Crashes between Heavy Vehicles and Bicyclists: Characteristics, Injury Patterns and Potentials for Driver Assistance Systems

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Abstract With the objective to identify main characteristics of collisions between heavy trucks (approximately 12,000 kg gross vehicle weight and over) and bicyclists, 62 crashes from the German Insurers Accident Database were analysed. Fatalities represented 18% of casualties among bicyclists, 61% of the survivors were MAIS3+ injured. The largest proportion of AIS3+ injuries was found in the lower extremities, often caused by run-over by the wheels of trucks. With approximately 60%, collisions during right-turn manoeuvres of the truck were the most frequent scenarios. One third of first contact with the bicyclist was located on the right front corner of the truck cab. Significantly more female than male bicyclists were involved in right-turn collisions and run-over crashes ($p < 0.05$ and $p < 0.001$, respectively). The theoretical potential for electronic turn-assistance was estimated based on manufacturer data for a production system. A proportion of 68% of all crashes in the study material was considered relevant for such driver-assistance systems. With most accidents occurring in good weather and few obstructions found at the crash sites to impair the detection of a bicyclist, high effectiveness is expected for such a system, given fitment of all truck types.

Keywords bicyclist, crash, driver assistance, heavy vehicle, injury severity, truck, turn-assistant,

I. INTRODUCTION

With bicycle use increasing in many western countries, the number of casualties is not decreasing as it does for other modes of transport. While the number of killed passenger car occupants dropped by 52% between 2003 and 2012 in Germany, the figures for bicyclists decreased by only 34%, with 406 fatalities remaining [1]. Though comparably small in number, crashes between bicyclists and heavy vehicles, particularly large trucks, are known to often have very severe outcomes. So far, technical approaches are mainly limited to side-underrun guards for N2 and N3 class trucks and large trailers as mandated by [2] and enhancing the field of indirect vision by larger main rear-view mirrors and the addition of wide-angle mirrors according to [3] in order to reduce the blind spot area near the vehicle.

Reference [4] analysed 149 fatal bicyclist accidents in Berlin, Germany, between 1993 and 2004. Trucks were involved in 73 crashes and responsible for 84% of collisions where the driver of a motor-vehicle failed to yield to a bicyclist riding alongside when turning right.

The German Highway Research Institute (BASt) recently published a report by [5] on requirements for electronic turn-assistance for trucks to address this particular collision scenario. Based on accident data from the German In-Depth Accident Study (GIDAS) and earlier cases from the German Insurers Accident Database (UDB), 23 fatally and 118 seriously injured bicyclists were estimated to result from such turning manoeuvres in 2012 by trucks with a gross vehicle weight (GVW) of 7,500 kg and over.

Reference [6] analysed 46 fatal bicyclist crashes in London, UK, in the years 2007 to 2011. With 28% of the investigated collisions, a left turn – the equivalent to a right turn in countries with right-hand traffic – of a truck with a GVW of 3,500 kg and over across the path of the bicyclist represented the most frequent scenario.

Reference [7], in a synthesis of past research on truck accidents and safety, quotes a study by [8] according to which 18% of all fatalities involving trucks in the Netherlands occur during right turns, 46% of which affect bicyclists. It is noted that there were substantial variations for the nine countries providing data. With reference to recommendations by [9] and a cost-benefit study by [10], pedestrian and cyclist protection systems to warn the driver and intervene if necessary were rated among the top three future safety approaches.

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In 2016, one truck manufacturer presented an electronic turn-assistant for series production, available for goods transport vehicles based on semi-tractors with a GVW of 18,000 kg and over and 3-axle rigid trucks. It is currently not available for lighter trucks and vehicles destined for special purposes like in the construction or the waste management industry. The system relies on radar sensors mounted at the right side of the vehicle in front of the rear axle to detect objects including bicyclists when they enter an area on the right-hand side of the vehicle that is 3.75 metres wide and covers slightly more than the length of the entire truck or truck-trailer combination [11] (Fig. 1). The turn-assistant is supposed to issue an optical warning to the driver, followed by an acoustical warning, when a relevant object is detected, but does not intervene into the vehicle motion.

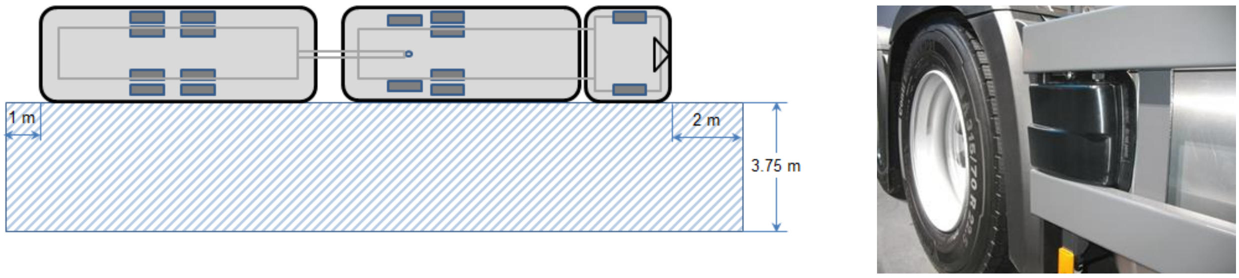

Fig. 1. Simplified representation of field of detection for turn-assistant (left) and radar sensors (right).

Our study aims at identifying typical collision scenarios between bicyclists and trucks with GVW of approximately 12,000 kg and over resulting in serious injuries. It includes, but is not limited to fatal outcome in order to provide information about the proportion of survivors and relevance to serious injury. Special focus is on configurations with right-turning trucks to provide an estimate for the potential that a generic turn-assistant with detection functionalities as described above would offer for collision avoidance or injury mitigation.

II. METHODS

Study Material and General Evaluation

Crash and injury data came from the German Insurers Accident Database (UDB). This database contains data from samples obtained retrospectively from claim files of German motor liability insurers. Cases recruited for the present study involving heavy trucks were required to have estimated initial claim costs of at least EUR 30,000, covering both personal and property damage, irrespective of the actual payments during claim processing and whether the truck driver or the bicyclist was at fault. Since crashes with bicyclists tend to result in higher bodily than material damage, these accidents present rather severe outcomes in terms of injury.

