Fatal Powered Two-Wheeler (PTW) crashes in Germany – an in-depth study of the events, injuries and injury sources

Rikard Fredriksson, Bo Sui

Abstract The powered two-wheeler (PTW) riders is a group where fatalities are not decreasing at the same rate as for other road-users. It is also a group that is likely to increase in the future due to traffic congestion. To develop countermeasures to protect PTW drivers, it is necessary to understand the accident event in detail, the injuries and their sources.

The German database GIDAS was queried for PTW crashes where the driver was injured (cases with passengers were excluded). During the time period 1999–2014, cases involving 3,361 PTW drivers were collected, sustaining 10,917 injuries. Eighty (80) drivers sustained fatal injuries in 79 crashes. The fatal cases were selected for detailed study regarding injuries and their sources.

Each case was studied in detail to conclude the detailed accident event and the most likely source of fatal injury. It was found that PTW losing control and PTW not being noticed by another vehicle were the most common accident scenarios leading to a fatal PTW crash. The most common injury sources were passenger cars, especially the lower parts of the cars, followed by surrounding objects, mainly guard-rails and trees.

A battery of countermeasures was proposed to improve the protection of PTW drivers from fatal accidents. Countermeasures that are worth promoting or investigating further are innovative helmet or jacket designs, improved PTW visibility, guard-rail redesign, anti-lock brakes and stability control, car-/truck-mounted warning and auto-brake systems, improved car frontal energy absorption and under-run protection for heavy vehicles.

Keywords powered two-wheelers (PTW), fatal, scenario, injury source, injury.

I. INTRODUCTION

Worldwide half of the 1.24 million traffic fatalities yearly are vulnerable road-users. The largest group of these are powered two-wheeler (PTW) riders: every year 285,000 PTW riders are killed in traffic accidents, which makes up 23% of all traffic deaths [1]. In Europe this group makes up 15% of fatalities in road traffic, and although there has been a reduction in PTW fatalities in Europe, it has been a slower decline than for overall traffic fatalities [2].

Two major accident studies have been performed for PTW accidents. The MAIDS report was presented in 2008, in which an extensive range of 921 PTW accidents in five countries in Europe were studied [3]. A large majority of the injured PTW riders were male, and the head was the most commonly injured body part, while for fatal accidents spine and chest were also commonly injured. A frequent accident partner and injury source were passenger cars, but for fatal accidents a larger share were single accidents. In the car crashes, the most common part impacted was the side of the car, and a majority of the car accidents occurred at intersections. In an earlier study from the 1980s, Hurt et al. performed an extensive study on US motorcycle accidents [4]. This study also showed the frequent scenario of motorcycle-to-car crashes at intersections, where the car violated the motorcycle’s right-of-way. Further, the Hurt et al. study pointed out the problem of conspicuity, i.e. the problem that other road-users failed to detect the powered two-wheeler.

Different countermeasures are available. Helmets are effective countermeasures to reduce head injury [4-6]. Anti-lock brakes have now been introduced broadly on powered two-wheelers and have proven to be effective in reducing accidents and injuries [7,8]. Other countermeasures introduced recently, although not yet proven in efficiency, include motorcycle airbags [9], inflatable jackets [10] and stability control [11]. Rizzi et al [12] studied the potential of different countermeasures using Swedish fatal PTW crashes from a retrospective database

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covering all fatal road traffic accidents in Sweden. This study concluded that anti-lock brakes on the PTW and safe intersections on rural roads to be most promising countermeasures.

The aim of this study was to study the most extensive on-scene, in-depth fatal accident data available with regard to injuries, accident scenarios and injury sources and consequently to provide input to possible countermeasures to mitigate those injuries.

II. METHODS

Database and inclusion criteria

The German In-Depth Accident Study (GIDAS) database was used to extract crash data for this study. GIDAS accident investigation teams operate in Dresden and Hannover and their surroundings. The sample area contains both rural and urban traffic and is chosen to represent, as closely as possible, a “mini Germany”. Work shifts are equally distributed between night and day, with investigators attending accident sites using “blue-light” vehicles, along with police and ambulance personnel, when personal injuries are suspected. To investigate both vehicular and human factors in maximum detail, the GIDAS teams consist of both technical and medical personnel. At least one confirmed personal injury is required for inclusion in the database.

The GIDAS database was queried for accidents with injured riders of PTWs. The parameter ZWART (type of two-wheeled vehicle) was used to define powered two-wheelers, where the following were included in the study: motorized bicycle, pedal moped, moped, moped with less than 50 cc, motorcycle with less than 125 cc, motorcycle, scooter up to 80 cc, scooter over 80 cc. Not included from the ZWART category were bicycle, motorcycle with sidecar, trike, quad, motorized scooter trikes, other and unknown. Cases with passengers were excluded, due to the complexity of understanding injury patterns. Only cases with complete reconstructions were included.

This query resulted in 3,360 injured PTW riders, with at least one AIS1+ injury (AIS 2005). Of these, 79 accidents were fatal, with 80 fatally injured riders (in one case, two PTWs crashed with each other and both riders were killed). In summary, the following inclusion criteria were applied:

- cases collected 1999–2014;
- powered (motorized) two-wheeler;
- driver-only cases (cases with passenger excluded);
- all PTW driver ages;
- fatally injured, within 30 days.

