Heliyon 10 (2024) e37989

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Research article

Safety barriers under changing operating conditions–An analysis of impact parameters in Germany

Tobias Berg

Section V4 Road Equipment, Federal Highway Research Institute (BASt), Bruederstraße 53, D-51427, Bergisch Gladbach, Germany

A R T I C L E I N F O

Keywords:
Road restraint systems
Vehicle restraint systems
Safety barriers
Vehicle impact
Road equipment
Accident data analysis

A B S T R A C T

Vehicle restraint systems and especially the impact of a collision on such are subject to various influencing variables. These systems are tested and approved through vehicle impact tests to ensure that safety standards are met as well as to ensure comparability amongst the systems. However, differences in the objectives of the standard DIN EN 1317 and the behaviour in practice have become apparent.

There is the standard DIN EN 1317 which defines the impact tests on testing grounds. Nevertheless, there are a number of influencing parameters such as developments in the vehicle fleet over the last years, available safety barriers, including their construction types and the impact itself. Previous research indicates that there could be a gap between these parameters.

This research uses an empirical analysis based on chiefly quantitative data sources to evaluate the differences between these parameters. It leads to a partial divergence between static requirements of the standard and the actual road traffic conditions. Additionaly, the differences are developed within a vulnerability analysis and for the purpose of comparison, the advantages as well as the disadvantages of the standardized impact tests are discussed in this paper.

As a result, a parameter based suggestion for a reevaluation of impact tests for safety barriers, according to the standard DIN EN 1317, is advisable due to the changing road traffic on the current stock and new barrier systems to be built. This research strives to illuminate the trend for new investigation methods such as the finite element method (FEM) simulation. It gives an outlook to further research needs in safety barriers, principally in the observation of the future development of the impact parameters. At the same time, impulses and potential for improvement can be identified for the future documentation of vehicle impacts on these barriers.

1. Introduction

Based on the publication of the Federal Highway Research Institute in the year 2021 over 16,000 accidents with personal injuries on highways in Germany occurred. This represents a minor increase compared to 2020 and is thus at the same level as in 1980, although the number of motor vehicles almost doubled between 1980 and 2021 [1]. At the same time road transport is one of the most important aspects in the economy and in the everyday life of each individual. The result of this is that through this volume of traffic, which includes the increasing number of motor vehicles, accidents may appear. On highways uncontrolled run-offs from the driving lane may result in a vehicle hitting an obstacle on the lateral edge of the carriageway, entering the opposite driving lane or ends up being rolled over [2]. In the year 2021 there were over 4800 accidents with personal injuries due to uncontrolled departures from the

E-mail address: berg@bast.de.

https://doi.org/10.1016/j.heliyon.2024.e37989
Received 25 June 2024; Received in revised form 5 September 2024; Accepted 16 September 2024
Available online 16 September 2024
2405-8440/© 2024 The Author. Published by Elsevier Ltd. This is an open access article under the CC BY-NC license (http://creativecommons.org/licenses/by-nc/4.0/).

left or the right side of the driving lane on German highways. At the same time over 5700 impacts with a safety barrier next to the carriageway on highways were registered in the database [3]. These numbers illustrate the significance of uncontrolled run-offs from the carriageway and the need for safety barriers. To provide vehicles from uncontrolled run-offs the European standard in German version DIN EN 1317 deals with"road restraint systems" as systems next to the road. These systems are intended to protect: firstly uninvolved persons or areas in need of protection when it comes to the consequences of an accident, and secondly, vehicle occupants from severe consequences due to leaving the roadway [4]. "Road restraint systems" (RRS), being the terminolgy from the standard, are today also called "vehicle restraint systems" (VRS) and are divided into construction types like "safety barriers" (see Fig. 2).

In this context safety barriers are used which are built alongside the outer edge of the carriageway or in median and dividing lanes. In principle, before installing a safety barrier, it must be checked whether a comparable or higher level of protection can be achieved by avoiding, eliminating, or structurally redesigning the dangerous areas. For examples increasing the distance to the area requiring protection, removing obstacles, or passive safety is generally possible [4]. In general the safety-related design of roads always represents a risk assessment. By estimating the risk level in regard to velocity, traffic volume, probability of a collision, and other site-specific parameters, a hazardous road section can benefit from incorporating the right choice of safety barriers. However, a 100 percent safety level cannot be achieved and a residual risk always remains. It should also be noted that the creation of new obstacles within areas that become hazard points through construction should be avoided, because this does not correspond to the basic principle of risk avoidance [4]. Finally, it should be noted that a collision with a safety barrier can also have undesirable consequences, since secondary impacts may occur as a result of the rebound [5].

However, at the point where a suitable safety barrier must be selected, the future conditions of use of this system must be considered and a constant improvement of traffic safety must be urged. Here it is necessary to investigate the relevant future impact parameters, which are influenced by the vehicle causing impact, safety barrier, and impact scenario. Finally, these variables are subject to constant change, which must be approached by analyzing real data and making reasonable assumptions. This change has already been recognized in preliminary studies and initial investigations focusing on safety barriers of the German Insurance Association by examining the difference between the standard and the current crash occurrence (see Section 2 Objective). This showed, for example, that there is a need for further research into whether the change in the vehicle fleet can still be represented by the standard. At the same time, it is to be expected that the impact parameters will continue to change and therefore need to be investigated further. At the same time, the current discussion in specialist circles as to whether the standard needs to be adapted is a further indication of the need for this study [6]. This study focuses on safety barriers primarily used on the German highway network, which is over 13,000 km long, to prevent a vehicle from leaving the driving lane [1]. The research questions to be addressed are, which influencing variables have an affect on a safety barrier impact that focuses on the containment capacity and whether the described tests of the standard DIN EN 1317 cover actual vehicle impacts.

2. Objective

The structure of this publication and the method for processing the objective is based on 4 basic steps (see Fig. 1).

In order to enable a transparent scientific discourse, the individual steps in the development of this publication are explained below and references are made to comparable publications from the field. First, a literature search is carried out with a focus on standards and the latest research concerning impact tests on safety barriers. Subsequently, the research question is defined more specifically, which is addressed methodically by evaluating, analyzing, and comparing suitable data sources (step 3) [7,8]. The choice of real impact processes and analysis is of particular importance here as well as the analysis of the vehicle fleet [2,9]. These results are critically correlated with the standard and essential statements are made on the limits of the current testing strategy [10]. In conclusion, this publication proposes to form the basis for further investigations into vehicle restraint systems, including impact tests and simulations.

To define the objective of this study, it is first necessary to describe the current standardized testing framework, the criteria of safety barrier usage and an excerpt of the current research status of safety barriers. Vehicle restraint systems are subdivided into four constructions based on the standard DIN EN 1317 part 1 to 3 and Technical Report (TR) 1317–10:2023 (see Fig. 2). The European Conformity (CE) marking, along with other requirements from the standard, is a mandatory requirement for the use on European roads. To obtain a CE marking, it is necessary, among other exigencies, to pass the impact tests specified in the standard for the restraint level to be achieved. The DIN EN 1317 standard defines containment levels, performance characteristics, and pass/fail criteria for the classification of VRS [2].

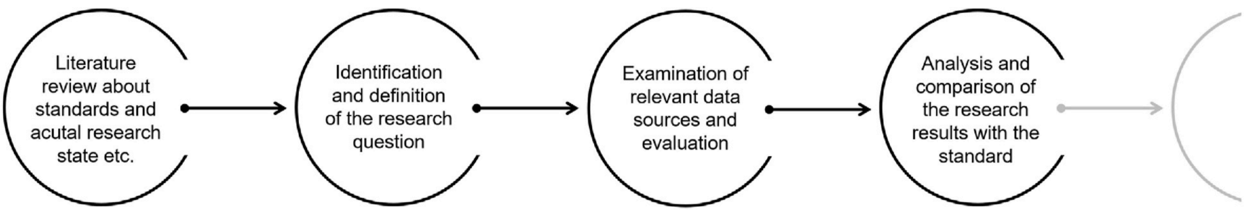

Fig. 1. Flow chart illustrating the structure of this paper.

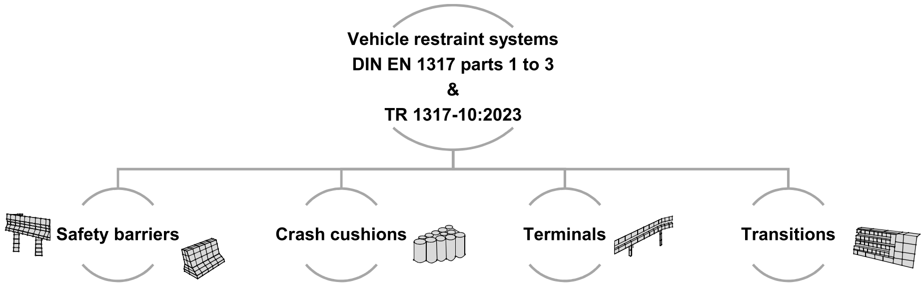

Fig. 2. Schematic illustration of the construction types regarding the standard EN 1317 and TR 1317–10:2023.

Using the generally known equation (1) for calculating the kinetic energy, $\boldsymbol{E_{kin}}$, the energy input into the safety barrier can be determined by applying the sinus to the impact angle, $\boldsymbol{\theta}$. The vehicle mass is $\boldsymbol{m}$ and $\boldsymbol{v}$ represents the vehicle speed at impact [2].

$$\boldsymbol{E_{kin}} = \frac{\mathbf{1}}{\mathbf{2}} \bullet \boldsymbol{m} \bullet (\boldsymbol{v}^* \boldsymbol{sin}(\boldsymbol{\theta}))^2 \tag{1}$$

This study focuses on longitudinally installed safety barriers, as these represent a significant proportion of the highway network in terms of distance share. As these safety barriers are used to prevent vehicles from leaving the road they are typically used on side edges, separating driving lanes from each other or driving lanes from alongside structures [2]. Depending on the area of application and the required containment capacity, the standard DIN EN 1317 defines the containment levels for safety barriers. For a safety barrier to be approved at a certain containment level, up to three impact tests must be performed on it. These impact tests differ in the test mass of the vehicle, the impact speed, and the impact angle (see Table 1) [11].

