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Road vehicles — Traffic accident analysis —

Part 4: Compilation of methodologies for assessment of vehicle safety system effectiveness

Véhicules routiers — Analyse des accidents de la circulation —

Partie 4: Compilation des méthodologies pour l'évaluation de l'efficacité des systèmes de sécurité des véhicules

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Foreword

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

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

A list of all parts in the ISO 12353 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

Many methodologies are used to analyse the effectiveness of various vehicle safety systems. Most methods are retrospective, have different applicability, advantages and limitations, and are often chosen depending on the structure and content of the data available. More recently, prospective methods have been presented and used.

The aim of this document is to compile commonly used methods for assessing the effectiveness of vehicle safety systems. The document covers assessment methods for active, passive and integrated safety systems including crash avoidance systems. The effectiveness in this context refers to the capability of a safety system or feature to avoid or mitigate injuries, fatalities or crashes.

The document provides a general overview of commonly used terms for the assessment methodologies, including exposure, risk, odds, effectiveness, benefit and safety performance.

Six methodologies, both prospective and retrospective, are described in the document. Each method is summarized in terms of its applicability, advantages and limitations. The methodology is described together with necessary input data and the resulting output data. Conclusions are given in terms of accuracy, sensitivity and validation for each method.

An overview of the applicability of prospective and retrospective assessment methods is also included (see Annex A).

The methods included in this document were considered to be in use and valid for this compilation by the time of development. If needed and requested, this document can be expanded with additional methods in a later revision.

Road vehicles — Traffic accident analysis —

Part 4: Compilation of methodologies for assessment of vehicle safety system effectiveness

1 Scope

This document compiles common methods for assessing the effectiveness of vehicle safety systems. This covers active, passive and integrated safety systems including crash avoidance systems.

Effectiveness in this context refers to the capability of a safety system or feature to avoid or mitigate injuries, fatalities or crashes.

The document covers both prospective and retrospective methodologies. Applicability, advantages, limitations, accuracy and sensitivity are described for each method. Necessary input and output data and format are also presented.

2 Normative references

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

ISO 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 in ISO 12353-1 and the following apply.

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

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

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

3.1
mitigate
reduce the consequences of a hazardous event

Note 1 to entry: In the context of this document, the consequences are injuries, fatalities or crash severity.

3.2
injury risk
IR
probability of occurrence of a personal injury at a specific level

Note 1 to entry: Injury level is often expressed with the abbreviated injury scale (AIS).

3.3
relative risk
risk ratio
ratio of risk of an event in one group versus the risk of the event in the other group

EXAMPLE An exposed group versus a non-exposed group.

3.4
odds
probability that the event occurs divided by the probability that the event does not occur

3.5
odds ratio
probability of an event occurring in one group versus the probability of the event occurring in the other group

3.6
eccentricity
distance between the impact force vector of the centres of gravity of the two vehicles in an eccentric impact

4 Symbols and abbreviated terms

A	number of accident situations sensitive to the system
AEB	autonomous emergency brake
ADAS	advanced driver assistance system
B	benefit
C	crash-momentum index
E	effectiveness
F	field of effect
IR	injury risk
N	number of (all) accident situations
n	number of crashes (of a certain type)
P	crash rate
PDO	property damage only
Q	penetration factor
R	relative risk (risk ratio)
S	safety performance
ΔV	change of velocity (delta-v)
X	exposure

5 Overview of assessment methodologies

5.1 Prospective and retrospective methods

Assessments are calculations of performance that tell the value of a subject in comparison to an aim or objective. This document describes commonly used assessment methodologies for traffic safety measures in vehicles in the complete driver-vehicle-traffic system (i.e. when the measure is deployed in the real-world traffic with the wide-ranging distribution of environments and traffic participants).

The two main types of assessments are studies performed before (prospectively) or after (retrospectively) the introduction of a safety measure, see Figure 1. The headings of the clauses in this document indicate whether the assessment method described is prospective or retrospective.

Methodologies to categorize traffic safety performance assessments use tools (e.g. virtual simulation, accident database analysis) and input data (e.g. crash data, naturalistic driving data). Tools and input data are discussed for each method in this document. Some applications of prospective and retrospective methods are given in Annex A.

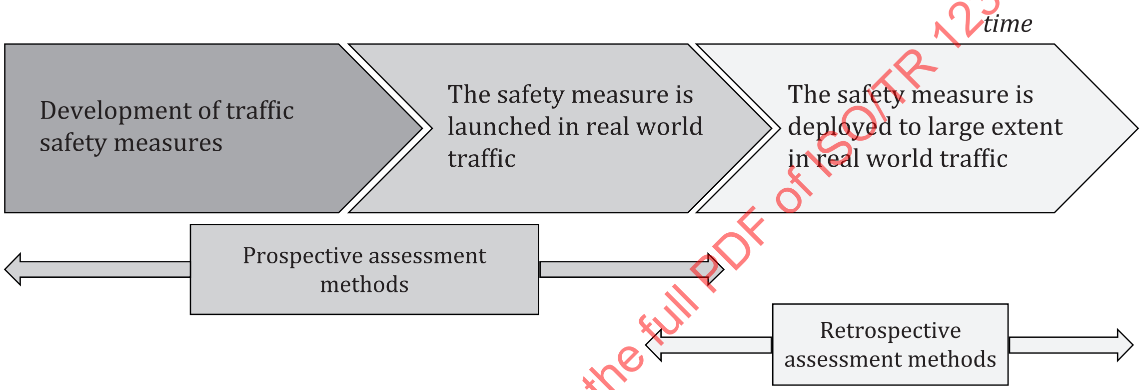


Figure 1 — Illustration of prospective and retrospective assessment methods

5.2 Exposure

The traditional definition of exposure is of being in a place or situation where there is no protection from something harmful or unpleasant. According to ISO 26262-1, exposure is defined under functional safety as the state of being in an operational situation that can be hazardous, which can occur at any point in a vehicle's lifetime (a combination of an operational situation and a potential source of harm). A similar interpretation is given in ISO 21448, which refers to the ISO 26262 series. In these documents, exposure is a factor for potential risk calculation that describes the (expected) frequency of occurrences of situations of interest. For prospective accident research, a similar approach is taken in case the frequency of scenarios is relevant for the calculation of the risk of accident.

For retrospective traffic accident research, the perspective is different, since the focus is on the calculation of accident rates for different groups. These groups can be defined by other parameters, such as technologies, vehicle types, road types and driver types. A simple comparison of the number of accidents can be misleading in the analysed data set. Therefore, a rate is calculated to correct the comparison for the different representation of the groups. In Reference [3] the problem is illustrated by asking which sex is more likely to be involved in accidents. Although there are copious data available on the number of accidents in which male and female drivers are involved, this question remains difficult to solve, since it requires comparison of the number of accidents per unit of exposure for each group. Typical units for exposure are travelled distance or time, traffic density and/or crash severity.

Thus, in retrospective accident analysis, exposure is defined according to ISO 12353-1 as a parameter describing the dose or amount of some physically measurable parameter(s) that are related to an accident or injury or both.

5.3 Risk

According to ISO 26262-1, risk is the combination of the probability of occurrence of harm and the severity of that harm.

In this document, risk is the probability of occurrence of an accident with a specific severity (due to the application of a safety system).

As for the risk of personal injury, injury risk (IR) is the probability of occurrence of a personal injury at a specific level.