Injury sources

In this study, sources of the fatal injury of the PTW driver were analyzed. Injury sources were grouped into “Surrounding”, “Car”, “Heavy vehicle” or “Other PTW”. Objects from the road, infrastructure and off-road objects were then defined as “Surrounding”. “Surrounding” was then further divided into the sub-groups “Guard-rail”, “Other fixed objects”, “Road surface”, “Off-road”. “Off-road” objects were defined as any object that was not part of the road or built-up infrastructure, so these then included trees, stones or ditches. Rails along the road designed to keep a vehicle from leaving the road were defined “guard-rail”. “Other fixed objects” included street poles, lamp-posts, buildings or parked cars. When a passenger car or van was concluded as the injury source, this was defined as “Car”. When the injury source on the car was concluded to be located below the waist line of the car, this was defined as a low impact. High impacts were then to the glass parts, or the A-, B- and C-pillars. In the “Heavy vehicle” category, vehicles such as trucks, buses or tractors were included. When it was concluded that the PTW driver was fatally injured from being driven over of the car of heavy vehicle, this was defined as “run over”.

III. RESULTS

As mentioned in the Methods section, cases with passengers were not included in the study. The average rider was a male (99%) and 37 years old. In all cases in the study the rider wore a helmet. Sixty-three (79%) of the drivers rode a motorcycle (>125 cc), 6% a light motorcycle (<125 cc) and 10% a moped (<50 cc). The mean travelling speed was 83 km/h before the event started, and reached an average speed of 69 km/h at the time of impact. Crashes occurred at impact speeds from 5 km/h up to 145 km/h, and 60% of the accidents happened in a rural setting (TABLE 1). Head injury was the most common cause of death (48%), followed by thorax injury (23%) and spine injury (10%), while 4% died from cumulative causes (Fig. 1).

TABLE 1
CRASH DETAILS (N=80)

	Mean	*Min.*	*Max.*
Age (years)	37	16	85
Travelling speed (km/h)	83	25	184
Impact speed (km/h)	69	5	145
Registration year	1996	1980	2009
Male	99%		
Helmet	100%		
Urban/rural	40%/60%		

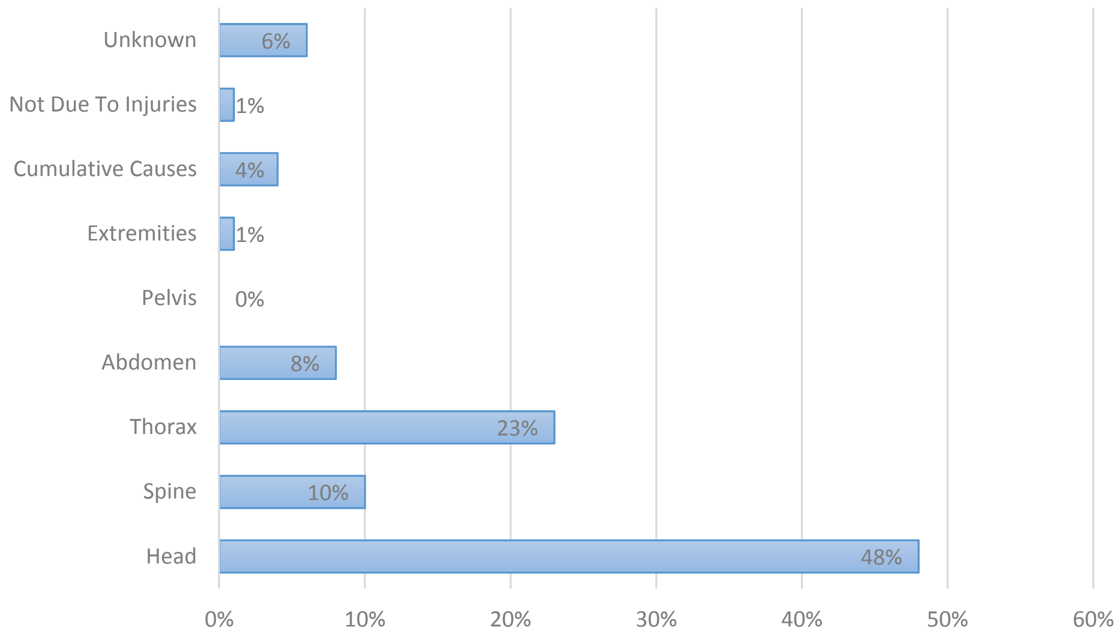

Fig. 1. Localization of fatal injury (N=80).

Scenario analysis – pre-crash event

Next, each case was studied closely to conclude the detailed scenario leading to the crash. The most common event was found to be the PTW losing control, leading to a crash, followed by an oncoming vehicle turning or overtaking in front of the PTW. In addition, the two events of either a PTW overtaking leading to a crash or a vehicle in the same direction turning in front of the PTW were also common (see Fig. 2).

