Injuries of Bicyclists and Pedestrians in Crashes with Powered Two-Wheelers

Axel Malczyk, Mike Lindenau

Abstract Collisions between powered two-wheelers (PTW) and vulnerable road users (VRU), like bicyclists and pedestrians, are relatively rare crashes in Western Europe, but are more frequent in other regions of the world with larger fleets of PTWs. This study determined the number of fatally, seriously and slightly injured among VRUs in collisions with PTWs in the German national accident statistics. Then, 167 of such crashes involving bicyclists and 140 involving pedestrians in the German Insurers Accident Database were analysed to look into the injury patterns and to characterise the typical crash events. The opponent PTWs were divided into L1e vehicles, like mofas and light scooters, and L3e vehicles, representing more powerful motorcycles.

MAIS3+ injury severity in pedestrians was nearly twice as frequent as in bicyclists. Generally, the resulting injury severities both in bicyclists and pedestrians were more severe when the opponent was an L3e PTW as opposed to an L1e PTW. The head and, particularly in pedestrians, the lower extremities accounted for large proportions of AIS3+ injuries.

Bicyclists and L1e PTWs were often moving in opposite directions before the collision, whereas L3e PTWs were moving rather in the same direction. Darkness and wet roads were relatively frequent in pedestrian crashes.

Keywords Powered two-wheeler crash, bicyclist, pedestrian, infrastructure, injury severity.

I. INTRODUCTION

Many studies have dealt with crashes of powered two-wheelers (PTWs) and the injuries sustained by their riders, such as Fredriksson *et al.* [1]. Most of them addressed almost exclusively collisions occurring between PTWs and passenger cars, which is justified considering that this appears to be the most frequent crash scenario, next to single-vehicle crashes of PTWs, and has the greatest potential for serious and critical injuries of PTW users.

Nevertheless, PTWs are also involved in accidents with other vulnerable road users (VRUs), which may include other PTWs [2] but also bicyclists and pedestrians. The latter two, in particular, are almost completely devoid of personal protection against injuries caused by impact, with the exception of bicyclist helmets, if worn. It can be surmised that collisions with PTWs cause injury patterns in bicyclists and pedestrians that differ considerably from those seen in collisions with passenger cars. Therefore, it is worthwhile to study the frequency of crashes between PTWs and bicyclists and pedestrians, as well as the injuries sustained in such situations. Depending on the role of PTWs in traffic, it can be expected that this problem varies largely between countries and regions. The World Health Organization (WHO), in its “road safety manual” [3] targeting powered two- and three-wheelers, states that the proportion of these vehicles among all registered motorised vehicles in 2019 was as low as approximately 10% in the European region, whereas it accounted for approximately 75% in South-east Asia, by far the largest proportion among all worldwide regions.

Even so, the body of research of PTW crashes with bicyclists or pedestrians appears to be very small. Some published studies come from Asia, where PTWs represent an important means of transport and mobility, particularly in developing countries. For Malaysia, an analysis of accidents with killed and seriously injured pedestrians in the database of the Malaysian Road Safety Institute (MIROS) over the period 2001–2010 revealed that nearly 25% of these crashes occurred with motorcyclists [4]. From 1,626 crashes between a PTW and a pedestrian between 2009 and 2013 in Malaysia, 18% had fatal outcomes, 29% resulted in serious injury and 53% in slight injury to the pedestrian. Multivariate logistic regression was employed to identify risk factors for fatal outcome. Advanced age and presence of head injury as well as darkness at the time of the accident were variables found to be associated with high-odds ratios of pedestrian death.

Jayaraman and Soni [5] analysed a sample of 97 collisions between a PTW and a pedestrian occurring in the

A. Malczyk, Ph.D., (e-mail: a.malczyk@gdv.de; tel. +49 (0) 30-20205879) and Mike Lindenau are Automotive Engineers at the German Insurers Accident Research (Unfallforschung der Versicherer UDV) in Berlin, Germany.

period 2011–2018 from the Road Accident Sampling System–India (RASSI) with the objective of determining injury characteristics and how they were associated with the orientation of the opponents and the contacted zones on the PTW and the pedestrian. Among killed pedestrians, 67% presented AIS3+ injuries to the head, which were attributed mostly to ground contact, whereas lower extremity injuries were the dominant injuries in non-fatal cases. Nearly all AIS2+ lower extremity injuries were caused by contact with front-end parts of the PTW.

In another study of VRU accidents [6], also based on RASSI data (April 2014 to March 2015), 151 injured or killed road users were analysed, including 30 pedestrians. Five of them and one bicyclist were reported to be involved in collisions with PTWs.

A study of 120 pedestrians receiving medical treatment at the emergency department of one hospital in Delhi, India, focused mainly on injuries of the lower extremities and treatment costs [7]. Powered two-wheelers accounted for 26% (three-wheelers, like rickshaws, for 11%) of the opponents, which – according to the authors – was below average considering that 56% of registered motor-vehicles in 2012 in Delhi were powered two- or three-wheelers. With the rising number of PTWs in India, the authors concluded that the importance of countermeasures against injuries from collisions with these motor-vehicles would increase.

An analysis of pedestrian accidents in police and hospital data from the city of Changsha, China [8], reported motorcycles as the most frequent opponent in pedestrian collisions in the police reports in 2005 (44% vs. 34% passenger cars), whereas motorcycles ranked second after passenger cars as opponents (15% vs. 58%) among pedestrians treated, apparently as in-patients, in the Changsha Wujing hospital between 2000 and 2005.

A number of studies from Europe focus on PTW crashes, but few address collisions with pedestrians, and even fewer collisions with bicyclists. One of the largest studies, the MAIDS project (Motorcycle Accident In-Depth Study), collected 921 injury crashes of PTWs and their riders in five European regions during 1999 and 2000 [9]. Collisions with pedestrians or bicyclists represented 2.1% of the cases.

Within the framework of the MAIDS project, a subset of 113 moped and 21 mofa accidents in the Netherlands during 1999–2001 was analysed [10]. Among head-on collisions, which made up 13% of the accident configurations, collisions with other mopeds or mofas were over-represented and occurred almost exclusively on bicycle/moped paths open for both directions. However, no collisions with bicyclists or pedestrians were mentioned.

In Barcelona, Spain, fatal crashes between motorcycles and pedestrians were analysed based on a sample of 38 cases from a total of 300 autopsies on pedestrians in the period of 2005–2014 from the Institute of Legal Medicine [11]. With nearly the same number of cases, the average age was 67.4 years for killed females and 72.3 years for killed males. More than 90% sustained AIS3+ injuries to the head. Regarding the frequency of AIS3+ injuries, the thorax region (46%) and the lower legs (20%) ranked second and third place. Pelvic fractures and tibia fractures were each seen in 29% of cases, representing the most frequent types of lower extremity injury.

While few research efforts relate to pedestrians as crash opponents of PTWs, bicyclists are even rarer in the records of PTW collisions.

In the Netherlands, SWOV analysed 216 collisions in the period 2005–2009 between mofas (PTWs with a maximum speed of 25 km/h) and bicyclists that resulted in fatal or serious injuries as part of a study focusing on light PTWs riding on bicycle paths, which is legal in this country [12]. The large majority of such collisions, 86%, occurred in built-up areas. Ninety-six accidents happened at intersections and 120 on regular stretches of the bicycle path. For both types, side collisions ranked first in frequency, followed by frontal collisions.

In Germany, the German Automobile Club ADAC evaluated data obtained from rescue helicopters dispatched to severe crashes involving PTWs outside built-up areas during the period 2005–2020 [13]. Among these crashes, collisions with bicycles accounted for 3%, while the percentage of collisions with pedestrians was below 1%.