The severity of an accident is estimated by the type of injuries and the extent of affected people, for example:

- property damage only (PDO);
- minor, major or lethal injuries;
- one or several persons, objects.

The probability of occurrence of harm depends on the exposure to the hazard, the occurrence of relevant situations and the possibility to avoid or limit harm by external factors:

- how often or how much time is spent with the hazardous object;
- relevant statistical, historical or reference information;
- skillset and awareness of user, experience, lead-time to harm.

5.4 Odds

Odds is defined as the probability that the event will occur divided by the probability that the event will not occur.

The odds ratio is the ratio of the odds of an event in one group versus the odds of the event in the other group.

NOTE See also Reference [4].

5.5 Field of effect

The field of effect, F, defines a specific subset within a superset of considered accident situations. The superset of traffic situations contains all occurrences recorded in a particular region. The accident situations in the field of effect are specified by common characteristics. These can be, for instance, accident causes, accident scenarios, involved participants and other concomitant circumstances.

In practice, the field of effect is the proportion of all accident situations in which a specific safety system can have a positive effect. The safety system is designed to become active in these situations in order to avoid or mitigate the accident. Thus, the field of effect describes all accident situations that are addressed by the safety system.

The field of effect is calculated using Formula (1):

$$F = \frac{A}{N} \times 100 \quad (1)$$

where

F is the field of effect, expressed in per cent;

A is the number of accident situations sensitive to the system;

N is the number of all accident situations.

EXAMPLE The field of effect of an autonomous emergency brake (AEB) system comprises all run-up accidents between cars. About 6 % of all injury accidents in Germany are car-to-car run-up accidents that can be addressed by AEB.

5.6 Effectiveness rate

The effectiveness rate defines the proportion of accident situations in the field of effect that are positively affected by the regarded safety system. It describes how well the safety system performs within its field of effect.

The effectiveness rate of the safety system depends on how well the system addresses all possible accident situations within the defined field of effect. It also relies on a reliable and functioning system performance. Ideally, all system-specific accident situations are avoided or at least mitigated by the safety system.

The effectiveness rate is calculated by Formula (2):

$$E_{\mathrm{Rate}} = \frac{A_{\mathrm{Reduction}}}{A} \times 100 \qquad (2)$$

where

E_{Rate} is the effectiveness rate, expressed in per cent;

$A_{\mathrm{Reduction}}$ is the number of avoided or mitigated accidents that are sensitive to the system;

A is the total number of accidents sensitive to the system.

EXAMPLE The effectiveness rate of an AEB system specifies the part of all car-to-car run-up accidents that are avoided or mitigated by AEB. The AEB effectiveness rate amounts to approximately 90 %.

5.7 Potential effectiveness

The potential effectiveness defines the maximal proportion of all accident situations that are positively affected by the safety system. It describes the overall benefit of a safety system if all vehicles in the field were equipped with such a system.

The potential effectiveness is calculated by Formula (3):

$$E_{\mathrm{Pot}} = \frac{A_{\mathrm{Reduction}}}{N} \times 100 \qquad (3)$$

where

E_{Pot} is the potential effectiveness, expressed in per cent;

$A_{\mathrm{Reduction}}$ is the number of avoided or mitigated accidents that are sensitive to the system;

N is the total number of all accidents.

If the field of effect and the effectiveness rate are known, the potential effectiveness can be calculated as in Formula (4):

$$E_{\mathrm{Pot}} = \frac{F \cdot E_{\mathrm{Rate}}}{100} \qquad (4)$$

where

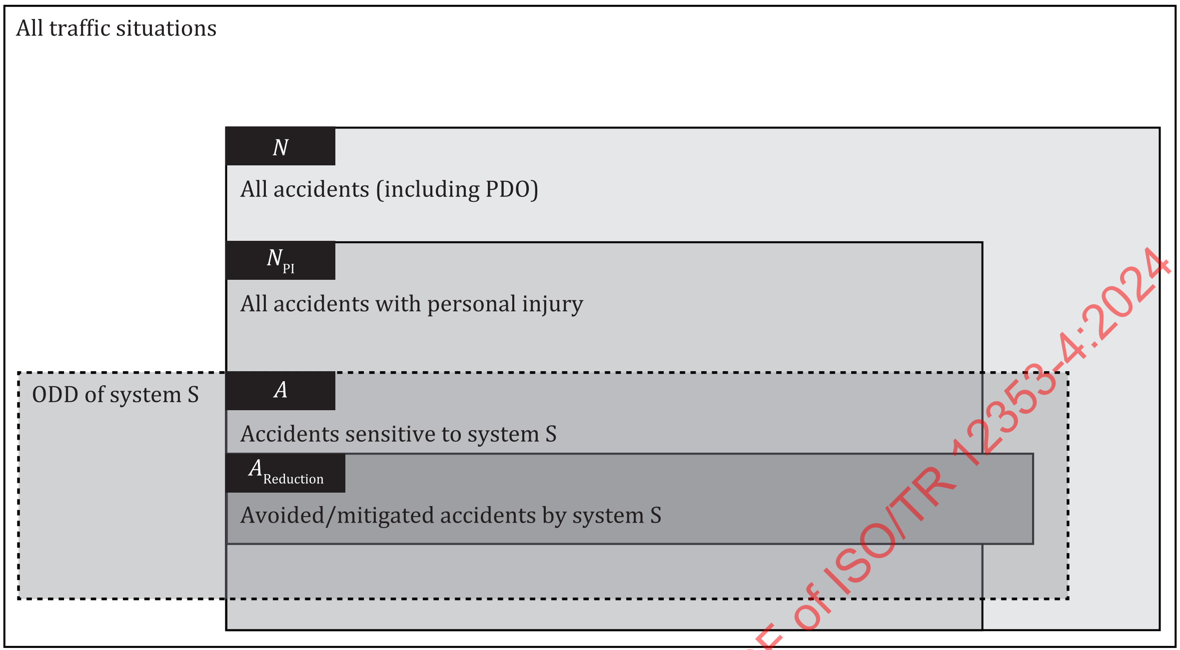
E_{Pot} is the potential effectiveness, expressed in per cent;

F is the field of effect, expressed in per cent;

E_{Rate} is the effectiveness rate, expressed in per cent.

EXAMPLE 1 The potential effectiveness of an AEB system specifies the part of all accidents that are avoided or mitigated by AEB. If the field of effect is 6 % and the effectiveness rate is 90 %, the potential effectiveness is 5,4 %.

Figure 2 shows an illustration of the exposure and effectiveness definitions.



Key

A	accidents sensitive to system S
$A_{Reduction}$	avoided/mitigated accidents by system S
N	all accidents, including property damage only
N_{PI}	all accidents with personal injury
ODD	operational design domain

Figure 2 — Qualitative visualization of the defined effectiveness terms

The overall effectiveness describes the proportion of accident situations that are positively affected, assuming a specific number of vehicles are equipped with the related safety system. It defines the concrete system effectiveness depending on a given market penetration.

The effectiveness is calculated by Formula (5):

$$E = \frac{E_{Pot} \cdot Q}{100} \tag{5}$$

where

E is the effectiveness, expressed in per cent;

E_{Pot} is the potential effectiveness, expressed in per cent;

Q is the penetration factor, expressed in per cent.

NOTE See also ISO 12353-1:2020, 6.4.