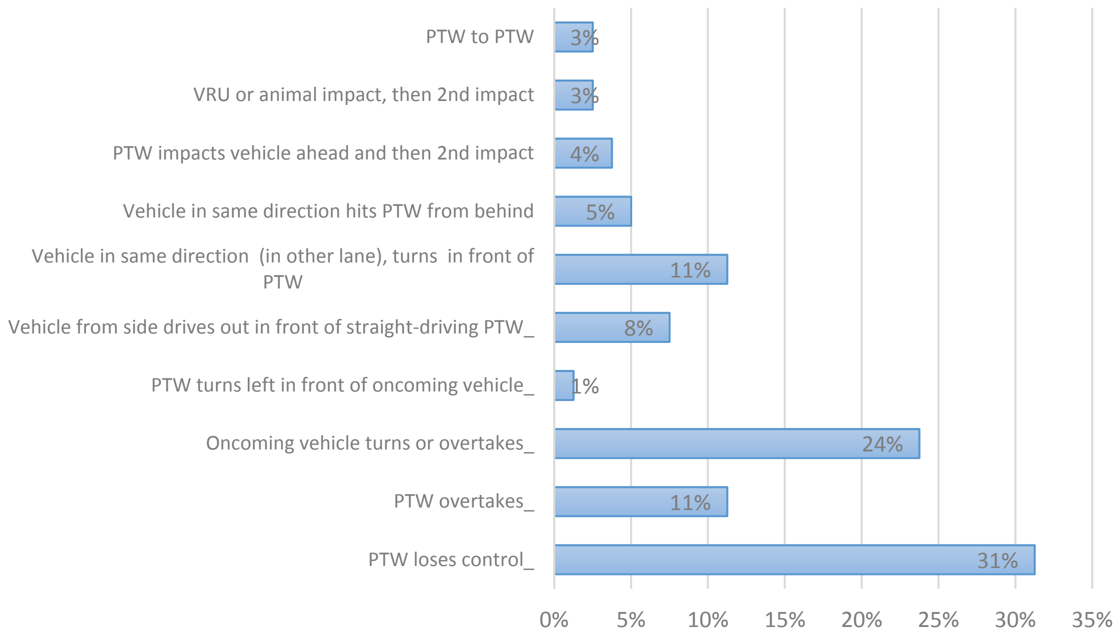

Fig. 2. Accident scenario distribution (N=80).

The most common events were studied in further detail in order to gain more understanding about the details of the events and the source of injury. When the "PTW loses control" occurred (n=25), the driver most commonly impacted an object (n=18) (see Fig. 3). The object was, in most cases, a guard-rail or a tree. In some of the cases the PTW driver impacted or was ridden over by an oncoming vehicle (n=7). For details, see also complete overview in Fig. A 1 in Appendix.

The second most common event was crash to an oncoming vehicle when it was turning or overtaking in front of the straight-driving PTW (n=19). In the large majority of these events, the PTW driver impacted the front or side of the oncoming vehicle (n=14). In four cases the PTW driver was ridden over by the vehicle, and in one case it could not be concluded if it was only a vehicle impact or if run over was involved (see Fig. 4).

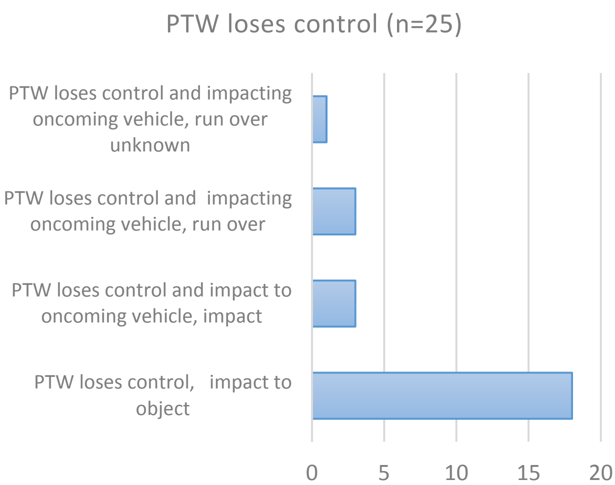

Fig. 3. Detailed scenario distribution of scenario "PTW loses control" (n=25).

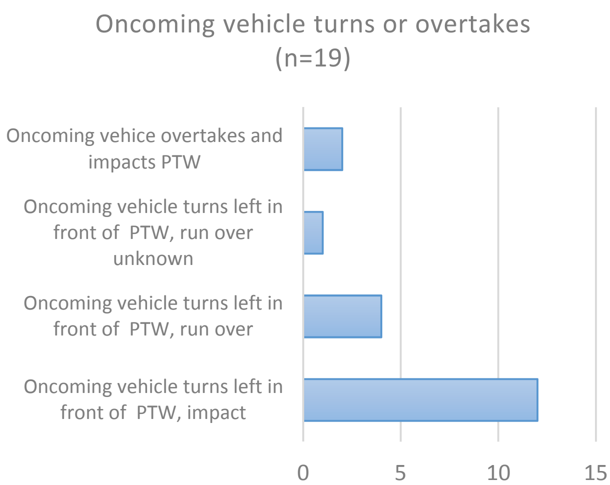

Fig. 4. Detailed scenario distribution of scenario "Oncoming vehicle turns or overtakes" (n=19).

The third most common event (n=9) leading to a fatal crash was the PTW overtaking another vehicle. It was then most common that the PTW driver impacted the front or side of an oncoming vehicle (n=3), or was run over by the oncoming vehicle (n=2). In two cases the PTW driver lost control when overtaking and slid into an object. (See Fig. 5)

Equally common was the event when a vehicle ahead and driving in the same direction as the PTW, but in another lane, turned in front of the straight-driving PTW (see Fig. 6). This most often led to an impact to the front or side of the vehicle (n=6), but in two cases it also led to a second impact to an object for the PTW driver.

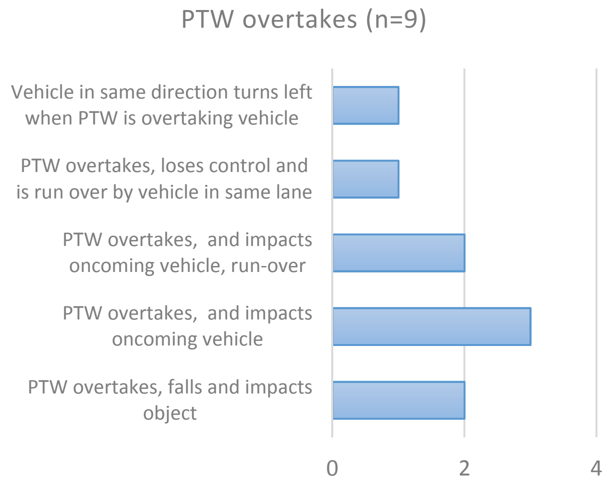

Fig. 5. Detailed scenario distribution of scenario "PTW overtakes" (n=9).