The absolute numbers of accidents between PTWs and bicyclists and pedestrians – the latter two representing the most vulnerable road user groups – may be comparably small in Europe and North America, but the problem is likely greater in other regions of the world, as available data suggest. Hence, research that addresses the injury situation of these vulnerable crash opponents and the conditions under which they occur is warranted, given the scarce data and very limited research conducted into this subject. The present study focuses on the injury severities and patterns of bicyclists and pedestrians, but largely omits the injury situation of the PTW riders. It can be expected that the latter is not much different from PTW single-vehicle crashes, including falls or collisions with roadside objects, which have been covered by past studies.

II. METHODS

Powered two-wheelers come in a variety of forms, sizes and engine power, and are classified in most countries by different legally permissible speeds that, in consequence, require different types of driving license and ultimately determine the minimum age to operate them. The latter often vary between countries but are important factors when judging potential driving experience and compliance with legal requirements.

PTWs fall into category "L" according to EC Regulation 168/2013 [14]. Further differentiation defines – among others – the sub-classes L1e and L3e. PTWs of sub-class L1e are specified as having up to 50 ccm engine displacement, up to 4 kW engine power and 45 km/h maximum speed by design. That includes mofas (up to 25 km/h maximum speed by design, including bicycles with a small auxiliary combustion engine attached) and light PTWs (up to 45 km/h maximum speed by design, like mopeds or light scooters) as the main types. In Germany, mofas can be operated by persons from age 15 and above, after passing a simple short theory test. PTWs with a maximum speed of more than 45 km/h by design require a full driver's license. The minimum age to operate them was reduced from 16 to 15 years of age in 2021. PTWs of sub-class L1e require third-party motor insurance and bear an insurer's identification plate at the rear. They are not subject to periodical technical inspection. PTWs of sub-class L3e are characterised by an engine displacement of more than 50 ccm and more than 45 km/h maximum speed. This sub-class is further divided depending on engine displacement, requiring different driver license classes and a minimum age of 16 or 18 years, respectively. The most powerful motorcycles can be operated from age 20 under certain conditions. Naturally, L3e PTWs require third-party motor insurance as well, and they bear an official license plate, as cars do. For all PTWs with a speed of more than 20 km/h, wearing a helmet is mandatory for the rider and pillion rider. For the purpose of this study, PTWs involved in crashes were divided into the sub-classes L1e and L3e.

Two different data sources were analysed with regards to accidents involving PTWs and bicyclists or pedestrians: the German national statistics, and the German Insurers Accident Database (UDB).

Analysis of the German national statistics for the period 2014–2022 is based on "Table UV" [15], which provides annual police-reported accidents with personal injury by type of road user and involving a maximum of two parties, i.e. single-vehicle crashes or crashes involving only one other road user. In crashes involving three or more road users, the standard German police report is unable to state which of the parties collided with one another. PTWs are further divided into PTWs with insurer's identification plates and PTWs with official license plates. In detail, the breakdown of "Table UV" provides the total number of casualties (slightly injured, seriously injured, fatally injured) among the parties. For instance, in accidents involving a PTW with insurance license plate and a bicyclist, the total number of casualties among users of the PTW and among the bicyclists is reported for each of the three injury outcome levels. In German national statistics, which is based on police-reported accidents, the term "killed" applies to road users who deceased within 30 days after the accident. "Seriously injured" are persons who received in-patient treatment for at least 24 hours immediately after the accident, and the category "slightly injured" covers all other injured. Vehicle users or pedestrians who remain uninjured are not reported.

Data for the detailed evaluation of crash circumstances and injuries sustained by bicyclists and pedestrians in accidents with PTWs comes from the German Insurers Accident Database (UDB). This database contains information from samples obtained retrospectively from claim files of German motor liability insurers. Crashes qualify for inclusion in UDB if at least one injury is present and the estimated claim costs amount to €15,000 or more, covering both personal and property damage, irrespective of the actual payments during claim processing, and which party was at fault. Crashes that occurred between 2006 and 2019 were analysed. Again, PTWs are differentiated between vehicles with insurer's identification plates and those with official license plates. Documentation of the crashes usually comprised police reports or completed questionnaires for the insurer, witness statements and, in many cases, scene photos. Information about injuries was retrieved from hospital discharge documentation or physician reports.

Individual injuries are coded according to AIS 2005, update 2008 [16]. Overall injury severity is described both according to the definition in national statistics and by Maximum AIS (MAIS).

In addition to MAIS, the highest injury severity per anatomical region is determined in order to identify focal points on the body of a bicyclist or pedestrian. These injury severities are grouped into three categories per region: AIS0–1 for no or only minor injury, AIS2 for moderate injury, and AIS3+ for serious to maximum injury severity. Particular analyses for anatomical regions will draw only on documented injury data.

In addition, information as to whether a bicyclist was wearing a helmet is included as it generally reduces the risk of severe head injury.

While the emphasis of the present study is on injury patterns sustained in collisions with PTWs, the association with the typical crash scenarios in which they occur is also of interest. General variables to describe the location of the crash (built-up or non-built-up area) and the present infrastructure, like the type of road (e.g. local, county or state road), type of intersection and type of roadway (e.g. paved road, pedestrian or cyclist path) are included, as well as light levels (daylight, dusk or dawn, darkness) and road conditions (dry, wet, slippery surface due to soiled road, snow or ice) at the time of the accident.

In order to characterise the approximate trajectories of the approaching opponents, the movement of the bicyclist or the pedestrian in relation to the direction of the moving PTW is evaluated. “Moving in opposite direction” includes both straight trajectories of the opponents and crashes where one of them initiates a turn manoeuvre. Similarly, “Moving in same direction” describes a situation where one road user, usually the PTW, approaches from behind and either side-sweeps or “rear-ends” the other. The bicyclist or pedestrian may be moving straight, or initiating a turning manoeuvre, or stepping to the side. “Approaching from the left (the right)” includes movements by bicyclists coming out of side road or a pedestrian stepping off the sidewalk and crossing the roadway. “Falls without collision” describe a situation of a bicyclist falling to the ground, e.g. after hard braking, due to a conflict with the PTW, but without physical contact. “Standing, lying on the ground” describes a situation in which a pedestrian does not present a movement like walking or running before the collision. Pertaining to the injury causation in bicyclists and pedestrians, the posture of the PTW and its rider are also of interest. Where testimonies of involved parties and witness statements allowed, the PTW position at the time of collision was differentiated between an “upright position” and an “inclined position” due to previous skidding or a rider fall, e.g. when losing control after braking. Other factors that are prone to increase crash risk, like being under the influence of alcohol or technical defects, are considered too, if documented. However, they are not standard items in police accident reporting and can therefore provide only conservative estimates in this study.

Rarely, some of the data was missing or deemed insufficient when specific variables were evaluated in detail. Therefore, percentage values in the respective analyses relate to the number of valid data. Differences of values based on continuous variables were tested for significance using the Wilcoxon test for independent samples, 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.).

III. RESULTS

Analysis of German National Statistics

The national statistics were evaluated for the time series 2014–2022 for casualties among bicyclists and pedestrians in accidents with PTWs. Figure 1, Fig. 2 and Fig. 3 show the absolute numbers separately for killed, seriously injured and slightly injured bicyclists and pedestrians, differentiated by L1e and L3e PTWs as collision opponents. Due to the large differences in these numbers, the graphs use differently scaled axes.

Both the total numbers of killed bicyclists and pedestrians are comparably small, with a peak for bicyclists in 2014 (14 killed bicyclists) and a low for pedestrians in 2017 and 2020 (three killed pedestrians in each year) (Fig. 1). For both, L3e PTWs were far more often the opponent. Fatalities with L1e PTWs being the opponent were a lot rarer, with no cases during some years.

