation might not be desired or required.

The baseline is to be used in virtual simulations, with and without the safety technology present. The complexity and the level of detail depend on the way the baseline has been represented and to which degree the safety technology interferes, e.g. to the way that the driver, the vehicle, the surrounding traffic etc. are modelled. The virtual simulation framework and the various models needed are described in Clause 7.

6 Input data

6.1 General

Input data are required for different tasks within the process of assessing a technology's safety performance by means of virtual simulation. These tasks are:

— establishing the baseline of the simulation (see Clause 5.2);

— development, training and parametrisation of models used in the simulation tool - in particular traffic participant (e.g. driver) behaviour models and injury risk function (see Clause 7);

— performing subsample weighting analysis and projection of simulation output (see Clause 8);

— validation and verification of the simulation as well as its models (see Clause 9).

In relation to these different tasks and with regard to the research question, the quality and representativeness of the data sample are important and relevant aspects throughout the process.

In general, a wide range of data is necessary for prospective safety performance assessment. Although in most cases, data from real world are used, the input data do not necessarily need to be gathered in the real world. Verified data from previous simulations or data collected in specific tests may be used as input data for the assessment as well. In the following, the most common relevant data sources are presented and discussed. These sources are (details on the different sources are provided in the sections below):

— safety technology related data;

— accident data (general and/or in-depth data);

— data from naturalistic driving studies (NDS) or field operation tests (FOT);

— infrastructure and traffic data;

— test data gained in a controlled environment, such as test track or driving simulators.

In Table 1 the typical data sources are mapped to the tasks of prospective safety performance assessment.

Table 1 — Overview on often used data types for the different tasks within the prospective safety performance assessment

	Active safety technology related data	Accident data (general data)	Accident data (in-depth data)	NDS/FOT data	Infra-structure and traffic data	Test data (test track, simulator)
Establishing the baseline – direct input (see 5.2)	X		X	X		(X)
Establishing the baseline – modified input (see 5.2)	X		X	X	(X)	(X)
Establishing the baseline – stochastically generated input (see 5.2)	X	(X)	X	X	X	(X)
Development of models (see 7.4)	(X)	(X)	X	X	X	X
Data projection (see Clause 8)		X	(X)	(X)	X	
Validation and verification (see Clause 9)	(X)	(X)	X	X	X	X
NOTE 'X' marks commonly used data sources, '(X)' marks rarely used data sources.						

6.2 Active safety technology related data

The purpose of the prospective safety performance assessment is to determine the safety effect of a certain technology. To perform the assessment, specific information about the technology under assessment is required. The information describes under which conditions (e.g. speed range and environmental conditions) the technology operates, which conditions lead to deactivation as well as how the technology performs its function – sensing, controlling, actuating.[30] For an active safety technology, the intended situation is typically a critical driving situation, such as a potential collision with another object or an unintended road departure. The relevant information can further be split

into information related to the activation of the technology and information related to the behaviour of the technology once activated (e.g. type and strength of technology intervention).[31]

The required data are provided by a description, by a model or is derived by means of separate tests [see further information in the subclause on data from tests in controlled environments (6.6)].

6.3 Accident data

One of the most important input data sources for the prospective safety performance assessment is data that describe accident situations. In general, two types of accident data are available: general accident data and in-depth data.

The general accident data describe the accident situation on macroscopic level – often on national or international representative level. Typically, the data of such databases provide parameters like the total number of accidents, or the number of accidents with a certain level of injury as reported by the police. Thus, most of these databases contain the exhaustiveness of the road accidents but with very few details. A classification of the pre-impact situation, the road type, at which the accident occurs, and/or the involved vehicle type is mainly available but not necessarily reported.[31]–[33] In-depth information such as intrusions or reconstruction parameters are not reported in these databases. An overview of a few selected databases that provide general accident data is given in Table 2.

Table 2 — Overview on selected general accident databases according to Reference [35]

Database	Collected information (examples)
UNO / WHO	Traffic fatalities and injuries
GES	Nationally-representative sample of police-reported motor vehicle crashes of all types, from minor to fatal
CARE	Combining different national European statistics including parameters, e.g. person class, gender, age group, vehicle group, collision type, lighting and weather conditions, day of the week
IRTAD	Crash data (e.g. fatalities injury crashes by road type, road user, age), exposure data (e.g. vehicle kilometres driven) and other safety data (e.g. seatbelt waring rates)
National statistics (e.g. in Germany Federal Statistical Office of Germany or BAAC in France)	Among other parameters traffic fatalities and injuries, the type of accident and VIN
Statistics on regional level (e.g. statistical offices of the German states)	Among other parameters traffic fatalities and injuries, more detailed type of accident

In-depth accident databases provide detailed information about the accident and the sequence of events but for a limited number of road accidents. Such databases exist in different countries as indicated by Table 3. These databases either cover specific regions of a country, the entire country, accidents for a specific car brand or accidents with different accident severity (e.g. with material damage, injuries, fatalities). In case only specific regions are covered by the database, the representativeness of the data for the country needs to be checked.[36][37] For single accidents many parameters are collected that describe the accident sequences, the condition of the involved vehicles as well as the environmental condition (see e.g. GIDAS Codebook[38]). The data can either be logged by accident event recorders[34] or are determined by means of accident reconstruction.[39] In the context of prospective safety performance assessment, the in-depth accident data are used for nearly all previously-described purposes (see Table 1).

Table 3 — Example in-depth accident databases

Name	Country	Number of parameters	Number of regions	Start year	Number of analysed accidents	Reference
CEDATU	Austria	~1 000 (approx. 400 core variables)	Whole country	2007	Up to 200 cases each year	[39]
CIDAS	China	~2 000	5	2011	~ 550 each year	[40]

Table 3 *(continued)*

Name	Country	Number of parameters	Number of regions	Start year	Number of analysed accidents	Reference
ETAC	Europe	~3 000	8	2004	624 (finished)	[41]
GIDAS	Germany	~2 000	2	1999	~ 2 00 each year	[42]
IGLAD	World	approx. 110	Worldwide	2007	~ 800-1 000 each year	[43]
ITARDA's J-TAD	Japan	~70	1	1993	~ 300 pro each year	[44]
NASS-GES	USA	~250	6	1997	~2 500- 5 000 each year	[33]
RAIDS	UK	~3 000	2	2012	>1300	[45]
RASSI	India	~700	5	2011	~2 000 (Jan. 2017)	[46]
Insurance in-depth database	Different company-specific databases are available that focus on material damage claims.					[47]

6.4 Data from naturalistic driving studies and field operation test

From field operational tests (FOT) and naturalistic driving studies (NDS) different information can be derived, which is of relevance for the safety-performance calculation. Basically, FOT and NDS[49] provide data of certain driving situations (e.g. critical driving situation) as measured by the vehicle's sensors. The vehicle records data regarding the environmental conditions (e.g. weather condition, road type[2]), the vehicle's condition and movement (velocity, acceleration etc.) as well as the driver behaviour and driver reaction (e.g. steering wheel angle, brake pedal position) possibly enriched with video data.[50] [51] In contrast to the detailed accident databases, the movement of the vehicle as well as the relative position of surrounding objects in (close to) critical situations are measured by on-board sensors of the host vehicle and not reconstructed from on-scene investigations. Example FOTs and NDSs are shown in Table 4.

During FOT and NDS studies typically only few critical situations and hardly any accidents are detected. Moreover, critical situations are not consistently defined between the different studies.[52]

Next to the situation related data, FOT and NDS provide aggregated data about the measured behaviour of drivers, technologies, and vehicles in the whole study. Consequently, the focus of the aggregated data is rather on general driving behaviour than on single driving situations.[49] Examples of such aggregated data are distributions of driven velocity or the travelled distance in the study. The aggregated data can be used for example for V&V, for development of models, and for data projection.

