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Road safety on German motorways



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Background and methodology

Almost a third of the total distance covered by motor vehicles registered in Germany is driven on the country's approximately 13,000 km of motorways (2 % of the entire German road network). Relative to the distance covered on them, Germany's motorways can be considered as the safest roads in the country when compared to roads outside of and within built-up areas [1]. However, with a total of 2,500 injuries and 32 fatalities per 1,000 kilometres, they also exhibit the highest density of traffic accident victims on roads away from built-up areas [1]. The accident occurrence on German motorways is characterised in particular by accidents in longitudinal traffic, which account for approximately 63 percent of accidents involving injury, as well as by driving accidents, which represent 24 percent of these accidents [2].

That is why the German Insurers Accident Research (UDV) decided to initiate a research project which it has conducted in cooperation with SHP Ingenieure. The aim of this research project was to identify and quantify the infrastructural, operational and traffic-specific factors influencing road safety on German motorways. In addition, the project set out to examine the interactions between the individual parameters.

Alongside a review of the literature on available experience of the safety-related aspects of motorway design, the accident occurrence observed on motorways throughout Germany was also analysed, sometimes accompanied by queries specially addressed to the German Federal Statistical Office in order to identify the key areas influencing the frequency and nature of accidents (macroscopic accident analysis). After this, the factors ascertainable from the road information databases of six German federal states were examined for their influence on road safety. This involved both an accident analysis and an analysis of the considered parameters on the basis of multivariate models. To do this, the examined motorway sections were subdivided into the following elements: open stretches of road, entry/exit areas and slip roads.

Overview of the state of research – safety on motorways

The review of the literature reveals that very few studies conducted in recent decades have addressed questions relating to motorway safety. In 2013, ROOS/ZIMMERMANN [3] examined the areas of use of slip roads in the light of traffic volume, speed and safety. Their study showed that the curve radii on entry/exit slip roads have a considerable influence on driving behaviour and are thus able to increase road safety at these motorway elements. The study therefore recommended defining a relation in the good or very good design zone of the radius relationship curve and restricting the lengths of straight sections along slip roads in the guidelines on the design of motorways (RAA) [4].

LIPPOLD/ZÖSCH/ZIMMERMANN [5] examined the ways in which deficits in three-dimensional alignment occur on motorways, the circumstances under which these occur and the conclusions with regard to road safety that can be drawn from these. The study showed that three-dimensional alignment deficits may occur even when the design parameters set out in the RAA are respected. However, it was not possible to identify any clearly negative influence on accident occurrence for any of the types of deficit. The authors assume that this is due to the much larger design elements involved (curve radii, the semidiameters of humps and troughs).

A study conducted by BAIER et al. [6] examines road safety at motorway entry areas. The main findings of the study were that the accident cost rate tends to fall if the area available for joining the motorway is longer, that the use of ramp meters during afternoon peak hours reduces the severity and number of accidents and that accidents resulting from merging vehicles are rare. The way in which motorways are operated can have a significant influence on road safety. That is why traffic control systems (TCS) are already in use on many highly-frequented motorways where they optimise the traffic flow and improve road safety. The use of TCS makes it possible to prevent up to 30% of accidents [7].

STRASSGÜTL/SANDER [8] investigated the effects of automatic emergency braking systems on changes to rear-end truck collisions on German motorways.

The authors examined the trucks and coaches vehicle groups with and without automatic emergency braking systems, AEBS). The study showed that the use of AEBS reduced the number of accidents in the examined comparison groups by 37%. The severity of the accidents also declined, as is clearly illustrated by the reduction in the number of accidents involving serious injury. The UDV has already been able to demonstrate the positive impact of emergency braking functions on the nature and frequency of accidents [9], [10].

The Handbuch für die Verkehrssicherheit (HVS, German manual on the assessment of road traffic safety) [11] describes a procedural approach that primarily provides for an assessment of road safety on motorways based on the accident cost rates of individual elements. The accident cost rates consist of the basic accident cost rates together with supplementary amounts for deviations from guideline-compliant construction.