The penetration factor defines how the percentage of equipped vehicles directly affects the effectiveness of the system. In other words, the penetration factor describes the system's dependency on other vehicles or infrastructure, that can be equipped with appropriate systems.

EXAMPLE 2 The penetration factor of an AEB system solely depends on the number of vehicles equipped. If the potential effectiveness of AEB is 5,4 %, 50 % of all vehicles have AEB fitted and we assume at least one vehicle per accident, then the overall effectiveness is at least 2,7 %. This implies that a minimum of 2,7 % of all traffic accidents would be prevented by AEB.

EXAMPLE 3 Vehicle to vehicle (V2V) applications rely on both participating vehicles to be fitted with the V2V system. Therefore, the penetration factor is always only half of the current fitting rate.

5.8 Benefit

The benefit of the safety system describes the absolute number of accident situations that are positively affected. It defines how many accident situations are avoided or mitigated.

The benefit is calculated by Formula (6):

$$B = \frac{E \cdot N}{100} \qquad (6)$$

where

B is the benefit, expressed in number of accidents;

E is the effectiveness, expressed in per cent;

N is the total number of all accidents.

EXAMPLE The benefit of an AEB system specifies the number of all accidents avoided or mitigated by AEB. With approximately 2,3 million traffic accidents in Germany in 2021 and given an AEB effectiveness of 2,7 % (see 5.7, EXAMPLE 2) the benefit of AEB would be 62 000 avoided accidents per year.

5.9 Safety performance

Safety performance, expressed in km or miles (mi), is the inverse of the accidents per distance measure, according to Formula (7):

$$S = \frac{1}{A_{\text{Rate}}} = \frac{d}{A} \qquad (7)$$

where

S is the safety performance, expressed in km or mi;

A_{Rate} is the accident rate, expressed in number of accidents per distance travelled (km or mi);

d is the distance travelled, expressed in km or mi;

A is the total number of accidents sensitive to the system.

The safety performance represents the distance travelled between two accidents, or more generally the distance travelled between two events of the same category. The bigger the value of the safety performance and therefore the distance between two events, the safer the vehicle which is observed.

EXAMPLE In 2019, 755 billion km were driven in Germany. The police recorded 2 685 661 accidents. This means one accident happened every 280 000 km. This gives a highway safety performance of 1 420 376 km[8].

6 Crash rate estimation using crash case and exposure data (retrospective assessment)

6.1 Introduction

The analysis of crash rates is a basic and straightforward method for evaluating traffic safety countermeasures. The crash rate can represent a meaningful and comparative measure since it reflects crash numbers in relation to a measure of exposure. However, some confounding factors can influence the crash rate of a particular car model, e.g. driver behaviour. If adjustments are made to control for confounding factors, crash rate can be used as a reference when evaluating effects from both injury- and crash-preventing arrangements in the traffic environment.

The principle of using crash rates in the traffic safety research community is frequently used or considered for many applications. For example, for ranking the performance of countries[9], comparing safety levels of road surface conditions[10], or, as in this document, evaluating vehicle safety performance (see References [12] to [16]).

6.2 Applicability, advantages and limitations

For retrospective assessments of traffic safety countermeasures using crash rate analysis, a precondition is that the technology under study has a sufficient penetration rate (for a certain vehicle subgroup or class) in the market and that sufficient crash cases with and without the technology are recorded.

Depending on the research question, traffic safety indicators can be evaluated using the case and exposure data method. However, different definitions of rates are being used related to the datasets available for the analysis. Exposure data measured in, for example, per capita, per registered vehicles, per km travelled or per insured vehicle years are frequently used to assess change in crash and/or injury risk. Many studies have also evaluated the probability of sustaining injuries in the vicinity of a crash.

6.3 Methodology

6.3.1 Description

Typically, the crash rate, P, is defined as in Formula (8):

$$P = \frac{n}{X} \quad (8)$$

where

P is the crash rate;

n is the number of crashes (of a certain type);

X is the exposure.

Crash involvement rates can be compared for relevant and corresponding groups of vehicles, with and without a traffic safety countermeasure.

Furthermore, it is possible to fit regression models to the data to estimate changes in crash involvement and control for contributing factors.

6.3.2 Input data

Case data on crashes and exposure data, with and without the traffic safety countermeasure in comparable situations (e.g. the same car make and models, the same time period, in similar overall traffic environments and in the countermeasure's specific target conflict situation or crash configuration) is a prerequisite for the analysis in a quantity that acknowledges the desired statistical significance and power.

The number of pre-crash factors that can be included in the analysis is limited to what is known for both case data (crashes) and exposure data.

6.3.3 Output data

In their basic form, output data provide comparisons of crash rates between situations with and without the traffic safety countermeasure.

6.4 Accuracy, sensitivity and validation

One main issue in retrospective effectiveness estimations is the availability of crash datasets large enough to provide statistically reliable results. Collecting data from crashes is a time-consuming activity. Further, traffic safety countermeasures are often not immediately deployed on a large scale, but rather are limited to geographical areas when considering infrastructural devices and as optional mounted equipment in new vehicles. In the latter case, it is often hard to know from current datasets whether the safety technology was turned on or off.

Another challenge is the fact that case and exposure data rarely coexist in the same database. In Reference [11] possible combinations of Swedish national databases for estimating crash rates for different situations and crash severities are shown. There were many factors the researchers could not include in the analysis.

7 Dose-response model (retrospective assessment)

7.1 Introduction

A general overview of parameters related to impact severity and injury outcome is shown in Figure 3, which illustrates a vehicle impact as the relation between impact severity and injury consequences in a chain of events that can be denoted as dose-response models.