Table 4 — Overview on example FOTs and NDSs based on Reference [53]

Name	Type of Study	Region	Number of vehicles	Number of test persons	Duration
100 car naturalistic driving study	NDS	USA	100	~240	2001 - 2002
Drive recorder database for accident/ incident study and its potential for active safety development	NDS	Japan	198	N. A.	2006 -
euroFOT	FOT	Europe (4 countries)	~1 000	~1 200	2008 – 2011
TeleFOT	FOT	Europe (8 countries)	N. A.	~3 000	2008 – 2012
SHRP2	NDS	USA	3 102	~3 000	2010 – 2012
Sim TD	FOT	Germany	400	N. A.	2008 – 2012
U-Drive	NDS	Europe (7 countries)	210	320	2012 – 2016

2) Road type in terms of infrastructure, meaning urban, extra-urban / rural road or motorways.

6.5 Infrastructure and traffic data

Data about infrastructure and traffic mainly link the occurrence of specific driving situations and accidents to the general traffic situation.[54] Governmental or public-sector institutions usually provide this kind of data. In Germany, information about traffic and infrastructure is for instance available at the Federal Motor Transport Authority (Kraftfahrtbundesamt - KBA), the Federal Highway Research Institute (BASt), the Federal Ministry of Transport and Digital Infrastructure, the Federal Statistical Office of Germany as well as at different departments on state level. In Sweden, such data can be acquired at, for example, the Swedish Transport Administration and the Swedish Transport Agency.

Infrastructure and traffic data can also be used for the parameterization of the baseline as well as for the validation and verification of conducted simulations.

6.6 Data from tests in controlled environments

Input data can also be collected from specific tests that are conducted under controlled conditions for instance on test tracks or in driving simulators.[55] This type of tests is specifically conducted in case required data for the development or validation of simulation models is lacking.

In the driving simulator both the environment and the vehicle are represented virtually.[56] Hence, the focus of studies using a driving simulator is mainly on the driver. Data are often used to define, parameterize and validate driver behaviour models.

Tests on a test track allow to take the real and realistic dynamic behaviour of the vehicle into account.[56] Therefore, typically test track data are used to define, parameterize and validate technical models used by the simulation. Additionally, studies investigating driver behaviour may be conducted on a test track.

7 Implementation of virtual simulation

7.1 General

This clause discusses the theoretic basis for conducting virtual simulation in the prospective safety performance assessment. In general, the actual implementation of simulation models strongly depends on the objective of the assessment as well as on the complexity of the analysed research question, and traffic situation. Therefore, this clause provides a general overview about the simulation framework including simulation models. Figure 5 shows the place in the process overview.

Figure 5 — Overview of the process — Implementation of virtual simulation

7.2 Simulation framework

The simulation framework describes the overall set-up of the simulation as well as the sub-models used and their interaction. Hence, the simulation framework is capable to handle all approaches as described in 5.2. Furthermore, it needs to be capable of simulating the technology under test. A general simulation framework architecture can be found in Figure 6.

The simulation framework consists of four main parts: the vehicle under test, the vehicle surrounding, a collision and a simulation control module. The vehicle under test consists of three models: vehicle model, sensor model and function logic model. The latter two are part of the safety technology under assessment. The driver model is an independent model that is mainly used in the vehicle with the tested

technology. However, the driver model can also be applied in the vehicles of the surrounding traffic. The vehicle surrounding holds three models: an environment model, a traffic situation model and a traffic model.

This general framework covers all possible aspects. However, not all mentioned models might be required for answering specific research questions.

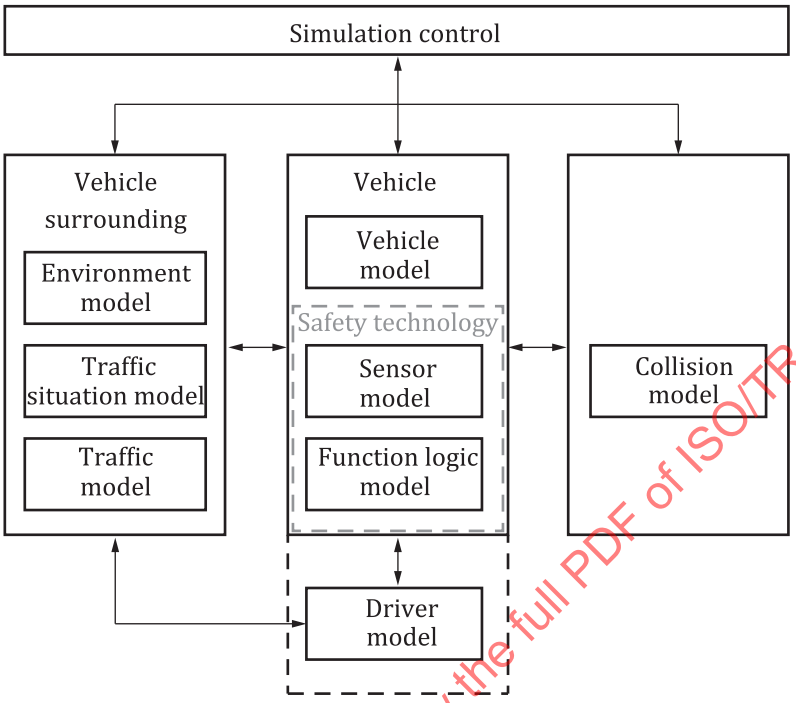


Figure 6 — Simulation framework architecture based on Reference [1]

7.3 Simulation tool

The execution of the prospective safety performance assessment requires the implementation of the framework in a tool (commercial or in-house developed). Currently, there are different commercial tools as well as in-house developments used for the prospective safety performance assessment. A list of different exemplary tools used for the virtual simulation is given in the Annex A.

7.4 Simulation models

In this subclause the individual simulation models of the architecture presented in Figure 6[1] are described. An overview about the interfaces of each model (input and output parameters) is given in Annex B.

7.4.1 Vehicle model

The vehicle model includes all relevant parameters to simulate vehicle dynamics in the required degree of freedom as a response to the driver, environment, and safety technology inputs. Typical input parameters are propulsion torque, brake torque, and steering or road wheel angle. Output parameters are, among others, global position, speed and accelerations. Furthermore, vehicle dimensions, shape, and coefficient of friction of the road-tire interface are essential. Independent of the application, a base vehicle model is needed to determine the effect of technology's response on the vehicle dynamics.

The complexity of the used vehicle model strongly depends on the research questions and the safety technology under assessment. Often simplified driving dynamics are considered to be sufficient, for example a point-mass model for longitudinal dynamics. When lateral dynamics are considered a linear or non-linear single track model is often required.[57]

In order to simulate the behaviour of certain components more realistically or when the technology under assessment requires specific input, the degree of freedom is typically increased or models might be constituted of more detailed sub-models. The degree of complexity of sub-models depends on the assessment scope. A detailed tyre model can be included in case the slip of the tires needs to be known or the vehicle interaction with the road under different conditions is an important factor.[58] This is especially the case if the limits of vehicle dynamics are triggered by the application. Another important sub-model – in particular for technologies that intervene in the longitudinal movement of the vehicle – is the brake model. Such models might consider the delays in the braking system, the brake jerk[59] or might provide results based on the control behaviour of the anti-lock systems. In case of intervention in the lateral vehicle movement and depending on the intervening system a detailed model of the steering system might be required. A detailed suspension sub-model might be required if road excitation is relevant or if the vehicle body motions (especially pitch and roll) induced by braking or steering interventions are used by other models, for example the collision model. Finally, a powertrain model might be included to consider the influence of motor acceleration and drag torque on vehicle dynamics.

Usually, vehicle model parameters and modelling details cannot be transferred from one solver to the other directly as no common input data format for vehicle dynamics solvers exists. Even if transferred manually, results might not be comparable due to different internal modelling approaches and numerical solver implementations.