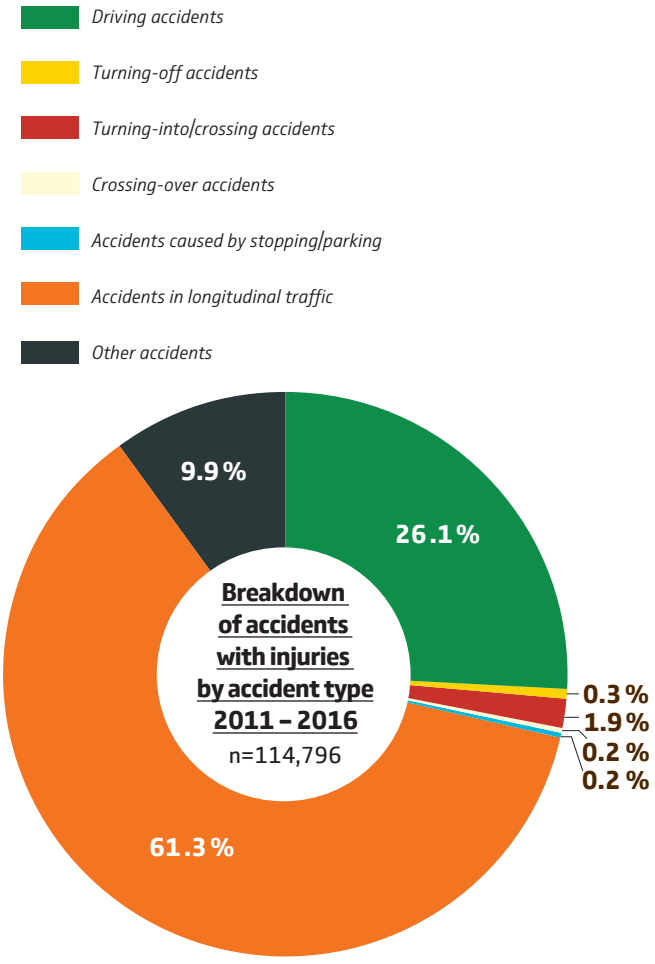
Macroscopic accident analysis

The basis for the macroscopic accident analysis was provided by the corresponding annual specialist publications on traffic accidents – Verkehrsunfälle [12] – and a survey specially designed for this study [13] and addressed to the German Federal Statistical Office for each of the years 2011 to 2016.

The analysis of accident types showed that the overwhelming majority of accidents could be attributed to the two accident types, namely accidents in longitudinal traffic (63 %) and driving accidents (24 %) (Figure 1). In the case of driving accidents, accident severity is slightly above the average and, by contrast, it is slightly below average for accidents in longitudinal traffic. Men cause approximately 70% of these types of accidents. The accidents with the most serious consequences occurred in connection with trucks, in particular for the accident type "accident in longitudinal traffic". In the case of accidents involving senior citizens (65 or more years of age), the severity of the accidents increases with the age of the person who is the primary cause of the accident.

The accident occurrence is dominated by accidents in longitudinal traffic

Figure 1 · **Breakdown of accidents with injuries (Acc(I) by accident type for the period 2011 to 2016**