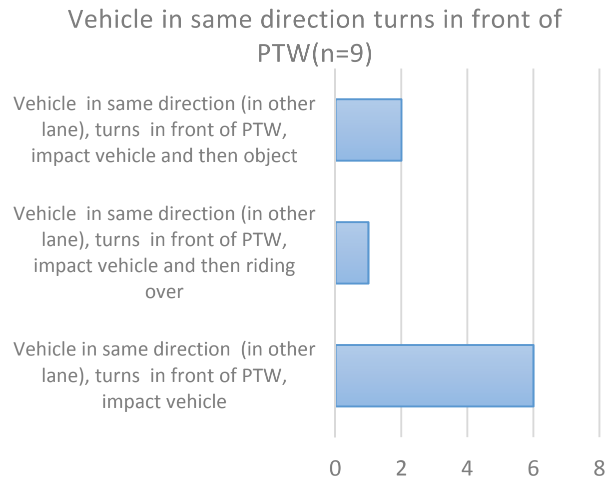

Fig. 6. Detailed scenario distribution of scenario "Vehicle in same direction turns in front of PTW" (n=9).

Injury sources: in-crash analysis

Further, in each case the most likely source of fatal injury was concluded. (See Fig. 7 and Fig. A 2) Car was estimated as the primary fatal injury source in 51% of the cases. In 33% of the cases the surrounding was estimated to cause the fatal injury. In 14% of the cases a heavy vehicle impact was estimated as fatal injury source. Run over by car or heavy vehicle was estimated as the cause in 11 of the 80 cases (14%).

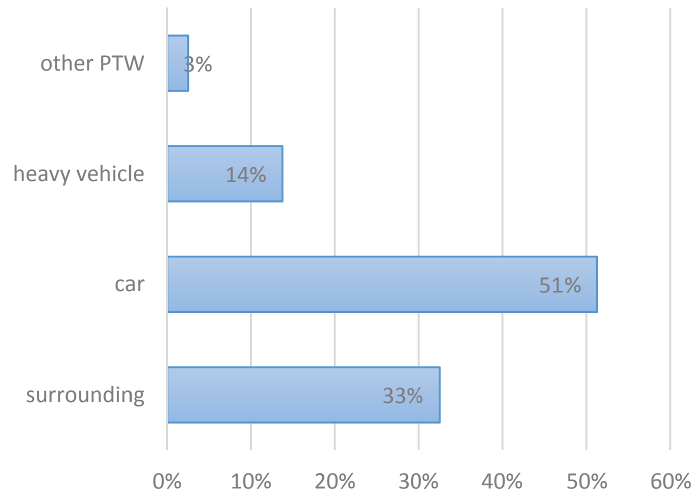

Fig. 7. Estimated fatal injury sources grouped, all cases (N=80); see Appendix for more detail.

As shown above, in the overview of injury sources (Fig. 7), in 33% (n=26) of the 80 fatal cases the surrounding was considered the main cause of fatal injury. The main injury causes in the surrounding was guard-rail and off-road objects (see Fig. 8). For the off-road objects trees were predominant (n=7), but ditches were also injury sources in a few cases (n=3).

Fig. 8. Distribution of “Surrounding” injury sources (*left*) (n=26) and case examples of “Surrounding” injury sources, guard-rail and off-road (tree) (*right*).

The car was the largest fatal injury source for the PTW drivers in the study, as shown earlier in the overview of injury sources (Fig. 7), with 51% of the fatal injury sources. Car injury sources were dominated by car front impacts (41%) and car side impacts (29%) (see Fig. 9 (*top*)). A large majority of the car injury sources were located low on the car, such as the bumper area in the front, or the door lower parts or fenders on the side – see examples in Fig. 9 (*bottom*). The car running over the PTW driver was estimated to cause the fatal injury in 15% of the car impacts, and in 10% it was not possible to determine whether it was a low car impact or a run-over that caused the fatal injury.