Based on Table 1, using equation (1), it can be shown that the mass of the impacting vehicle, the impact speed and the impact angle affect the total kinetic energy. This indicates that high impact energies must also be able to be absorbed by the safety barrier with increasing containment levels. However, when selecting the containment level for the area to be protected, it should be noted that safety barriers with a higher containment level are generally associated with a higher impact severity for the vehicle occupants, than systems with a lower containment level [5]. This means that the choice of safety barrier depends on the impact energy and therefore the expected impacting vehicles. It should therefore be avoided to install systems that have an unnecessarily high containment level for the use case.

While the European standard DIN EN 1317 gives the rules for the approval and classification of vehicle restraint systems, the use and selection of systems is regulated at a national level. Here, national road authorities usually create national guidelines, which differ within Europe [5]. In Germany there are national guidelines for passive protection on roads by using vehicle restraint systems, which fill the gap between approval and the use of vehicle restraint systems [4]. It is worth noting that in the European area, especially the German guidelines serve as a blueprint for many other countries [5].

A review of the standard DIN EN 1317 and the German guidelines already delinate the limitations of similar approaches for passive protection on roads. The current version of standard DIN EN 1317 from 2010 replaced the previous version from 1998 [12]. In particular the impact tests defined in the standard for the approval of safety barriers were established in the 1990s. Since then, there has been no further adaptation to the development of the vehicle fleet and the associated properties of the test vehicle and impact parameters. As a result, this is the main limitation of the standard. A similar picture emerges with the German guidelines. The current version from 2009 replaces the previous version from 1989 and is linked to the standard, so that the limits from the standard also occur here [4]. Given the history context, this alludes to a revision cycle for the standard ranging from 10 to 20 years. It is important to

Table 1
Summary of containment levels and test types for safety barriers for permanent use based on the standard DIN EN 1317–2:2010.

Containment level		Test type	Additional test type	Vehicle mass	Impact speed	Impact angle	Impact energy
–	–	TB 11	–	900 kg	100 km/h	20°	41 kNm
N1	Normal containment	TB 31	–	1500 kg	80 km/h	20°	43 kNm
N2		TB 32	TB 11	1500 kg	110 km/h	20°	82 kNm
H1	High containment	TB 42	TB 11	10,000 kg	70 km/h	15°	127 kNm
L1		TB 42	TB 32 + TB 11	“	“	“	“
H2		TB 51	TB 11	13,000 kg	70 km/h	20°	287 kNm
L2		TB 51	TB 32 + TB 11	“	“	“	“
H3		TB 61	TB 11	16,000 kg	80 km/h	20°	462 kNm
L3		TB 61	TB 32 + TB 11	“	“	“	“
H4a	extra high containment	TB 71	TB 11	30,000 kg	65 km/h	20°	572 kNm
L4a		TB 71	TB 32 + TB 11	“	“	“	“
H4b		TB 81	TB 11	38,000 kg	65 km/h	20°	724 kNm
L4b		TB 81	TB 32 + TB 11	“	“	“	“

highlight that such updates typically only involve incremental modifications. Consequently, it is impossible to take contemporary developments into account. Additionaly, the selection of vehicle restraint systems is predominately determinded by the type of obstacle, the area requiring protection and the volume of traffic, rather than considering real world.

The limitations in translating the performance parameters of a safety barrier from the standard to practical application has already been acknowledged in recent discussions, particulary in relation to key areas of investigation [6,10]. The following scientific papers and public discussions highlight the need for further research into the influencing variables of the impacting vehicle such as the vehicle mass, the impact angle or impact speed as well as the vehicle segment. The following variables that were identified with an influence on the impact are highlighted.

- The impact angle was identified as an influencing factor. Initial preliminary studies have led to the hypothesis that a maximum impact angle of 20° from the standard DIN EN 1317 is too conservative [13]. Moreover, the current version of the standard directs the development of safety barriers towards accommodating smaller impact angles (<20°), which may not be reflected in real traffic accident data [13]. A comparable picture emerges for the impact velocities defined in the standard. These can also be regarded as conservative, whereas the greater significance is expressed for the impact angle [13]. Further investigation of the impact angle and impact speed grounded in current traffic accident data is therefore essential.
- A similar assumption can also be made regarding vehicle mass. According to the following referenced study, the vehicle mass is identified as an influencing variable, suggesting potential need for an adaptation of the standardized test frame. For example, the test mass of the TB 11 appears to be approximately 20 % lower than the average mass of passenger vehicles in Spain, used here as a European country [2]. A comparable study of the vehicle fleet in Germany is therefore urgently required. Existing studies on occupant exposure indicate that standard DIN EN 1317 may not fully address all crash-related risks such as head injuries [10]. This issue underscores the necessity of investigation current vehicle segments, as these significantly impact crash outcomes.
- Furthermore, the use of old vehicle models in impact tests is cited as a possible cause for this. It is possible that these no longer represent the current vehicle fleet and, above all, are no longer representative in terms of deformation behavior [10]. In addition it is unclear how the changed vehicle weight in combination with new vehicle segments will affect the working width of a safety barrier [6].

The analysis of the current state of research shows a need for further studies based on actual accident data. The need for research depends on the data basis to be evaluated, which must be constantly reassessed and updated. Finally, the research question can be derived as to whether the test parameter (vehicle type, mass, angle and speed), defined in DIN EN 1317 cover real vehicle impacts on safety barriers.

3. Methods

The primary aim of this research paper is to test the hypothesis that the impact tests defined in DIN EN 1317 accurately represent high-energy impacts as they occur in present-day scenarios. This hypothesis is formulated to answer the aforementioned research questionand must be specified, confirmed by data selection, and data analysis. Here, the generally accepted research method of a combination of an inductive as well as deductive approach is used [14]. With the purpose of methodically gaining new scientific knowledge, the established hypothesis is investigated through individual observations, analysis, and conclusions are drawn. These individual observations are evaluated in relation to the European standard DIN EN 1317. This research employs a strengths, weaknesses, opportunities and threats (SWOT) analysis, to critically evaluate the divergences between the objective of the European standard and the realities of actual vehicle impacts.

3.1. Data sources

In addition to the preceding literature review of scientific journal publications, four main data sources were used and analyzed. These data sources are either freely available (see Section 3.1.1 and 3.1.4) or were provided particularly for this study by the Federal Highway Administration and Federal Highway Research Institute (see Section 3.1.2 and 3.1.3). Care was taken to ensure that the data examined focused on parameters that were qualitatively or quantitatively comparable to the impact parameters from DIN EN 1317. Given the relative scarcity of data sources in the investigated field of vehicle restraint systems, the linking of data sources presents significant potential for advancing research and analysis.

3.1.1. Vehicle fleet data

To assess the development of vehicles in Germany, data from publications of the Federal Motor Transport Authority (KBA) are utilized. The publications generally cover an observation period between 2011 and 2021. The publications “New registrations of motor vehicles by environmental characteristics (FZ 14)" and “New registrations of commercial vehicles, motor vehicles as a whole and motor vehicle trailers by technical data (size classes, engine size, vehicle classes and body types) (FZ 26)" are the sources used [15,16]. The number of new registrations of cars, trucks and buses is evaluated from these data sources. In addition, data from the axle load measurement of the Federal Highway Research Institute from 2019 are employed to provide detailed insights into heavy traffic patterns. To investigate the stress on roadways, the BASt has a nationwide axle load measurement network, utilizing sensors to record traffic data and can thus deliver data about the weight distribution of the traffic on roadways [17]. The data used is the number of heavy goods vehicles that have driven over the axle load measuring point.

3.1.2. Road accident data in Germany of the Federal Highway Research Institute

The Official German Road Accident Statistics contains data of accidents on German roads which is collected by the police. The statistics is made available for research purposes to the section "Accident Analysis and Accident Statistics" of the Federal Highway Research Institute by the Statistical Offices of the 16 German states. In this article, data on single vehicle accidents on motorways in Germany for the years 2012–2021 are evaluated. The data contains information on vehicle segments, drive technology and vehicle weights as well as crash severity [18]. From this data source, the number of accidents is used, which is filtered and sorted according to the aforementioned information.

3.1.3. German in-depth accident study

The German In-Depth Accident Study (GIDAS) is a cooperation of the Federal Highway Research Institute and the Research Association of Automotive Technology (FAT) since 1999. GIDAS is a project in the field of traffic accident research, whereby real traffic accidents with at least one injured person each are documented and reconstructed. Since July 2023, there has been an additional location and a total of around 2000 road traffic accidents with personal injury are now investigated in depth at three locations in Germany each year. In addition to the original teams from the Hanover Medical School and the Traffic Accident Research Unit at the Technical University of Dresden GmbH, a team from the Ludwig Maximilians University and Munich University of Applied Sciences now also conducts investigations in an area east of Munich using the established GIDAS methodology. The BASt is commissioning and financing the teams from Hanover and Munich, while the FAT is commissioning and financing the team from Dresden. The accident data collected from all investigation sites is compiled in the GIDAS database. For each road accident, up to 3000 accident-characterizing features are recorded in a uniform manner [19]. From this data source, the number of crashes involving safety barriers for cars and trucks is used, broken down by impact speed and impact angle. In addition, the type of safety barrier impacted and the system height are used.