7.4.2 Safety technology model

The model describing the safety technology consists of three different components: the sensors that sense the environment of the vehicle including the other traffic participants, the function logic that describes the response according to the given situations from the output of the sensor system and the actuators that put the decision of the logic into a vehicle response. For the simulation in the context of the prospective safety performance assessment, the focus is mainly on the sensor and the function logic.[60] The first two sub-models are described in more detail in 7.4.2.1 and 7.4.2.2. The actuators are often considered in a simpler way or are considered as a part of the vehicle model (see above braking sub-model).

7.4.2.1 Sensor model

The sensor model describes the relevant parameters of a specific sensor used by the technology under assessment. The sensing of the environment is a crucial part of the active safety technologies and therefore, needs to be addressed carefully. Typically, sensor types used for active safety technologies are cameras, LIDAR, radar and ultra-sonic sensors. Since this document addresses the method to evaluate technologies, details for the sensors are not discussed here.

The level of sensor modelling can range from very straightforward ideal sensor models based on sensor position at the vehicle, sensor orientation, 2D field-of-view and range, latency times, visibility restrictions and update rates[61] to detailed physics-based models. Detailed physics-based sensor models may additionally consider parameters like detection characteristics and probabilistic effects.[62] In contrast to studies that consider sensor effectiveness, the need for a high level of detail for the sensor model is limited for safety performance analysis dedicated to the entire active safety system. Each sensor type has different characteristics and therefore, a different relevant set of parameters.

Depending on the evaluated technology, different numbers and types of sensor models need to be considered. For instance, an AEB system can use a camera and radar sensor to observe the front environment of the vehicle. If more than one sensor is used also the aspect of fusing the information of different sensors gains more importance.[63] To which extent this aspect is considered for the simulation depends on the scope and purpose of the assessment.

A further important aspect in the context of sensor models is the simulation of failure behaviour of the sensor. Herewith a distinction is made between simplified ideal models that consider no failure of the sensor measurements and models that consider failures like measurement inaccuracies, detection losses and ghost detections.

7.4.2.2 Function logic model

The model for the ADAS and safety function logic describes the characteristics of the safety technology itself. The model defines the technology's reaction/interaction based on the sensor and vehicle model inputs (including system latencies). The safety technology model is the focus of the assessment.

A model of the function logic of the safety technology is a combination of processing the information from the sensor model(s), derivation of the decision and control models (algorithms).

The decision and control algorithm could be a detailed model (often proprietary),[19] a model derived based on data from experimental testing of an existing system,[17] or a simple, conceptual model description.[30] For the assessment, the function needs to be integrated in the simulation. This can either be done using hardware-in-the-loop (HIL), software-in-the-loop (SIL) or model-in-the-loop (MIL) simulation. For simulation, the function logic is often implemented in Matlab/Simulink, C-code, real production code, controller or system.

7.4.3 Environment model

The environment model describes the characteristics of the simulated surroundings in which the simulation is conducted. Environment models are typically used to determine the sensitivity of a technology under assessment with respect to certain limitations such as view blocking obstructions, deteriorated visibility conditions (low light, glare, fog), or road conditions.

Depending on the required details, the environmental model can include information about the following aspects: road/infrastructure characteristics (e.g. width, length, curvature, surface, profile, friction, pavement, and lane markings), traffic regulations (e.g. traffic signs, traffic lights), (temporarily) static objects (e.g. trees, parked cars, buildings), illumination (e.g. diffuse or spot with separate street lights), and weather (e.g. rain, snow). The characteristics of single objects (such as reflectivity as function of wavelength) could also be specified by this model. Typically, the level of provided details of the objects is aligned with the specification of the sensor model.

In general, the environment model including the road is defined in accordance with the requirements of evaluation scope. Environment condition or roads, for which it is certain that the technology in question does not operate, are typically not modelled. Whether the environment represents an artificial or real environment depends on the chosen baseline approach and the evaluation scope (see 5.2). In case the model represents a real environment, data are required to describe this real environment. These can either be provided by dedicated measurements, by information collected in an accident investigation and/or from map data. These data need then be translated to the format required by the simulation tool. The simulation formats to describe the environment range from proprietary formats up to standardized formats, e.g. OpenDrive.[152]

7.4.4 Traffic situation model

The traffic situation model describes the specific test scenario that involves the course of the event, initial longitudinal and lateral trajectories for each of the surrounding traffic participants as well as other parameters relevant for the assessment. Examples of relatively simple test scenarios can be found in References [11]–[13]. These were developed based on accident-data analysis and further specified for test-track verification of crash avoidance systems. For prospective assessments as described in this document, test scenarios can be derived in numerous ways. The data to describe the test scenario for the traffic situation model can be taken directly from a database such as PCM,[22] or identified from naturalistic driving tests such as UDRIVE.[64] It can also be generated based on analysis of traffic safety data, by using a stochastic approach, for instance Monte Carlo simulations,[29] or from (detailed) traffic simulations (see also traffic model). Similar as for the road environment the format of describing the traffic situation varies among the tools. A format which has gained more attention in recent times is OpenScenario.[153]

Next to predefined trajectories, the trajectories of other traffic participants can also be determined in the simulation. In this case, a (driver/rider/pedestrian) model that calculates the individual behaviour based on the given situation is required. Typical, such models transfer the information about the

traffic participant (position, orientation, etc.) to a second model in the simulation, which collects this information. It represents a kind of ground truth model. From these models a sensor model can receive the information necessary to decide, whether a traffic participant is detected or not. If an exchange of traffic participant models between different simulation tools is targeted, the specification of the interfaces is a crucial aspect.

7.4.5 Traffic model

Closely related to the traffic situation model is the traffic model. In most cases only a small number of known traffic participants are included, therefore the situation and traffic model appear to be completely integrated. Literature reports different approaches for simulating traffic. The approaches can be distinguished by the level of detail, at which the vehicles are modelled in the simulation.

— Macroscopic simulations model the flow of traffic according to high-level mathematical models which were originally intended to model fluid dynamics. This type of simulation handles every vehicle in the same way and combines single vehicles to a group respectively to a traffic stream.[65] This macroscopic perspective does not allow to determine effects for single vehicles, which makes them less applicable for the prospective safety performance assessment.

— Mesoscopic simulations move single vehicles but according to a macroscopic flow. However, vehicles can also be grouped in packets, which are treated then as one entity. From an analytical point of view, mesoscopic models can be viewed as the time-space discretization of macroscopic models (that are generally continuous on time and space).[66]

— Microscopic simulations model individual entities or agents (e.g. vehicle, driver) separately at a high level of detail. This simulation type is classified as a discrete simulation. Interactions are usually governed by car following and lane-changing models (see Table 5). Microscopic simulators are widely used to evaluate new traffic control measures and management technologies as well as performing analysis of existing traffic operations.[65]

  Sometimes also the terms “sub-microscopic” or “nanoscopic” simulations are used in this context in order to point out that a simulation uses even more detailed simulation models, which allow to explicitly consider individual technologies (e.g. ADAS) as well as the interactions of technologies in a vehicle. The nanoscopic modelling addresses the explicit simulation of the mechanism of the vehicle kinematics. It is explicitly modelled how the driver behaves, how he/she interacts with the vehicle and how the driver’s actions effect vehicle dynamics. Nanoscopic traffic simulation, based on a microscopic city traffic simulator and modelling of driver behaviour, are able to combine the technical and human dimensions of the traffic system into one entity.[67]

Table 5 — Overview on selected traffic simulation tools and the used models according to References [34] and [67]

Traffic-simulation tool	Type of simulation			Applied models										
				Car following							Lane change			
	Microscopic	Mesocopic	Macroscopic	[68]	[69]	[70]	[71]	[72]	[73]	[74]	[75]	[76]	[71]	[77]
AIMSUN	X	X	X			X						X		
MITSIMLab	X			X					X	X		X		
PARAMICS	X						X						X	
PELOPS	X				X						X	X		
SUMO	X							X						X
VISSIM	X				X						X			

Regarding actual modelling of the traffic participants’ behaviour in the simulation, two approaches are reported. The first approach uses fixed trajectories (including information about the path and

speed) for traffic participants without any response to other traffic participants. All trajectories are pre-calculated and not adapted according to the situation flow. This approach can be chosen in case a short time frame is simulated or in case it is presumed that the action of the function under assessment does not influence the behaviour of the other traffic participants. The second approach simulates the behaviour of each traffic participant, which means that their trajectories in simulation are not pre-calculated. This approach requires a (driver) model not only for the vehicle with the tested technology, but for each traffic participant as well. For this approach only the initial conditions for the simulation need to be defined. Once the simulation is running, each traffic participant determines its next movement step according to the perceived surrounding.