Heavy trucks were defined as goods and service vehicles with a gross vehicle weight starting just under 12,000 kg and included their trailers and semi-trailers where present. According to [12], goods transport vehicles over 12,000 kg fall into the N3, or N3G category, respectively. They include most tractors for semi-trailers, trucks for long distance transport, either as rigid units or in combination with drawbar trailers, and heavy-duty trucks used in the construction and the waste management industry. Trucks with a GVW of just below 12,000 kg, often registered with a weight of 11,990 kg, are popular particularly for regional distribution services. These trucks belong to the N2 or N2G category, respectively, and were included in the study as well. Buses, farm tractors and special equipment like mobile cranes, etc., were not considered.

For the purpose of studying the potential of crash avoidance by means of a turn-assistant, trucks were separated into two categories: semi-trucks and 3-axle rigid trucks intended for long distance hauling or regional distribution (turn-assistance currently available) versus rigid trucks with two axles or trucks intended for operation in the construction or waste management industry (turn-assistance currently not available). These parameters were determined from registration data and images of the involved vehicles.

Bicyclists were included if they had mounted their bicycle at the time of collision. Bicyclists walking their bike were disregarded as their characteristics resemble rather those of pedestrians when moving in traffic. E-bikes and tricycles based on the design of conventional bicycles were taken into account, too, though rarely involved.

The documentation of individual crashes comprised police reports, witness statements, hospital discharge information and sometimes accident reconstructions and post-mortem reports. Several variables were used to characterise the location of the crash and the actual event as well as the phase preceding the collision. These included the presence of traffic lights and bicycle paths at the crash site, the geometric relation between the truck and the bicyclist at the time of collision as well as the situation when the opponents approached each other, like the approximate trajectories or stops at a red light before the opponents' paths crossed each other.

Injuries were coded according to [13], and injury severities given per body region: Head/face (including skull and brain), thorax, upper extremities (including shoulder and hands), abdomen, lower extremities (including pelvic bones and feet) and spine (cervical, thoracic and lumbar spine). For clarity, injury severities were grouped into three categories: AIS0-1 for no or only minor injury, AIS2 for moderate injury, and AIS3+ for serious to maximum injury severity.

For the purpose of localising the area on the truck or its trailer where the first contact with the bicyclist occurred, twelve zones, each, were defined (Fig. 2). These zones provide only qualitative information since – on one hand – their widths vary depending on the individual vehicle and since – on the other hand – an exact point of contact is often impossible to determine due to no or little resulting damage on the truck.

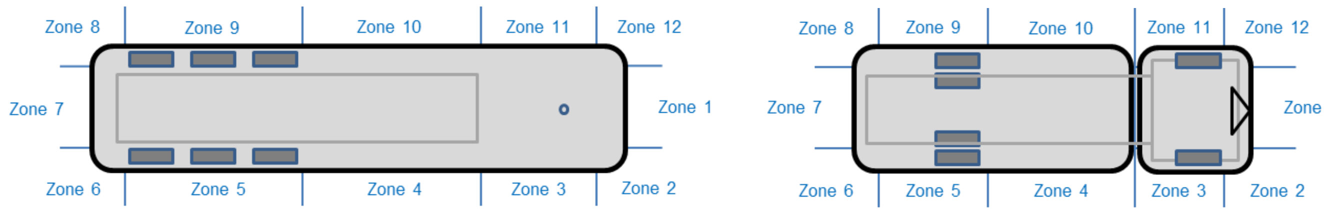

Fig. 2. Schematic representation of definition of contact zones on rigid truck (right) and trailer (left).

With regard to the injury mechanism in vulnerable road users run-over may be of particular importance. For the purpose of this study, run-over is defined as one or more wheels of the vehicle rolling over a portion of the victim's body or at least wedging a body part between a wheel and the ground with resulting injury. The few cases where bicyclists got under the vehicle and possibly contacted the underbody, but not the wheels, were not counted as run-overs.

Depending on the detail and reliability of data, some of the cases had to be excluded from certain analyses. Therefore, percentage values from the data analysis relate to the number of valid cases.

Differences of values based on continuous variables were tested for significance using the t-test, for dichotomous variables the Chi-square test was applied. Statistical significance was assumed at a p-level of 0.05, otherwise the difference was considered non-significant (n. s.).

Assessment of Potential for Electronic Turn-Assistant

The assessment of the theoretical potential of a generic electronic turn-assistant was based on the performance data as described by the truck manufacturer [11]. The system is designed primarily to address collisions in which the truck crosses the path of a bicyclist who is riding parallel on the right-hand side of the vehicle, often when the truck makes a right-turn manoeuvre into a cross-street or a property entrance. The system is expected to cover other collision scenarios only to a limited degree or not at all. Therefore, for the purpose of this study each of the documented crash situations was assigned to one of three categories:

A) Truck-to-bicyclist collisions relevant for electronic turn-assistance. These include right-turn manoeuvres by the truck while the bicyclist is moving more or less parallel to the vehicle with the same direction of travel, but possibly at a different speed. A truck closing in on a bicyclist riding in the same direction while overtaking or making a lane change to the right lane are additional scenarios considered relevant (Fig. 3).

B) Truck-to-bicyclist collisions with doubtful relevance for electronic turn-assistance. These include scenarios where the bicyclist moves into the field of detection so late in the course of the crash that a timely detection, warning and driver reaction, are unlikely. Examples are situations in which the bicyclist approaches the truck more or less perpendicularly from the right, i.e., on a cycle path or pedestrian path while the truck is waiting at a junction. A cyclist riding parallel and on the right-hand side of the truck's trajectory, but in the opposite direction, is another scenario that leaves little time to initiate a driver reaction as the bicyclist moves quickly through the field of detection before the collision (Fig. 4).