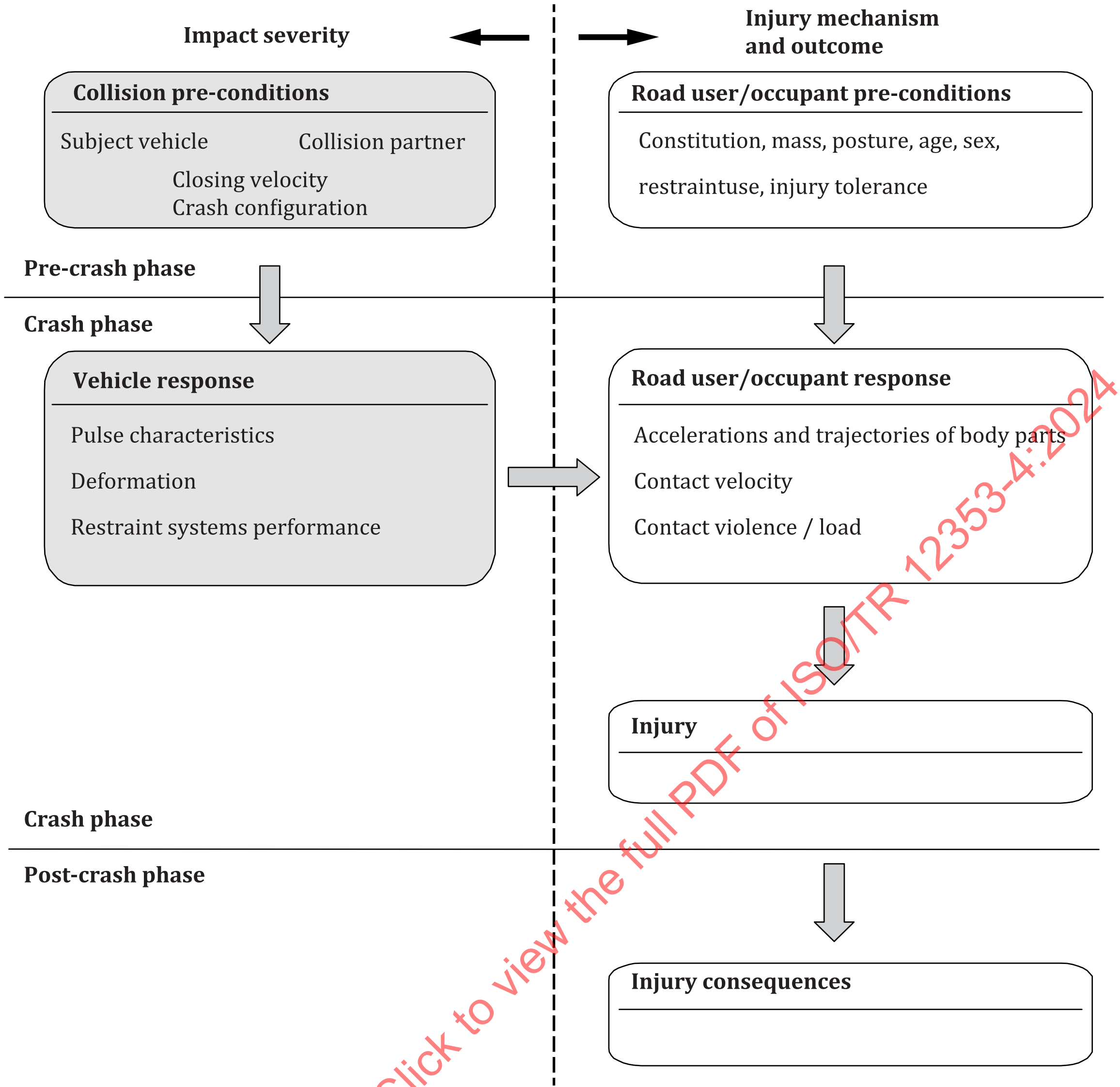


Figure 3 — Parameters related to impact severity and injury outcome, application in the dose–response model

Three aspects of an accident sample are important for the analysis of safety systems:

— the exposure in terms of frequency of collisions;

— frequency of injured occupants;

— injury risk versus impact severity, in the event of a collision.

This is illustrated by the three curves in Figure 4.

These three curves are assessed and used in analyses in several studies, e.g. in References [17] to [21]. This way of describing the three aspects of accidents can be denoted as a dose-response model. The link deciding the response of the dose is the injury risk function.

There are three options for reducing the number of injured occupants in car collisions:

a) by reducing the severity of the impacts, or

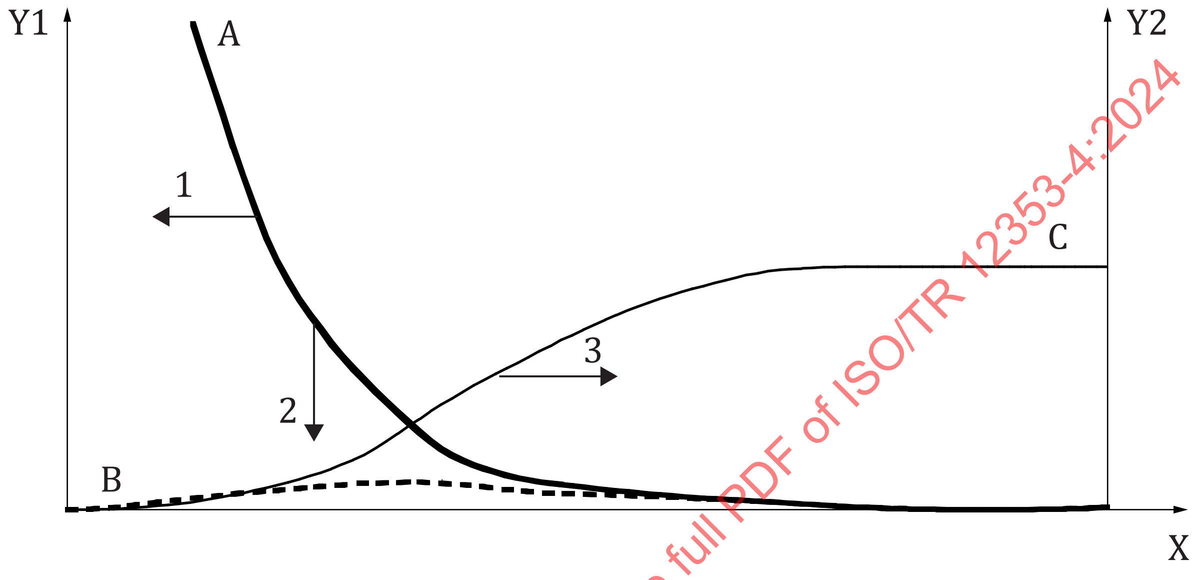
b) by reducing the number of collisions, or

c) by reducing the injury risk at a given impact severity.

The three options are illustrated in Figure 4 by the arrows at numbers 1, 2 and 3 (see Reference [21]).

The first option can be achieved by, for example, reducing speed limits, by reducing impact speed or by redesigning the infrastructure. The second can be achieved by active safety measures aimed at preventing collisions from occurring. The third can be achieved by the passive safety of the vehicle and the road infrastructure safety features to prevent injuries from occurring.

The dose-response model can be used to evaluate the effectiveness of various safety technologies. Safety technologies aimed at mitigating crash severity and at increasing the protection by preparing for a crash situation can address all three options.



Key

X impact severity

Y_1 number of crashes and number of injured occupants

Y_2 injury risk

1 reducing the severity of the impacts

2 reducing the number of collisions

3 reducing the injury risk at a given impact severity

A number of crashes (exposure)

B number of injured occupants

C injury risk

Figure 4 — Dose-response model including the three methods of reducing the number of injured occupants

7.2 Applicability, advantages and limitations

Dose-response models can be used to study the effectiveness of new safety technologies, especially those aimed at mitigating crash severity, preparing for crash protection or even avoiding collisions. At least one of the functions needs to be known depending on what will be analysed.

If the injury or fatality risk functions as well as the crash distribution are known, it is possible to estimate the effect on injury outcome depending on the crash severity possible to be reduced.

7.3 Methodology

7.3.1 Description

The three approaches to reducing the number of injured occupants described in Figure 4 can be studied separately. If the injury risk remains the same, a reduced number of injuries can be calculated based on a reduction of delta-v for all or part of the crashes. A reduction of injured occupants can also be calculated based on a reduced number of collisions. Similarly, a reduction of injured occupants can be calculated for a car with lower injury risk. In this case, the injury risk for a new and old car needs to be known, which is uncommon. Expected reductions of injured car occupants have been calculated in studies, see for example References [22] and [23].

Similar calculations can also be made by reducing the mean acceleration instead of change of velocity. Reducing mean acceleration is relevant to use, especially in the design of road infrastructure, such as deformable posts, guardrails or mid barriers, see ISO 12353-2.

The dose-response model can also be used to calculate injury risk curves if the distribution of crashes and injured occupants for a selected crash severity parameter is known.

7.3.2 Input data

Crash distribution for crash severity can be, for example, change of velocity or mean acceleration. The distribution can, for example, be derived from crash recorder/EDR data (see ISO/TR 12353-3). It is also necessary to have injury or fatality risk functions for the selected crash severity parameter.