7.4.6 Driver model

The driver (behaviour) model describes the human behaviour – including perception, decision, and action – in order to fulfil the driving task under consideration of the external influences such as the surround traffic.[79][80] Typically, the models are applied for drivers of passenger cars or trucks. Nevertheless, also models for motorized two-wheelers, cyclist or pedestrians are available (for simplicity, in the document it is referred to the driver model irrespective of the road transport mode). The main purpose of the driver model is to qualify or quantify the time and force of action, the level of distraction (e.g. leading to delay in response), the perception process of the driver, the decision-making process of the driver, different driving styles, situational awareness, workload, emotion, normative and erratic behaviour, and / or even learning and long-term effects with respect to usage of ADAS functions.[81]–[85]

In general, the driver models fulfil two tasks: a control task related to the movement of the vehicle and an interaction task with the environment and function under assessment. The first task is mainly important for normal driving and consists of following a given trajectory and following a speed profile. For the second task different types of models are used:

— “empiric” reactive driver model in which the interaction with the environment and ADAS warnings is based on (semi)-empiric models;

— “control” predictive driver model in which the interaction with the environment and ADAS warnings are based on a reproduction of control processes.[85]

Typical common outputs of both model types are: reaction time, type and strength of the reaction. Here, also different characteristics of drivers might be considered.

The application of driver models is also not limited to the driver of the vehicle with the safety technology under assessment. The driver model can also be applied for surrounding traffic participants. In this case the requirements for the driver model are linked to the chosen approach for simulating the surrounding traffic. In simulations, in which the trajectories are predefined (see traffic model), a (driver) model is used that focuses on the controlling tasks (trajectory following) and implements a reaction behaviour (e.g. delay until action upon a warning of the technology). In case the trajectory is not pre-defined, driver models are needed that cover the interaction process in addition to the control process.

7.4.7 Collision model

The collision model determines the consequences of a collision between two or more traffic participants (e.g. cars, pedestrians, and objects) respectively a collision between a vehicle and any object. These consequences are usually expressed in terms of injuries of car occupants or other traffic participants involved (pedestrian, cyclist, PTW) in the collision. Some models also describe the consequences in terms of damages to the vehicles involved in the collision.

For injury prediction in general, three main approaches can be distinguished (sorted in ascending complexity and calculation time):

1) direct assessment of the impact based on collision parameters (e.g. relative change of the velocity during the collision) and corresponding injury risk functions, or risk models[20][86]–[90];

2) usage of accident-reconstruction software[91] for simulating human kinematics during the collision and its relation to injury[92];

3) Usage of multi-body simulations or finite element analysis taking into account the vehicle structure, and models for anthropometric devices (impactor, dummy) or human body. Obviously, this approach can provide the most detailed results in respect to biomechanics-based injury criteria values. However, the approach requires more complex and resource-consuming (time and cost) simulations.

For the development of an injury risk function model, accident data can be analysed regarding the accident severity to persons and the related input parameters. Input parameters for injury risk functions are for instance:

— personal information of occupants, such as, e.g. age, gender, height, weight;

— technical information, such as, e.g. delta-V (longitudinal/lateral/resultant), initial speed, collision speed, direction of force, impact point, rollover yes/no, EES, rotational speed;

— restraint information, such as, e.g. belted/unbelted, airbag activation, other restraint activation.

Regarding the topic of injury risk functions please see also Reference [2].

Once the relevant data are extracted, mathematical procedures are used for determining injury risk functions.[93] The injury risk functions are strongly dependent of the initial data used and the applied methods. Hence, it is important for their applicability to be checked and ensured beforehand. More detail on the use of injury risk functions is given in Clause 8.

7.5 Simulation control

Within the simulation framework (as given in Figure 6), the flow of information between the different models is either pre-defined or needs to be controlled. Different options for a simulation process exist.

— Single simulation: input is provided once by the simulation engineer, not only on the physics of the simulation, but also the simulation control parameters, and a single run is performed.

— Batch of pre-defined simulations: input is provided once by the simulation engineer by preparing the batch of input parameter combinations, and subsequent simulations are started by the simulation control module, irrespective of the results of previous simulations.

— Batch of simulations that involve stochastic processes. Different options exist to control these simulations:

  — Control of the simulations by an observer function: this function tracks, which parameters taken from distributions have been selected for a simulation run. If it is a random selection, then observation might not be necessary, as with a sufficiently large number of simulations it can be shown that the distribution is sufficiently covered. When there is a deviation from random sampling it is important to track, what parameters were chosen to define a simulation run.

    The complexity of the observer function may vary from a simple watch dog to an executable linear temporal logic function.

  — Control of the simulations by a guiding function: a simulation guide can be used for time efficient sampling. It defines which parameter values or combination of values are taken to ensure a proper coverage of different distributions as input for the simulation. When the simulated scenarios are not limited to only crashes, and therefore represents normal traffic, it will require several thousand simulations until an accident will occur. Then, to collect a sufficiently high number of accidents, a very large number of simulations is required. This might be beyond the efficiency of a simulation task. A guiding function will direct the simulation towards the incorporation of rarer events, e.g. to increase the probability to simulate accidents. Depending on the guiding strategy (importance splitting/importance sampling) there might be additional

requirements to other models like snapshotting or “white-box” access.[94] Typically, observer functions are used to provide input to the guiding function.

Next to models and tools used for the virtual assessment, there are questions related to execution of simulation. One of these is how many simulations are required at minimum to achieve a statistically representative result. The reported number of simulation runs varies strongly. Reasons for this include the approach taken for establishing the baseline (see 5.2) as well as the required accuracy and confidence of the results.

8 Estimating safety technology safety performance

For estimation of safety technology performance, the outcome of the simulations with and without the safety technology are compared. Figure 7 shows the place in the process overview.

Figure 7 — Overview of the process — Estimating safety technology safety performance

The basis for the performance estimation is established in the initial phase of the project, see 5.1. Here, the study target population is defined. By this, undesirable effects of a given safety technology could also be considered, and thus set requirements on baseline data to be used in the study. A set of traffic situations is derived by, for example, analysis of retrospective crash data and naturalistic driving studies providing the study target population: an overall description and quantification of the traffic situations and the involved traffic participants.

Then, the relative change in the target population due to the technology under study can be estimated and, if desired, further used for, e.g. projection in order to make the results representative for a specific region (more on this topic below).

There are different approaches to quantify the outcome of the comparison of the simulations with and without the safety technology under study - depending on the research question, the purpose of the expected results on the analysis procedure and also the relevant stakeholders. For instance, the *change of the velocity at the time of collision* may not yield the required detail of information and requires further interpretation (e.g. by means of injury risk functions) if a statement on the overall effect of a technology related to traffic safety on international level is needed. On the other hand, in the development phase of the technology it can be a useful indicator.

Yet another indicator such as *functional years lost due to personal injury*, quantifies social benefits well, but is less adequate in the detailed technology development phase.

Most commonly used metrics for safety performance are changes in the percentage of accidents, injury severity, or property damage.[96] [97] Other examples for metrics are field of view coverage, sensor detection rates, minimum time-to-collision to avoid collision, and change in impact speed or crash configuration.[97] Another important aspect which can be analysed is the consequences of autonomous interventions for the surrounding traffic.