3.1.4. Technical overview list for vehicle restraint systems in Germany

The "Technical Overview List for Vehicle Restraint Systems in Germany" is published by the Federal Highway Research Institute and represents the result of a preliminary review of the documents and test reports submitted by vehicle restraint systems manufacturers. The basis for this preliminary review is the "Technical Criteria for the Use of Vehicle Restraint Systems in Germany (TK FRS)". In the technical overview list, all relevant performance characteristics of vehicle restraint systems, including the containment level and system properties are presented, and thus represent the market availability in Germany for these systems based on a status from the year 2022. This publication evaluates the data source concerning safety barriers [20]. The number of systems, the material, the containment level, as well as the system heights and widths are evaluated from the data source.

3.2. Data screening and analysis

In order to make statements about the parameters relevant for a vehicle impact on a safety barrier, the data sources mentioned in Section 3.1 were filtered and analyzed in detail. In the selection of the data sources, the focus is on sources that contain parameters that are directly addressed by the standard and the impact tests defined there. These parameters are mainly related to the impact speed, the impact angle, the impacting vehicle and the type of safety barriers. At the same time, the data sources must relate to the area of application of the European standard and the national regulation in Germany. This means that data sources relating to Germany were used. This includes for example the use of GIDAS data for the analysis of impact angles and speeds and KBA data for the characterization of the vehicle fleet. Outliers in the sense of implausible and/or not technically explainable data points are removed and critically evaluated. Examples of this are incomplete data records in the GIDAS data. The focus is on determining the relevance of the examined data to factors influencing the vehicle impact. This means that the selected data is filtered on the basis of the limits defined in the standard and set in direct relation to the impact tests defined there. As a standardized test framework through the DIN EN 1317 standard, care is taken to ensure that all test parameters specified in the standard match the data sources by classifying the data according to collision scenarios like vehicle weights, speeds, and angles. This publication examines several key impact parameters,

Fig. 3. Schematic illustration of the to be investigated impact parameters.

including vehicle segmentation encompassing vehicle weight, drive technology, impact angle, and impact speed, as well as the type of safety barrier. Additionally, relevant aspects from accident statistica are considered (see Fig. 3). A comprehensive approach is taken to ensure that all data sources pertaining specifically to road types where safety barriers are applicable, thereby aligning these systems with the appropriate road classification. The same applies to the investigation of the vehicle segments, which is based on the segment classification of the Federal Motor Transport Authority in Germany.

3.3. Strengths, weaknesses, opportunities and threats analysis

In order to critically evaluate the conclusions drawn from the hypothesis about a possible research gap between the static test framework of the standard and real impact events, a weak point analysis in the form of a SWOT (strengths, weaknesses, opportunities and threats) analysis is performed. The SWOT analysis is a method to gain knowledge about the strategic starting position and future orientation of a company or the object of investigation. The strengths, weaknesses, opportunities and threats related to the object of investigation and its environment are considered. The object to be examined can be transferred to the test standard DIN EN 1317 and the positioning of this standard in the environment of real vehicle impacts can be evaluated. At the same time, the different objectives of the standard can be taken into account in comparison to the real impact situation [21].

By means of the same analyses, the basic hypothesis that the standardized static test framework does not cover all real-world vehicle impacts should be confirmed or refuted, and the effects on the test environment and the future direction of the standard should be shown. For this purpose, the results of the previously mentioned data analysis methods can be combined and evaluated as a whole.

4. Results and discussion

In the following section, the data from the data sources previously mentioned are presented, described, and evaluated. The focus is on the relation of the analysis results to the standard DIN EN 1317. At the same time, synergies and knowledge gaps between the data sources and results are identified and addressed.

4.1. Development of the vehicle fleet in Germany

The diagrams shown below each refer to extracts of the data source described in Section 3.1.1. According to the figures, the statistical population per diagram refers to the data set being analyzed.Furthermore, Fig. 4 presents new vehicle registrations for passenger cars between 2011 and 2021.

In this figure the primary axis displays the percentage distribution of vehicle segments as a stacked bar chart, while the secondary axis illustrates the annual average weight of all passenger cars as a dot chart. During the time, the number of new registrations annually is around 3 million vehicles. A notable trend, is the steady increase in the SUV and off-road vehicle segment from over 10 % in 2011 to nearly 40 % in 2021, representing the most substantial rise among all the segments. Conversely, the shares of the vehicle segments minis and compact cars as well as sports and utility cars can be assumed to remain relatively constant. In all other segments, however, a downward trend can be observed. The average kerb weight rose from just over 1450 kg to over 1600 kg over the period analyzed. Although not depicted separately in the figure, the average vehicle empty weight of an SUV was approximately 1600 kg and it was approximately 2000 kg for an off-road vehicle in the year 2021.

As an evaluation, it should be noted that the SUV and off-road vehicle segment together with the mini, small, and compact classes

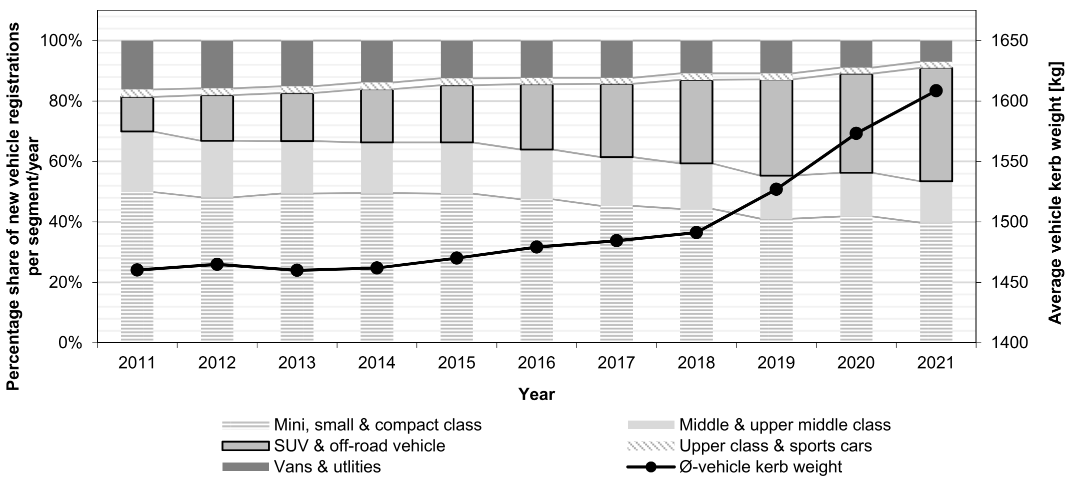

Fig. 4. Stacked bar chart illustrating passenger car vehicle segments with a dot chart illustrating the average vehicle weight in Germany based on KBA data.

represent the largest shares of the vehicle segments. This leads to the thesis that these car segments should be focused on in the long term or tested within the framework of DIN EN 1317–2:2010. The standard aims to maximizing safety for the most frequently occurring crash scenarios. Given the trends observed in new passenger vehicle registrations, it can therefore be assumed that the previously identified vehicle segments will have to be addressed in the future. The reason for this is the expected change in the vehicle stock due to the new registrations analyzed. In addition, there is a critical discrepancy between the real vehicle fleet and the standard. It is important to emphasize that a definition of the vehicle segment used in the impact test urgently needs to be introduced in the standard. This has not yet been defined in the standard. The test framework of DIN EN 1317–2:2010 only describes the vehicle weight. So far most impact tests will be conducted with vehicles up to the upper middle class segment. The reason for this is that older vehicles are often used for cost reasons, with fewer SUVs being registered as the vehicle age increases. Impact tests with SUVs or off-road vehicles are not yet performed, although a changed impact behavior can be expected due to the vehicle structure and center of gravity position. The increasing average weight of new registrations in Germany only partially corresponds to the test weight in the standard, as this ends at 1500 kg for passenger cars with the TB 32 test. This also represents a difference between the vehicle fleet development and the standard because a further increase in vehicle weight can be assumed. In order to also examine vehicle masses for other vehicle types, Fig. 5 investigates data from buses.

Fig. 5 shows the distribution of new bus registrations between 2012 and 2021, categorized by percentage share across representative weight classes as a stacked bar chart format. Weight classes were combined here in alignment with the previous test weight from DIN EN 1317–2:2010. The data indicates that there is a slight increase in the proportion of buses with a gross vehicle weight of exceeding 14,000 kg, whereas the proportion of buses in the range up to 5000 kg tends to decrease. Notably, buses exceeding 14,000 kg comprise over 80 % of new registrations, which represent the largest share of new registrations.

During the analysis period, no significant trend emerges based on the weight classes considered. However, it can be inferred that the previous test weight of 13,000 kg stipulated by the standard can be regarded as underestimated. A detailed examination of the data set reveals that newly registered buses in Germany predominantly fall within the weight range of approximately 18,000 to 20,000 kg. Due to the fact that the weight distributions shown deviate substantially from the test weights within the standard, this prompted further examination into the vehicle weight of buses in the mid-1990s. This showed that approximately 50 % of newly registered buses were already within the 16,000 to 18,000 kg range in the years around the writing of the standard in 1998. This indicates a pre-existing disparity between the bus fleet under investigation and the standard at the time of its creation. A more detailed analysis of heavy goods vehicles is presented in Fig. 6.

Fig. 6 presents the new vehicle registrations for trucks from 2012 to 2021, categorized by percentage share according to weight class, represented as a stacked bar chart. The data set was divided into weight classes here to align with the standard, similar to what was employed in Fig. 5. Semi-trailer trucks, which are predominantly in a weight range above 16,000, are excluded from this analysis. Throughout the entire period under review, there was a slight but steady increase in the weight segment up to 5000 kg. In contrast, there was a slight decrease in the 5000 to 10,000 kg weight segment during the period under assessment. Overall there is no discernible trend toward heavier vehicles.