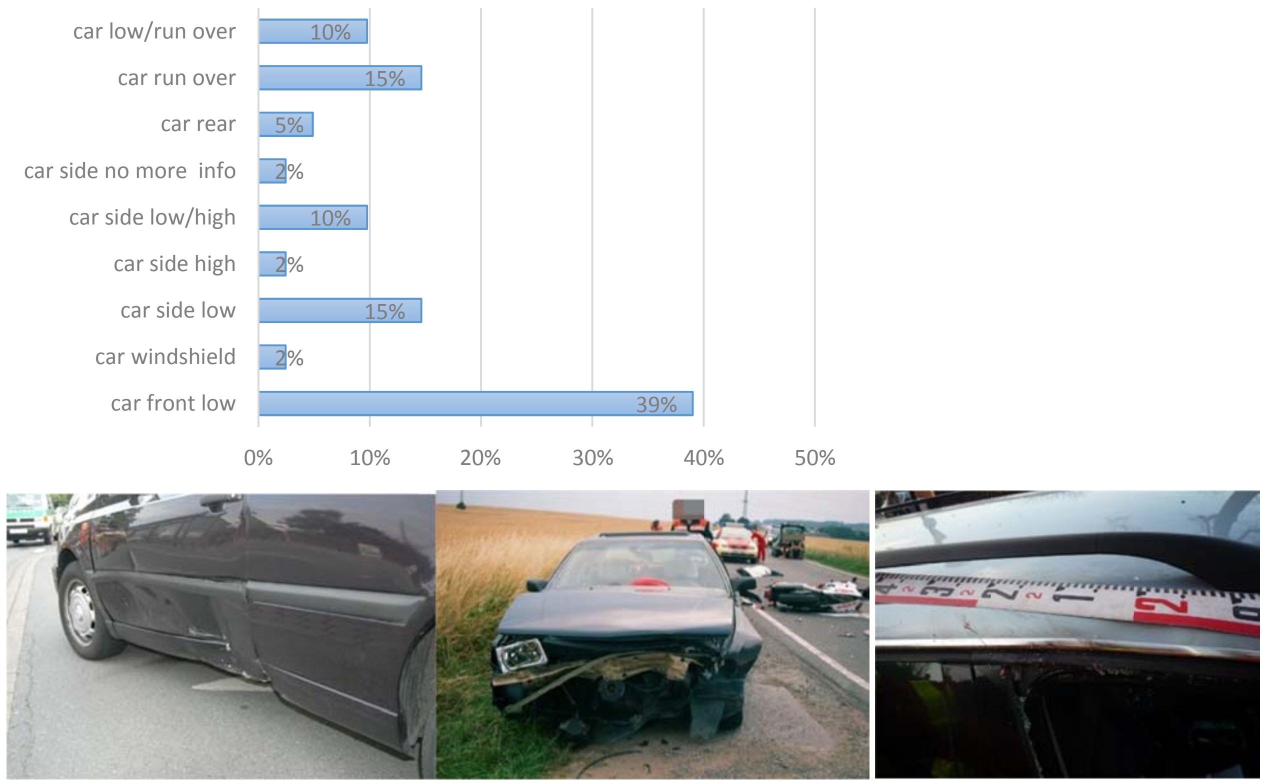

Fig. 9. Distribution of “Car” injury sources (*top*) (n=41), and case examples of Car injury sources “car side low”, “car front”, “car side high”(*bottom, from left to right*).

Heavy vehicles were estimated as the main cause of fatal injury in 14% of the fatally injured PTW drivers in the study, as shown earlier in the overview of injury sources (Fig. 7). A larger share, compared to car impacts, were estimated to be caused by run-over for heavy vehicles (Fig. 10).

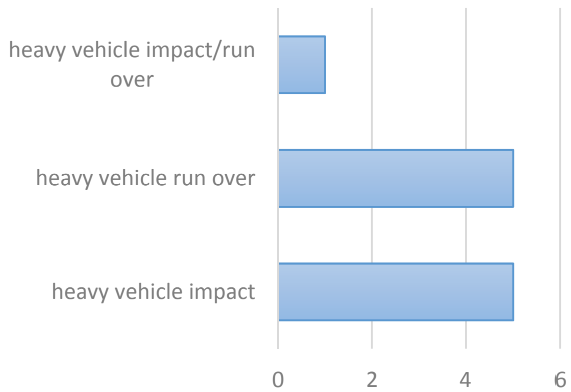

Fig. 10. Distribution of “Heavy vehicle” injury sources (n=11).

Injuries in detail

The distribution of fatally injured body regions was compared between different counterparts causing the fatal injury of the PTW driver. For both vehicles and surrounding as injury sources, the head was the most common. Thorax was more commonly fatally injured for vehicles, compared to the surrounding as injury sources (Fig. 11). However, caution should be taken since some sub-groups have low number of cases, e.g. heavy vehicle is only 11 cases.

For vehicle injury sources, when dividing vehicle impact and run-over it is difficult to draw a conclusion if there is a different injury distribution (Fig. 12). This may again be due to the low number of cases in one of the sub-groups (run-over only consisted of 11 cases).

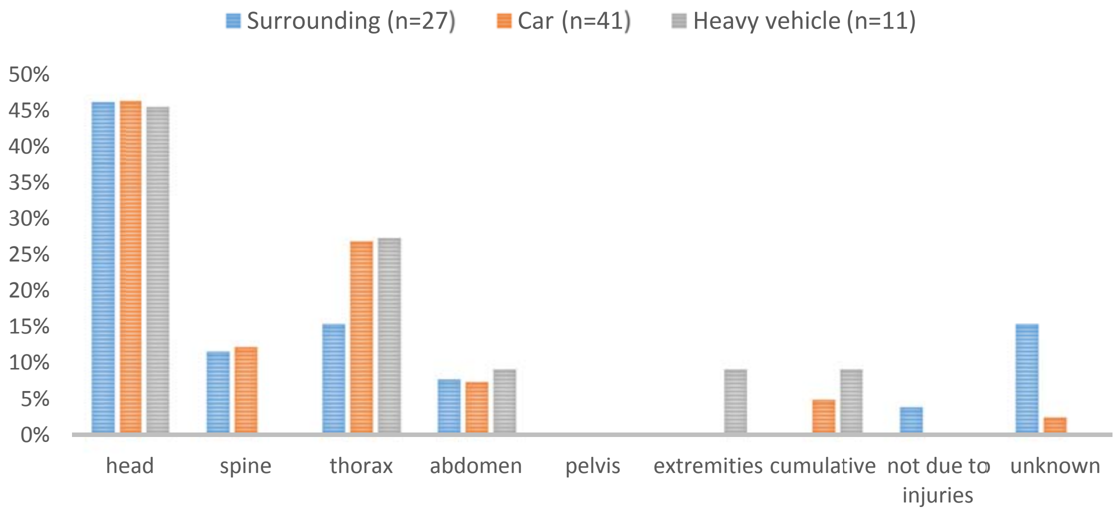

Fig. 11. Distribution of fatally injured body regions for different injury sources (N=80).