When comparing the number of seriously injured bicyclists and pedestrians, the total number of bicyclists per year exceeds that of the pedestrians (Fig. 2). Moreover, no decline is visible for the number of seriously injured bicyclists over the years whereas a decrease occurs for seriously injured pedestrians after 2018. Among both groups, L3e PTWs are more often the opponent than L1e vehicles.

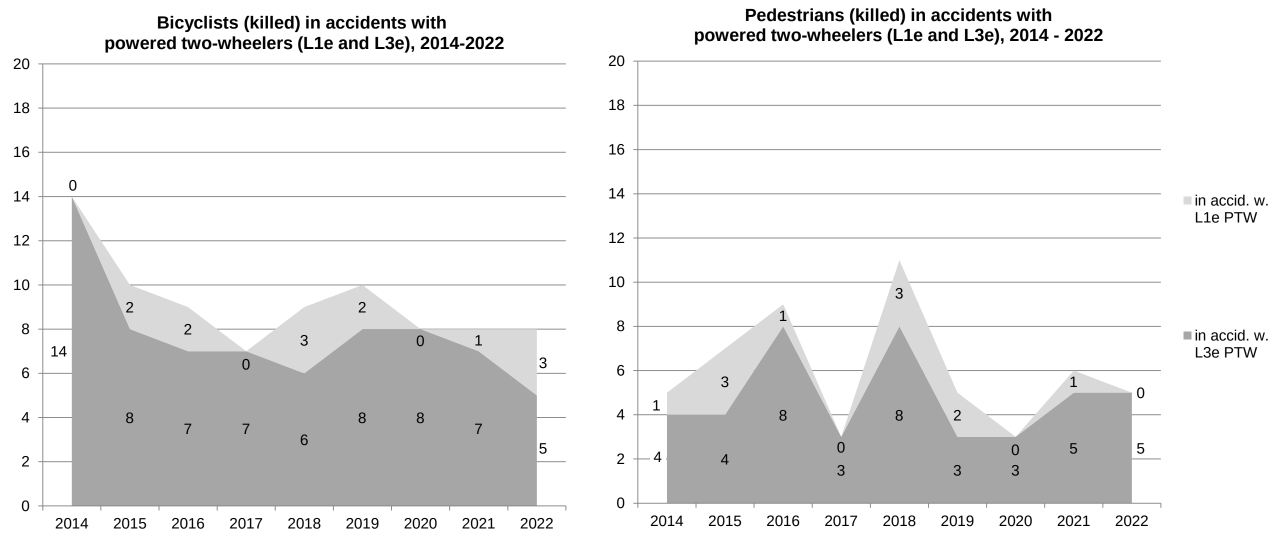

Fig. 1. Number of killed bicyclists (left) and killed pedestrians (right) in accidents with PTWs in the period 2014–2022 in German national statistics.

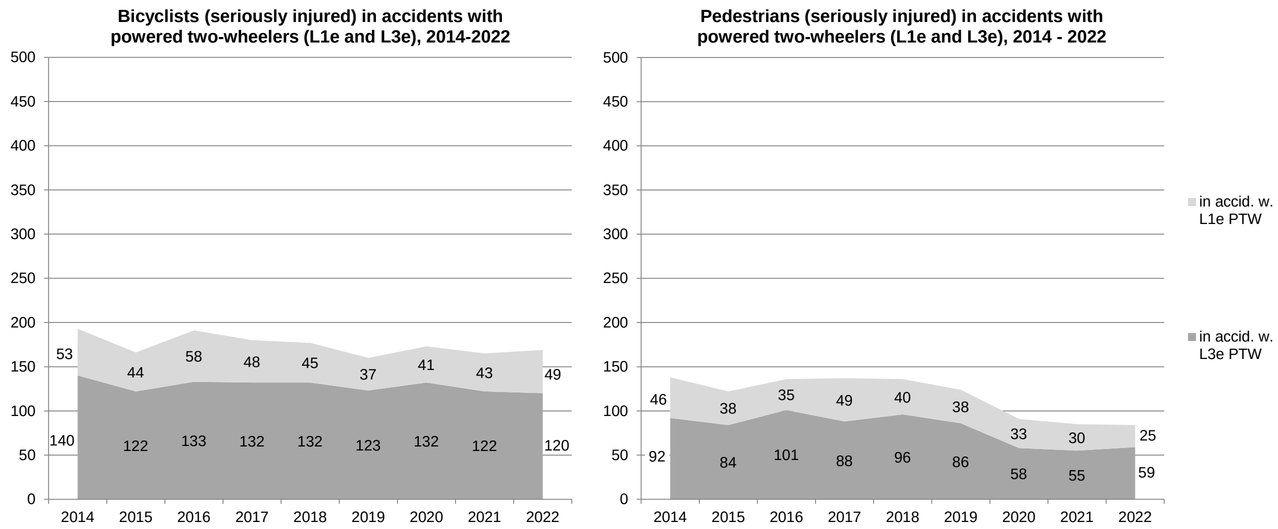

Fig. 2. Number of seriously injured bicyclists (left) and seriously injured pedestrians (right) in accidents with PTWs in the period 2014–2022 in German national statistics.

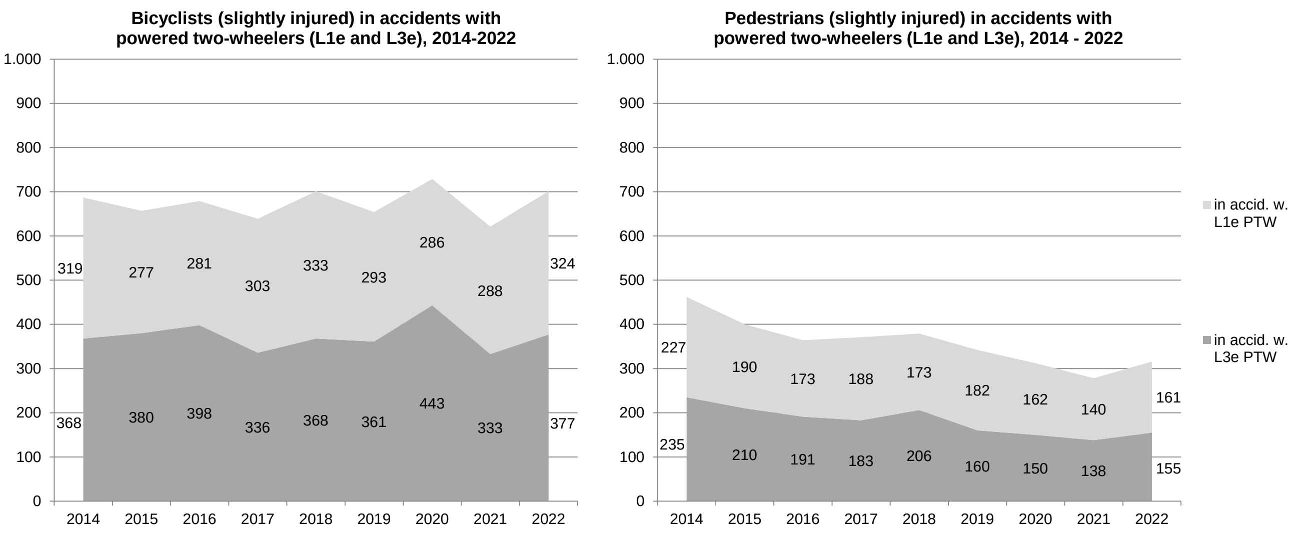

Fig. 3. Number of slightly injured bicyclists (left) and slightly injured pedestrians (right) in accidents with PTWs in the period 2014–2022 in German national statistics.