Based on the weight classification presented, it can be inferred that the truck test vehicle weights in the standard (see Table 1 with 10,000 kg and 16,000 kg) continue to provide adequate coverage. New trucks (here not tractor trucks) are mainly in the range within 3500 kg and 5000 kg likely representing transportation vans. Despite all this, the number of trucks in the higher weight ranges must not be overlooked, their omitted percentage share is attributable to the high number of lighter vehicles. It is also essential to consider, that these figures represent new registrations rather than the vehicle stock; generally heavy goods vehicles have a longer lifespan than

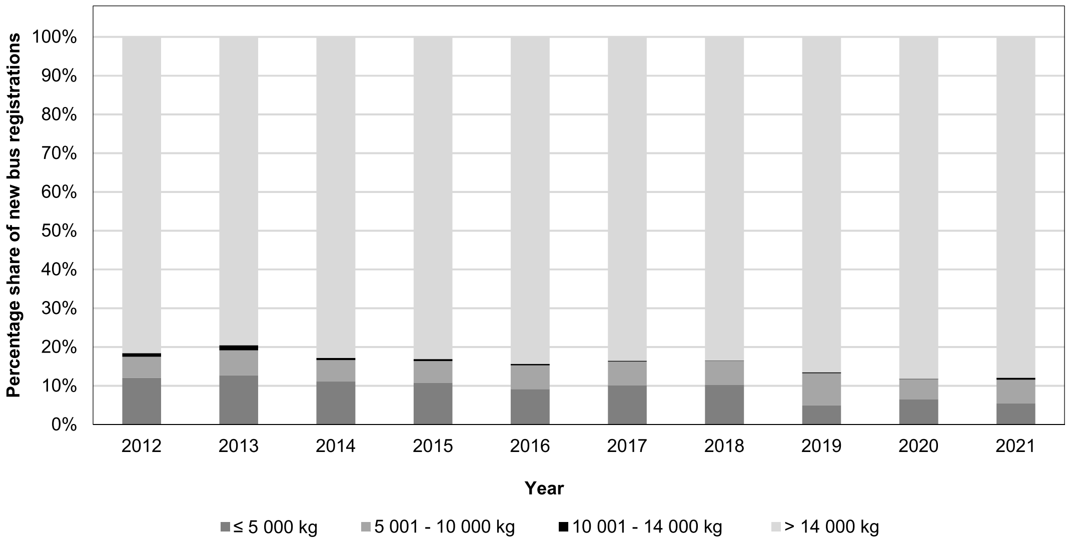

Fig. 5. Stacked bar chart illustrating the percentage share of the bus permissible total mass in Germany.

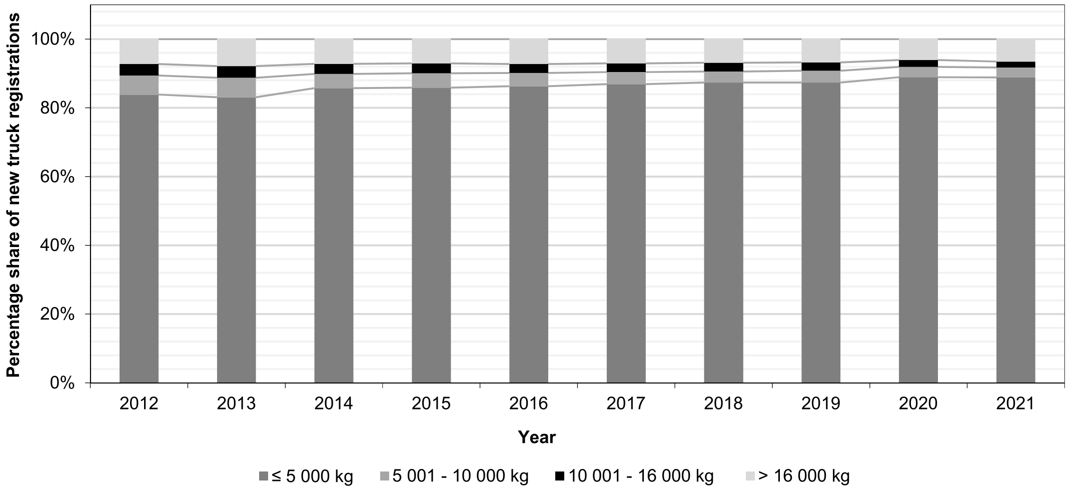

Fig. 6. Stacked bar chart illustrating the percentage share of truck (without tractor trucks) total weight classes in Germany.

lighter vehicles. In summary, it can be stated that the standard continues to achieve good coverage with regard to the vehicle weight of trucks. Only a vehicle mass in the range of 5000 kg should be incorporated in the future. At the same time, it should also be considered whether the transportation van vehicle segment should be introduced. This has not yet been addressed in the standard. Additionally, the test weights above 16,000 kg are primarily associated with tractor trucks, which are not considered in Fig. 6. In order to address heavier vehicles and articulated trucks, the following example for consideration is of axle load measuring points (see Fig. 7).

Fig. 7 shows the frequency distribution of heavy traffic based on the classified total weight at the axle load measurement points in 2019, serving as a representative approximation for heavy traffic on German highways. This data is characterized with a weighing accuracy of 10 %. In accordance with this, three peaking ranges are evident: firstly, the range up to 8000 kg, another with the range up to 16,000 kg and a third with the range up to 41,000 kg. Furthermore, there is a slight plateau formation ranging from 16,000 to 22,000 kg and from 29,000 to 35,000 kg. To illustrate the test masses from the standard for trucks (incl. semitrailer trucks) and buses, these were plotted in the respective value ranges of the diagram.

In principle, there is sufficient overlap between the test masses from the standard and the actual heavy goods traffic measured in Germany, particularly in the range around 16,000 kg, where the test weight of a truck is closely aligned with the observed data, accounting for over 23 % of the traffic volume in Fig. 7. In contrast, the test weight designated for buses appears to be underestimated when Fig. 5 is taken into account. It can also be inferred that a semitruck ranging from 38,000 to 41,000 kg corresponds to the 38,000 kg test vehicle from the standard. It should be noted that 38,000 kg is a minimal underestimate compared with real traffic and focuses on the peak at 41,000 kg, but cumulatively takes into account over 80 % of the traffic volume shown here. However, it should be noted

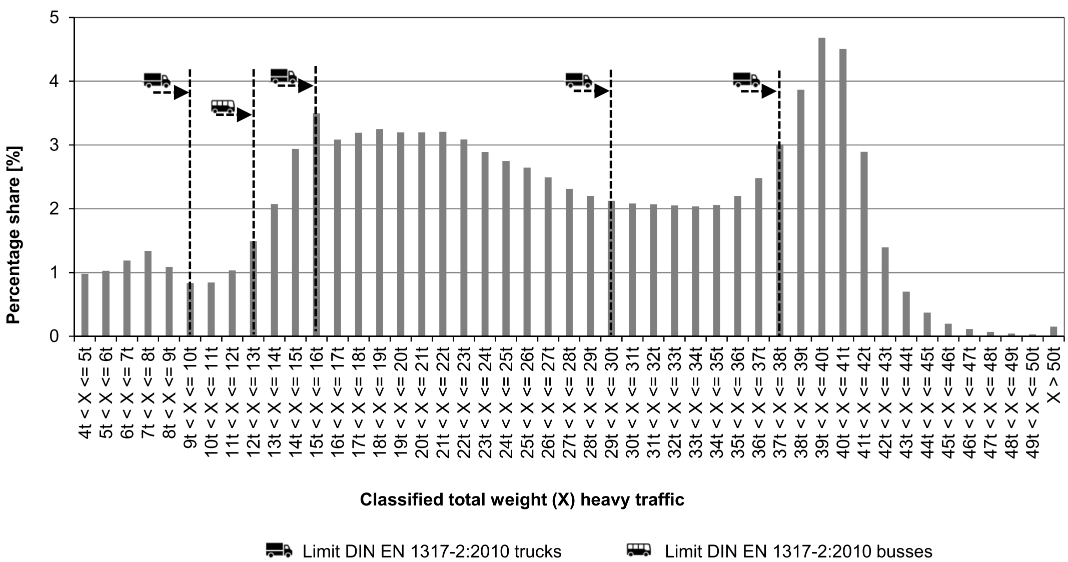

Fig. 7. Bar chart illustrating the axle load distribution on German highways in 2019 with focus on heavy truck traffic based on.

that the figure is only a limited representation of the entire highway network in Germany, offering only a snapshot of heavy traffic, due to the limited number of operational measuring points which have high demands placed on them. Year-to-year comparisons are constrained, since the results are influenced by the respective measuring points operated. Consequently, this diagram should be viewed as a supplementary tool in evaluating the distribution of the individual vehicle types and their weights.

4.2. Road accident statistics

The data presented below in Table 2 has been pre-filtered to exclusively include single accidents of passenger cars resulting in an impact against a safety barrier. In general, it should be noted that a certain degree of uncertainty is inherent in this analysis, given the lack of a precise defintion for the term “safety barrier” in accident statistics. Additionally, motor homes have been excluded from the analysis as a vehicle segment.

Table 2 shows a compilation of traffic accident data for selected vehicle segments on German highways. It refers specifically to accidents involving only one passenger car during the period from 2012 to 2021. The weight class evaluated is based on the permissible gross weight, rather than the vehicle empty weight. The distribution of single accidents of passenger cars according to weight classes, as based on DIN EN 1317–2:2010 shows that accidents occur more frequently in the 1500 to 2000 kg and over 2000 kg weight ranges. This is also reflected in the figures for serious injuries and fatalities, in which both categories also exhibit the highest absolute numbers. An indicative trend has been derived from a decrease in the absolute number of accidents in all weight categories except those over 2000 kg and is therefore also outside the maximum test weight for a passenger car in the standard. For this purpose, the first year under consideration, 2012 and the last pre-pandemic year, 2019, were used as a reference for the accident figures shown in the last column of the table’s first section. An annual analysis further reveals that the number of accidents in the small car segment is decreasing, contrasted by an increase in the number of accidents in the SUV and off-road segment. The number of fatalities appears to remain in the single-digit range in the segments considered (see second subheading in Table 2), whereas the number of serious injuries seems to be trending downward in the small car vehicle segment. Regarding drive technologies (see third subheading in Table 2), the share of conventional combustion engines is decreasing, whereas the share of hybrid and purely electric vehicles is increasing. However, the absolute share of such alternative technologies remains relatively small, with the remaining percentages attributed to other types of fuel or missing information.