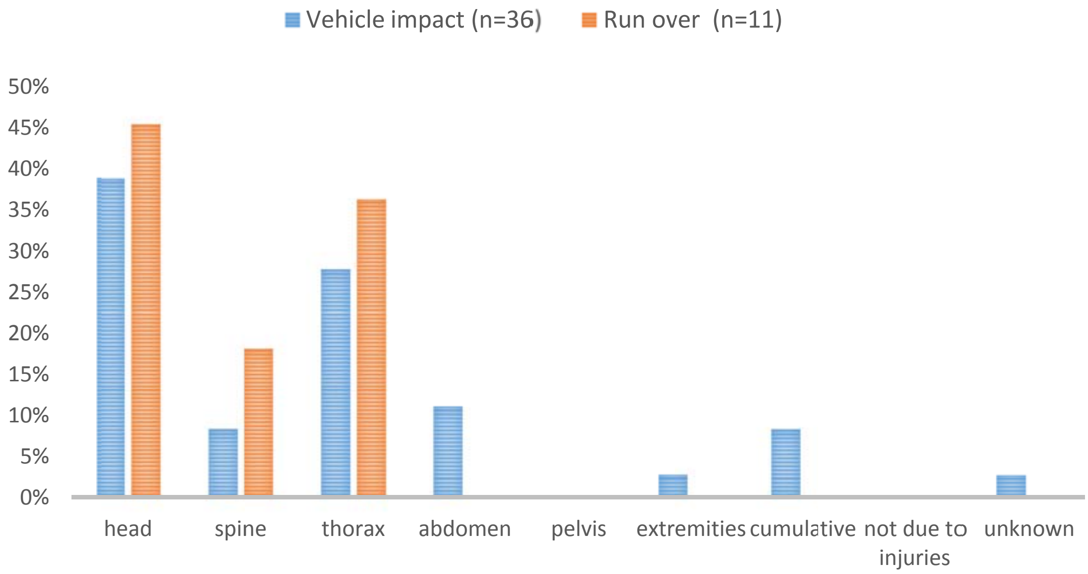

Fig. 12. Distribution of fatally injured body regions for different types of vehicle injury sources (n=47).

Potential countermeasures

An analysis combining accident scenarios and injury sources was performed to conclude possible countermeasures designed from infrastructure, car and PTW perspectives (Fig. 13). For the infrastructure, better designed guard-rails would potentially address 14% of the fatal accidents. The PTW was losing control in 35% of the accidents, indicating that ABS or stability control could be a potential countermeasure in these cases (all scenarios called "PTW loses control" plus the overtaking scenarios where the PTW driver lost control when overtaking and hit an object or was driven over by a vehicle in the same lane: all scenarios in Fig. 3 and two scenarios in Fig. 5). In 45% of the fatal cases it seemed that the PTW was not noticed by the car or heavy vehicle driver before impact, and therefore better PTW conspicuity or vehicle-based warning or AEB systems able to detect PTWs could be effective in these cases (all scenarios where the opponent vehicle was turning in front of the PTW or driving out in front of a straight-driving PTW or impacting straight-driving PTW from rear: all scenarios in Fig. 4 and Fig. 6 plus scenario "Vehicle from side drives out…" in Fig. 2). If a PTW-based warning system could be developed, this could be effective in 14% of the cases where it seemed that the PTW driver did not notice the other vehicle, which it later impacted (all scenarios where the PTW turns or overtakes in front of another vehicle). If the cars could be designed with better energy absorption all around the car body, this could address up to 39% of the fatal cases in this study (all accidents where a car was the injury source and run-over was not involved: see Fig. 9). Finally, if cars or heavy vehicles could be designed with protection to prevent running over the PTW driver, this would address 14% of the fatal accidents.

Since some of these fatal cases are potentially addressed by more than one countermeasure, it is not possible to simply add them up. Therefore, this was checked case-by-case. It was found that in each case the accident was addressed by at least one countermeasure, so when combining all countermeasures 100% of the accidents were addressed.

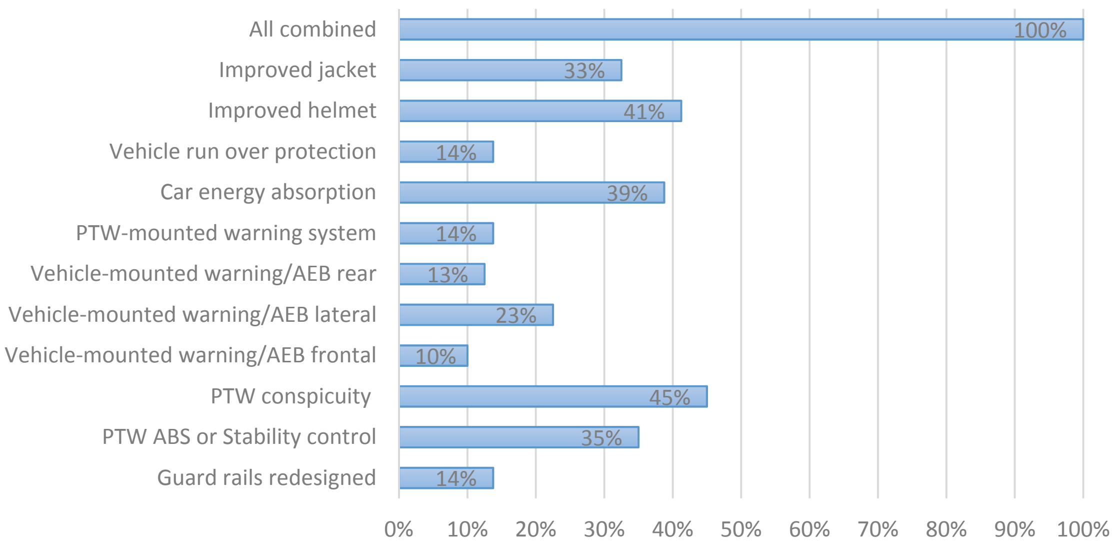

Fig. 13. Distribution of fatal accidents potentially addressed by various countermeasures (N=80).