C) Truck-to-bicyclist collisions not relevant for electronic turn-assistance. These include situations in which the bicyclist is moving in an area that is not covered by the turn-assistant, for instance, when the truck turns left and crosses the path of a bicyclist on the left. Also, bicyclists riding in front or behind the truck within the vehicle's width are not expected to be detected by the turn-assistant. Evidently, accidents where the moving cyclist crashes into a stationary or parked truck belong to this category as well (Fig. 5).

This categorisation does not yet account for constraints that may further reduce the potential of crash avoidance. For instance, a high differential speed between the opponents may reduce the possibility for the truck driver to avoid the cyclist during a passing manoeuvre or to bring the truck to a halt and prevent that a fallen bicyclist is being run-over. On the other hand, the detection of a bicyclist by the turn-assistant may be obstructed by objects like parked cars shortly before the opponents' trajectories meet. Also, the bicyclist may have moved into the field of detection only some metres before the collision point due to a specific bicycle path layout. This period immediately before the crash is of particular importance for its avoidability, but the temporal and spatial relation of the opponents is usually impossible to determine with sufficient precision due to unknown cycling speed, lack of reliable witness statements and other uncertainties.

Therefore, a simple method was employed to assess how demanding the pre-collision phase was for electronic turn-assistance. For each case with a relevant collision situation, it was determined whether the bicyclist would have been present in the detection field of the turn-assistant, taking into account his or her lateral distance to the truck, at 10 metres and 20 metres measured from the point of the actual collision. For instance, for a cyclist going at 18 km/h, approximately the average urban cycling speed [14], a distance of 10 metres from the point of collision would allow two seconds for the turn-assistant of a stationary truck to detect him or her, issue a warning to the truck driver and initiate a timely reaction. The principal perceptibility of the bicyclist on his or her trajectory by the system was determined from scale sketches from crash reconstruction documentation or aerial views of the accident location available on the internet.

III. RESULTS

The German Insurers Accident Database (UDB) provided 62 crashes between a heavy truck (GVW of 11,900 kg and over) and a person riding a bicycle that occurred in Germany between 2007 and 2012, the majority of them (41 cases) in 2012 due to a larger sample of truck accidents drawn for this year. Below, results are not only given for the entire case material, but are also separated – where useful – between collision scenarios considered relevant for an electronic turn-assistant and scenarios which were deemed not relevant or doubtfully relevant for such a system. The latter two scenarios will be subsumed under the term *non-relevant for electronic turn-assistant* where useful.

Road Infrastructure and Environmental Conditions

The large majority of crashes occurred in built-up areas (n = 57; 92%). Most accidents were located at or in the immediate vicinity of crossings (n = 32; 52%), followed by T-junctions (n = 19; 31%). In 11 cases (18%), the collision occurred either on a stretch of road without any junctions or at a property entrance, like a shopping centre. Traffic at junctions (n = 51; 82%) was controlled by traffic lights in 32 cases and traffic signs in 19 cases.

The incidents were quite evenly distributed over the weekdays from Monday to Friday, ranging between 11 and 14 crashes, each. Only one accident on a weekend was reported. Half of the accidents (n = 31; 50%) occurred in the morning hours between 6.00 AM and 12.00 AM, another 44% (n = 27) in the afternoon hours until 6.00 PM. Only four cases were reported for the early morning hours between 12.00 PM and 6.00 AM and none for the evening hours between 6.00 PM and 12.00 PM. Accordingly, the large majority of collisions took place during daylight (n = 52; 84%), and only 10 during twilight or darkness (16%). Road surfaces were dry except for five accidents (8%) occurring on wet roads.

Collision Scenarios

In German police reports, conflicts between road users preceding a crash are characterised by so-called accident types (*Unfalltyp*) [15], a catalogue consisting of seven categories to describe the situation shortly before a crash. Based on these accident types and taking into account available crash documentation, 42 collisions (68%) were deemed relevant in principle for an electronic turn-assistant, nine (15%) were considered doubtfully relevant and 11 (18%) were non-relevant because the bicyclist was moving in an area near the truck that would not have been covered by the sensors. Two cases in which the truck was parked at nighttime and the bicyclist hit the rear of the trailer were included in this category as well.

Of the 42 collisions relevant for a turn-assistant, 35 cases (56% of all collisions) involved a truck turning right and a bicyclist travelling alongside on its right side, but moving straight on. In one case (2% of all collisions), not only the truck, but also the bicyclist intended to make a right turn at a junction and six bicyclists collided with a truck that was overtaking (10% of all collisions) (Fig. 3).

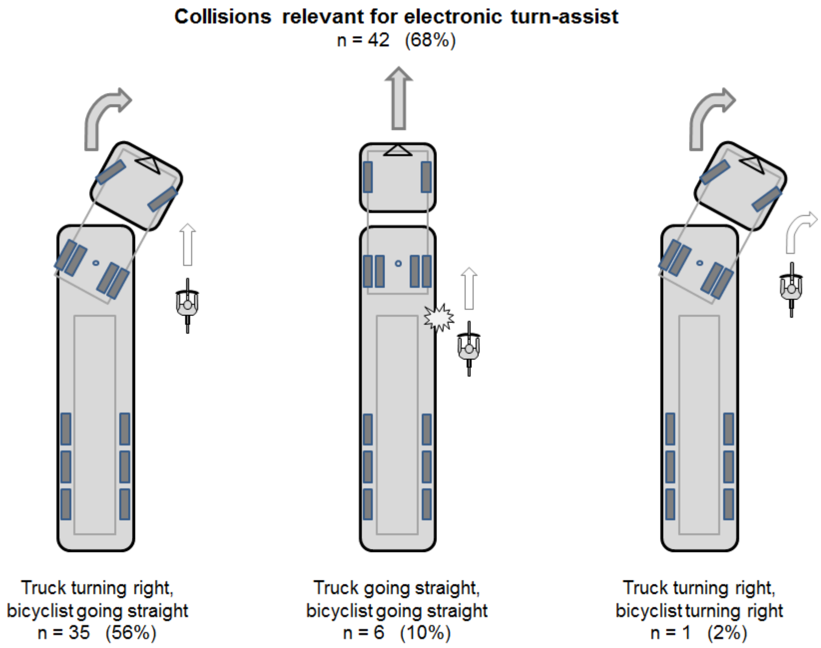

Fig. 3. Typical scenarios relevant for turn-assist, case numbers and percentages relative to all 62 crashes.