The increase in the number of accidents involving SUVs and off-road vehicles is presumably due to the increasing number of new

Table 2
Summary of single accidents of passenger cars on German highways by impact on safety barriers in the period from 2012 to 2021 [18].

Accident year	Vehicle weight classes	Number of vehicles involved in accidents	Number of fatalities	Seriously injured persons in accidents	Percentage change of the number of accidents between 2012 and 2019
2012–2021	$<$901 kg	17	0	4	−83.33 %
	901 $\leq$ 1300 kg	1969	7	1	−50.34 %
	1301 $\leq$ 1500 kg	6745	14	778	−33.59 %
	1501 $\leq$ 2000 kg	24,199	65	2605	−27.71 %
	$>$2000 kg	16,791	75	1575	33.78 %
Accident year	**Accidental vehicles (small cars)**	**Accidental vehicles (SUV and off-road)**	**Percentage accidents share (small cars/SUV and off-road)**	**Fatalities/seriously injured persons (small cars)**	**Fatalities/seriously injured persons (SUV and off-road)**
2012	1268	158	20.16 %/2.51 %	1/125	2/7
2013	1221	164	20.12 %/2.70 %	0/102	2/11
2014	984	180	17.75 %/3.25 %	1/115	3/28
2015	1062	180	20.19 %/3.42 %	1/133	2/33
2016	1098	254	19.15 %/4.43 %	4/145	1/31
2017	1157	275	19.19 %/4.56 %	1/131	0/43
2018	892	283	17.79 %/5.64 %	2/126	2/39
2019	900	349	17.07 %/6.62 %	2/107	4/41
2020	725	138	15.28 %/2.91 %	2/89	1/36
2021	789	522	13.84 %/9.16 %	1/88	1/39
Accident year	**Share of internal combustion engine vehicle accidents**	**Share of hybrids (w/o Plug-In) accidents**	**Share of pure electric vehicle accidents**		
2012	89.29 %	0.08 %	0.00 %		
2013	89.55 %	0.03 %	0.02 %		
2014	86.74 %	0.09 %	0.00 %		
2015	89.62 %	0.13 %	0.00 %		
2016	89.28 %	0.19 %	0.05 %		
2017	89.22 %	0.20 %	0.02 %		
2018	88.97 %	0.40 %	0.00 %		
2019	89.77 %	0.55 %	0.13 %		
2020	88.24 %	1.12 %	0.21 %		
2021	85.75 %	3.05 %	0.35 %		

registrations of the same vehicle segment. The total number of fatalities is slightly higher compared to small cars, but the number of serious injuries for SUVs and off-road vehicles is lower during the period under review. In the testing of safety barriers, both types of vehicles should be tested. SUVs (including off-road vehicles) representing an increasingly relevant segment alongside small cars. This once again underlines the necessity of incorporating vehicle segments in the DIN EN 1317 standard in the future. Alternative drive technologies in vehicles involved in accidents represent a small percentage so far. However, these drive technologies should continue to be monitored and investigated in the future, since an increase in new registrations and thus in the number of accidents can be expected. So far, the drive technology of the test car has not been specified in the standard. Overall, it can be assumed that the vehicle fleet will increase towards higher permissible gross weights, consitstent with the developing trends in vehicle empty weight from Section 4.1. It can also be assumed that the trend in new vehicle registrations will have the same effect on the accident involvement due to the continued growth in the number of vehicles in the previously described segments.

4.3. Impact parameters in real accidents

The GIDAS data utilized in this study has been pre-processed to focus on specific variables relevant for examination in the following diagrams (see Figs. 8–11) [22]. Only accidents where vehicles collided with safety barriers as a collision object on highways, federal highways or state/county roads are taken into account. The data sets are restricted to reconstructed accidents from the year 2005 until 2022. With outliers, implausible or missing values being excluded. Therefore, depending on the specific filter criteria, a different number of absolute evaluable data per diagram results. It should be noted that the data collection area only covers the Hannover and

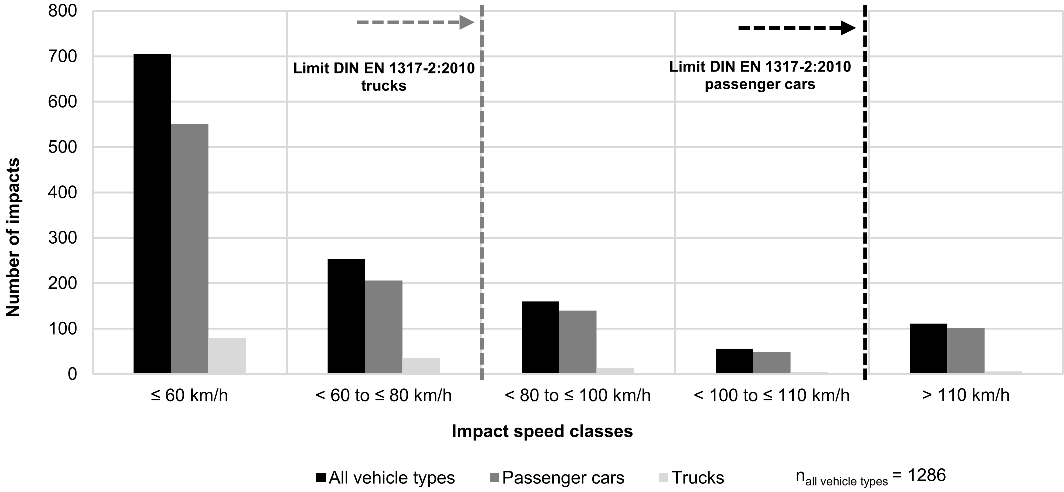

Fig. 8. Grouped bar chart illustrating the impact speed classes in the investigated vehicle impact cases.

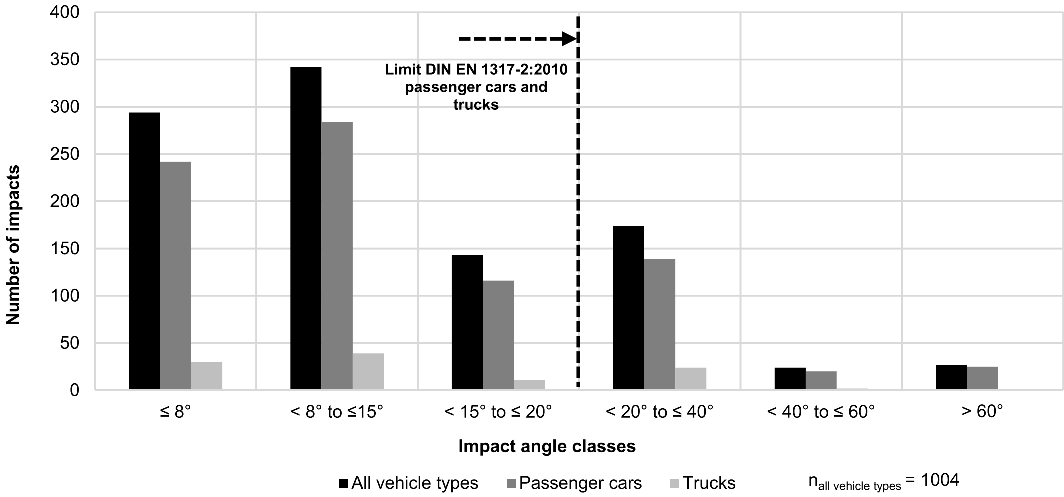

Fig. 9. Grouped bar chart illustrating the impact angle classes in the investigated vehicle impact cases.

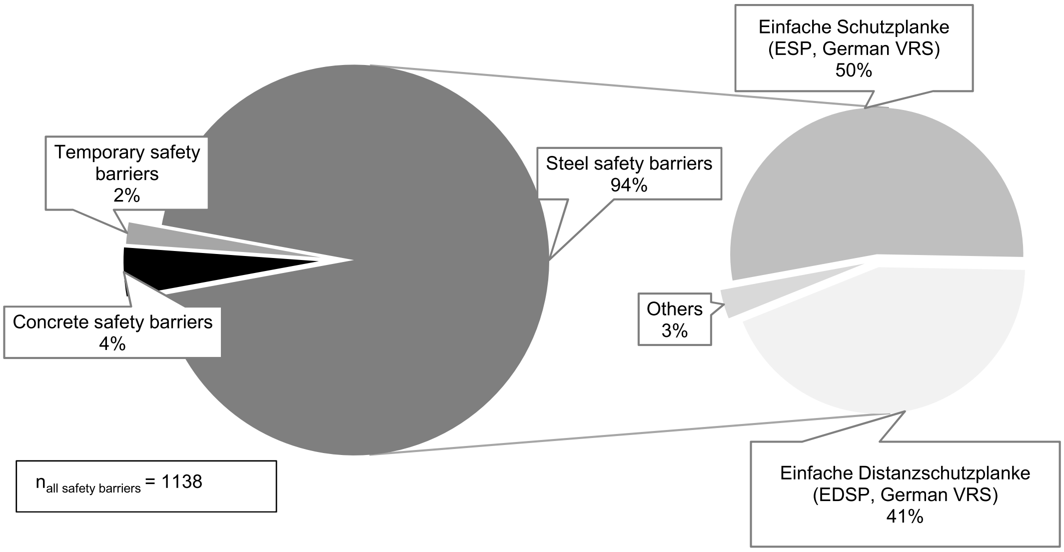

Fig. 10. Circle chart illustrating safety barrier material or type in the investigated vehicle impact cases.