IV. DISCUSSION

Head was the most common body region for fatal injury, followed by thorax, so it is important to closely assess the helmet design. It is worth studying whether it is possible to make significant improvements in the helmets. Possibly, it is also worth looking into innovative designs of PTW jackets for better protection. Inflatable jackets exist on the market, but it is important to have a reliable sensor to ensure it activates only when needed [10].

From infrastructure point of view, the guard-rail was a common injury source and if they could be redesigned, this could potentially be an effective countermeasure to reduce PTW driver injury. Off-road objects, such as trees, were also common injury sources, so removal of trees close to roads is also important. Rizzi et al also pointed out improvements of barriers and road-side as effective countermeasures [12]. But for both of these injury sources, anti-lock brakes (ABS) and stability control could be effective countermeasures to avoid the impact occurring. ABS is now common on new motorcycles and has proven to be effective [7,8] and stability control has also been introduced [11]. Rizzi et al also estimated ABS to be an efficient countermeasure [12].

Looking from passive protection point of view and using the injury sources as input, the cars were the main injury source. It they could be redesigned with energy-absorbing outer structure, this could potentially address 39% of the fatal accidents. Since the large majority of those impacts were to low locations on the car, below the waist line, it would be those areas of the car that would need to be addressed, especially the car front (bumper area), but also the lower side of the car (fender and door). For car frontal impacts these areas are already under redesign for pedestrian impact protection, so those countermeasures may be effective also for PTW drivers in car crashes. For the PTW-to-car side impacts, it may be difficult to improve the car energy absorption due to conflicting requirements on fuel consumption and structure stiffness needed for car side impact crashes. But introduction of ABS and stability control on PTWs may lead to more impacts with the PTW in upright position, instead of sliding or even separating from the PTW, and in this case PTW airbags could potentially be important countermeasures. Such airbags have been introduced on the market, although on a limited scale [9]. If a run-over protection could be designed, this would also address a considerable amount of the fatal cases, both for cars and heavy vehicles. This may be difficult for passenger cars, due to ramp-climbing requirements, but the heavy vehicles may have room for improvement here.

The most common reasons for the fatal accidents from pre-crash (or active safety point of view) in the study were the PTW losing control or that the PTW was not noticed by another vehicle. Together, these two reasons accounted for 80% of the accidents. The MAIDS report showed almost identical figures on losing control, and they also reported that visibility limitations or obstructions were frequent [3]. Losing control could potentially be addressed by ABS (anti-lock brake systems) or stability control. Conspicuity could be improved by the PTW drivers wearing clothing with better visibility or by changing the design of the lighting on the PTW. Proposals have been made to equip PTWs with two headlights beside each other, to give a unique PTW signature. Regarding vehicle-mounted sensors to detect PTWs and potentially warn or automatically activate the vehicle brakes, it should be noted that these systems would need to cover both frontal, lateral and rear directions. Of these cases (n=36), half of them (n=18) occur when the vehicle is driving out in front of a PTW coming from the side, so a lateral sensor or a frontal sensor with a 180 degree field of view would be necessary (see Fig. A 1 in Appendix for details). About 25% of these cases (n=8) occur when the vehicle turns or overtakes in front of an oncoming PTW, which could potentially be covered by a forward-looking sensor and the remaining sensor would need a rearward-looking sensor, since these occur typically when the vehicle is changing lane in front of a PTW coming from behind.

V. CONCLUSIONS

In this study an overview was conducted of all fatal PTW driver accidents in the GIDAS database, a database that aims to be representative of Germany. We studied each case in detail, using accident descriptions and pictures, to conclude the injury pattern, pre-crash motion of the PTW and possible surrounding vehicles, as well as the injury sources.

It was found, not surprisingly, that head followed by thorax were the main body regions for fatal injury. Further, PTW losing control and that the PTW was not noticed by another vehicle were the most common accident scenarios leading to a fatal PTW crash. The most common injury sources were passenger cars, especially the lower parts of the cars, followed by surrounding objects, mainly guard-rails and trees.

A battery of countermeasures was proposed to improve the protection of PTW drivers from fatal accidents. Countermeasures that are worth promoting and investigating further are innovative helmet or jacket designs, improved PTW visibility, guard-rail redesign, anti-lock brakes and stability control, vehicle-mounted warning and auto-brake systems, improved car frontal energy absorption and under-run protection for heavy vehicles.