Lastly, the number of slightly injured bicyclists remains stable over the entire period 2014–2022, with accidents involving L1e PTWs amounting to almost the same number as for accidents with L3e PTWs (Fig. 3). For slightly injured pedestrians, a decline is seen after 2018, but a slight increase again in 2022. After 2018, L1e PTWs slightly outweigh L3e PTWs as opponents.

Analysis of Insurers Accident Database

For the second part of the study, the German Insurers Accident Database (UDB) was filtered and provided 167 bicyclists involved in an accident with a PTW and 140 pedestrians who collided with a PTW in the period between 2006 and 2019 (Table I). All bicyclists and pedestrians in the study material sustained injuries of various severities. A few crashes that involved all-terrain vehicles (ATV or "quad") and one mobility scooter of an elderly person were excluded from the evaluation. One crash with a motorcycle with twin front wheels was included and analysed together with L3e motorcycles, though technically falling into the L5e class (three wheels and maximum speed of more than 45 km/h). Four bicyclists who were walking their bikes when the collision occurred were analysed together with pedestrians because their characteristics resemble those of a walking person when moving in traffic. This complies with the definition used in German police reports. For 13 VRUs (4%), the injury pattern was not completely available, but only the most severe single injuries. Hence, it can be safely assumed that MAIS calculation is not affected by that. For the total count of individuals and their injury severities per anatomical region, the number is reduced depending on the missing injury information from these few VRUs.

Among bicyclists, 63 were slightly injured and 103 were seriously injured according to the national statistics definition. One bicyclist fatality was documented. At least 10 of the crashes (6%) did not come to the attention of the police, according to documentation, but were reported only to the insurer. In the group of pedestrians, 21 were slightly injured, 109 were seriously injured and 10 were fatally injured. Six crashes (4%) were reported to the insurer, but apparently not to the police.

TABLE I

BICYCLISTS AND PEDESTRIANS IN CRASHES WITH PTWS IN INSURERS ACCIDENT DATABASE (UDB)

		Bicyclist		Pedestrian		
		Number of bicyclists	Percentage	Number of pedestrians	Percentage	
Sex	*males*	122	73.1%	73	52.1%	
	females	45	26.9%	67	47.9%	< .01
Age	*age (median) [yrs.]*	50	-	52	-	
	age (average) [yrs.]	49.1	-	48.7	-	n.s.
Injury severity (national statistics definition)	*slightly injured*	63	37.7%	21	15.0%	< .01
	seriously injured	103	61.7%	109	77.9%	
	killed	1	0.6%	10	7.1%	
Maximum injury severity	*MAIS1*	34	20.4%	12	8.6%	
	MAIS2	91	54.5%	61	43.6%	
	MAIS3+	42	25.1%	67	47.9%	< .01
Crash opponent	*versus L1e PTW*	92	55.1%	65	46.4%	
	versus L3e PTW	75	44.9%	75	53.6%	n.s.

Bicyclist demographics and maximum injury severity:

With nearly three-quarters of injured bicyclists, males dominated in crashes with PTWs. Children (aged 14 years or younger) represented a small portion among involved bicyclists (n=13; 7.8%). Bicyclists from 15 to 64 years of age accounted for nearly two-thirds (n=110; 65.9%), elder persons (age 65 and over) for over one-quarter (n=44; 26.3%). The average age of bicyclists was 49.1 years (median: 50 years). Alcohol was documented only for one bicyclist.

Bicycle helmet use could be determined for 132 persons. Fifty-seven were wearing a helmet while 75 bicyclists were not. Among male bicyclists, 51 were documented as wearing a helmet as opposed to 49 not wearing one (unknown: 22 male bicyclists), which was likely an effect of a large percentage of apparently sports-minded cyclists. It is not meaningful to provide a helmet-wearing rate here as the relatively large number of bicyclists without documentation about helmet use (35 of 167 bicyclists) may be biased towards non-wearers.

MAIS could be determined for all bicyclists. MAIS1 was found in 34 and MAIS2 in 91 bicyclists. MAIS3+ was present in the remaining 42 cases, including the only fatality, an unhelmeted amateur cyclist. He was riding parallel to an L1e PTW when the handlebars of both vehicles became entangled and the cyclist hit his head on the ground. The records contained only one “pillion rider”, who was sitting on the handlebars while his companion was pedaling. He received MAIS4 injuries when they collided head-on with an L1e PTW whose driver had lost control of his vehicle.

Altogether, 15 bicyclists (9.0%) experienced a fall without an actual preceding collision due to hard braking or being startled at the sudden sight of the PTW.

Pedestrian demographics and maximum injury severity:

In contrast to bicyclists, the proportion of male and female pedestrians in crashes with PTWs was nearly equal. Children (aged 14 or younger) as pedestrians accounted for 19 cases (13.6%) and adolescents and adults aged 15–64 years represented more than half of the injured pedestrians (n=76; 54.3%). Nearly one-third (n=45; 32.1%) were seniors aged 65 and older. The average age of pedestrians was 48.7 years (median: 52 years). Nineteen pedestrians (13.6%) were under the influence of alcohol at the time of the crash.

MAIS1 was present in 12 and MAIS2 in 61 pedestrians, with 67 persons displaying MAIS3+, showing that serious, severe and critical injuries were more frequent among pedestrians than among bicyclists ($p<0.01$).

For a more detailed look at injury patterns among bicyclists and pedestrians, the circumstances of the accidents are further distinguished by the class of PTWs, i.e. L1e or L3e vehicles as crash opponents, thus, creating four sub-groups. Appendix I, Table AI provides the relative frequencies of the injury severity levels AIS0–1, AIS2 and AIS3+ for different anatomical regions. The percentages refer to the number of individuals presenting such levels of injury severity, not to the number of particular injuries. In Appendix I, Table AII, the AIS2 and AIS3+ severities are consolidated (AIS2+) to facilitate statistical testing of percentage differences in injury severity between VRU sub-groups.

Bicyclist injury patterns:

Bicyclist maximum injury severities were lower in collisions with L1e PTWs as opposed to L3e vehicles, reflected by a smaller percentage of MAIS3+ (15.2% vs. 37.3%, $p<0.01$; Table AI) as well as a smaller percentage of MAIS2+ (71.7% vs. 89.3%, $p<0.01$; Table AII). There was only a small difference in frequency of AIS2+ head injury severity in accidents with L1e PTWs as opposed to L3e PTWs (20.2% vs. 21.3%, n.s.). AIS3+ head injury was seen solely in 16 bicyclists documented as not wearing a bicycle helmet and one indivdual with unknown helmet use, but none among helmet users. Percentages of facial injuries AIS2+ in bicyclists were also similar between L1e and L3e crashes (11.4% vs. 10.8%, n.s.), but among the latter, half of them (5.4%) were in fact of AIS3 severity. Thoracic injuries AIS2+ were less frequent in collisions with L1e than L3e vehicles (6.8% vs. 19.2%; $p<0.05$). Also, pelvic injuries AIS2+, while relatively rare in both sub-groups, were less frequent when colliding with an L1e instead of an L3e PTW (3.3% vs. 13.7%, $p<0.05$). More than one-third of bicyclists in both sub-groups presented injury severities of AIS2+ in the upper extremities (34.4% vs. 39.2%, n.s.). AIS2+ injury severities in the lower extremities region, i.e. the thigh, lower leg and foot, were less prominent in L1e crashes compared to L3e crashes (14.8% vs. 38.4%, $p<0.01$). In particular, crashes with L1e PTWs caused no AIS3 injuries in the lower extremities, like femur or open fractures, whereas AIS3+ injuries accounted for 8.2% in collisions with L3e PTWs.