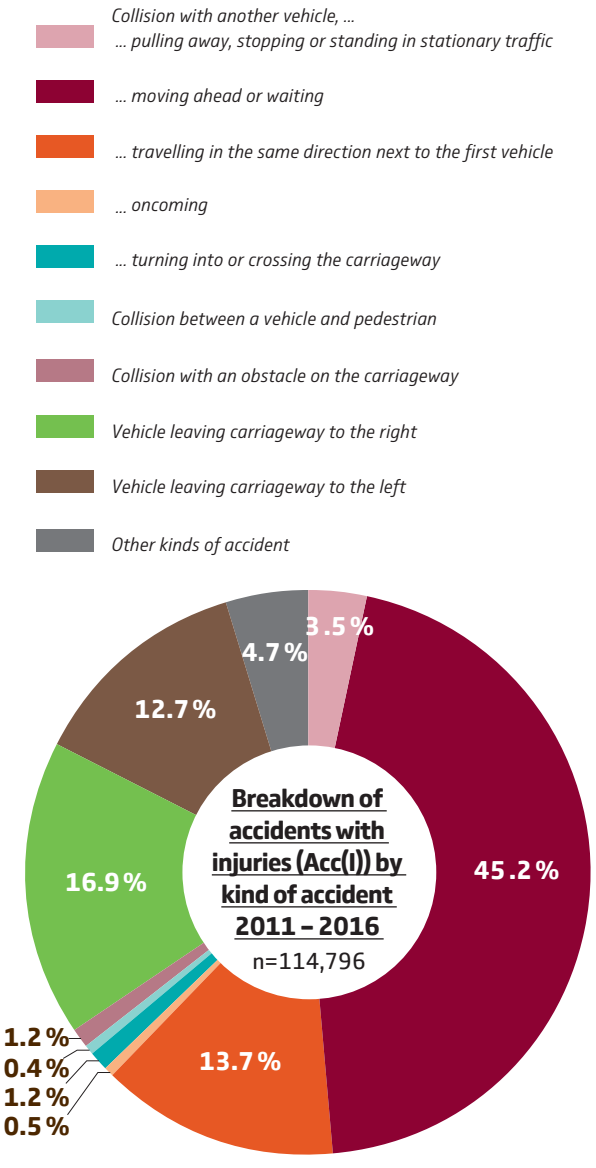


Source: German Federal Statistical Office, 2017

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Three-quarters of accidents are caused by rear-end collisions or vehicles leaving the carriageway

Figure 2 · **Breakdown of accidents with injuries (Acc(I)) by kind of accident for the period 2011 to 2016**



Source: German Federal Statistical Office, 2017 © UDV 2021

The most frequently observed kinds of accident are as follows (Figure 2):

- Collision with a vehicle moving ahead or waiting,
- Collision with a vehicle travelling in the same direction next to the first vehicle,
- Vehicle leaving carriageway to the left,
- Vehicle leaving carriageway to the right.
- An examination of the accidents with fatalities showed that trucks were frequently involved in accidents with a vehicle moving ahead or waiting.

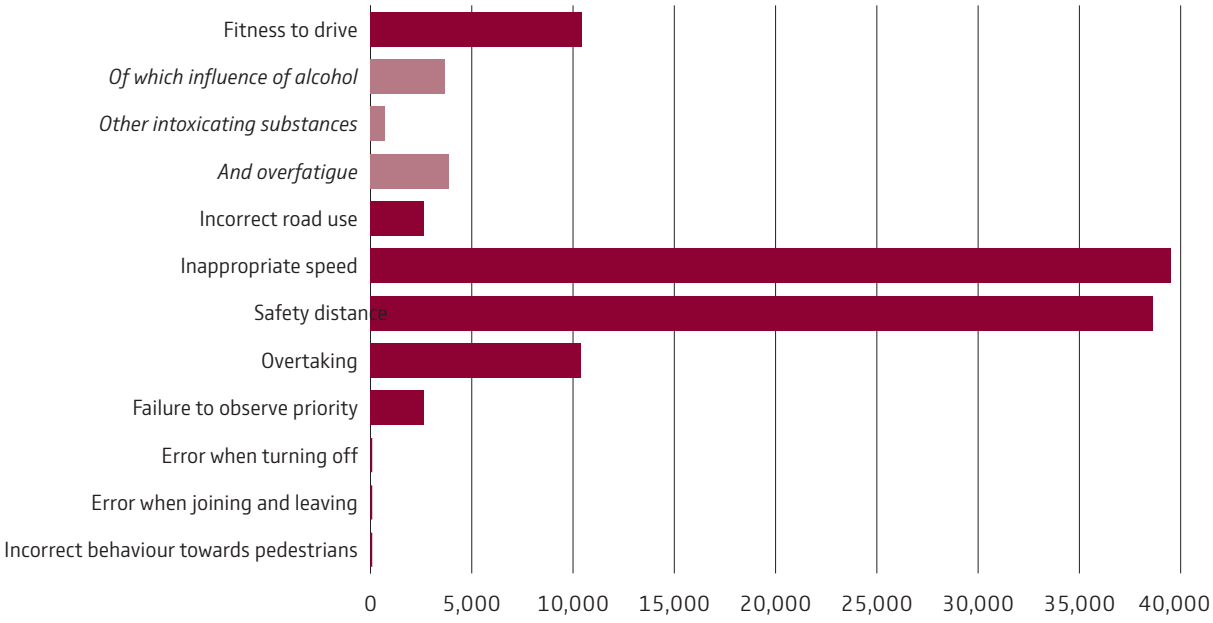
The most frequent causes of accidents were inappropriate speeds, insufficient safety distances and errors during overtaking manoeuvres (Figure 3). In the case of the composite cause of accidents constituted by "fitness to drive", the very high proportion of men (90%) was particularly striking, with alcohol representing a similarly high proportion as "overfatigue".