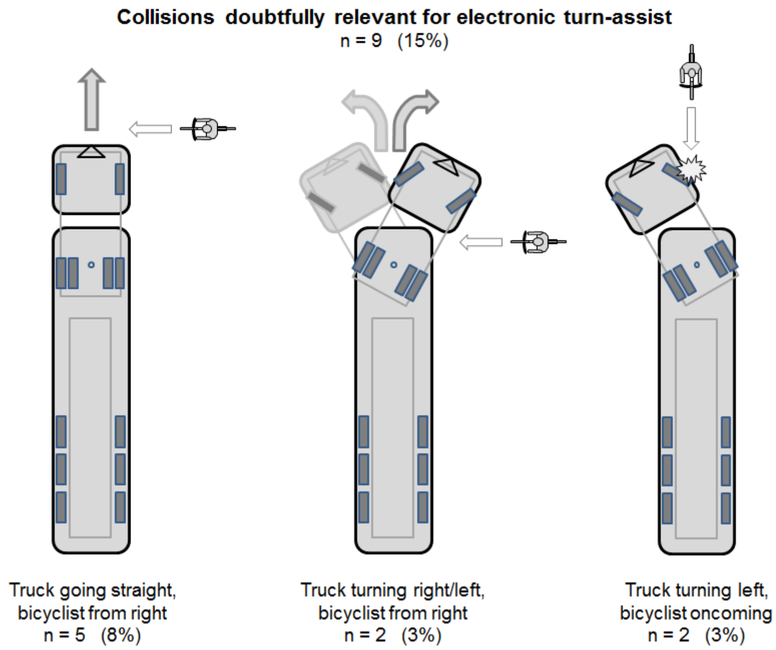

Fig. 4. Typical scenarios doubtfully relevant for electronic turn-assist, case numbers and percentages relative to all 62 crashes.

Nine collisions were judged as doubtfully relevant for a turn-assistant because the bicyclist was coming approximately perpendicularly from the right, thus leaving a very short period of time between entering the 3.75 metre wide field of detection and contacting the vehicle. In five of these collisions the truck was going straight and in four cases it turned either left or right crossing the path of an oncoming or crossing bicyclist who collided with the right side of the truck (Fig. 4).

Eleven collisions non-relevant for a turn-assistant included a variety of scenarios, among them two cases in which the truck made a left-turn while the bicyclist came perpendicularly from the left and four cases in which the bicyclist was approaching from the opposite direction and collided with the left side of the truck that was either going straight or making a left turn. In one accident, the truck was reversing and hit a bicyclist who was approaching from behind (Fig. 5).

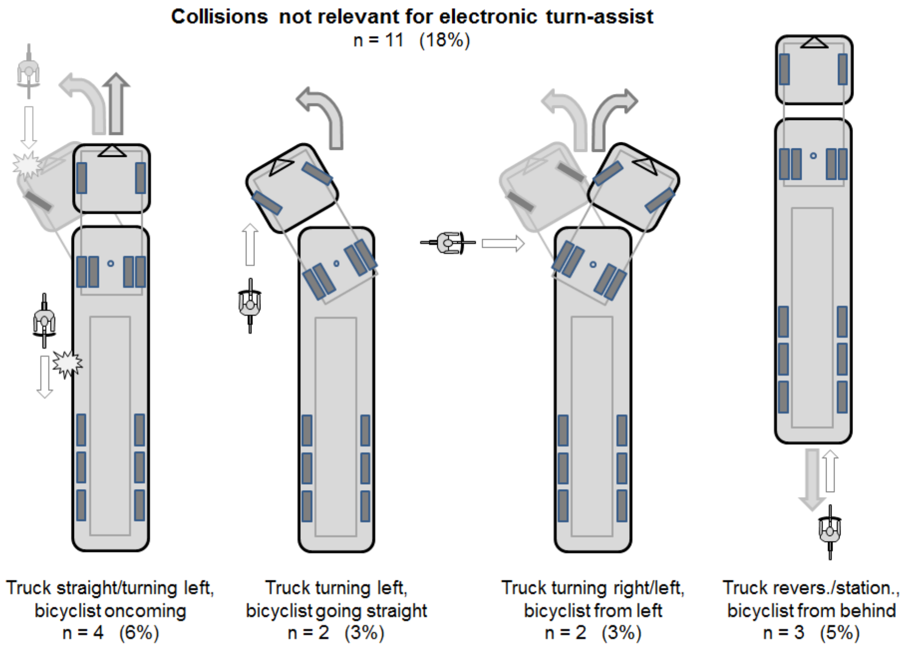

Fig. 5. Typical scenarios non-relevant for turn-assist, case numbers and percentages relative to all 62 crashes.

The zone of the first contact (see Fig. 2) between the bicyclist and the truck or the trailer was determined for 57 of the collisions. Table I provides the absolute number of affected zones on single rigid trucks and on truck-trailer combinations, separated by the truck or tractor and the drawbar-trailer or semi-trailer, respectively. Zone 2, i.e., the right front corner of the truck or tractor, was involved in more than one third of all crashes, followed by first contact in the right-hand area between the front and rear axle (zone 4). Areas like the left-hand side (zones 8 to 12) and the rear (zones 6 to 8) of the vehicle were only involved rarely.