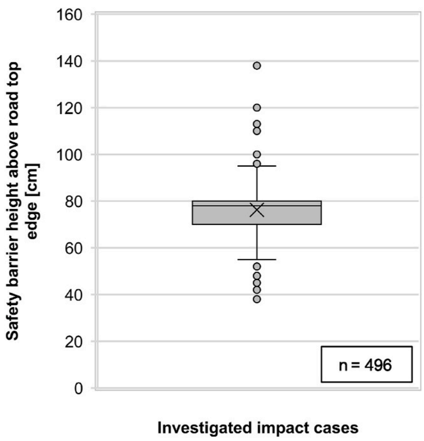

Fig. 11. Boxplot chart illustrating the safety barrier height above road top edge in the investigated vehicle impact cases.

Dresden regions, implying that the data evaluated below only represents a sample rather than a comprehensive national overview. For cases where the presence of a terminal was suspected, a visual inspection of the accident images was conducted to filter out such cases, ensuring the analysis is focused on safety barriers. In the data sets analyzed here, accident events can be counted multiple times if more than one particpant was involved per accident or there was a multiple impact of a participant.

In the datasets used in this study, it has been shown that the majority of the vehicles involved in collisions are passenger cars, accounting for more than 80 %. At the same time, trucks account for just over 10 %, whereas no bus impacts were documented. The remaining impacts are distributed among other vehicle types. One characteristic worth mentioning, is that the distribution of vehicle segments shows that over 60 %, are mainly small to medium-sized vehicles that are involved in accidents, whereas SUVs, including off-road vehicles, account for less than 5 % over the entire period under review. In addition, the accident data examined shows that trucks weighing up to 20,000 kg are primarily involved in accidents with safety barriers. Furthermore, Fig. 8 presents the impact speeds, without reconstruction tolerances, as documented in GIDAS as a specific vehicle type.

Fig. 8 presents impact speeds which are divided into speed classes and set in relation to the standard DIN EN 1317–2:2010 (dotted bars, at 80 km/h and 110 km/h). The impact speeds shown are subdivided according to vehicle type (car/truck). The majority of the impact events of passenger cars and trucks fall within the ranges specified by the previous standard. For trucks, a smaller proportion of impacts occurs in the speed range of up to 100 km/h. A small proportion, predominantly involing passenger cars, is also found to be within the speed range set by the standard. For passenger cars, there is only a small number of impact events in GIDAS that are above 110 km/h and analyzed in this study. It should be noted that the bar for all vehicle types also includes other vehicle types or data without specifying a vehicle type.

For the impact speeds investigated, there is sufficient overlap with the impact tests required by the standard. As illustrated in Fig. 8, the maximum impact speed of a passenger car in the standard is 110 km/h. Even if the share of documented collisions above 110 km/h is only a small proportion, it should be noted that the recommended speed on German highways is 130 km/h. This means that increasing the maximum impact speed in the standard should be discussed. A significance for higher impact speeds of cars compared to trucks cannot be proven. In addition, the investigation of a significance for higher impact angles is shown in Fig. 9.

Fig. 9 shows the number of impact events divided into angle classes. The classes are based on the impact angles from DIN EN 1317–2:2010. The limit of the currently largest angle of an impact test of 20° for both cars and trucks is indicated by the dotted line. The impact angles are subdivided by vehicle type (car/truck). A high number of the examined impact events lie in a range up to 20° and thus within the limits of the standard. However, there is a significant number of impacts ranging from 20° to 40°, which lies outside the standard test strategy parameters. Although larger impact angles are also documented, they are of lesser relevance. There are no noteworthy differences between the impact angles of passenger cars and trucks, as they are basically equally distributed. It should be noted that the bar for all vehicle types also includes other vehicle types or data without specifying a vehicle type.

For both cars and trucks, an increase in the maximum tested angle of impact against a safety barrier seems reasonable. The previous maximum impact angle of 20° in the standard can therefore be considered too limited in certain cases. An extension of the impact angle in a range of 20°–40° should be discussed. In the evaluation, it should be noted that the angle of departure from the road in GIDAS is used to determine the angle of impact. This is determined from the resulting speed vector of the vehicle, which in principle can also be influenced by yaw movements. But this angle can also be influenced by the type of road. Documented impact angles at the higher value range should be critically assessed because rural roads were also evaluated and thus, for example, turning accidents can falsify the impact angle against a safety barrier. Despite this, there is no significant evidence to suggest that passengers cars exhibit higher departure angles compared to trucks. In order to approach an inventory of safety barriers and to investigate which systems are mainly involved in impact events, the material and/or type of safety barriers are depicted in Fig. 10.

In the first pie chart, the shares of the materials concrete and steel as well as the type of temporary safety barrier are shown and differentiated. In this study, no distinction was made between the different types of safety barriers as to whether or not an accident occurred in a workplace. With a proportion of over 90 %, steel systems make up the largest share of accident involvement. In the second pie chart, the proportion of steel systems is further subdivided into two German steel systems with proper name ESP and EDSP as well as others.

Due to the variety of similar steel safety barriers currently available on the market, there is a need to critically assess whether these systems are always accurately identified and named in the documented impact accidents. Additionally, only some of the newer systems are recorded. Nevertheless, it can be assumed that a distinction according to material is considered generally reliable. In the cases considered, it is mainly steel systems that have been impacted. This may have been caused by the fact that these systems were installed in a large number of cases. However, this may also be an indication that steel systems are increasingly being used in the investigation areas. Despite this, the data presented still provides a usefull indication of their relative prevalence. Finally, it is important to note that the standard does not differentiate between this two materials. In order to further investigate the existence of safety barriers, Fig. 11 shows the documented heights of these systems, measured in centimeters from the top edge of the safety barrier to the road surface.

In Fig. 11 the height measured at the collision point is assumed to be the system height. On average, the measured height of the safety barriers is less than 80 cm in the height range. The areas of the upper and lower quartile exhibit heights ranging between 80 and 70 cm. Heights below around 55 cm and above 95 cm are generally considered to be outliers in this analysis.

The mean height of the systems under consideration lies in a value range around 75 cm, which aligns with the standard installation height of steel barriers and corresponds with the identification of the barriers ESP and EDSP, that have a lower standard height of 75 cm. Based on the data examined, the outliers in the upper and lower value ranges cannot be clarified through the use of certain systems with a characteristic height profile, such as the use of low, transportable barriers in workplaces. Thus, outliers are likely genuine and may be attributable to measurement inaccuracies, which may possibly arise when recording the height profile of the safety barrier, possibly justified by the significant deformation of the original system. Furthermore, it is also conceivable that the installation height of the safety barriers is reduced due to construction activities, such as the application of new asphalt layers. In principle, it is advisable to compare the actual system heights with the heights from the standardized tests of DIN EN 1317, as the containment level was only tested with the specific tested system heights. However, it is not possible to make a general statement on this, as the system heights vary depending on the tested system.

When utilizing and evaluating GIDAS data, it is important to recognize that the documented accidents involving personal injury do not provide any information about collisions without personal injury. However, it can be assumed that accidents involving personal injury are critical incidents that warrant attention. Therefore, by focusing on impacts with personal injury, a conservative approach to safety assessment is considered.

4.4. *Current available safety barriers in Germany*

In addition to the evaluation of accident data, the range of systems available in Germany can also be utilized to estimate the existing stock of safety barriers (see Fig. 12).

Fig. 12 shows a selection of performance parameters and properties of steel and concrete safety barriers that are available in

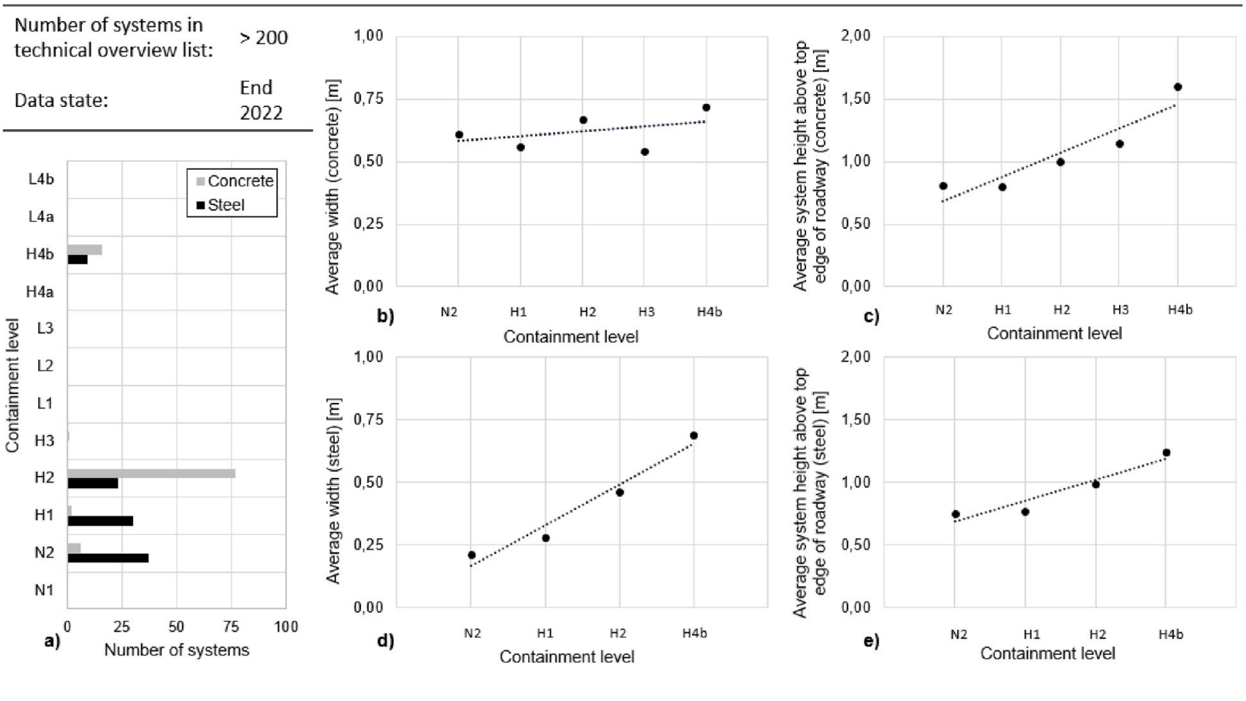

Fig. 12. Information overview chart illustrating the safety barrier characteristics of available systems in Germany.