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VII. APPENDIX

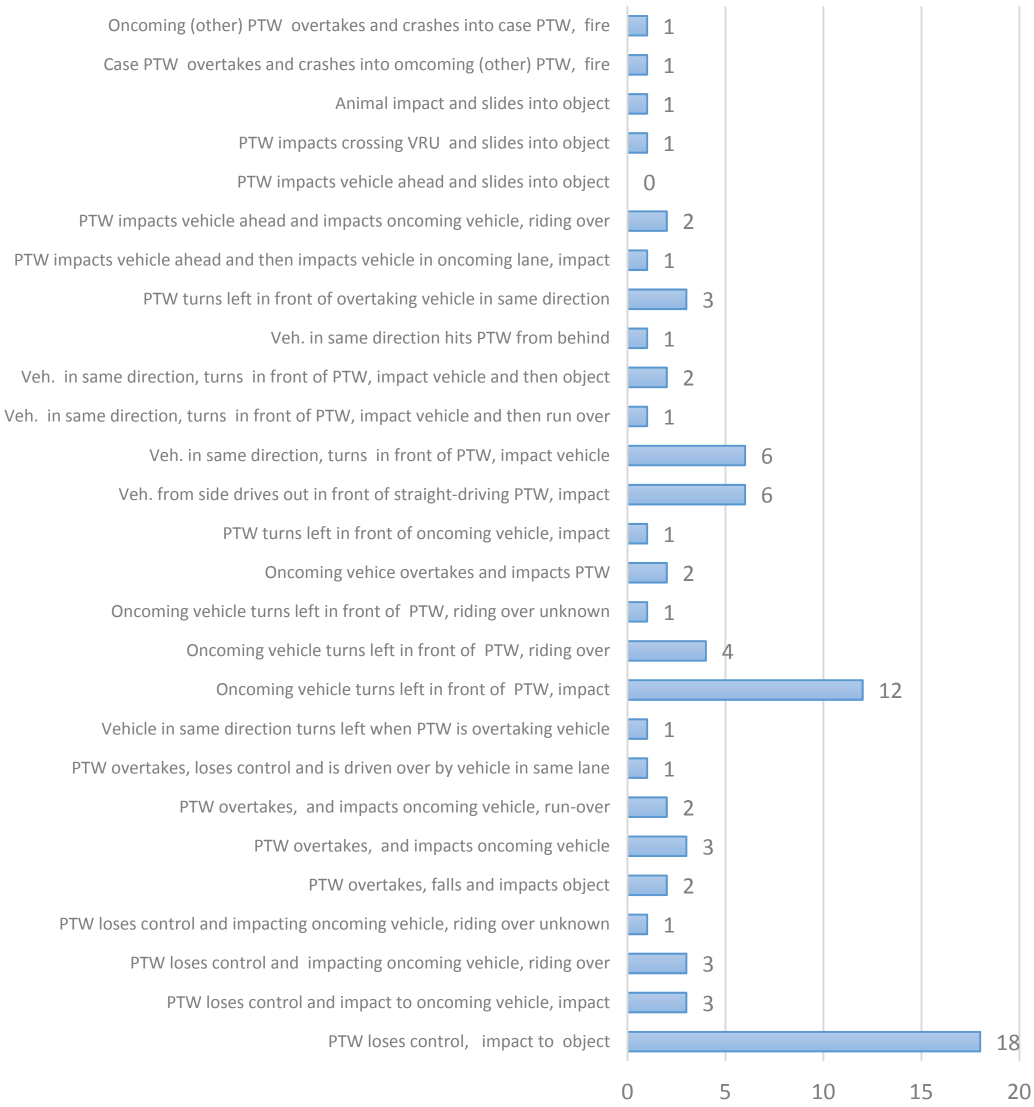

Fig. A 1. Distribution of detailed accident scenarios for all cases (N=80).

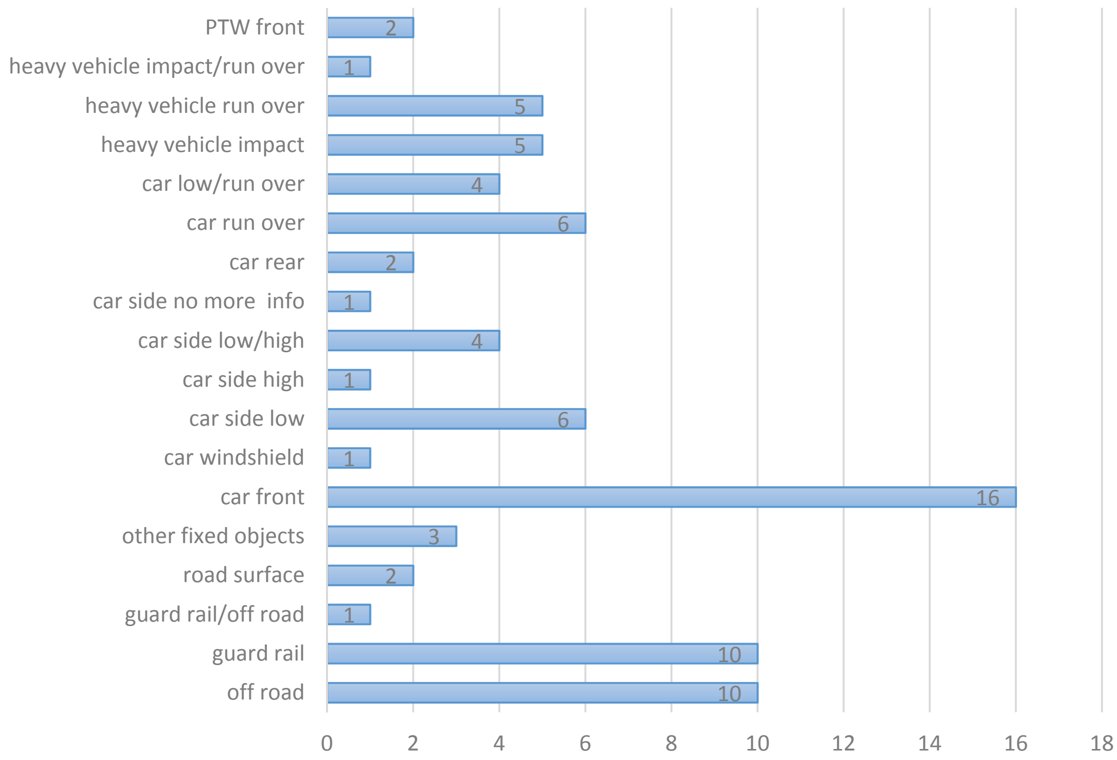

Fig. A 2. Estimated fatal injury sources in detail, all cases (N=80).