Pedestrian injury patterns:

Pedestrians struck by L1e vehicles generally sustained less severe injuries than in collisions with L3e PTWs. While the percentages of MAIS2+ were similar in crashes with L1e and L3e PTWs (90.8% vs. 92.0%, n.s.), the proportion of MAIS3+ in pedestrians who collided with an L1e PTW was smaller (41.5% vs. 54.7%, n.s.). Collisions with L1e vehicles also had a lower incidence of head injury than L3e PTWs although these differences were not significant (head AIS2+: 24.7% vs. 36.5%, n.s.; head AIS3+: 18.5% vs. 25.7%, n.s.). Crashes with L1e PTWs were also associated with a lower frequency of AIS2+ facial injury severity (6.3% vs. 18.3%, $p<0.05$) and AIS2+ thoracic injury (6.3% vs. 21.1%; $p<0.05$) than L3e PTWs. In both sub-groups, AIS2+ injury severities in the abdominal region (6.3% vs.

14.3%, n.s.) and in the pelvis (7.8% vs. 12.7%, n.s.) were relatively rare, and even fewer when an L1e was involved. Crashes involving L1e PTWs showed a slightly lower incidence of AIS2+ injury severity in the two extremities regions than those with L3e PTWs (upper extremities AIS2+: 23.4% vs. 36.6%, n.s.; lower extremities AIS2+: 50.0% vs. 65.8%, n.s.). Collisions with L1e PTWs also presented a lower percentage of AIS3+ injury severity in the lower extremities as opposed to L3e vehicles, which were associated with a particularly high proportion of AIS3+ in this anatomical region (18.8% vs. 30.1%, n.s.).

Road infrastructure and environmental conditions:
An overview of external factors to characterise the infrastructure, weather and light levels at the crash site, as well as the approximate direction of movement of the opponents before the collision, is provided in Appendix II, Table III.

The majority of crashes took place in built-up areas, i.e. within the limits of a city or municipality. This was the case particularly for collisions between pedestrians and L1e PTWs (84.6%) and L3e PTWs (93.2%). Bicyclist crashes generally occurred more often in non-built-up areas, i.e. in rural settings, than pedestrian crashes (36.1% vs. 10.8%, $p<0.01$), particularly with L3e involvement (48.6%). Appendix II also provides information about the class of roads, but one needs to consider that even higher class roads, e.g. state roads or federal highways, may lead through city centres.

Crashes that occurred not at intersections, but on stretches of the road or sometimes on tracks and trails in fields or forests with no crossing or junction in the immediate vicinity were less frequent for bicyclists than for pedestrians (39.8% vs. 58.6%, n.s.). Accidents between bicyclists and L3e PTWs, by contrast, happened at intersections of various kinds in nearly two-thirds of cases (62.7%).

The immediate collision site was located on the actual roadway in the large majority of cases, yet a noteworthy 43.5% of collisions between bicyclists and L1e PTWs took place on a pedestrian path, a cyclist path or a combined pedestrian-cyclist path.

Unfavourable roadway conditions, like wet or slippery road surfaces, were found less often in bicycle crashes than in pedestrian collisions (9.3% vs. 20.4%, $p<0.01$). In particular, in nearly one in four collisions (24.6%) between a pedestrian and an L1e PTW, wet road surface was reported.

Similarly, only collisions with bicyclists occurred much less frequently during darkness, dusk or dawn than those with pedestrians (10.2% vs. 39.3%, n.s.). Here again, collisions between an L1e PTW and a pedestrian were prominent with 43.1% happening during hours of limited or no daylight.

As to the movements of the crash opponents before the collision occurred, large differences were seen also when comparing sub-groups with L1e and L3e vehicles as crash opponents. Bicyclists were moving in the opposite direction before the collision much more often when the opponent was an L1e PTW as opposed to an L3e PTW (46.2% vs. 20.0%, $p<0.01$). On the other hand, the two crash opponents were moving in the same direction before the collision more frequently when an L3e PTW was involved instead of an L1e PTW (37.3% vs. 17.6%, $p<0.01$).

A pedestrian moving in the same direction as the PTW, i.e. the PTW approaching from behind, was seen more often with an L1e PTW than with an L3e vehicle (20.3% vs. 5.4%, $p<0.01$). L3e PTWs, by contrast, collided more frequently than L1e vehicles with pedestrians who where approaching from the left or right side of the road (86.5% vs. 62.5%, $p<0.01$), typically representing crossing situations at or near intersections, but also on stretches of the road. Furthermore, 7.8% of pedestrians were standing – or in one case drunk and lying on the road – before they were hit by an L1e PTW.

Direct comparisons between bicyclists and pedestrians regarding particular categories of movement are not meaningful due to the very different natures of these two VRU groups when moving in traffic.

PTW rider demographics and pre-crash kinematics:
Characteristics of the PTW riders differed primarily in relation to the types of vehicle operated. Among the 157 L1e riders, 21 were females as opposed to merely six females in the group of 150 L3e riders (13.4% vs. 4.0%, $p<0.01$), not counting the few pillion riders on PTWs (L1e: 7.6%, L3e: 5.3%). Large differences between the L1e and L3e vehicles were seen for their riders' age. L1e PTW riders were on average 29.8 years old (median: 21 yrs.), and approximately nine years younger than L3e PTW riders with an average age of 38.6 yrs. (median: 39 yrs.), the difference being statistically significant ($p<0.01$). L1e PTWs demonstrated a large percentage of riders under 21 years (47.7%) and only a small percentage older than 54 years (9.3%). Among riders of L3e PTW, 17.1% were younger than 21 years, but 15.8% were older than 54 years.

Significantly more L3e riders than L1e riders were killed or seriously injured in collisions with VRUs ($p<0.05$). Only a small proportion of L1e riders was seriously injured (11.1%), the rest being slightly injured (42.5%) or remaining uninjured (46.4%), according to the available documentation. Of the L3e riders, however, four were killed (2.8%) and nearly one in five was seriously injured (19.1%). Slightly injured L3e riders accounted for 44.7%, and 33.3% remained without injuries.

With regards to the rider and PTW posture at the moment of collision, approximately 12% both of the L1e and L3e vehicles (L1e: 11.7%; unknown posture: n=12; L3e: 13.2%; unknown posture: n=14, n.s.) were documented as being in an "inclined position" due to some kind of preceding loss of control.

IV. Discussion

The German national accident statistics show that accidents between a PTW and a bicyclist or a pedestrian represent a relatively rare crash scenario among all injury crashes in road traffic, but analysis of the injury patterns in the German Insurers Accident Database (UDB) suggests that the injuries sustained by the latter two are often severe. The 2014–2022 national statistics reported more than twice as many bicyclist than pedestrian casualties in crashes with PTWs, whereas the UDB provided a much smaller ratio with 167 bicyclists vs. 140 pedestrians. In particular, the relative frequency of killed and seriously injured, according to the definition in police reports, was higher in UDB among pedestrians than among bicyclists (85.0% vs. 62.3%). In the national statistics, the average ratio of killed and seriously injured among all casualties for the period 2014–2022 was higher for pedestrians than for bicyclists (25.6% vs. 21.4%) too, but not as pronounced as in the UDB material. As to MAIS3+ injury severities, their proportion among pedestrians was much larger than among bicyclists (47.9% vs. 25.1%) in the UDB material.

One limitation of the present study is the fact that case samples based on motor liability insurance claim files enter the accident database only if their estimated claim costs exceeds €15,000, which includes third-party property and personal damage. The amount of third-party property damage will be relatively small in collisions with bicyclists and pedestrians. Therefore, the remaining difference in cost is likely related to personal damage and may bias the material towards more severe injury outcomes. Furthermore, bicycle use in Germany has increased steadily over the past 10 years or so, which has resulted in a general incline in cycling accidents. While an increase in exposure is likely reflected in the 2014–2022 national statistics, where the number of bicyclist casualties in crashes with PTWs has not decreased even through the COVID-19 pandemic years, this effect may not be seen in the samples from the 2006–2019 period in the UDB database.