TABLE I
FREQUENCY DISTRIBUTION OF CONTACT ZONES ON TRUCK AND TRAILER

Type of vehicle with contact		Contact zones on truck/semi-tractor or trailer/semi-trailer												
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**total**
single rigid truck		2	9	2	4	1	-	-	-	1	-	1	-	**20**
truck-trailer combination	truck/semi-tractor	3	13	2	2	1	-	-	-	1	-	-	4	**26**
	trailer/semi-trailer	-	-	-	5	3	1	1	1	-	-	-	-	**11**
total per zone		**5**	**22**	**4**	**11**	**5**	**1**	**1**	**1**	**2**	**-**	**1**	**4**	57

single rigid truck, right side (zone unknown): 2
truck-trailer combination, right side (zone unknown): 3

In the majority of crashes (n = 58), it could be safely established whether the truck was braking before the collision; in four cases it was unknown. In only seven accidents (12%) the driver was actually braking before the collision, in six of which the truck was going straight. In contrast to this, there was no pre-impact braking in 51 crashes (88%), evidently because the imminent collision was unnoticed. In fact, several drivers stated that they noticed something peculiar only because of noises from the bicycle being dragged over the pavement by their vehicle or because witnesses signalled them to stop after the collision. In more than half of all crashes the bicyclist got under at least one of the truck's wheels. Run-over took place in 33 cases (53%) whereas 29 cyclists were thrown to the ground after the first impact on the truck, but had no further contact with the wheels.

Truck Characteristics, Truck Driver and Bicyclist Demography

Among the 61 trucks of known body type 36 (59%) were vehicles for goods transport with curtain-sider or box superstructures. Nineteen of them were tractors with semi-trailers, eight were single rigid units and nine were rigid units with a drawbar trailer. Twenty-five trucks (41%) were vehicles typical of the construction and waste management industry, including dumpers, concrete mixers, garbage and sewage collecting trucks. Six were tractors with semi-trailers, 15 were single rigid units and four were rigid units with a drawbar trailer.

Vehicle age at the time of the accident could be determined for 57 trucks and semi-tractors, averaging 5.5 years of service and ranging between practically new vehicles to 20 years of age.

The truck drivers were male without exemption, their age ranging between 21 and 69 years (average 44.6 yrs.; median: 45.5 yrs.). Age was unknown for two drivers.

Among bicyclists, females accounted for 36 of the 62 cyclists (58%), males for 26 (42%), accordingly (Fig. 6). Female bicyclists were 49.7 years of age on average (median: 50.5 yrs.), males were 54.2 years of age on average (median: 56.0 yrs.), the difference not being significant (t-test; n.s.; $p = 0.47$). Of the 59 bicyclist for whom bicycle helmet wearing could be determined, only six (10%) were actually wearing a helmet.

Use of alcohol was reported by the police for none of the truck drivers and only in two cases for the bicyclist.

Bicyclist Injury Patterns and Severity

Due to the selection criteria for the cases, all involved bicyclists sustained injuries which were often quite severe. Eleven bicyclists were fatally (18%), 47 seriously (76%) and four slightly injured (6%) according to the definition used in German national statistics. The complete injury pattern could be established for all but four casualties. Even then, it was possible to derive the injury severity for the most severely affected body region and determine the MAIS value. Fig. 7–10 provide an overview of the injury patterns and severities.

MAIS3+ cases accounted for approximately two thirds among all casualties (n = 42; 68%) including fatalities, whereas only five injured (8%) were MAIS1. In 24 cases (40%), serious to critical injuries (AIS3+) were most prominent in the lower extremities which included fractures of the femur and open fractures of the lower leg to the same degree as instable fractures of the pelvic bones. Often, decollement injuries or injuries reaching into deep layers of the skin, rated as AIS2, were present either as the only injury to the leg or foot or in combination with fractures. Only about one third of the bicyclists received no or only slight injuries (AIS0 or AIS1) in this body region. The thorax ranked second in frequency of AIS3+ injuries with 18 cases (30%), consisting mostly of rib series fractures and lung lacerations. Serious to critical head/face injuries (AIS3+) occurred in 13 bicyclists (21%) which comprised primarily basilar fractures and a small number of brain contusions and subdural hematoma. In three of these cases, however, AIS6 head injury was found in the form of head crush or brain stem laceration. Serious to fatal (AIS3+) spinal injuries were present in six bicyclists (10%), the three most severe ones were related to run-over and occurred in conjunction with fatal injuries to the head or thorax. Nine bicyclists (15%) displayed AIS3+ abdominal injuries. With the exception of two cases, they were associated with run-over, too.

Collision Scenarios Relevant for Electronic Turn-Assist

Below, data analysis focuses on the collision scenarios that are considered to be relevant for an electronic turn-assist with the functionality described above. According to Fig. 3, this pertained to 42 collisions, 35 of which featured a truck turning right and a bicyclist moving alongside. These 42 crashes have been compared to the remaining 20 incidents which were deemed non-relevant for electronic turn-assist, i.e., being of doubtful or no relevance due to the course of the crash and the contact zones on the truck or trailer. The latter serve as controls for the analysis. Percentages are given relative to the size of the respective subgroup, i.e., 42 for relevant and 20 cases for non-relevant scenarios.

Road infrastructure and environmental conditions: With only one of the 42 relevant collisions occurring outside of built-up areas (2%) compared to four among the 20 non-relevant collisions (20%), this difference was statistically significant (Chi^2; $p < 0.05$), although based on small numbers. The proportion of collisions relevant for turn-assist that did not occur at crossings or T-junctions was slightly smaller than among non-relevant scenarios (17% vs. 20%), but not significantly (Chi^2; n.s.; $p = 0.75$). The distribution of incidents by weekday (Monday to Friday) was quite random and did not indicate a pattern depending on the subgroups of collision scenarios. None of the crashes that occurred during the early morning hours between 12.00 PM and 6.00 AM was related to collisions relevant for turn-assist, but only to non-relevant scenarios. In other words, all relevant crashes took place between 6.00 AM and 6.00 PM. In accordance with the time of the day, collisions relevant for turn-assist happened during daylight in 90% of relevant crashes as opposed to 60% for non-relevant incidents, the difference being significant (Chi^2; $p < 0.05$).