The analysis of the temporal distribution of the accidents showed, in particular, that noticeably more accidents with injuries occurred on Fridays as well as on Mondays (Figure 4). However, the road user group aged 65 years or more causes disproportionately more accidents with injuries during weekends and on Sundays, in particular. Accidents involving motorcycles primarily occur during the summer months.

Furthermore, it was possible to note that whereas 25 percent of accidents with injuries occurred during the hours of darkness, this same period accounts for 40 percent of accidents with fatalities. This shows that accidents during the hours of darkness have disproportionately serious consequences.

Most frequent causes of accidents: Speed and safety distance

Figure 3 · **Breakdown of accident causes for accidents with injuries**

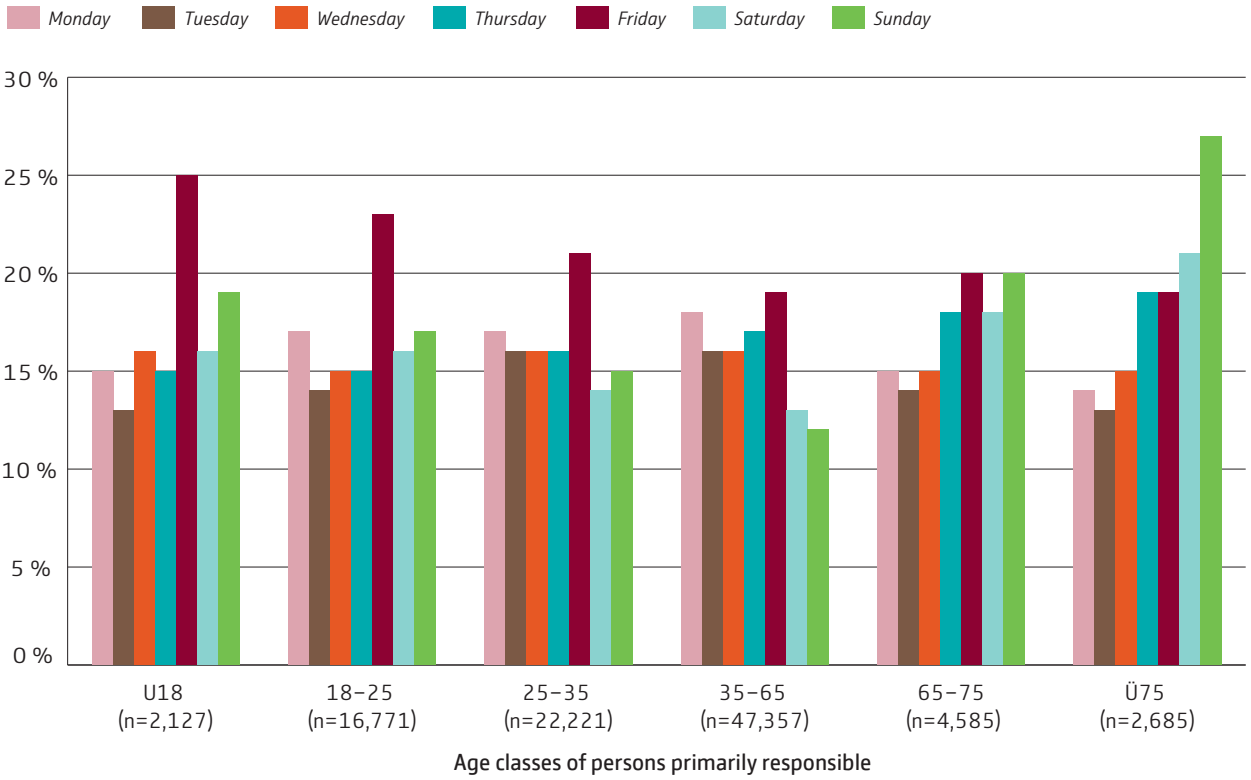


Multiple attributions possible; Source: German Federal Statistical Office, 2017

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Disproportionately high numbers of accidents on Fridays

Figure 4 · **Temporal breakdown (weekdays) of accidents with injuries**



Source: Special survey, Destatis

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Infrastructure-related accident analysis

Fundamentals and approach

InfInfrastructure data from the following German federal states was used: Brandenburg, Baden-Württemberg, North Rhine-Westphalia, Rheinland-Palatinate, Saxony and Saxony-Anhalt. In total, data for 5,889 kilometres of motorway was available. The available road information databases cover all stretches of German motorways, including the junctions together with the associated slip roads. The present study focused on sections of the intersection-free stretches, sub-sections (sections of the intersection-free stretch that are subdivided by changes in the geometry of the element of the layout (straight, curve) as well as by changes of speed limit), entrances, exits and slip roads.