With regards to the maximum injury severity, pedestrians presented a considerably larger percentage of MAIS3+ than bicyclists. In both groups, that percentage was even higher when the crash opponent was an L3e PTW instead of an L1e PTW.

As to the anatomical regions, a lower incidence of AIS2+ injury severity for the head was seen in bicyclists in comparison to pedestrians (20.1% vs. 31.7%, $p<0.05$) which was even more pronounced for head AIS3+ (10.4 vs. 23.0, $p<0.01$). However, when comparing the rates of head AIS2+ among solely unhelmeted bicyclists and pedestrians in our study, no significant differences remained. Apparently, the lower overall head injury severity seen in bicyclists was driven primarily by those who were wearing bicycle helmets since none of the helmet-wearers sustained head AIS3+ injuries. In several collisions the available documentation indicated that the head of the bicyclist or the pedestrian directly contacted the helmeted head of the PTW rider, likely contributing to facial fractures and traumatic brain injury.

The importance of head injuries for fatal outcomes among pedestrians was also stressed both by Ariffin *et al.* [4] for Malaysian accident data and by Rebollo-Soria *et al.* [11] for fatal PTW-to-pedestrian crashes in Barcelona.

Facial injuries AIS2+ were found in 18 bicyclists (11.1%), among them also four helmet-wearers, and 17 pedestrians (12.6%). AIS3+ facial injuries were found almost exclusively in collisions with L3e PTWs, suggesting that higher impact speeds may have contributed to these serious injuries.

The proportion of AIS3+ thoracic injuries did not differ much when comparing the groups of bicyclists and pedestrians, however crashes involving L3e vehicles were associated with a three to four times greater percentage of AIS3+ injuries than crashes with an L1e as opponent. Cases with reliable and detailed documentation suggest that the greater mass and higher collision speed of an L3e PTW resulted in a more violent direct contact with the body of the vulnerable person.

The frequencies of AIS2 and AIS3+ lower extremity injuries, the vast majority being fractures of the upper and lower leg or foot, presented a large range of percentages, depending on the crash scenario: in bicyclists who collided with an L1e PTW, AIS3+ injuries were absent and AIS2 injuries were few (14.8%), but they were quite frequent in collisions with L3e PTWs (AIS2+: 38.4%). The proportion of these injuries was even higher for pedestrians, particularly in crashes with an L3e vehicle, where the frequency of lower extremity injuries peaked at 34.7% for AIS2 and 29.3% for AIS3+. Where detailed documentation of crashes between pedestrians and L3e vehicles was available, it suggests that these types of injury were caused mainly by direct contact with the motorcycle, either with its front or front wheel when crashing in an upright position, or with other structures when the motorcycle had fallen prior to the collision and was in an inclined or lying position when sliding into the pedestrian. The data did not indicate that the PTW position – upright or inclined – would have an effect on the frequency of lower extremity injuries. Rebollo-Soria *et al.* [11] reported approximately 29% tibia and 20% fibula fractures, but no femur fractures, in their descriptions of killed pedestrians, but they did note that closed and non-displaced fractures might sometimes go unnoticed during autopsy. They reported approximately 29% of pelvic fractures as well. Pelvic injuries were less frequent in our study and notable mostly among bicyclists (AIS2+: 13.7%) and pedestrians (AIS2+: 12.7%) in accidents with L3e PTWs. AIS2 and AIS3+ abdominal injuries were relatively rare in the UDB material. The majority of these occurred in pedestrians and exclusively when the PTW was in an upright position during the collision. This suggests that they were the result of direct contact with hard and possibly protruding structures on the vehicle front at waist height, like the handlebars or lights. For other anatomical regions, however, like the thorax or the upper extremities, it was often difficult to attribute injuries either to the contact with the PTW or to the impact to the ground. It appears that these kinds of collisions often lack basic research as a foundation for technical reconstructions and also lack reliable input data that would allow even simple determination of the geometric relationships between the PTW and the VRU, not to mention body motion and trajectories after the initial contact phase between the opponents.

The crash events, in general, displayed a wide variety of external conditions and causes, many of which were atypical of the collisions that are common between passenger cars and bicyclists or pedestrians. While it seems only natural that the majority of the crashes studied here occurred in built-up areas where bicyclists, and particularly pedestrians, are more present, the relatively large proportion of collisions on minor roads or even trails and tracks in forests or fields is remarkable. It is common in Germany to arrange combined pedestrian and bicycle paths along county or federal highways that connect smaller communities or suburbs with the city centre. Usually, they are laid out some metres away from the main roadway for bi-directional use, without any roadway markings. In non-built-up areas, it is legal for L1e vehicles with a maximum speed of 25 km/h to use these paths as well. Most bicycle paths in built-up areas, by contrast, run directly alongside the roadway and may be used only by bicyclists, depending on the specific layout in one or in both directions. Although illegal, L1e PTWs often used these bicycle paths to make short-cuts, or for other reasons. This is reflected in a number of perpendicular crashes with pedestrians who were crossing the bicycle path or with bicyclists coming out of a driveway or the like. Head-on collisions between L1e PTWs and oncoming bicyclists occurred frequently on combined pedestrian-and-bicycle paths. A notable percentage of bicyclists were riding racing bikes or mountain bikes, which suggests they were pedaling at considerable speed and which explains the relatively high rate of helmet-wearing in the present study. In several of these cases, it was noted that trees or brush near the bicycle path had obstructed the view for both opponents. In addition, riders of L1e vehicles with 25 km/h allowable speed had often removed the manufacturer-installed throttles or devices to limit engine displacement to increase the PTW power and achievable speed. Consequently, many of these riders were operating their vehicles without a proper license and, thus, illegally.

In data on accidents between PTWs and bicyclists from The Netherlands [12], one country where such crashes were studied, frontal collisions ranked second in frequency behind side collisions. In built-up areas, PTWs up to 45 km/h maximum speed by design are allowed to ride on bicycle paths with up to 30 km/h.

Crashes between L3e vehicles and bicyclists in our study occurred outside of built-up areas in nearly half of the cases. Common scenarios included amateur cyclists riding on the right-hand side of the roadway as well as elderly bicyclists riding near the centre of the roadway or crossing the road from a bicycle path in order to make a left-turn at an intersection, sometimes not properly signaling their intended manoeuvre. In such collisions, nearly 70% of the bicyclists were aged 50 years or older. Usually, the bicyclist was struck from behind or side-swept by the approaching PTW, whose rider was either attempting to overtake or simply recognised the slower bicyclist ahead too late to avoid a collision. Of the PTW collisions with pedestrians, approximately one-third took place under limited light conditions. Crashes between an L3e and a pedestrian during darkness were characterised by typical crossing situations, with the pedestrian crossing the motorcyclist's line of travel nearly perpendicularly from the side of the road, coming from the left side nearly as often as coming from the right. Most of these collisions happened in built-up areas, and in nearly 40% of these cases the pedestrian was under the influence of alcohol. Contrary to this, in L1e crashes with pedestrians during hours of darkness both opponents were often found either moving in the same direction or in the opposite direction. A considerable proportion of these collisions occurred outside the boundaries of a municipality in unlit areas when L1e riders and people walking near the side of the road, on paved or on unpaved paths, noticed each other too late to avoid the collision.

Again, several L1e riders were found to have committed an offence, like being under the influence of alcohol (7%) or operating the vehicle without an appropriate license (15%). In L3e crashes, in comparison, the kind of rider misdemeanour most frequently noted as a contributing factor included speeding in collisions with pedestrians and inappropriate overtaking in collisions with bicyclists. Due to official police reports missing for some of the accidents or investigations into crash speeds or alcohol consumption often not being conducted, these values represent rough approximations.