Truck characteristics and bicyclist demography: Based on the body type, 19 of the 42 trucks (45%) involved in collisions relevant for turn-assist were vehicles destined for goods transport meeting current manufacturer criteria for turn-assist availability. The remaining 23 consisted of 16 trucks used in the construction and waste management industry and seven distribution trucks with two axles for which an electronic turn-assistant is not yet scheduled. The distribution of vehicle ages of the 37 trucks involved in relevant crashes (age unknown for five trucks) did not differ much from that of trucks in non-relevant collisions.

There was a significantly higher proportion of female bicyclists among victims in crashes relevant for electronic turn-assist (n = 28; 67%) than in non-relevant collisions (n = 8; 40%) (Chi^2; $p < 0.05$). The average age of bicyclists involved in relevant collisions (54.2 yrs.; median: 53.5 yrs.) was higher than for those involved in non-relevant collisions (46.0 yrs.; median: 51.5 yrs.), but not significantly (t-test; n.s.; $p = 0.20$). Seniors 65 years of age and above accounted for 16 of the 42 cases (38%) relevant for turn-assistance and six of the 20 non-relevant cases (30%), also not significant (Chi^2; n.s.; $p = 0.53$).

Bicyclist injury patterns and severity: Fatally injured bicyclists accounted for nine of the 42 casualties (21%) in conjunction with scenarios relevant for turn-assistance, opposed to two fatalities among the 20 victims (10%) from collisions non-relevant for turn-assistance. However, the difference was not significant (Chi^2; n.s.; $p = 0.27$). The relative frequency of injuries per body region and grouped by AIS categories is given in Fig. 7–10. It also shows the proportions that relevant and non-relevant collisions contributed to the affected body regions and the injury severities found there. Considering that relevant scenarios accounted for 42 of all 62 collisions (68%), the differences in frequency between the two groups did not reach statistical significance, neither when separating between injury severities of AIS0-1 and AIS2+, nor when separating between injury severities of AIS0-2 and AIS3+ (Chi^2; n.s.; $p > 0.05$). With a 48% share (20 of the 42 bicyclists with known lower extremity injury severity) of AIS3+ for relevant collisions and a 22% share (four of the 18 bicyclists with known lower extremity injury severity) of AIS3+ for non-relevant collisions, the lower extremity region came closest to a significant difference (Chi^2; n.s.; $p = 0.07$) (Fig. 10, right). Also, AIS3+ abdominal injuries appear to be more prominent in collisions with relevance for turn-assistance: 19% (eight of the 42 bicyclists with known abdomen injury severity) in relevant collisions and 6% (one of the 17 bicyclists with known abdomen injury severity) in non-relevant collisions. AIS3+ thorax injuries, on the other hand, seem to be more frequent in non-relevant collisions: these accounted for 42% (eight of the 19 bicyclists with known thorax injury severity) compared to 24% (10 of the 41 bicyclists with known thorax injury severity) in relevant collisions.

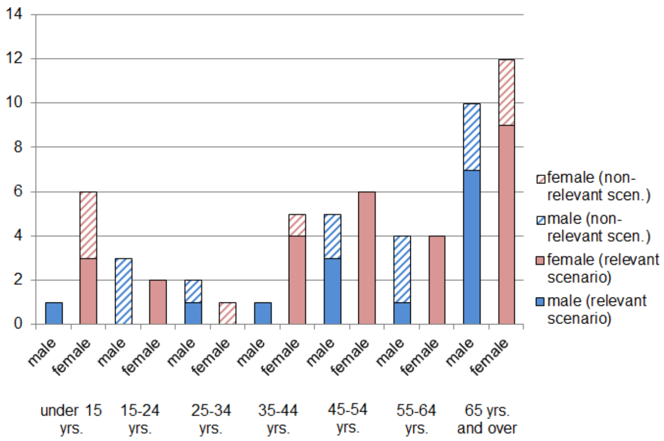

Fig. 6. Bicyclist gender and age distribution.

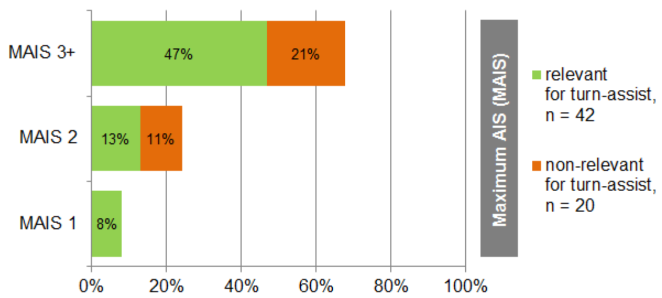

Fig. 7. Relative frequency of MAIS categories and proportion of relevant and non-relevant scenarios.

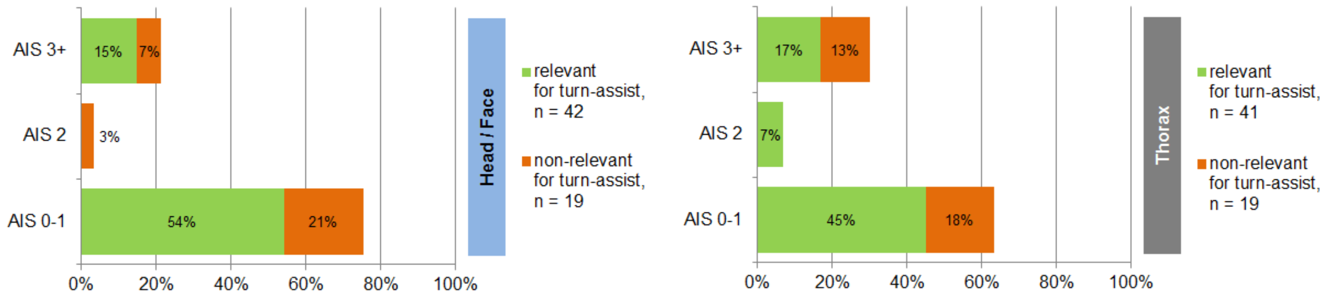

Fig. 8. Relative frequency of AIS categories and proportion of relevant and non-relevant scenarios for head/face (left) and thorax (right).