For the network in question, accident data was available for the years 2011 to 2016, and in North Rhine-Westphalia the years 2011 to 2017 (without accident descriptions).

The accident cost rate (for sections of the intersection-free stretch and for sub-sections) and the accident cost density (for slip roads, entrances and exits) were calculated in accordance with the Merkblatt zur Örtlichen Unfalluntersuchung in Unfallkommissionen (Code of practice for local accident investigation in accident commissions, (M Uko)) [14] to provide key indicators for the description of road safety. Accident severity is also considered. This is defined as the number of fatalities and victims of serious injuries relative to the number of accidents with injuries. The number of stretches on which accidents had occurred was also determined. This is a dichotomous variable that indicates whether at least one accident of categories 1 to 3 had been recorded during the years in question. Accident black spots were also considered.

We first produced a stratified description of the data. The term stratification refers to the breaking down of a file into different layers that are defined by a chosen variable. Care is taken during the analysis to ensure a traceable sequence of stratifying variables. Depending on the analysis level and branch in the layer structure, the groups are formed on an exemplary basis starting with the type of motorway (arterial or regional motorway) and number of lanes, followed by the radius or curvature and maximum speed, and on to the traffic volume, longitudinal gradient (or the presence of undulating terrain and hills) and the proportion of large trucks. The corresponding accident indicators are then determined for the ever smaller and more homogeneous subgroups, which are compared on the basis of further features.

Due to the small number of features, it is not possible to perform stratification for the slip roads, entrances and exits. Nevertheless, it is possible to derive results for these elements.

The following seven independent variables are included in the models for the sub-sections (Figure 5): Motorway type (regional or long-distance motorway), number of lanes in each carriageway, curve radius range, longitudinal gradient, permitted maximum speed, traffic volume (Average Daily Traffic (ADT), Proportion of Large Trucks (PLT)).

Motorway type, number of lanes, permitted maximum speed, traffic volume (ADT and proportion of large trucks), curvature and undulations were considered in the models for the intersection-free stretches.

Models for similar subsections

Figure 5 · **Example presentation of the stratification for subsections**



During every stage of the construction and verification of the models, it was observed that there was no difference between the two types of motorway in terms of the occurrence of accident black spots and that no modifications of the effects occurred. This item was therefore removed as a differentiating factor in the models. All the other variables had effects and were retained in the definitive models.

Experience of road information databases

The experience gathered from the data of the road information databases (RID) of the six German federal states included in the study can be summarised as follows:

- The different states used different data structures in their RID.
- Most of the examined RID did not contain any data of importance for road safety work and traffic control (e.g. vehicle restraint systems, permitted maximum speeds, no-overtaking sections).
- Even the data that was present in the RID was usually incomplete or is not updated regularly.
- All of this made it more difficult to create a database that could be used for the conduct of the multivariate accident analysis.
- As a result, only the following parameters from the RID could be used during the creation of the multivariate models: Number of lanes, curve radius, longitudinal gradient, permitted maximum speed (in some cases using data from other sources [13]), traffic volume (ADT and proportion of large trucks). The curvature and undulation were also calculated.

Ergebnisse der Modellierungen

The results of the modelling can be summarised as follows.

Open road

The results with regard to curvature show that low curvatures (less than 10 gon/km) and high curvatures (more than 30 gon/km) should be evaluated as being considerably less beneficial than medium curvatures.

In the case of two-lane motorway sections, it was found that both the accident cost rate and the probability of black spots is smallest in the medium radius classes (between 3,000 m and 6,000 m). The accident cost rate increases at smaller and greater radii.

No comparable results can be unequivocally claimed for three-lane motorway sections. A trend towards a higher accident cost rate and a higher probability of accident black spots could be observed for radii of more than 6,000 m.

Entrances

The results show entrance types E1 and E4 (Figure 6) to be particularly favourable in terms of accident cost density, whereas types E3 and E5 must be considered considerably less favourable. In the latter types, a new lane is added, meaning that vehicles in the right-hand lane upstream of the entry (and in particular trucks) have to make a lane change to the right in order to reach the right-hand lane downstream of the entrance. However, using accident severity as an indicator only partially supports this result: When this indicator is used, types E1 and E4 are only in the middle of the ranking. With regard to the proportion of entrances at which accidents have occurred, the results for type E1 are again positive.