Our study depicts the situation in Germany, where collisions of PTWs with VRUs are not limited to pedestrians. As cycling is not only a popular sports and leisure activity but has grown over the last decades as an important mode of daily transportation, collisions with bicyclists outnumber those with pedestrians, as indicated by national statistics and the Insurers Accident Database. A small percentage of crashes in the UDB material apparently did not come to the attention of the police and thus points to slight underreporting in official accident statistics.

The primary use patterns of PTWs differ depending on type class. While many L3e PTWs are primarily ridden for fun, L1e PTWs serve also as a relatively inexpensive means for commuting on a daily basis, especially where public transport facilities are under-developed, as in many rural regions. In addition, the legal age to ride an L1e mofa or scooter starts considerably earlier than that allowing operation of powerful motorcycles. These facts provide an explanation as to why a large percentage of young people under age 21 were found as riders of L1e vehicles (47.1%) as opposed to L3e vehicles (17.1%). Younger riders can be expected to be less experienced compared to the older population found to operate L3e PTWs. On the other hand, L3e riders were more severely injured, by definition in police reports, than L1e riders in crashes with VRUs, likely as a result of higher collision speeds. Judging from case documentation, these injuries were not a consequence of the collision itself with the VRU, but were rather caused by the L3e rider subsequently falling or impacting a roadside obstacle.

V. Conclusions

The injury patterns determined in the course of this study are probably typical under certain crash conditions, which are primarily governed by the general geometrical relationship between the crash opponents and the collision speed, particularly that of the PTW. Yet, as to the individual collision, these conditions are often unknown and conclusions can be drawn only on the basis of larger case numbers. While this study builds on a relatively good foundation of documented injuries and crash circumstances, one needs to keep in mind that they were sourced from German cases. Their incidence will likely differ from crashes in other countries or regions not only regarding the proportion of involved bicyclists and pedestrians, but also regarding the prevalent type of PTWs, the driving and collision speeds and the infrastructure present at the crash site.

Several kinds of injuries were likely due to contact with the PTW's front structure. Depending on the type of PTW, e.g. a sport or a chopper-style motorcycle, one can expect differences in the injury patterns, particularly for pedestrians. Given sufficient case numbers and details on the crash, it would be worthwhile to investigate whether, for instance, front cowls on a motorcycle that cover at least part of the "aggressive" structures, like handlebars and the front wheel fork, offer potential to reduce the injury risk.

As to the prevention of crashes with bicyclists and pedestrians, not only the visibility of the PTW itself for other road users appears to be of importance but also the illumination of the roadway ahead during darkness. Many L1e vehicles appear to have deficiencies in this regard, as seen in several nighttime collisions with pedestrians at relatively low speed. While illegal technical alterations of the vehicles, mostly in order to achieve higher top speeds, were not necessarily the main cause of the crashes, it is still worrying that this practice was relatively widespread. With electric PTWs being on the rise and with their power controlled solely through electronics, such "performance tuning" may become even easier to carry out.

Lastly, the rider remains an important variable in PTW crashes. As lack of driving experience is paired with more risk-taking, the recently introduced reduction of the minimum legal age in Germany to operate an L1e PTW should be put under close scrutiny. Among riders of heavier motorcycles, many traffic violations appear to be related to the performance and agility of these vehicles, calling for more intense enforcement in general and increased sanctions where reckless driving is concerned.

VI. References

[1] Fredriksson, R., Sui, B. (2015) Fatal Powered Two-Wheeler (PTW) crashes in Germany – an in-depth study of the events, injuries and injury sources. *Proceedings of IRCOBI Conference*, 2015, Lyon, France.

[2] Lang, A., Kühn, M. (2020) Gesamtverband der Deutschen Versicherungswirtschaft e.V., Unfallforschung der Versicherer, *Motorradfahren in Gruppen*. *Unfallforschung kompakt Nr. 103,* Berlin, [https://www.udv.de/resource/blob/79260/7367a6dd08bb798dc21abda32dbe70a2/103-motorradfahren-in-gruppen-data.pdf], Date Updated [1 April 2024].

[3] World Health Organization (WHO) (2020) *Powered Two- and Three-Wheeler Safety. A road safety manual for decision-makers and practitioners. Second edition. 2020*, [https://iris.who.int/bitstream/handle/10665/367419/9789240072497-eng.pdf?sequence=1], Date Updated [1 April 2024].

[4] Ariffin, A. H., *et al.* (2016) Pedestrian-motorcycle collisions: associated risks and issues. *Proceedings of The 2nd International Conference on Automotive Innovation and Green Vehicle (AiGEV)*, 2016, Cyberjaya, Malaysia [https://www.matec-conferences.org/articles/matecconf/pdf/2017/04/matecconf_aigev2017_01066.pdf], Date Updated [1 April 2024].

[5] Jayaraman, A., Soni, J. (2019) Who is more vulnerable in crashes between motorized 2-wheelers and pedestrians? Short Communications from the AAAM 63rd Annual Scientific Conference 2019. *Traffic Injury Prevention*, **20**(Supplement 2): pp. 157–159.

[6] Shaikh, J., Fredriksson, R. (2016) Vulnerable Road User Accidents in India. *Proceedings of IRCOBI Conference*, 2016, Malaga, Spain.

[7] Subramanian, H., *et al*. (2015) Pedestrian Injuries in Delhi, India: Analysis of Hospital Data. *Proceedings of IRCOBI Conference*, 2015, Lyon, France.

[8] Kong, C. Y., *et al*. (2013) In-Depth Investigation of Vehicle Traffic Injuries in Changsha in China. *Proceedings of ESAR Conference,* 2013, Hanover, Germany. *Internationale Konferenz ESAR*, *Expert Symposium Accident Research, Berichte der Bundesanstalt für Straßenwesen*, Heft F 87. pp. 38–46, *Bundesanstalt für Straßenwesen*, Bergisch-Gladbach, Germany, 2013.

[9] ACEM (2009) *MAIDS In-depth investigations of accidents involving powered two-wheelers. Final Report 2.0*, https://www.maids-study.eu, Date Updated [2 February 2024].

[10] De Vries, Y. W. R., Margaritis, D., Mooi, H. G. (2015) Moped and Mofa Accidents in The Netherlands from 1999-2001: Accident and Injury Causation. *Proceedings of 18th International Conference on the Enhanced Safety of Vehicles (ESV)*, 2015, Nagoya, Japan.

[11] Rebollo-Soria, M. C., *et al*. (2016) Injury pattern in lethal motorbikes-pedestrian collisions, in the area of Barcelona, Spain. *Journal of Forensic Legal Medicine*, **43**(10): p. 80–84.

[12] Methorst, R., Schepers, J. P., Vermeulen, W. (2011) Rijkswaterstaat, Dienst Verkeer en Scheepvaart DVS, *Snorfiets op het fietspad*, Delft, [https://zoek.officielebekendmakingen.nl/blg-107423.pdf], Date Updated [1 April 2024].

[13] ADAC e.V. Ressort Test und Technik (2023) *Analyse von schweren Motorradunfällen in der ADAC Unfalldatenbank außerhalb von Ortschaften*, Landsberg am Lech, [https://assets.adac.de/image/upload/v1701080239/ADAC-eV/KOR/Text/PDF/ADAC_Unfalldatenbank_Analyse_Motorradunfa%CC%88lle_bebonp.pdf], Date Updated [1 April 2024].

[14] European Commission (2013) *Regulation (EU) No 168/2013 of the European Parliament and of the Council of 15 January 2013 on the approval and market surveillance of two- or three-wheel vehicles and quadricycles.* Official Journal of the European Union, Internet: [https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32013R0168], Date Updated [1 April 2024].