In case an accident is not avoided, but mitigated, the consequences of the accident might be reduced. The extent to which the injury level is reduced, is calculated by making use of injury risk functions during or after the virtual simulation (7.4). The design of injury risk functions is depending on access to accident data and the method used for modelling these functions. Also, crash tests or virtual simulation of crashes are used for establishing injury risk functions.[98] [99] [100] [101]

To make the results representative for a specific region or country, projection of the data is often necessary.[102] Different weighting methods such as stratum-based weighting, n-dimensional

clustering,[58] decision tree, and random forest analysis[93] have been applied. The biggest challenge in the process of data projection is the lack of adequate data that provides the details needed for performing this analysis. In general, results are - according to the research question to be assessed - projected to target regions as:

— direct use of the simulation results without projection,

— projection of the simulation results to national level,

— projection of the simulation results to international level (e.g. continent),

— projection of the simulation results to global level.

Weighting may also be applied if sampling methods are used when, e.g. naturalistic driving data including near crashes are used to predict the safety performance of a safety technology for accident mitigation.[60]

The market penetration rate of safety technologies in the vehicle fleet is also needed for safety performance assessment. Many safety performance assessments assume a 100 % market penetration in the vehicle population though this might require several decades[103] to become a fact. Statistical models for the probability of collisions between vehicles with or without the safety technology available has been presented.[104]

In Table 6 different generic approaches to assess the safety performance of safety technologies are summarized, as previously applied in different studies. The methods are listed along the order from (as described above) technical to societal assessments. The approaches are independent from the input data used for the analysis, the considered technology (AEB, FCW, C2X, etc.) as well as the algorithms / functions used to calculate accident outcome (see 7.4.7).

Table 6 — Overview on approaches of estimating safety technologies' safety performance

Analysis target	Description	Influences	Example reference
Change in collision parameters	Analysis of influence of safety technology on specific collision parameters, like e.g. EES, dV, collision speed, etc.	Performance of a safety technology or a part of the technology (sensor, algorithm, actuator)	[105]
Estimation of relative change	Amount of change in the target population comparing the baseline and treatment simulation output. Relative change (often: effectiveness): $E=(N-N')/N$	The study target population (as a subset of all accidents)	[106], [107], [108]
Change of probability to have a certain injury	Using, for example injury risk functions and the estimated relative change/ effectiveness, an injury reducing benefit from a safety technology can be estimated.	The injury risk in the study target population.	[21], [109], [110], [23]
Estimation of societal benefit, e.g. numbers of lives saved	By using cost factors for specific injuries, a societal benefit can be calculated.		[111], [112]

In the context of quantification of the safety technology's safety performance, statistical methods can be applied. Examples of these approaches are:

— determination of the receiver-operating-characteristic curve in order to analyse the relation between true positive and false positive activations of the systems; this approach can also be applied in the analysis of sensor technologies;

— odds-ratios can be used in order to quantify the presence or absence of a property is associated with the presence or absence of another property in a given population;

— the effect size (e.g. Cohen's d) quantifies the determined effect of a technology.

Furthermore, confidence intervals for the injury probability function can be derived,[113] the variance caused by the input data error can be estimated,[114] or receiver-operator characteristics can be utilized[115] to assess the risk function models.

However, the significance of the estimated results always depends on the validity of the methods used to derive them. This is the subject of next clause.

9 Validation and verification

In this clause, the validation and verification processes of prospective safety performance assessment approaches are presented. Figure 8 shows the place in the process overview.

Figure 8 — Overview of the process — Validation and verification

In the context of prospective safety performance assessment, the product, service or technology is defined as the method itself - including its components and models. The assessment results are of interest for customers and stakeholders. Hence, for the prospective safety performance assessment by virtual simulation, "validation" means that the results need to be reasonably accurate. In contrast, "verification" is the check of the process and its results and of models versus specifications and requirements. This means that the mathematical / physical correctness of the models as well as the quality of the framework need to be ensured.

It is important that the validation and verification process covers the prospective safety performance assessment method and all sub-elements, such as models, metrics and tools.

Based on published literature (see Table 7) it can be concluded that prospective safety performance assessments are validated and verified in different ways and to different extents on a non-regular basis. Often, validation is focused on the whole method, whereas the verification is directed on single models. Most effort is spent for validation and verification of the safety technology under investigation. A common approach is found to be performing a review of simulation models and comparing results with other studies.

Different general approaches for the validation and verification have been applied. A list is presented in Table 7. The second column presents different references from the assessment of safety technology in which the approach has been applied.

Table 7 — Overview on validation and verification methods

Approach	References	Technique	Description
Comparison of results	[116]	Analysis/ demonstration/ test	This V&V approach focuses on the whole methodology. It compares results derived by the prospective safety performance assessment method with the results derived in another analysis. This analysis can either be done by a different validated simulation approach or by a different approach (e.g. analysis of accident data or test track). One example for this approach is that the overall simulation approach that determined safety performance of an AEB is compared with the result of accident analysis for the same system. Of course this is only possible if the AEB has been launched and has already reached a market penetration that allows to conduct a retrospective assessment.
Review of the whole method or the simulation models	[28]	Inspection	This V&V tactic is a (logical) review of the whole method or (simulation) models used by the method. The review can be conducted by experts. A typical example is that the implementation of an AEB model in the simulation is compared to the technology description in order to check, whether the technology has been implemented correctly.
Check by means of test data	[116][117]	Analysis/ demonstration/ test	This V&V approach focuses on the applied simulations and models for the simulation. Here, the results of the simulation are compared to results determined based on experimental data. Typically, the data are obtained on test tracks or in another controlled environment. An example in this context is that the deceleration profile of an AEB measured in the simulation is compared with the deceleration profile measured in a test track test.
Sensitivity analysis	[118]	Sampling / test	This approach checks the robustness of the applied method or single steps of the method (e.g. simulation or simulation models) against uncertainties. The input parameters are varied in order to check, whether the input leads to a stable or instable behaviour of the model or method. An example for this approach would be if the controller of an adaptive cruise control is fed with different input parameters in order to show that the control is stable and does not provide unrealistic acceleration in the simulated test space.
Propagation of uncertainty	[116][119]	Sampling / test	This method checks the propagation of uncertainties over the whole process or within a single step of the whole process. First, the single uncertainties for each (sub-) step needs to be determined. Afterwards the uncertainties for the whole process can be calculated. The overall uncertainties need to be below a defined threshold. In case the minimum and maximum error of the collision speed for AEB activation between the simulation and real world is known, this information can be applied to an injury risk curve in order to determine the resulting error in terms of accident severity.

Table 7 *(continued)*

Approach	References	Technique	Description
Model fit of statistical models	[120]	Analysis	This V&V approach is used for statistical models that approximate the real world by a mathematic model, such as injury risk function models. By comparing the difference between the real data and the by the model determined data, it can be quantified how well a regression model fits the original dataset. Typically, the threshold is defined in order to decide whether the quality of the fit model is sufficient. An example for the application of this approach is the development of injury risk functions.
Statistical testing of differences in model vs input data	[121]	Analysis	This process includes different statistical methods that are used to state that two distributions differ from each other or not. A distribution of value determined by the method or a model of the method is compared to the reference distribution. A certain statistic method for test needs to be chosen according to the data. Based on pre-defined criteria, it is decided whether the tested distributions differ from each other or not. The approach can then be applied to check for the baseline, whether the resulting collision speeds are in line with collision speeds of accident databases and if they are representative.
Back-to-back-test	[122]	Analogy / similarity	This V&V approach checks and quantifies the difference between two (sub-) models (or elements of the methodology). The precondition is that the first model is validated and verified. First, the results are determined with this model. Afterwards the second model that is under check test is applied. Thus, the difference between both models can be quantified and checked. In a third step, the original model is again applied to ensure that the results are remaining the same and that the results were not influenced by side effects. The example for this approach is that there are two versions of an AEB model for simulation. The first one is validated and the second one is in question. Then both models are simulated with the same input in order to determine the difference.
Test validity (construct validity, content validity, criterion validity, face validity)	[123]	Inspection / analysis	The focus for these approaches is checking the validity of the whole methodology or the sub-models. The test validity is the extent to which a test accurately measures what it is supposed to measure. The test validity is often divided into different "validities", such as construct validity, content validity, criterion validity and face validity.