7.3.3 Output data

The direct output is the distribution of injury or fatality. Based on the distributions, reduction of injury or fatality can be calculated.

7.4 Accuracy, sensitivity and validation

Crash distributions can be estimated based on previous research. It is more difficult and important to find a suitable risk function. Accuracy depends on the accuracy in the risk function and in the distribution. The accuracy of the risk function in the low severity segment is especially important since it has a large influence on the number of injured due to the distribution of crashes.

8 Induced exposure (retrospective assessment)

8.1 Introduction

Real exposure in terms of vehicle mileage or number or registered vehicles is often not available. The accident sample can also be associated with several confounding variables, influencing bias, for example, those who choose to purchase vehicles with a certain safety technology are probably more concerned about their safety in the first place (i.e. selective recruitment). There are some indirect statistical methods that can be used to overcome this. One is called induced exposure. Instead of comparing crash or injury outcomes with real exposure, changes in distribution of crashes can be studied to estimate the effectiveness of a safety technology. See References [25] to [27].

8.2 Applicability, advantages and limitations

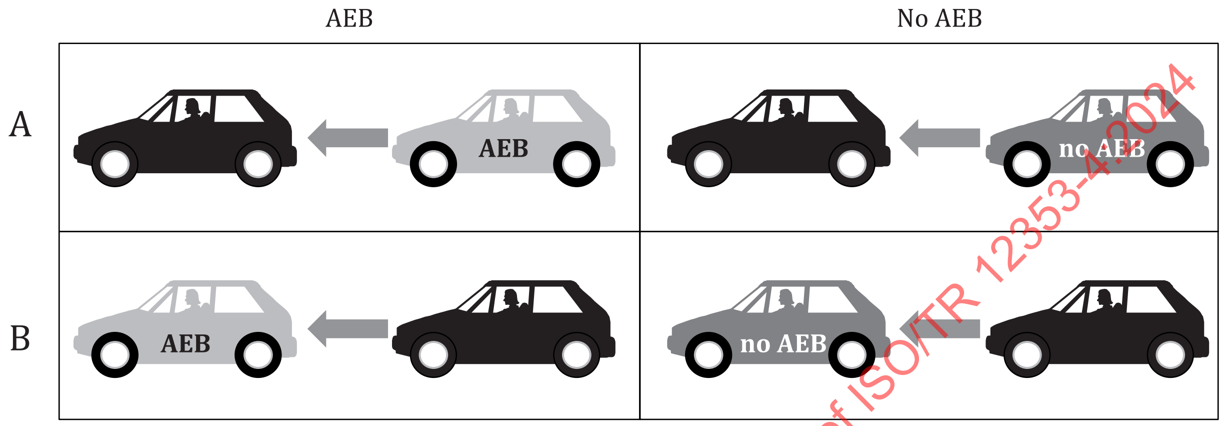
A key point is to identify at least one crash type in which the countermeasure under analysis can be reasonably assumed (or known) not to be effective.

In the case given in 8.3.1, cars with and without low-speed AEB were compared. If the only noteworthy difference in terms of involvement in rear-end crashes is AEB, the relation between cars with and without AEB in that non-sensitive situation is considered as the true exposure relation. If the influence of other parameters can be regarded as small, any deviation from the relation in non-sensitive situations can be assumed to be a result of AEB.

8.3 Methodology

8.3.1 Description

Striking rear-end crashes are intended to be sensitive to low-speed AEB, while struck rear-end crashes are non-sensitive to AEB (see Figure 5).



Key

A striking in rear-end crashes

B struck in rear-end crashes

Figure 5 — The induced exposure approach: analyzing the relation between striking and struck rear-end crashes, with and without AEB

Risk ratios can be derived according to Formula (9).

$$R = \frac{A_{\text{AEB}}}{B_{\text{AEB}}} / \frac{A_{\text{no AEB}}}{B_{\text{no AEB}}} \quad (9)$$

where

A_{AEB} is the number of striking rear-end crashes involving AEB cars;

$A_{\text{no AEB}}$ is the number of striking rear-end crashes involving non-AEB cars;

B_{AEB} is the number of struck rear-end crashes involving AEB cars;

$B_{\text{no AEB}}$ is the number of struck rear-end crashes involving non-AEB cars;

R is the risk ratio.

The effectiveness in terms of crash reduction can be expressed as in Formula (10):

$$E = 100 \times (1 - R) \quad (10)$$

where

E is the effectiveness, expressed in per cent;

R is the risk ratio.

8.3.2 Input data

The input data is the number of crashes regarded to be sensitive and non-sensitive with and without the feature or specification to be studied.

8.3.3 Output data

The output is the risk ratio that gives the effectiveness in terms of crash or injury reduction.

8.4 Accuracy, sensitivity and validation

The method is less sensitive to confounding variables than when using real exposure data, which means that the calculated effectiveness is more reliable. Even though a variable is known to affect the overall crash or injury risk (e.g. driver age), the same variable can only confound the induced exposure results by deviating from the overall sensitive/non-sensitive ratio.

The method is also easier to use as no exposure data is necessary. Often this is the only possible method due to the lack of exposure in most databases.

The induced exposure approach is based on a number of assumptions and limitations. The most critical assumption with the induced exposure approach is to determine the non-sensitive crash type. While the main method for selecting non-sensitive crashes is a-priori analysis of in-depth studies, as done in previous research, the distribution of crash types within the analysed data can also provide insights into the non-sensitivity of certain crash types. However, it is important that such assumptions are based on an actual hypothesis, rather than “trial and error” in the analysis steps.

9 Paired comparisons (retrospective assessment)

9.1 Introduction

Two-car crashes are used to create relative risks. The method was initially developed by Evans [28] but has been developed further for car-to-car collisions by, for example, Hägg et. al. .[29] The concept of paired comparisons has also been thoroughly evaluated in research projects (SARAC 2001, SARAC II 2006) [30],[31].

9.2 Applicability, advantages and limitations

By studying two-car crashes in which both cars are involved in the same impact, the paired comparison method can control for variation in impact severity, apart from the influence of car mass. The relative injury risk for a specific group of vehicles is calculated by comparing the injury outcome for that group with the injury outcome for the vehicles they collide with.

The assumption for the method is that the risk of injury is a continuous function of change of velocity. This assumption can conflict with safety features, such as airbags that generate a step-function. Another assumption is that injuries in one car are independent from the injuries in the other car, given a certain crash severity.

In car-to-car crashes, mass differences can influence the relative injury risk, because they alter the impact severity distribution between the groups. This can be taken into account in the model. The influence of mass on the relative injury risk can be controlled for.

9.3 Methodology

9.3.1 Description

Based on the injury outcome in two-car crashes, the number of collisions with different combinations of injured drivers in the involved cars can be used to calculate the relative injury risk, see Table 1.

Table 1 — Number of collisions with different combinations of injured drivers

		Driver of car 2		Total
		injured	not injured	
Driver of car 1	injured	x_1	x_2	$x_1 + x_2$
	not injured	x_3	x_4	
	Total	$x_1 + x_3$		

Key

x_1 number of crashes with injured drivers in both cars

x_2 number of crashes with injured drivers in the case car only

x_3 number of crashes with injured drivers in the other vehicle only

x_4 indicates that no one is injured in the crash (often little or no data are available here).

When calculating relative risk, x_4 is not used as it does not add any important extra information. The collision partners can be a sample of the whole car population and therefore provide the exposure basis to allow comparisons across all case vehicles.