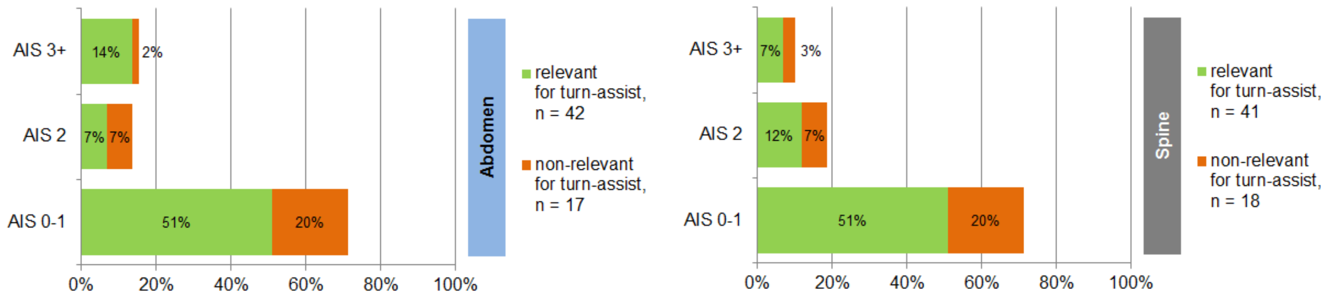

Fig. 9. Relative frequency of AIS categories and proportion of relevant and non-relevant scenarios for abdomen (left) and spine (right).

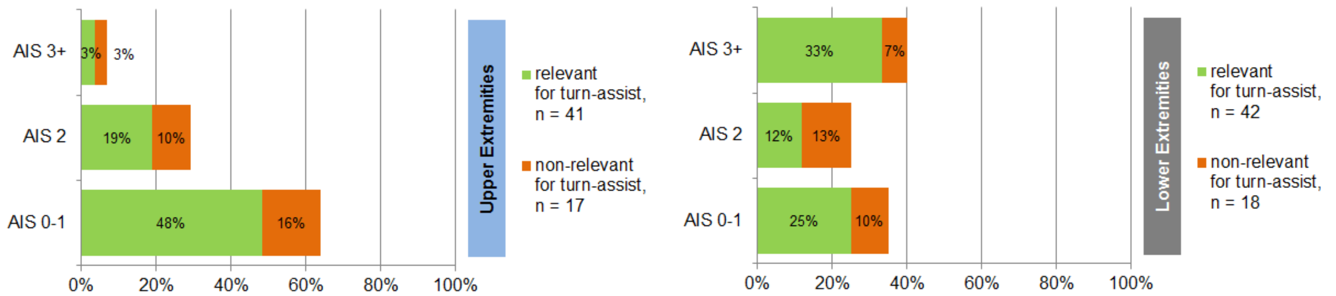

Fig. 10. Relative frequency of AIS categories and proportion of relevant and non-relevant scenarios for upper extremities (left) and lower extremities, including pelvis (right).

Run-over mechanism: In 64%, collisions relevant for a turn-assistant showed a high proportion of an injury mechanism caused by the truck or trailer running over parts of the bicyclist's body compared to 30% in collisions deemed non-relevant for turn-assistance (Chi^2; $p < 0.05$). Moreover, women were overly represented in accidents involving run-over. 79% of these victims were females as opposed to 34% females in non-run-over crashes (Chi^2; $p < 0.001$). With 27% fatalities in contrast to 7% without run-over, this mechanism is closely related to very severe outcome, too (Chi^2; $p < 0.05$). For other variables, like the type of truck, infrastructure or lighting conditions, there was no indication of any relation to run-over.

Perceptibility of bicyclists by turn-assistance: Based on photos and layouts of the accident site, the areas 10 metres and 20 metres before the point of collision were visually inspected regarding any impairment for the detection of the bicyclist on its path. Out of the 42 collisions relevant for turn-assist, this check was carried out for 39 crashes with sufficient information. In 34 cases (87%) there was not any obstruction identified at 10 metres or 20 metres and the path of the bicyclist was well within 3.75 metres distance from the right side of the truck. This included 28 right-turn situations and the six overtaking and lane-change manoeuvres. Of the five cases with insufficient perceptibility, one bicyclist would have been in the field of detection at 10 metres from the point of collision, but not at 20 metres due to the S-shaped layout of the bicycle path just before the junction. Vice versa, another bicyclist would have been detectable at 20 metres, but likely had a lateral distance of more than 3.75 metres at 10 metres before the point of collision. A lateral distance of more than 3.75 metres for the entire length was present only once. A blocked view on the bicyclist by other vehicles at 20 metres was suspected in another case.

IV. DISCUSSION

The proportion of bicyclists killed in crashes with heavy trucks lies in the low two-digit percentage range of all fatally injured bicyclists in Germany [1, 16]. For 2015, the German national statistics reported 56 bicyclists who had died in accidents with semi-tractors, trucks over 3,500 kg GVW and *other goods vehicles*, amounting to 15% of all 383 bicyclists killed in road traffic [16]. The magnitude of surviving victims with very severe and potentially disabling injuries is largely unknown, however. A large percentage of these accidents are presumed to be attributed to trucks turning and crossing the path of a bicyclist who is riding alongside. With bicycle use becoming more popular also as a daily mode of transport and similar problems being reported from other European countries like the UK and the Netherlands, the need for development of technical countermeasures rises. Recently, an electronic turn-assistant for heavy trucks became commercially available, however, as an option and only for a certain range of truck models.

Our study was aimed at providing a comprehensive view of crashes between bicyclists and heavy trucks in order to identify particularly the share of right-turn manoeuvres and similar collision configurations that are most likely to be addressed by turn-assistance in comparison to other crash scenarios. Moreover, our intention was to provide further detail on the circumstances of these crashes and the resulting injuries for better understanding of the factors leading to these accidents and their outcome.