Most of the approaches rely on techniques that are described in Reference [124], see Table 8. The techniques have been mapped to the different validation and verification approaches.

Table 8 — Verification techniques [124]

Verification technique	Description
Inspection	Technique based on visual or dimensional examination of an element; the verification relies on the human senses or uses simple methods of measurement and handling. Inspection is generally non-destructive, and typically includes the use of sight, hearing, smell, touch, and taste, simple physical manipulation, mechanical and electrical gauging, and measurement. No stimuli (tests) are necessary. The technique is used to check properties or characteristics best determined by observation (e.g. paint colour, weight, documentation, listing of code).

Table 8 *(continued)*

Verification technique	Description
Analysis	Technique based on analytical evidence obtained without any intervention on the submitted element using mathematical or probabilistic calculation, logical reasoning (including the theory of predicates), modelling, and/or simulation under defined conditions to show theoretical compliance. Mainly used where testing to realistic conditions cannot be achieved or is not cost-effective.
Analogy or similarity	Technique based on evidence of similar elements to the submitted element or on experience feedback. It is absolutely necessary to show by prediction that the context is invariant that the outcomes are transposable (models, investigations, experience feedback, etc.). Similarity can only be used if the submitted element is similar in design, manufacture, and use; equivalent or more stringent verification actions were used for the similar element, and the intended operational environment is identical to or less rigorous than the similar element.
Demonstration	Technique used to demonstrate correct operation of the submitted element against operational and observable characteristics without using physical measurements (no or minimal instrumentation or test equipment). Demonstration is sometimes called 'field testing'. It generally consists of a set of tests selected by the supplier to show that the element response to stimuli is suitable or to show that operators can perform their assigned tasks when using the element. Observations are made and compared with predetermined/expected responses. Demonstration may be appropriate when requirements or specification are given in statistical terms (e.g. mean time to repair, average power consumption).
Test	Technique performed onto the submitted element by which functional, measurable characteristics, operability, supportability, or performance capability is quantitatively verified when subjected to controlled conditions that are real or simulated. Testing often uses special test equipment or instrumentation to obtain accurate quantitative data to be analysed.
Sampling	Technique based on verification of characteristics using samples. The number, tolerance, and other characteristics are specified to be in agreement with the experience feedback.

10 Practical experience

10.1 General

While the majority of this document described the theoretical background, the implementation, and the validation and verification of the method, this clause focuses on the lessons learned from practically conducting prospective safety performance assessments by virtual simulation. As the assessment depends strongly on the circumstances (resources, tools, etc.) and on its scope resulting from the research questions, it is hardly possible to describe a general way for executing an assessment. The input of the P.E.A.R.S. initiative was taken into account in a study, which compared different implementations of a safety performance assessment of an AEB system for preventing collision with cyclists as conducted by several P.E.A.R.S. partners. The lessons learned and the outcome of this study is used to derive recommendations for future assessment studies and also for the application towards automated and connected driving systems.

10.2 Establishment of baseline

Regarding input data, it is necessary to add certain variables in the data describing the baseline. As described in 5.2, accident databases are frequently utilized. Along with basic information, which is available in some databases, such as trajectories, speed related measures, crash configurations, sight obstructions, and occupant information, variables such as vehicle pitch, road topography, map data, traffic flow, driver behaviour in the pre-crash phase, and final static position of vehicles would be helpful.

Next to this additional information that would help to get to more accurate simulations, the quality of data is also an issue in this context. Furthermore, reliable databases for certain geographic regions, respectively markets, are currently missing. An attempted to harmonize accident data for different regions of the world was initiated by the IGLAD consortium.[125][126] IGLAD harmonized data set among

the cover regions. However, although IGLAD covers different regions there are still other regions in the world, for which accident databases with detailed data are missing.

10.3 Simulation framework

The research question and the considered baseline in the assessment have a strong influence on the complexity of the simulation. To decide on the required complexity of the environment in a simulation, it is typically determined beforehand, whether the environment is to be considered statically or dynamically.

In case moving traffic participants influence the functionality of a technology under assessment, it could be required to simulate the moving behaviour of these participants by a simulation either for an individual traffic participant or through traffic simulation for multiple traffic participants simultaneously. Here, the information about other traffic participants except the ego and principal other vehicle might not be available from accessible databases. If the technology response significantly influences the behaviour of the other traffic participants, then the interactive behaviour is to be modelled. The interaction is particularly important in case of strong interventions into the traffic situation, by either acute unexpected braking or swerving. It is important that possible negative safety effects of a technology, such as causing a collision because of the technology intervention, are considered in evaluations as well. In addition, effects such as false-positive interventions need to be considered. For example, an automated brake intervention could lead to a rear-end collision with the following vehicle, particularly in case of a false positive response.

10.4 Comparative study of different simulation tools

Several partners of the P.E.A.R.S. consortium have performed a study analysing possible differences between different simulation tools. In this example, the same baseline – conflict with a crossing bicycle – has been implemented in different tools.[127] The technology under assessment is an exemplary AEB that is intended to prevent the collision with the cyclist. For this report, the focus was applied to the main parameters that need to be defined to be able to compare results of the separately-conducted assessment studies. The results of this investigation will be reported in another publication.

To be capable of comparing the outcome of the different tools, the relevant real-world situations are to be defined as clearly and explicitly as possible. First, the definition of the baseline is considered. The geometry of the vehicle and the cyclist needs to be defined explicitly in detail, since the shape of the objects might have a strong effect on the object and collision detection, and thus the results.

Further, the definition of the baseline requires a description of the AEB system to be assessed, including its subcomponents – sensor, function logic, and actuator. For the sensor, the basic parameters (position, angle of view / beam, maximum range and orientation) are defined explicitly. Furthermore, the sensors parameters regarding the object detection are set. This includes the criteria for object detection (e.g. required amount of information to detect an object, delays, false positive and false negative behaviour) as well as the measurement of the target position and speed (reference point of the object, accuracy, etc.). Next to the sensor, aspects for the function logic also need to be defined. Obviously, the threshold and intensity of the response (TTC of intervention, maximum deceleration, deceleration profile, etc.) are defined. Additionally, the definition of the technology's reaction in case the object is no longer visible to the sensor is to be implemented. Finally, delays of the actuators need to be defined.

For the evaluation, a comparable list of the output parameters is required. The Round Robin study reveals the ways in which the different partners calculate these output parameters.

Currently, the responsible partners for the simulations in the study are conducting evaluations in more detail and are analysing the results. The outcome will be published in the future. This will also make allowance to describe the aspects that need to be harmonized in order to make results comparable from the process side.

10.5 Estimating the safety performance

Regarding the estimation of the safety performance, the main issue is the lack of adequate injury risk functions for pre-impact situations or methods to generate such functions for different pre-impact situations. Currently available injury risk functions focus rather on certain crash configurations. An improvement in this area would support the quality of the prospective simulation studies with respect to the quantification of injury severities.

Also, the projection of data – scaling up the results of studies that are based on a limited data-set to larger areas for instance national or international level –lacks of adequate methods and is in need of harmonization. However, population data for certain regions could be either missing or not accessible.

10.6 Validation and verification

As stated in Clause 9, the main issue related to validation and verification is that nearly no information on this process is reported in literature. It can be expected that validation and verification activities are performed. The conclusion from the reported activities is that more effort is put on validation than on verification.

The most often used methods for validation and verification are a) the review of "simulation models" and b) the "comparison of results" with other studies. Further used approaches are the "sensitivity analysis", the use of "statistical methods" as well as the "verification by means of real-world data" for verification.