The relative risk of an injury for car 1 in relation to car 2 can therefore be calculated as the number of crashes with injured drivers in car 1 in relation to the number of crashes with injured drivers in car 2 (Formula 11):

$$R = (x_1 + x_2) / (x_1 + x_3) \tag{11}$$

where R is the relative risk.

Some factors, apart from the design, can influence the relative injury risk for a car model, namely the impact severity, the mass relation and the structural related aggressivity.

In all impact configurations, the mass of a particular car model has an influence on its relative injury risk in car-to-car crashes. The change of velocity for a car model is lower than the change of velocity for its collision partner if its mass is higher than its collision partner. This results in an advantage for the case car and a disadvantage for the collision partner. The disadvantage for the other car can be regarded as aggressivity due to the increased mass of the case car. The aggressivity due to the structure and geometry of the case car can also influence the results. Here, aggressivity is defined as the influence on injury risk for the other vehicle due to the structure and geometry of the case vehicle. The mass factor can easily be calculated and adjusted for, while the aggressivity factor is difficult to calculate and adjust for using paired comparisons.

If one group of cars is fitted with a certain safety technology to be analysed and another group not fitted, the effectiveness of the safety technology can be described by relation of relative injury risks for the two groups of cars.

NOTE Adjustment for the influence of mass on the injury risk in the other vehicles are made for comparisons of relative injury risk between several vehicles.

9.3.2 Input data

To be able to do the calculations the number of crashes with injuries in each of the vehicles or both is used. However, the number of crashes with uninjured is not necessary for the paired comparison method.

9.3.3 Output data

The output is the relative injury risk for vehicles or groups of vehicles. It can also be the ratio between relative injury risk in two vehicles or groups of vehicles.

9.4 Accuracy, sensitivity and validation

Influence of mass on the relative injury risk can be verified and adjusted for by grouping vehicles in mass categories and studying how the relative risk varies for the various combinations of mass categories chosen.

Influence of crash severity for the various cars or groups of cars is controlled for by the method when using large data samples, as both vehicles are exposed to the same crash severity on average. However, differences in aggressivity due to vehicle structure is a factor that is difficult to remove. It is important to consider when comparing vehicles that have large differences in its structure, such as stiffness. Using larger data samples, the methods can be used for calculating relative risk on an average basis for all car-to-car impact configurations. But vehicles or vehicle groups involved in accidents with the same impact configuration can also be compared, especially when using smaller data samples.

10 Prospective assessment based on virtual simulations according to ISO/TR 21934-1

10.1 Introduction

This is a summary of ISO/TR 21934-1, which comprises a comprehensive literature review on the topic.

In prospective assessments of traffic safety effects for vehicle-integrated technologies acting in the pre-crash phase, a common procedure is to compare the results of virtual simulations of numerical representations of crashes (and other traffic situations) in baseline and treatment conditions. Here, baseline and treatment denote simulations without and with the technology under assessment, respectively.

The prospective assessment approach discussed in Clause 10 focuses on accident avoidance and the technology's contribution to the mitigation of crash 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 also be considered an important input to determine the consequences for these.

10.2 Applicability, advantages and limitations

Effectiveness assessment by virtual simulation can be used at different stages of the technologies' development and for different purposes.

— At a very early stage in concept or product development, virtual simulation can be utilized to define potentials, requirements and specifications.

— During the product development phase, virtual simulation can be used to optimize the technology's performance towards maximum real-world safety benefit while understanding and controlling potential side-effects.

— With the market introduction of a technology, an expected traffic safety benefit can be estimated that is not only based on single exemplary tests, but on real-world distributions of relevant parameters.

In general, the virtual simulation-based assessment approach has the advantage that it allows users to investigate a large number of cases representing situations in real world traffic and variations of these. The simulation approach represents an integrative method to combine different knowledge areas in order to achieve the results. Here, the complex interaction of environment, vehicle and driver can be considered in the assessment. This prospective approach offers a promising combination of speed, flexibility, reproducibility, reliability and experimental control.

Prospective safety performance assessment validation procedures are an area for further research, as today they are validated and verified in different ways and extents, on a non-regular basis. Often, validation is focused on the whole method, and unique simulation models are verified. Most effort currently seems to be spent on the validation and verification of the safety technology under investigation.

The use of 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. For this reason, the automotive industry, research institutes and academia joined in the Prospective Effectiveness Assessment for Road Safety (P.E.A.R.S.) initiative to develop a comprehensible, reliable, transparent and accepted methodology for quantitative traffic safety assessment of crash avoidance technology by virtual simulation.

10.3 Methodology

10.3.1 General

The assessment of active safety technologies takes into consideration the interaction between the vehicle, its driver, the traffic environment and the surrounding traffic. These interactions outline the complexity of the assessment and is represented by a large number of descriptive variables.

Consequently, for a comprehensive assessment, the technology's safety performance is supposed to be analysed in a large number of test scenarios in order to cover the distribution of relevant circumstances in traffic situations and crashes. The virtual simulation-based assessment approach allows us to effectively investigate a large number of cases of real-world traffic situations and variations of these.

In general, the methodology aims at comparing the results of virtual simulations of numerical representations of crashes (and other traffic situations) in baseline and treatment conditions. Baseline and treatment can be interpreted as the simulations without and the simulations with the vehicle-integrate technology under assessment, respectively.

The process of prospective simulation studies is outlined in Figure 6.

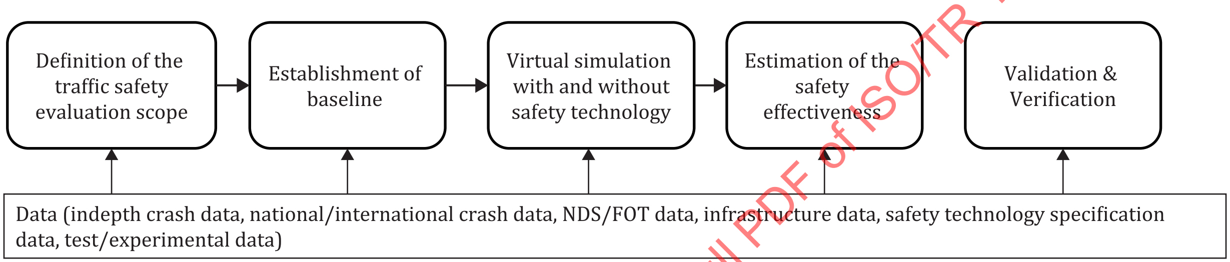


Figure 6 — Overview of the process of prospective assessment of traffic safety for vehicle-integrated safety technologies by means of virtual simulation according to ISO/TR 21934-1

Once the scope of the assessment is defined and specified by a relevant research question, a baseline for simulations is created.

The baseline consists of numerical representations of crashes and other traffic situations that can be used in virtual simulations. Typical categories of baselines are:

a) sets of reconstructed cases of real-world traffic situations;

b) sets of reconstructed and/or modified cases of real-world traffic situations;

c) sets of synthetic cases generated based on traffic accident and traffic flow research.

Then, the baseline is used in virtual simulations, with and without the safety technology present. Simulation complexity and the level of detail depend on the way the baseline is represented and to which degree the safety technology interferes, such as to the way that the driver, the vehicle and the surrounding traffic are modelled. A general simulation framework consists of the main parts given in Figure 7:

— the vehicle surrounding (three models: an environment model, a traffic situation model and a traffic model);

— a collision- and a simulation control module;

— the vehicle under test (three models: vehicle model, sensor model, and function logic model).