Germany, as documented in the technical overview list released late 2022. This list encompasses approximately 200 systems. To determine the containment level of the systems, this systems were tested in accordance with DIN EN 1317.The figure highlights that steel systems in particular are increasingly found in the N2 and H1 ranges (a). Concrete systems are more commonly found at higher containment levels, such as H2 and H4b (a). However, it should be reiterated that systems made of both materials are available across a variety of containment levels. An analysis of the average system widths and heights (b-e), suggests a correlation between the width and height of steel systems and the containment level achieved. In contrast, for concrete systems, only the system height appears to have a tendential influence on the containment level. In principle, there are other influences on the performance characteristics of the safety barriers, such as anchoring, but these are not directly considered in the technical overview list. It should also be noted that double ratings are possible if a system has several containment levels.

Assuming that, according to Fig. 11, the average height of steel and concrete systems for containment levels N2 and H1 are in a range around 75 cm, this results in a plausible overlap with the real system heights from Fig. 11. This is also consistent with the increased prevalence of steel systems (see Fig. 10), which are also predominantly found within containment levels N2 and H1 as depicted in Fig. 12.

4.5. SWOT analysis of the standard DIN EN 1317

In the data analysis shown previously, it was shown that there is a gap between the standard and real-world impact events. To address this gap not only quantitatively but also qualitatively, it is necessary to analyze the objectives. The DIN EN 1317 standard is primarily aimed to ensuring the safe design of roads generally through the implemenation of safety barriers as well as the definition of containment levels for these systems. The standard defines test procedures and sets pass/fail criteria. It can thus be understood that the main objective of the standard is to create a standardized test framework for all types of vehicle restraint systems. However, it is conceivable that the interpretation of the standard, particularly in relation to the described test procedures and for the performance parameters to be fulfilled, could differ if the underlying objective were redefined. This critical discussion is thoroughly depicted in Fig. 13.

In the context of the objective analysis performed, the original intent of the standard can be regarded as a strength. The standard provides a vital framework for comparability of different types of vehicle restraint systems, thereby creating a reproducible test framework. However, this standard should also be subject to periodic evaluation to ensure that the existing test strategy can be adapted to evolving conditions as needed. A standard that no longer aligns with current application scenarios loses its relevance and effectiveness.

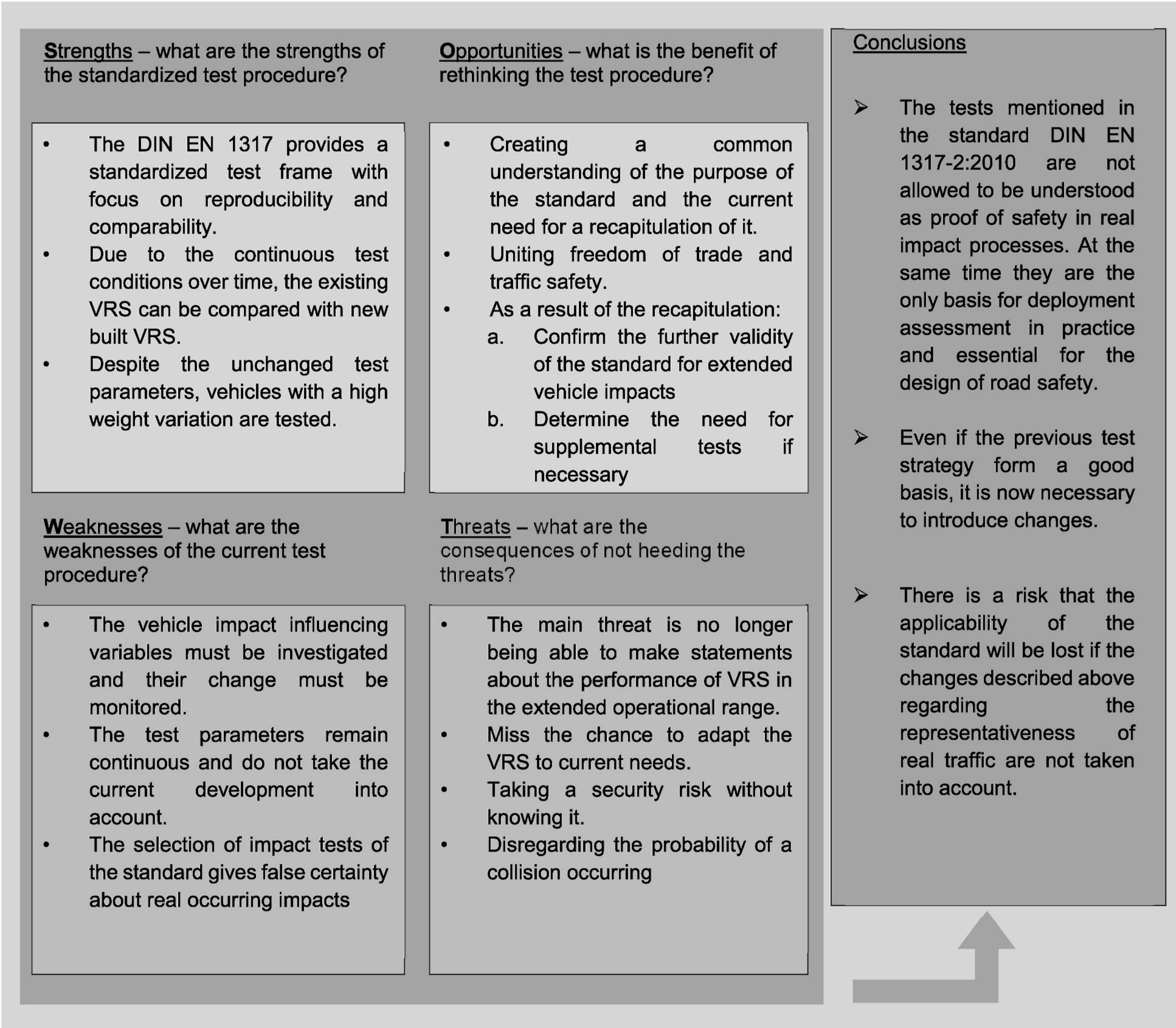

Fig. 13. Illustration of the DIN EN 1317 SWOT analysis - illustration design based on [21].

5. Conclusion

This article utilized various data sources to evaluate whether the existing test strategy for safety barriers based on the standard DIN EN 1317, accurately reflects real-world impact events on German highways and rural roads. The fundamental focus of the standard on reproducibility and comparability of safety barrier systems or their impact tests is essential to ensure the safe design of roads. Nevertheless, the standardized test parameters should be evaluated against actual impact scenarios and adapted or extended as necessary. The reason for this is that the original orientation of the standard was not necessarily designed to reflect real-world impact scenarios. The hypothesis posed in this study, whether or not the impact tests defined in DIN EN 1317–2:2010 represents the actual real time presumed high-energy impacts in today's context, was investigated in this study. The results, categorized by vehicle type, are presented below.

- Passenger cars: Based on the data examined, vehicles from the small to medium class segment continue to dominate new vehicle registrations. Thus, the previous test strategy remains generally effective. However, the registration figures suggest that the involvement of SUVs, including off-road vehicles, will potentially rise in future collisions. In addition, new vehicles are increasingly heavier, a trend likely to persist due to the adoption of alternative drive technologies. Consequently, it is within reason to consider an SUV impact in a weight range of 1600 kg to 2000 kg as the average weight investigated with an average test weight of 1800 kg representing a midpoint between a SUV and an off-road vehicle. This would account for the increasing average weight of vehicles in Germany. Regarding impact speed and impact angle, the speed captures a small number of impacts exceeding the previous test range. In contrast, in the data extract considered, the previous test strategy for impact angle appears to be insufficient. A potential adjustment could involve considering impact speeds above 110 km/h, aligning with the guideline speed of 130 km/h on German highways, where higher impact speeds are more likely compared to rural roads. By increasing the impact speed to 130 km/h, over 95 % of the passenger car accidents analyzed in the GIDAS database would be encompassed. Simultaneously, it would be prudent to test additional impact angles within the 20° and 40° range, covering a similar proportion of analyzed accidents as the suggested impact speed adjustment. Lastly, it is important to note that the passenger car vehicle segments considered here are based on the classification of the Federal Motor Transport Authority which is based on visual, technical, and market-oriented characteristics. For the specific investigation of vehicle collisions with safety barriers, strict adherence to there segments is not mandatory.