The data used for validation and verification also form an important aspect. From the known examples, the data that is used for the validation and verification is mostly taken from in-depth accident databases. However, data from national accident databases, data logged on a test track and other simulation data are also frequently used. Less common, field operation test (FOT) data and naturalistic driving study (NDS) data is taken in account for verification. Data that are rarely used for verification are data from event recorders, test data from simulators, stochastically generated data or data from consumer rating tests. In this context, the availability and access to certain data sources might have had a high influence on the answers.

11 Conclusions and limitations

This document gives an overview of the state-of-the-art methods for assessing the safety performance of vehicle-integrated (active) safety systems respectively technologies using virtual simulation, as they were performed by different types of organizations applying various simulation tools. This document was generated to provide a state-of-the-art and to identify commonalities and differences in currently used approaches. So far, no guideline has been drafted; this is subject of further research, based on the knowledge on the state-of-the-art of prospective safety performance assessment methods.

Prospective safety performance assessment methods predict the effect of vehicle-integrated technologies on traffic safety before the technology is introduced on the market. Tools that are used, generally comprise of virtual simulations with validated virtual (sub-) models. However, prospective safety performance assessment by virtual simulation is not a sole solution and it is as a complement to retrospective assessment of safety technologies introduced to the market. Thus, the forecast generated by virtual simulation needs to be followed up by review of the actual effects in real-world. These determined real-world effects can be used to verify and validate as well as to improve virtual assessment.

Although the taken approaches might differ in terms of the baseline or the complexity and detail of the used models, the overall process and its steps are similar. The relevant steps are:

— define the scope of the assessment study and the target population (Clause 5),

— establish a baseline (Clause 5),

— conduct the simulations with and without the safety technology under assessment (Clause 7),

— and eventually, calculate the safety benefit using an adequate metric (Clause 8).

Input data are required for the models and for the description of the baseline and the traffic situations that are subject of the study (Clause 6).

Different users have different demands and requirements regarding the assessment process. Answering different research questions puts different demands to the approach, the level of complexity of the assessment, the level of detail and quality of the data and the models used within the simulation. The followed assessment process itself even depends on the availability or accessibility of data sources.

Variations in the assessment approach and lack of process descriptions make it often difficult or even impossible to compare safety performance results from different studies. The interpretation of the results consequently requires a detailed description of the process that has been followed, the assumptions that have been made, the models and tools that have been used, and the input data that have been referenced. Ideally, the interpretation of the results of a safety performance assessment study comes with a formulation of the original research question. To ensure that the results of the assessment study are reliable and trustable, a validation and verification process needs to be in place (Clause 9). It is important that the validation and verification process does not only cover the virtual models, but also the input data, the simulation tools and the applied methods.

The document shows the current capabilities and limitations of state-of-the-art methods.

— The results of virtual simulation are sensitive to variations in the models and variations in the input data. Such variations might result from the use of different sources, however also on different choices that are implicitly made in the complete simulation process. Such sensitivity for, for example variations in the geometrical definition of the target and host vehicle, lead to differences in the results, although the methods show a large similarity in trend. In case an absolute value for the safety performance of a certain technology is required from the assessment study, a very strict description of all input is needed. However, to get a basic understanding of the influence of, for example the field-of-view of a sensor, the current methods are very well capable of providing the required results.

— Different approaches are possible for the description of the (active) safety technology that is subject of the assessment study. Each technology consists of a sensor system, possibly consisting of multiple sensors, a decision and control unit for interpretation of the manoeuvres of the surrounding traffic in relation to the intended movement of the host vehicle, and an actuation system to provide a required response of the host vehicle, such as a change of velocity or a change in direction. Each of these sub-systems, and their relations can be described in different ways, from simple straightforward rule-based models, to detailed highly complex models that are based on physics. In general, detailed complex models require an extensive process to acquire the input data, and computation and analysis takes generally much longer than for more straightforward models that give a fast indication of trends, with generally larger confidence intervals around the results.

  Both approaches lead to viable results, however with differences in detail and accuracy. Depending on the type of research question, a choice is made on the approach to be followed.

— A selected approach is strongly influenced by the accessibility of data, either from in-depth accident databases, naturalistic driving studies, or test track and driving simulator studies. The different data sources all have in common that they are specific for a certain region, prone to bias due to sampling criteria, and may have limited content on specific information. Furthermore, analysing this data is usually costly and time-consuming. The assessment methodology as discussed in this document might also benefit from harmonization in the collection and interpretation of data out of such data bases.

The extensive use of virtual simulations by different partners in order to assess the safety performance of technologies (ADAS and active safety system) points out the importance of simulation tools to answer different relevant research questions. The lack of any standard has led to different approaches within the overall virtual simulation process. Since the results of the virtual assessment depend on many factors (input data, used models, simulation tool and used metric), they can hardly be compared between different studies. It is difficult or even impossible to validate these without knowing all details.

The difference in results between different studies might lead to a reliability issue. Thus, harmonization actions are required in order to make the different assessment approaches more comparable and trustworthy.

12 Outlook

12.1 General

The prospective safety performance assessment by virtual simulation is facing some issues. Some are related to the process, others to the extension to new and upcoming technologies. Both aspects are covered by this clause. First, issues related to the method itself are discussed. Afterwards the extension of the approach towards automated driving and the application of V2X technologies are discussed.

The major challenges for the prospective safety performance assessment by virtual simulation is to generate trust and acceptance for its results. A valid question for the interpretation of simulation results is how well models are able to describe real-world effects. Furthermore, the variety in the implementation of the approach (see, for example the baseline definition in 5.2) can lead to different results for the same research questions. In case there are only small deviations, this can be accepted. However, large differences might undermine the trustworthiness of results.

One approach to tackle this issue is to harmonize the assessment approach and to define standards or minimum requirements for virtual assessment. This harmonization aspect is encouraged by the authors. Another important aspect is the validation and verification of the simulation models and tools. This aspect needs to be strengthened in the future.

As stated in the introduction this document is mainly dedicated to the assessment of ADAS and active safety systems. Besides to these technologies there also other functionalities of interest to be assessed regarding their potential impact on traffic safety. Two particular types of technologies that gained more and more importance in the recent time are systems dealing with automated driving and/or V2X technologies. Therefore, this subclause discusses the capabilities and limitations assessing these types of technologies.

Since not many results related to the prospective assessment by virtual simulation of these technologies have been published yet, this subclause represents the current opinion of the authors based on their experience and work.

12.2 Automated driving

In recent times, a development of functions addressing higher levels of automation[8] can be observed.[128][129] With the developments towards higher levels of automation, the safety performance assessment by simulation also needs to evolve for these technologies.

The importance of prospective assessment by making use of virtual simulations will grow with increasing level of automation as the number of different test scenarios will become hardly possible to test on a test track or in a laboratory.[130]

The following topics may need to be taken into consideration from simulation point of view for the assessment of automated driving functions:

Increasing number of covered test scenarios: automated driving systems continuously act and no longer wait for the one critical situation to act upon. For automated systems, the requirements consequently shift from safety performance to mitigate injuries and collisions in specific situations towards a continuous complete collision avoidance and normal comfortable driving. The number of test scenarios, however, increases drastically in order to be able to assess the response of the system for all relevant situations, all possible disturbances, all possible system interactions and all possible interactions with other traffic participants on the road. This means that the number, as well as the complexity of the simulated traffic situations need to evolve. Consequently, it needs to be discussed, to which extent simulation of single test scenarios are adequate for automated driving function, and to which extent larger samples of traffic scenarios are of relevance.

Increased horizon of active operation: higher SAE-level technologies are continuously acting and anticipating upon traffic. Whereas a traditional ADAS or safety system monitors the surroundings of the vehicle to determine the one single critical situation, systems at higher levels of automation need to make the correct interpretation at every moment in time. Herewith, also the time horizon of active operation increases, and the prediction of road users' intention becomes increasingly important. With respect to the simulation, this means that longer time periods need to be considered. A simulation that covers only a couple of seconds might not cover that an automated driving system avoids the conflict at all. This might require more complex simulations than for ADAS. Furthermore, the modelling of other road user behaviour gets more important. With fully automated systems, there might be traffic situations that the automated system may not handle equivalently well as the average driver does. Here, new reasons of critical situations may occur that are not yet present or dominant in the accident data.