In addition, driver models can be used in the vehicle under test and in the vehicles of the surrounding traffic.

Finally, for estimation of safety technology effectiveness, the outcome of the simulations with and without the safety technology can be compared in terms of changes in the percentage of accidents, crash configuration parameters for remaining crashes and further related metrics.

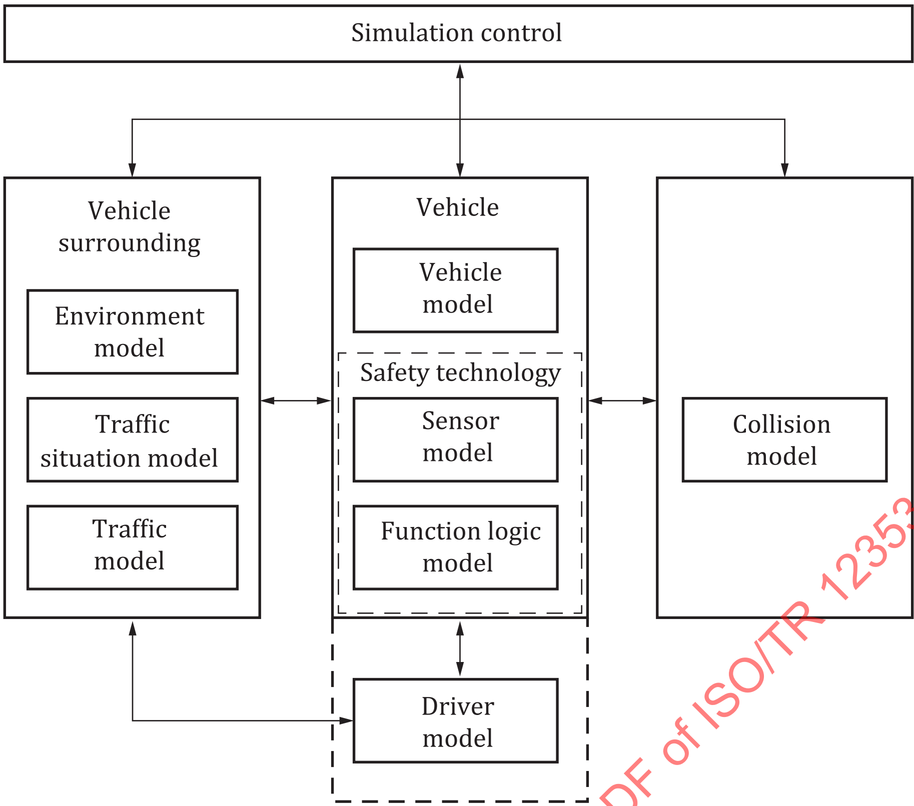


Figure 7 — Simulation framework architecture

10.3.2 Input data

As depicted in Figure 7, input data are provided for the different steps within the process of assessing a technology's effectiveness by means of virtual simulation, i.e. for establishing the baseline, for development, training and parametrisation of models used in the simulation tool, for analysis and projection of simulation outputs and for validation of simulation and models used. In relation to these different tasks and with regard to the research question, the quality and representativeness of the data sample are recognised.

A wide range of input information can be provided for the prospective effectiveness assessment. Although in most cases, data from real-world traffic are used, data collected in, for example, specific tests, can be used as complements. The most relevant information needed for prospective assessment based on virtual simulations are safety technology specification data, traffic accident data, data from naturalistic driving studies (NDS) or field operation tests (FOT), infrastructure and traffic flow data and test data from controlled environments such as test track or driving simulators.

In Table 2, some data sources are mapped to the steps in the prospective effectiveness assessment process.

Table 2 — Overview on used data types for the different tasks within the prospective effectiveness assessment

	Active safety technology related data	Accident data (general data)	Accident data (in-depth data)	NDS/FOT data	Infra-struct-ure and traffic data	Test data (test track, simulator)
Establishing the baseline – reconstructed cases	X		X	X		(X)
Establishing the baseline – reconstructed and/or modified cases	X		X	X	(X)	(X)
Establishing the baseline – synthetic cases generated based on traffic accident and traffic flow research	X	(X)	X	X	X	(X)
Development of simulation models	(X)	(X)	X	X	X	X
Data projection		X	(X)	(X)	X	
Validation and verification	(X)	(X)	X	X	X	X

Key

X commonly used data sources

(X) rarely used data sources

10.3.3 Output data

To estimate safety technology effectiveness, the outcome of the baseline and treatment simulations (with and without the safety technology) are compared.

The basis for the effectiveness estimation reporting is established as the study target population is defined. A set of cases for the baseline represents this target population. The relative change in crashes due to the technology under study is estimated by simulations and used for further analysis.

There are different approaches to quantify the outcome of the simulations. For example, the change of the velocity at the time of collision can be a useful metric in the development phase of the technology, as can the indicator functional years lost due to personal injury quantifies social benefits. Based on the general simulation output (e.g. the indication of crash/no crash, crash configurations for crashes including impact speeds, pre-crash accelerations), a range of metrics can be derived to present benefits or flaws from the technology under study.

The most commonly used metrics for effectiveness are changes in the percentage of accidents, injury severity or property damage. Other metrics are field of view coverage, sensor detection rates, minimum time-to-collision to avoid collision and change in impact speed or crash configuration. Also, the consequences of autonomous interventions for the surrounding traffic have been considered. In case an accident is not avoided but mitigated, the consequences of the accident can be reduced. The extent to which the injury level is reduced is often calculated by making use of injury risk functions during or after the virtual simulation.

Finally, to make the results representative for a specific region or country, projection of the data can be applied.

10.4 Accuracy, sensitivity and validation

The main challenge in prospective effectiveness estimations is to ensure that the simulation provides realistic results. A prerequisite for this is the availability of (real-world) data to parameterize the used model and simulated scenarios at sufficient quality.

To check the quality of the simulation and its models (i.e. simulation models) a validation and verification process is applied. This process checks the outcome of the simulation or a simulation model against a reference result that is derived typically from real-world data. In addition, the reporting of limitations and assumptions that are made or arise during the study are important aspects to achieve a credible result. Other methods, such as sensitivity analysis to identify the influence of certain parameters on the overall results, support the credibility of a results further. However, these methods can be quite resource consuming.

Despite the validation and verification, reporting and addition efforts, it is important to keep in mind that the assessment is done prospectively. This means that actual results are only known a time after the assessment, often years later. During the assessment and the actual results, which can be derived by the methods presented in this document, other factors can change. This can lead to a different result than derived by the prospective assessment. Therefore, it is important to document the assumptions and limitations of the assessment.