- Trucks: An examination of new registrations and axle load measurements indicates that the weight classes selected from DIN EN 1317–2:2010 remain representative of the actual weight distribution of trucks, and that there have been no significant developments towards higher weight classes. It should be noted that new truck registrations also include vans in a low weight range, which reduces the relative proportion of heavy trucks investigated in this study. However, the accident data (GIDAS) examined also shows predominantly trucks in a gross weight of up to 20,000 kg that have accidents with safety barriers. These are still covered by the previous test strategy. For the protection of lighter trucks or vans, it is advisable to consider a test weight of up to 5000 kg, representing a weight class that exceeds the weight of passenger cars, but remains below the test weight of the lightest truck currently tested under DIN EN 1317–2:2010. With reference to the axle load measuring points, it is theoretically feasible to test the previous test weight of 16,000 kg across a broader angular range at impact speeds between 60 and 80 km/h. With an impact speed of up to 80 km/h, more than 80 % of the accidents evaluated would still be covered. No significant conclusions can be derived for collision speeds above 80 km/h, as the total number of documented accidents above 80 km/h is limited and complete data on vehicle weights is partial unavailable. The impact events investigated show that impacts within the 20°–40° angle range continue to occur, representing approximately 25 % of the investigated accidents, suggesting that expanding the angle range, similar to the adjustment proposed for passenger car testing strategies, could be warranted. Impact angles greater than 40° occurring in reality were not to be statistically significant. When considering real world impact speeds, a small number of impact events with impact speeds of more than 80 km/h occurred, likely involving lighter trucks given their ability to reach higher speeds.
- Buses: Based on the criteria examined in this study, it was not possible to evaluate any accidents involving buses on the selected road types. Based on the registration figures it can be deduced that the previous test weight of a bus of 13,000 kg is likely insufficient. It can be assumed that newly registered buses typically weigh 18,000 kg or more. Therefore, it is recommended that future testing uses a coach type bus, as these vehicles are more representative of the considered speed range on country roads and highways, compared to the commonly used low-floor buses. The data sources examined here do not indicate a heightened frequency of bus-related accidents, this may warrant further investigation. As such, the primary conclusion is that this previous test strategy for buses needs adjustment, specifically in terms of weight.

Various installation situations of safety barriers (e.g. installation on sloping banquet) are not considered in this paper. However, the investigation of the energy input remains crucial, especially for the future safety assessment. Particularly in the segmentation of passenger cars but also in the design of buses, it can be expected that, depending on the design of the test vehicle, there will be a non-negligible influence on the deformation behavior and thus the energy absorption. In conclusion, it should be noted that the data sources considered here only represent a sample as a basis for evaluation, serving as a basis for approximating real world impact events on safety barriers in Germany. However, such approximations represent an important instrument for evaluating and assessing the safe design of roads in Germany. Therefore, further monitoring of the aforementioned impact parameters and investigating of the identified knowledge gaps between the standard DIN EN 1317 and this publication are vital. Last but not least, while real impact tests are associated with high costs, by using simulation methods, particularly finite elemente method (FEM) simulations, are a viable alternative to check the performance of safety barriers. Simulations are particularly useful in the extended application that is beyond the standard testing scope, where real-world tests are less common.

Moreover, it is important to critically acknowledge the frequent lack of accuracy in the definition and documentation of safety barriers, as well as the often unkown stock of such systems in various cases or regions. Therefore, the recording of safety barriers in the stock and in the context of accidents have a potential for optimization. It should also be noted that further aspects can be evaluated in the event of a vehicle collision with a safety barrier. This publication presents only a partial analysis, with the focus specifically on Germany, whereas the referenced standard is valid throughout the European Union. This conveys that the need for an adaptation of the standard based on Germany's perspective is hereby presented and thus the basis for further European discussions can be implemented.

CRediT authorship contribution statement

Tobias Berg: Writing – original draft.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Tobias Berg reports a relationship with Federal Highway Research Institute that includes: employment. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used for this study is confidental and was partly exported only for the purpose of evaluation in this paper. It is therefore not possible to provide the data used.

Acknowledgment

The author would like to express gratitude to the Federal Highway Research Institute (BASt, Germany) and especially the section responsible for road equipment, for their invaluable support and professional guidance. Special thanks are extended to all colleagues who assisted with language support, writing assistance and the proof reading of this article. The author also acknowledges the contributions of all entities and individuals who provided data. Special thanks are due to Prof. Dr. Markus Oeser for his scientific and administrative support of this publication.

Further the author declares that this research did not receive any specific grant from agencies in the public, commercial or not-for-profit sectors. The author is employed by the Federal Highway Research Institute which provides the research infrastructure and pays the publication costs, without any possible references regarding third parties.

References

[1] Bundesanstalt für Straßenwesen, Verkehrs- und Unfalldaten: Kurzzusammenstellung der Entwicklung in Deutschland, 2023.
[2] Zenaida A. Hernández, Felipe Álvarez, Mar Alonso, Luis Sañudo, Analysis of the test criteria for vehicle containment systems in the Standard EN 1317 regarding the number of vehicles in use, Transport. Res. Procedia 33 (2018) 315–322, https://doi.org/10.1016/j.trpro.2018.10.108.
[3] Statistisches Bundesamt, Verkehr - Verkehrsunfälle, Fachserie 8 Reihe 7, 2022.
[4] Forschungsgesellschaft für Straßen- und Verkehrswesen, Richtlinien für passiven Schutz an Straßen durch Fahrzeug-Rückhaltesysteme: RPS, Ausg. März, FGSV, Köln, 2009.
[5] Francesca La Torre, Ceki Erginbas, Robert Thomson, Giuseppina Amato, Bine Pengal, Christian Stefan, Graham Hemmings, selection of the most appropriate roadside vehicle restraint system – the SAVeRS project, Transport. Res. Procedia 14 (2016) 4237–4246, https://doi.org/10.1016/j.trpro.2016.05.395.
[6] J. Ziegler, T. Unger, F. Spitzhüttl, A. Malczyk (Eds.), Anforderungen an Schutzeinrichtungen neben der Fahrbahn, Gesamtverband der Deutschen Versicherungswirtschaft e.V. Unfallforschung der Versicherer, Berlin, 2022.
[7] Brendan J. Russo, Peter T. Savolainen, A comparison of freeway median crash frequency, severity, and barrier strike outcomes by median barrier type, Accid. Anal. Prev. 117 (2018) 216–224, https://doi.org/10.1016/j.aap.2018.04.023.
[8] Douglas J. Gabauer, Hampton C. Gabler, Comparison of roadside crash injury metrics using event data recorders, Accid. Anal. Prev. 40 (2008) 548–558, https://doi.org/10.1016/j.aap.2007.08.011.
[9] N.S. Johnson, R. Thomson, H.C. Gabler, Improved method for roadside barrier length of need modeling using real-world trajectories, Accid. Anal. Prev. (2015) 162–171, https://doi.org/10.1016/j.aap.2015.03.020.
[10] Jasper Chell, Carola Elea Brandani, Stefano Fraschetti, Joe Chakraverty, Valentina Camomilla, Limitations of the European barrier crash testing regulation relating to occupant safety, Accid. Anal. Prev. 133 (2019) 105239, https://doi.org/10.1016/j.aap.2019.07.015.
[11] CEN – European Committee for Standardisation, DIN EN 1317-2:2011-01, Rückhaltesysteme an Straßen_- Teil_2: Leistungsklassen, Abnahmekriterien für Anprallprüfungen und Prüfverfahren für Schutzeinrichtungen und Fahrzeugbrüstungen; Deutsche Fassung EN_1317-2:2010, Beuth Verlag GmbH, Berlin, 2011.
[12] CEN – European Committee for Standardisation, DIN EN 1317-1:2011-01, Rückhaltesysteme an Straßen_- Teil_1: Terminologie und allgemeine Kriterien für Prüfverfahren; Deutsche Fassung EN_1317-1:2010, Beuth Verlag GmbH, Berlin, 2011.
[13] Nikil Abraham, Bidisha Ghosh, Ciaran Simms, Robert Thomson, Giuseppina Amato, Assessment of the impact speed and angle conditions for the EN1317 barrier tests, Int. J. Crashworthiness 21 (2016) 211–221, https://doi.org/10.1080/13588265.2016.1164444.
[14] H. Balzert, M. Schröder, C. Schäfer, P. Motte, Wissenschaftliches Arbeiten Ethik, Inhalt & form wiss. Arbeiten. Handwerkszeug, Quellen, Projektmanagement, Präsentation, Zweite Aufl., Zweite Nachdruck, W3L-Verlag <Herdecke>, Herdecke, 2014.
[15] Federal Motor Transport Authority, Neuzulassungen von Kraftfahrzeugen nach Umwelt-Merkmalen, FZ 14, 2021.
[16] Federal Motor Transport Authority, Neuzulassungen von Nutzfahrzeugen, Kraftfahrzeugen insgesamt und Kraftfahrzeuganhängern nach technischen Daten (Größenklassen, Motorisierung, Fahrzeugklassen und Aufbauarten), FZ 26, 2021. Jahr 2021.
[17] A. Fitschen, Bundesanstalt für Straßenwesen. Gesamtgewichtsverteilung Achslasterfassung 2019: Schwerverkehr, 2020.
[18] Bundesanstalt für Straßenwesen, Sonderauswertung der amtlichen Straßenverkehrsunfallstatistik: Alleinunfälle von PKW auf Bundesautobahnen 2012-2021, 2024.
[19] VDI-Gesellschaft Fahrzeug- und Verkehrstechnik, VDI Wissensforum GmbH, Fahrzeugsicherheit: Fahrzeugsicherheit im Kontext neuer, nachhaltiger Mobilitätskonzepte 8. und 9. November 2023, Berlin. Datengrundlage zur Beantwortung der Verkehrssicherheitsfragen von morgen – GIDAS 4.0, VDI Verlag, Düsseldorf, 2023.
[20] Bundesanstalt für Straßenwesen, Technical overview list for vehicle restraint systems. https://www.bast.de/DE/Verkehrstechnik/Qualitaetsbewertung/Listen/pdf/uebersicht-frs-04-01-2019.html, 2022. (Accessed 1 December 2022).
[21] Benjamin Künzli, SWOT-Analyse: Ein klassisches Instrument der Strategieentwicklung mit viel ungenutztem Potenzial. http://www.clc-consulting.ch/fileadmin/CONTENT/SWOT_Analyse_Benjamin_Kuenzli.pdf, 2012. (Accessed 1 February 2024).
[22] Bundesanstalt für Straßenwesen, Sonderauswertung von GIDAS Unfalldaten: Anprall an Schutzplanken 2005-2022, 2024.