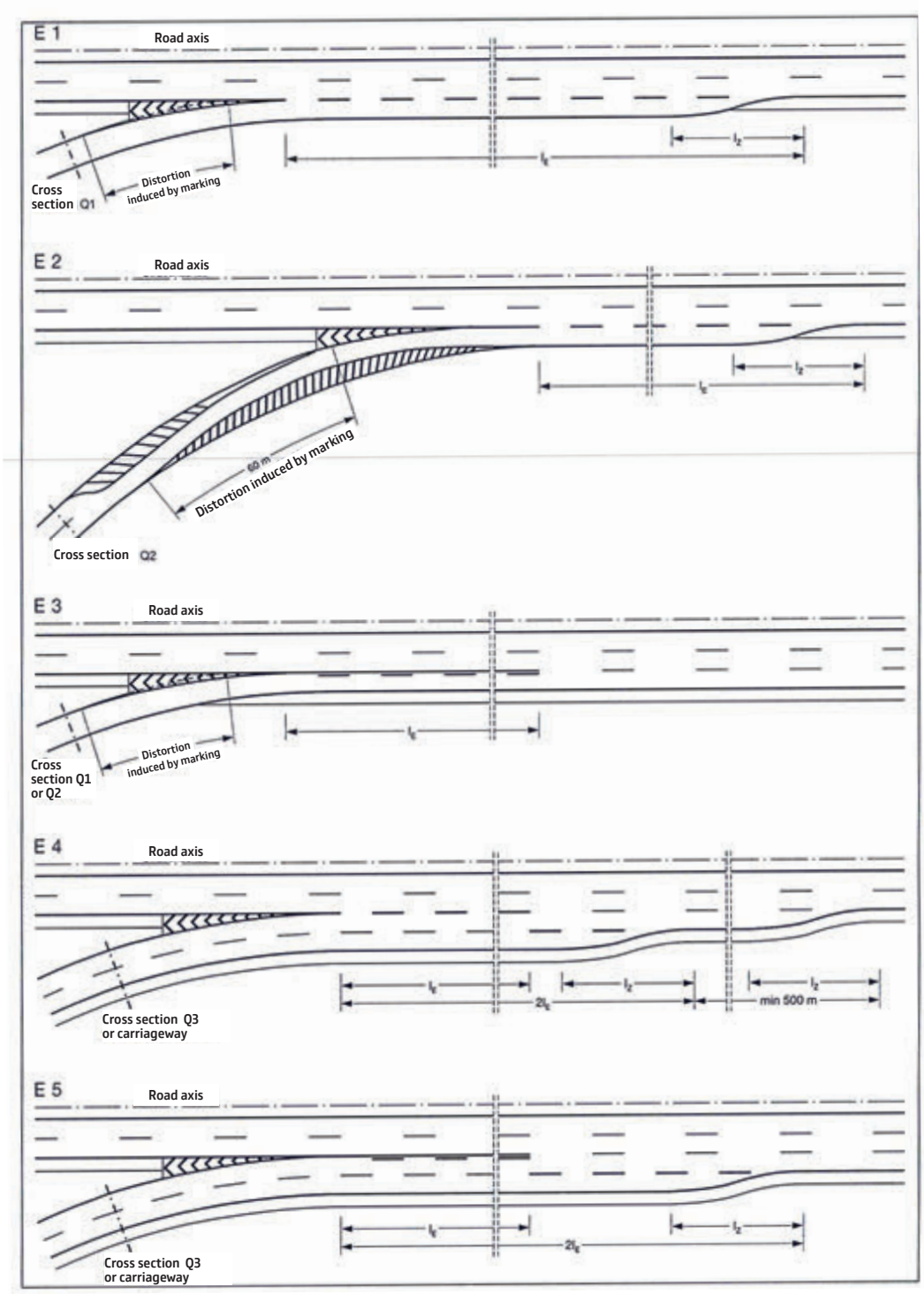


Figure 6 · Types of entrance to the main carriageway as set out in the guidelines on the design of motorways (RAA) [4]

Exits

The pattern of results is similar to that found for the entrances: The exit types in which a lane is removed (Figure 7) must be considered to be considerably less favourable than the other types. Drivers who do not want to use the exit all have to make a lane change to the left (in particular in the case of trucks). In some areas, these results differ from the research results reported by WEISER et al. [15]. These latter authors found that type A3, in particular, was considerably less beneficial than types A4 and A5.