11 Crash momentum index, C–V_r plane (prospective or retrospective assessment)

11.1 Introduction

In critical road scenarios resulting in vehicle-to-vehicle crashes, different types of advanced driver assistance systems (ADAS) intervention logic can be compared in terms of IR. The modelling of IR as a function of the ex-post variable ΔV is well-established. Nevertheless, as a consequence of the impact, ΔV does not provide direct suggestions regarding how the ADAS intervention on braking and steering can be driven to decrease IR. From this standpoint, ΔV can be disaggregated in two pre-crash contributions: V_r, which is the closing velocity between the vehicles at the collision instant, and C, the crash-momentum index, which represents impact eccentricity, so that $\Delta V = C \cdot V_r$ [44],[38]. Each ADAS intervention on braking and steering leads to diverse kinematics and impact configuration if the crash is not avoided, and, hence, coordinates in the C-V_r plane. C-V_r plane evaluations provide qualitative and quantitative highlights regarding ADAS intervention compatibility with the best possible outcome (minimum ΔV and IR) and allow assessing the ADAS performance in:

— a prospective approach, by predictively identifying the impact configuration associated with the ADAS intervention logic in reference scenarios (useful during the design phase of the ADAS);

— a prospective approach, as a tool to quantitatively evaluate the outcome of consumer/manufacturer tests[39];

— a retrospective approach for estimates in correspondence with real accident scenarios.

11.2 Applicability, advantages and limitations

The C-V_r plane makes it possible to assess the severity of a collision between vehicles in terms of kinematic parameters and impact configuration. These kinematic parameters and impact configurations can be modified by the intervention of an ADAS but also by changes to the infrastructure that, for example, induce speed reductions or different vehicle impact configurations (e.g. the introduction of a roundabout at an intersection). The approach thus makes it possible to quantitatively assess the effect of such interventions on the outcome of accidents.

In case of ADAS intervention, let us assume a critical road scenario identified by specific positions and velocities for the subject vehicle (the one whose effectiveness of ADAS is to be assessed). This is the reference scenario. From this point, maximum braking does not always result in the maximum decrease in IR. In fact, impact eccentricity (affecting C) also plays an important role in IR decrease.[40] This latter effect has also been highlighted in Reference [41] from a statistical standpoint, which demonstrates that the single contributions V_r and C directly affect the injury outcome.

The ADAS intervention on braking and steering substantially affects the values of V_r and C at the collision instant. The primary advantage of employing the C-V_r plane thus results, i.e. the option to visually monitor how a specific intervention logic on braking and steering modifies IR compared to a reference condition. An additional benefit deriving from such approach is that it provides indications on how the ADAS intervention can be optimized to allow for a decrease in IR. By the visualization in the C-V_r plane, the best possible intervention on braking and steering associated with the specific scenario is directly evidenced, i.e, the one leading to V_r and C values compatible with the lowest possible ΔV (and IR).[42]

The method cannot be applied to sliding impacts, for which the principal direction of force differs substantially from the V_r direction.[43]

11.3 Methodology

11.3.1 Description

In a retrospective analysis, the method can be applied to evaluate, starting from a real accident, the difference in IR in presence or absence of the ADAS. If in the real accident the ADAS was absent (reference scenario), the hypothetic scenario with ADAS presence (modified scenario) is evaluated. If the ADAS is present in the real scenario (reference), the hypothetic scenario with ADAS presence is evaluated (modified). In a prospective analysis, both reference and modified scenario are not real but hypothetic: the cases with ADAS absence (reference) and presence (modified) are both evaluated.

In real car-to-car impacts, it is possible to obtain ΔV and V_r from the reconstruction of accident kinematics. From $\Delta V = C \cdot V_r$, it is possible to obtain C and hence the coordinates in the C-V_r plane. In the hypothetic scenarios, C for the subject vehicle (C_A) can be obtained as in Formula (12):

$$C_A = \frac{\gamma_A \cdot \gamma_B \cdot (1+\varepsilon)}{\gamma_A + \gamma_B \cdot m_A / m_B} \tag{12}$$

where

$$\gamma_A = \frac{k_A^2}{k_A^2 + h_A^2}$$

where h_A and k_A are the arm of the force (Figure 8) and the radius of gyration for the subject vehicle, respectively, and

$$\gamma_B = \frac{k_B^2}{k_B^2 + h_B^2}$$

where

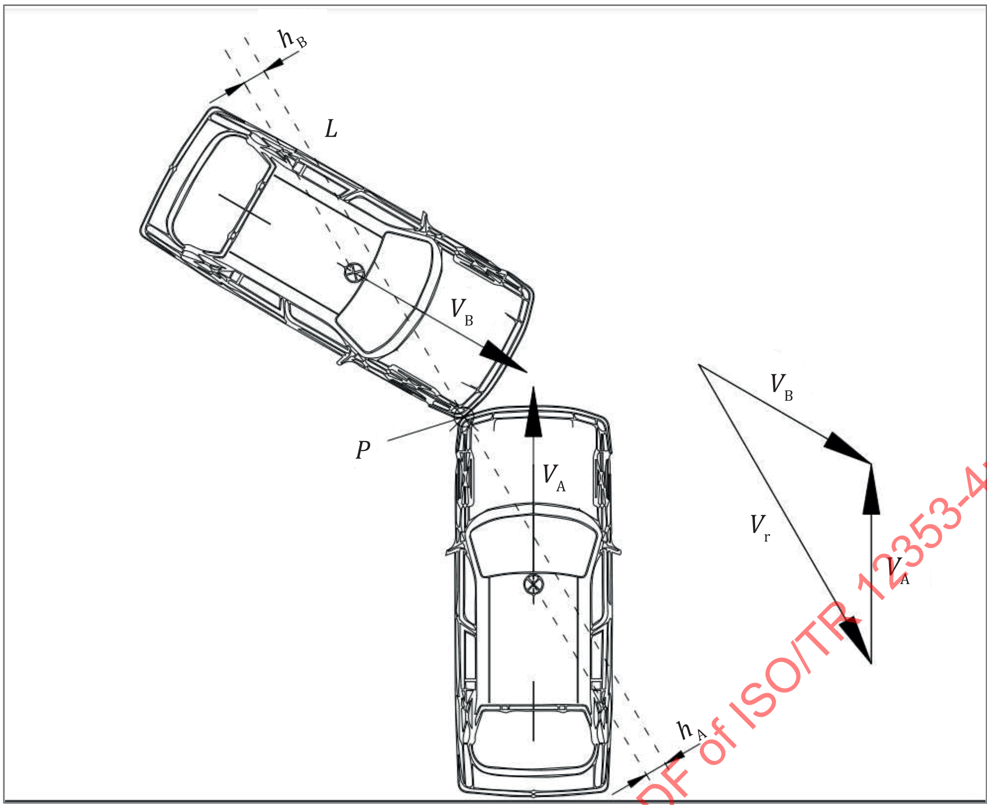
h_B is the arm of the force (Figure 8);

k_B is the radius of gyration for the opponent;

ε is the restitution coefficient in correspondence of the point of impact, a strong function of V_r [45];

m_A is the mass of the subject vehicle;

m_B is the mass of the opponent vehicle.



Key

P point of impact

L line representing the direction of principal force

V_A initial velocity of subject vehicle

V_B initial velocity of opponent vehicle

V_r relative velocity

h_A eccentricity of the subject vehicle

h_B eccentricity of the opponent vehicle

Figure 8 — Elements of a crash configuration that allow determining *C*

The representation of the intervention on the C-V_r plane, in which curves at constant ΔV (and IR, if directly correlated to ΔV) are equilateral hyperbolas, is reported in Figure 9. Starting from the "No action" condition, several options of intervention on braking and steering are available for an ADAS device. "Logic 2" in Figure 9 is superior if compared to "Logic 1". Following "Logic 2", the ADAS activates so that a higher IR gradient is sought (lower C, lower V_r and lower ΔV as a consequence). If an accident is avoided, there is no impact and therefore the IR is zero (V_r = 0).