Increased technology integration and interaction: the number of technologies increases, and likewise the number of sensors. Moreover, sensor output is used for more than one technology in general and the interaction between technologies will continue to increase, so that the assessment can no longer be performed independently for the different technologies. This implies two major changes compared to existing simulation. First, the simulation can no longer focus on the simulation of single functionalities. Furthermore, the baseline needs to describe which functionalities are considered in the baseline simulation and which in the treatment simulation.

Driver state: for higher automated driving systems with higher SAE level, the driver does not need to observe the traffic. This means that the driver is – compared to today's situation – no longer part of the driving loop. This has a strong effect on the used driver models – in particular in situations, in which the driver needs to take action, e.g. take-over requests. Here the driver behaviour in terms of reaction time, type and strength needs to be modelled. However, also in the time period in which the driver is not in the loop, new models for the driver behaviour are expected to be required.

Increased relevance for real life traffic situations: it becomes an essential key task to collect information on traffic situations in all its variations in traffic, including all "normal" driving situations, critical situations, near-crashes, slight accidents with material damage, and accidents with injuries. This data provides an overview of the relevant ranges in real life driving behaviour, for instance time headway. Therefore, the data are essential to describe test scenarios adequately and realistically. Besides, the data can contribute the definition, implementation and verification of models used in the simulation – in particular those models that describe the general behaviour of road users.

12.3 V2X technologies

V2X-communication technologies, in which cars or traffic participants communicate with each other and with infrastructure, pose an additional dimension to the prospective safety performance assessment. These technologies do not only operate in one vehicle, but in different vehicles at the same time. Examples are a cooperative ACC (C-ACC),[131] in which the distances and speeds are adjusted in the host vehicle according to other road participants.

More advanced technologies might not only set a certain speed or distance but plan and execute entire joint manoeuvres of road users. One example is the Cooperative Manoeuvre Planning that avoids collisions of multiple road users[132] by generating cooperative manoeuvres for all involved road users. This kind of technology poses high requirements for validation and assessment.

Receiving information: information that is received by the vehicle can be treated as input from an additional sensor. In safety performance assessment of technologies that make use of input from connected systems, the sensitivity for disturbances in the quality and reliability of the data needs to be determined. This will require models that can mimic realistic disturbances, e.g. based on environmental conditions, the presence of objects that might influence data reception, etc.

Broadcasting information: active communication towards other traffic participants has similarities to an actuator and assessment will focus at the type and the quality of the data that is broadcasted.

Safety performance assessment: with the introduction of cooperative driving systems, such as Cooperative-ACC or Cooperative Manoeuvre Planning,[131][132] the assessment is no longer limited to the behaviour or response of one single vehicle system. To determine the safety performance of such

a technology the system boundaries will need to be extended to cover at least two communicating vehicles or more in case more vehicles are interacting through communication with each other. Overall, this will result in more complex test scenarios that need to be handled by the simulation framework.

Annex A
(informative)

List of tools

The tools in Table A.1 are listed in alphabetical order and do not imply any statement regarding the usefulness or quality of the tools for the virtual simulations in the field of prospective safety performance assessment. Furthermore, it is also not claimed that this list is exhaustive.

Table A.1 — List of example commercial simulation tools used in the prospective safety performance assessment

Tool	Reference
AIMSUN	[133]
CarMaker	[134]
CarSim	[135]
DYMOLA	[136]
ITS modeler	[137]
MADYMO	[98],[138]
MATLAB / Simulink	[139]
MITSIM	[140]
OpenDS	[141]
openPASS	[142]
PC Crash	[143]
PELOPS	[144]
PreScan	[145],[146]
Pro-Impact	[147]
Sceneinspector	[148]
VI-CarRealTime	[149]
Virtual Test Drive	[150]
VSM	[151]

Annex B
(informative)

Input and output of simulation models

A simulation consists of different models which are linked to simulation by means of interfaces. Table B.1 provides an overview of the typical input and output parameters of relevant simulation models.

Table B.1 — Typical input and output parameters

		Driver model	Environment model	Collision model	Function logic model	Traffic situation model	Sensor model	Traffic model	Vehicle model	Simulation control
Driver model	Inputs from	N/A	Environment characteristics [c]		HMI outputs	Trajectories		Other traffic participants' trajectories	Vehicle dynamic state [a]	
	Outputs to	N/A			Driver actuation state [d]				Driver actuation state [d]	
Environment model	Inputs from		N/A					Position	Position	
	Outputs to	Relevant environment characteristics	N/A	Object positions, velocity (if applicable)			Environment characteristics [c]	Road information [b]	Road information [b]	
Collision model	Inputs from		Obstacle positions	N/A				Other traffic participants' positions, velocities	Vehicle dynamic state [a]	
	Outputs to			N/A						Impact status

[a] Vehicle dynamic state, including translational dynamics (e.g. position, velocity, acceleration) and rotational dynamics (orientation, slip angle).

[b] Road information, like course of the road, friction, etc.

[c] Environment characteristics including, e.g. road edges, lane marking, traffic signs/lights, static object positions (e.g. parked vehicles, buildings), sensor specific properties (e.g. reflection characteristics).

[d] Driver actuation state including, e.g. steering wheel angle and angle rate, pedal position, gear lever position, turn indicator status.

Table B.1 *(continued)*

		Driver model	Environment model	Collision model	Function logic model	Traffic situation model	Sensor model	Traffic model	Vehicle model	Simulation control
Function logic model	Inputs from	Driver actuation state [d]			N/A		Objects in field of view, object positions (sensor quality), sensing delays		Vehicle dynamic state [a] Function state Driver actuation state [d]	
	Outputs to	HMI outputs			N/A				Actuation of brakes, steering, etc. (depending on type of intervention)	
Traffic situation model	Inputs from					N/A				Test scenario specific simulation points
	Outputs to	Trajectories	Trajectories		Safety system specification	N/A			Trajectories	

[a] Vehicle dynamic state, including translational dynamics (e.g. position, velocity, acceleration) and rotational dynamics (orientation, slip angle).

[b] Road information, like course of the road, friction, etc.

[c] Environment characteristics including, e.g. road edges, lane marking, traffic signs/lights, static object positions (e.g. parked vehicles, buildings), sensor specific properties (e.g. reflection characteristics).

[d] Driver actuation state including, e.g. steering wheel angle and angle rate, pedal position, gear lever position, turn indicator status.

Table B.1 *(continued)*

		Driver model	Environment model	Collision model	Function logic model	Traffic situation model	Sensor model	Traffic model	Vehicle model	Simulation control
Sensor model	Inputs from		Environment characteristics [c]				N/A	Other traffic participants' positions, sensor specific properties (e.g. reflection characteristics)		
	Outputs to				Objects in field of view, object positions (sensor quality), sensing delays		N/A			
Traffic model	Inputs from		Road information [b]					N/A	Vehicle dynamic state [a]	
	Outputs to	Other traffic participants' trajectories	Other traffic participants' positions	Other traffic participants' position and velocity			Other traffic participants' positions, sensor specific properties (e.g. reflection characteristics)	N/A		

[a] Vehicle dynamic state, including translational dynamics (e.g. position, velocity, acceleration) and rotational dynamics (orientation, slip angle).

[b] Road information, like course of the road, friction, etc.

[c] Environment characteristics including, e.g. road edges, lane marking, traffic signs/lights, static object positions (e.g. parked vehicles, buildings), sensor specific properties (e.g. reflection characteristics).

[d] Driver actuation state including, e.g. steering wheel angle and angle rate, pedal position, gear lever position, turn indicator status.