Our study has some limitations, the relatively small number of cases being the most obvious one. This is due to the comparably low frequency of these types of accidents and common to all in-depth studies on this subject. The minimum amount of EUR 30,000 of estimated claim costs used as a selection criterion for the cases may have caused a slight bias towards more severe injuries. Still, our study sheds a light also on collisions beyond accidents with right-turning trucks and fatal outcome and may therefore contribute to a bigger picture of the conflicts between heavy trucks and bicyclists. The relatively large proportion of cases from 2012 in the material is not expected to skew the picture since neither road infrastructure nor heavy vehicle technology geared to protecting vulnerable road users changed substantially between 2007 and 2012.

In fact, right-turn manoeuvres of trucks at junctions represented more than half of all collisions though there were also a few accidents during left turns. Consequently, the majority of impacts against the truck or its trailer took place on their right side or right front corner. These results are in line with findings of other studies that noted a strong prevalence of nearside-turns and nearside locations for the first contact. Over one-third of first contacts in our material took place on the right front corner of the driver's cab, with nearly three quarters of these collisions resulting in subsequent run-over. The side area in front of the rear wheels which is protected by a side-underrun guard, except on N2G and N3G vehicles, was involved only half as frequently and presented a few cases of run-over, still. Not surprisingly, nine of the 11 fatalities in the material were associated with a run-over mechanism, often occurring at low speed of both the truck and the bicyclist.

Nevertheless, a fatality rate of 18% and 61% of MAIS3+ injured among the survivors underscore the magnitude of severe outcome in collisions with heavy trucks, in general. The large proportion of multiple and complex fractures in combination with severe soft tissue and muscular damage that was found particularly in the lower extremities including the pelvis is a major reason for long clinical treatment and the high potential for resulting disabilities. The formally assigned AIS for the affected body region often cannot reflect the physical damage due to several and extensive injuries. These injury patterns among survivors were associated with run-over by one or several of the vehicle's wheels and were twice as frequent in collisions with turning trucks as in the remainder of crash scenarios. On the other hand, serious thoracic and head injuries were of considerable importance for the overall injury severity as well. While some appeared in conjunction with run-over of these body regions, others likely resulted from the impact of the bicyclist on the ground, especially in elderly bicyclists.

The results from our study give rise to the assumption that electronic turn-assistance that recognises bicyclists present in a field of approximately four metres to the right of the vehicle has a considerable potential to avoid fatal and severe injuries. With the truck travelling at low speed in most turning manoeuvres in good weather and lighting conditions, the prerequisites for safe detection are comparably favourable for such a system. For the majority of cases analysed, there was neither a significant obstruction present for at least 20 metres before the point of collision, nor was the bicyclist riding alongside the vehicle outside of the lateral range of the sensor field. However, it is not known how the effective field of detection would be reduced during the period when the truck, particularly when pulling a trailer or semi-trailer, conducts a hook-shaped manoeuvre when negotiating around tight street corners. Therefore, early detection while the truck's motion is still parallel to the bicyclist's path may be of particular importance to alert the driver in time. It is obvious that an understanding of the system's capabilities and limitations by the truck driver is crucial for accepting electronic turn-assistance and correctly interpreting its warnings. Under no circumstances should the driver rely solely on the system, on the one hand, or misinterpret or disregard its warnings, on the other hand. These human-machine interface aspects could not be addressed in the present study. The most limiting factor, however, was – assuming the present sales policy for the system – that a turn-assistant would have been available for only about half of the heavy trucks (11,900 kg GVW and over) involved in relevant collisions in the material. On the other hand, the relatively fast renewal of the fleet among heavy trucks offers the possibility to introduce electronic turn-assistance within a relatively short period of time. Based on the age of the vehicles involved in relevant crashes one can expect that over 70% would feature turn-assistance after six years, given that fitment of newly registered trucks of all types would be obligatory in Germany.

Regarding the population at risk and the course of the crash, the findings in our study differ somewhat from the characteristics of bicycle crashes in general. Usually, males represent the larger proportion of casualties among bicyclists. For instance, men represented 61% of injured cyclists who collided with passenger cars in Germany [17]. In contrast to this, females accounted for 58% of the injured bicyclists who collided with heavy trucks and in 67% they were especially prominent in collisions relevant for turn-assistance. The reasons for this phenomenon are not quite clear, yet. It can be speculated that more women ride their bicycle during the time of the day when trucks operate in urban areas, thus, their over-representation being primarily a result of exposure. On the other hand, a closer look at the pre-crash phase of many collisions, particularly in truck right-turn situations, suggests that many of these bicyclists may not have been aware of the potentially dangerous situation and were riding alongside the truck for several seconds, apparently often near the truck cab, and did not reduce their speed or make any evasive manoeuvres until the last moment. In fact, bicyclist gender was related stronger to run-over than to right-turning situations. One could hypothesize that either the turning manoeuvre came unexpectedly for the bicyclists or they felt rather safe when riding near the cab and perhaps expected the driver to be aware of their presence. However, this area next to the driver's cab is particularly difficult to monitor by means of direct and indirect vision. The driver's behaviour, especially whether he had checked the vicinity properly when initiating the turning manoeuvre, is largely unknown, but would be important to know, also with regards to future interaction with electronic turn-assistance systems.

V. CONCLUSIONS

Truck-to bicyclist crashes are comparably infrequent but bear a large risk for fatal or very severe injuries when happening. With increasing use of bicycles as a healthy and environmentally friendly means of transport, stronger efforts to prevent these kinds of accidents are required.

With respect to real-world crash configurations, electronic turn-assistance is a promising approach to reduce the number of incidents or at least mitigate their outcome. The prevailing conditions at the accident site are mostly favourable to ensure high effectiveness of such driver-assistance systems. However, the fitment of turn-assistance should not only include heavy goods transport vehicles, but also specialty trucks like dumpers, concrete mixers or garbage trucks as these represent a significant proportion among involved heavy vehicles.

Many of the analysed crashes were considered preventable, but seemed to be caused largely by misunderstanding of the situation, both on the part of truck drivers and bicyclists. This aspect requires further research. Trainings and campaigns to increase awareness should be tailored to the specific population at risk.

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