Slip roads

Accident severity increases with increasing radius, while the accident cost density is particularly low for medium curve radii (80 to 125 m).

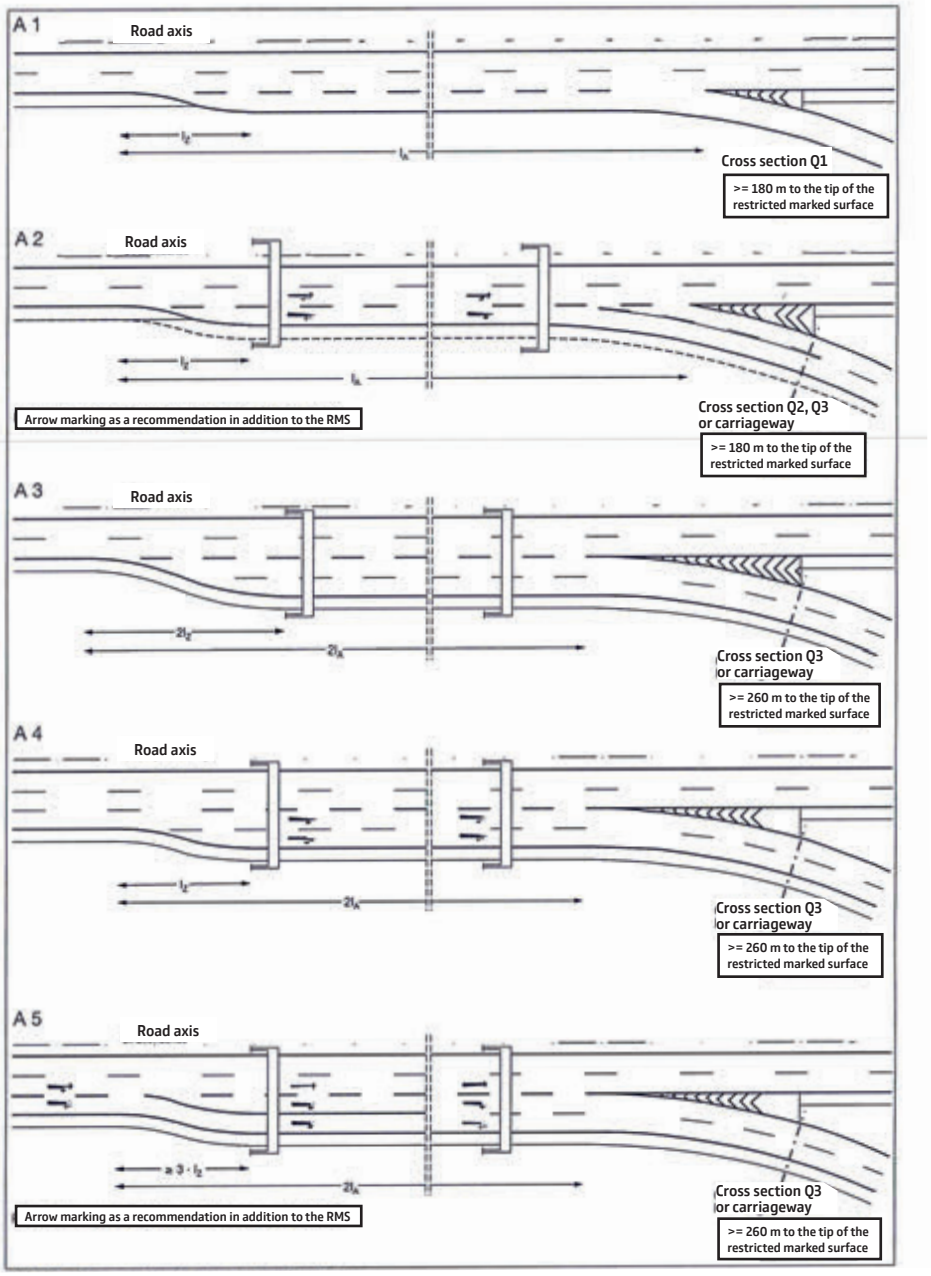


Figure 7 · Types of exits at main carriageways as per RAA [4]

Summary

The most important results of the modelling can be summarized as follows:

Macroscopic accident analysis

- The accident occurrence on motorways is dominated by accidents in longitudinal traffic (61 %) and driving accidents (26 %). Men cause approximately 70 percent of these two types of accidents. The most serious accidents are caused by trucks, in particular in the form of collisions in longitudinal traffic.
- The most frequent kinds of accidents include collisions with vehicles that are moving ahead or waiting (45 %), collisions with vehicles travelling alongside in the same direction (14 %), vehicles leaving the carriageway to the right (17 %) or left (13 %).
- Inappropriate speed (35 %), insufficient safety distance (34 %) and overtaking errors (approximately 9 %) are the most frequent causes of accidents (multiple attributions possible).
- There are considerably more accidents with injuries on motorways on Mondays and Fridays. On Sundays, road users aged 65 years or over cause disproportionately more accidents than other road users.
- Approximately 40% of the accidents with fatalities on motorways happen during the hours of darkness. On the other types of road (i.e. roads inside and outside of built-up areas), the figure is only approximately 28 percent.
- The condition of the road (dry, wet/damp or icy during the winter) does not seem to have any influence on the level of injury.

Results of the multivariate accident analyses - Design of the infrastructure r

- Sections with medium curvatures (between 10 gon/km and 30 gon/km) tend to be safer than sections with very low or excessively high curvatures.
- The accident cost rates and the probability of accident black spots are at their lowest for curve radii between 3,000 m and 6,000 m along two-lane carriageways.
- On slip roads, medium radii (80 m to 125 m) tend to have a lower accident cost density.
- With regard to entrances, entrance types E1 and E4 (Figure 6) are particularly favourable in terms of accident cost density.
- Exits in which lanes are removed (Figure 7) are considerably less favourable than the other types.
- No statistically reliable impact on road safety could be determined for the following parameters: Undulations, hilly terrain, longitudinal gradient, traffic volume, permitted maximum speed. This also applies to the studied combinations (e.g. speed limit together with average daily traffic (ADT) or with curve radius.)

Recommendations and outlook

In the light of the results of the studies performed within the framework of this research project, the following recommendations are made in order to help improve road safety on German motorways:

- Balanced alignment with medium curvatures and curve radii is desirable in order to reduce the high proportion of accidents in longitudinal traffic (61 %). The use of driver assistance systems to provide warnings and prevent such collisions can also make a significant contribution.

- A curvature of between 10 gon/km and 30 gon/km is desirable for long curves or sequences of curves on open stretches of road.

- Curves with radii of between 3,000 m and 6,000 m should be preferred on newly constructed motorways and when converting existing motorways.

- During new construction and conversion work, entrances of type E1 and E4 (Figure 6) should be preferred. Exits in which lanes are removed should be avoided if possible. Slip roads with radii of between 80 m and 125 m are preferable.

- No general recommendation for a specific speed limit on motorways can be derived from these studies. A comparison of sections with and without speed limits along stretches yielded no unambiguous results.

- The automatic emergency braking systems for HGVs which are already required for new vehicles should be examined with regard to their impact on accident occurrence and, if necessary, adapted in order to substantially reduce the particularly serious rear-end collisions with fatal consequences or completely eliminate these in the future.

- The following measures may be of value in reducing the high proportion of fatalities that occur during the hours of darkness:
  - Campaigns that highlight the particular danger of driving in the dark and that encourage drivers to adapt their driving behaviour to the reduced visibility at night-time.
  - Further driver assistance systems such as driver status detection (e.g. fatigue, sudden health problems), lane departure warning, distance and speed control with traffic sign recognition in the form of ISA (Intelligent Speed Adaptation). To this end, the technical requirements resulting from the Regulation adopted by the EU Parliament and Council [16] should not only be implemented by manufacturers but should also be examined with regard to their impacts on road safety. In this context, special attention should be paid to the influence of darkness on the occurrence of accidents on motorways. The technical development of assisted and automated driving functions (level 2 and level 3) should also be the object of critical examination and support in terms of their role in accident prevention.

- Safety-related information (e.g. vehicle restraint systems (both in the space at the side of the carriageway and in the central reservation), permitted maximum speed, no-overtaking sections, traffic control systems) should always be entered in the road information databases (RID) and should be continuously updated. The presence of complete and up-to-date data in the RIDs would considerably simplify the systematic analysis of the influence of infrastructure on carriageway-departure accidents and the definition of corresponding measures.

- The completeness and plausibility of the data that is already present in the RIDs should also be regularly checked and this data should be extended if necessary.

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