[15] Statistisches Bundesamt (2015) *Verkehr – Verkehrsunfälle – 2014. Fachserie 8, Reihe 7*, Wiesbaden, Germany.

[16] Association for the Advancement of Automotive Medicine (2011) *Course Training Manual, A specialized Course on: Injury Scaling: Uses and Techniques, Introducing The Abbreviated Injury Scale - 2005 Update 2008, Version January 2011*. Barrington, Illinois, USA.

VII. Appendix

Appendix I

TABLE AI
DISTRIBUTION OF INJURY SEVERITIES BY ANATOMICAL REGION AND CRASH OPPONENTS

		Bicyclist vs. PTW L1e (n = 92)	Bicyclist vs. PTW L3e (n = 75)	Pedestrian vs. PTW L1e (n = 65)	Pedestrian vs. PTW L3e (n = 75)
MAIS	MAIS1	28.3%	10.7%	9.2%	8.0%
	MAIS2	56.5%	52.0%	49.2%	37.3%
	MAIS3+	15.2%	37.3%	41.5%	54.7%
Head AIS	AIS0–1	79.8%	78.7%	75.4%	63.5%
	AIS2	10.1%	10.7%	6.2%	10.8%
	AIS3+	10.1%	10.7%	18.5%	25.7%
Face AIS	AIS0–1	88.6%	89.2%	93.8%	81.7%
	AIS2	11.4%	5.4%	4.7%	9.9%
	AIS3+	0.0%	5.4%	1.6%	8.5%
Thorax AIS	AIS0–1	93.2%	80.8%	93.8%	78.9%
	AIS2	2.3%	2.7%	1.6%	4.2%
	AIS3+	4.5%	16.4%	4.7%	16.9%
Abdomen AIS	AIS0–1	98.9%	95.9%	93.8%	85.7%
	AIS2	1.1%	1.4%	4.7%	2.9%
	AIS3+	0.0%	2.7%	1.6%	11.4%
Pelvis AIS	AIS0–1	96.7%	86.3%	92.2%	87.3%
	AIS2	2.2%	8.2%	7.8%	5.6%
	AIS3+	1.1%	5.5%	0.0%	7.0%
Upper extremities AIS	AIS0–1	65.6%	60.8%	76.6%	63.4%
	AIS2	33.3%	37.8%	21.9%	35.2%
	AIS3+	1.1%	1.4%	1.6%	1.4%
Lower extremities AIS	AIS0–1	85.2%	61.6%	50.0%	34.2%
	AIS2	14.8%	30.1%	31.3%	35.6%
	AIS3+	0.0%	8.2%	18.8%	30.1%
Spine AIS	AIS0–1	94.3%	83.6%	95.3%	93.0%
	AIS2	4.5%	16.4%	4.7%	5.6%
	AIS3+	1.1%	0.0%	0.0%	1.4%

Note: This table provides the percentage of VRUs that fall in the respective crash category with opponents being L1e or L3e PTWs, differentiated by anatomical region and injury severity levels AIS0–1, AIS2, AIS3+. Percentage values relate to the absolute number of valid data.
AIS percentage values give the frequency of the largest AIS severity found in that anatomical region (for individuals with respective injury documentation), e.g. 4.7% "Face AIS2" in "Pedestrian vs. PTW L1e" means: 4.7% of pedestrians (with documentation of facial injuries) who crashed with involvement of an L1e PTW sustained one or more facial injuries with the highest injury severity being AIS2. "AIS0–1" means no injury or the highest injury severity being AIS1. One pillion rider is contained in the sub-group of "Bicyclist vs. PTW L1e".

APPENDIX I

TABLE AII
DISTRIBUTION OF INJURY SEVERITIES BY ANATOMICAL REGION AND CRASH OPPONENTS

		Bicyclist vs. PTW L1e (n = 92)	Bicyclist vs. PTW L3e (n = 75)	p	Pedestrian vs. PTW L1e (n = 65)	Pedestrian vs. PTW L3e (n = 75)	p
MAIS	MAIS1	28.3%	10.7%		9.2%	8.0%	
	MAIS2+	71.7%	89.3%	< .01	90.8%	92.0%	n.s.
Head AIS	AIS0–1	79.8%	78.7%		75.4%	63.5%	
	AIS2+	20.2%	21.3%	n.s.	24.6%	36.5%	n.s.
Face AIS	AIS0–1	88.6%	89.2%		93.8%	81.7%	
	AIS2+	11.4%	10.8%	n.s.	6.3% *	18.3%	< .05
Thorax AIS	AIS0–1	93.2%	80.8%		93.8%	78.9%	
	AIS2+	6.8%	19.2%	< .05	6.3% *	21.1%	< .05
Abdomen AIS	AIS0–1	98.9%	95.9%		93.8%	85.7%	
	AIS2+	1.1% *	4.1% *		6.3% *	14.3%	n.s.
Pelvis AIS	AIS0–1	96.7%	86.3%		92.2%	87.3%	
	AIS2+	3.3% *	13.7%	< .05	7.8%	12.7%	n.s.
Upper extremities AIS	AIS0–1	65.6%	60.8%		76.6%	63.4%	
	AIS2+	34.4%	39.2%	n.s.	23.4%	36.6%	n.s.
Lower extremities AIS	AIS0–1	85.2%	61.6%		50.0%	34.2%	
	AIS2+	14.8%	38.4%	< .01	50.0%	65.8%	n.s.
Spine AIS	AIS0–1	94.3%	83.6%		95.3%	93.0%	
	AIS2+	5.6%	16.4%	< .05	4.7 *%	7.0%	n.s.

Note: This table is based on the same data as in Table AI, but consolidates data for AIS2 and AIS3+. It provides the percentage of VRUs that fall in the respective crash category with opponents being L1e or L3e PTWs, differentiated by anatomical region and injury severity levels AIS0–1 and AIS2+. Percentage values relate to the absolute number of valid data. The level of statistical significance for AIS2+ differences within VRU groups (“VRU vs. L1e” versus “VRU vs. L3e”) and their anatomical regions is provided in columns “p”.
An asterisk * indicates that the number of individuals in the respective category and injury severity was smaller than five.
AIS percentage values give the frequency of the largest AIS severity found in that region (for cases with respective injury documentation), e.g. 6.3% “Face AIS2+“ in “Pedestrian vs. PTW L1e” means: 6.3% of pedestrians (with documentation of facial injuries) who crashed with involvement of an L1e PTW sustained one or more facial injuries with the highest injury severity being AIS2+. “AIS0–1“ means no injury or the highest injury severity being AIS1. One pillion rider is contained in the sub-group of “Bicyclist vs. PTW L1e”.

APPENDIX II

TABLE AIII
DISTRIBUTION OF CRASH CIRCUMSTANCES BY CRASH OPPONENTS

		Bicyclist vs. PTW L1e (n=92)	Bicyclist vs. PTW L3e (n=75)	Pedestrian vs. PTW L1e (n=65)	Pedestrian vs. PTW L3e (n=75)
Location of crash	Built-up (urban) area	73.9%	51.4%	84.6%	93.2%
	Non-built-up (rural) area	26.1%	48.6%	15.4%	6.8%
Type of road	Local street or minor road	59.8%%	37.3%	41.5%	56.0%
	County road	14.1%	14.7%	23.1%	4.0%
	State road	17.4%	33.3%	23.1%	20.0%
	Federal road	8.7%	14.7%	12.3%	20.0%
Type of intersection	Crossing	14.3%	28.0%	13.8%	24.0%
	Junction w. other road	31.9%	28.0%	15.4%	20.0%
	Junction w. driveway	12.1%	6.7%	4.6%	4.0%
	No junction	41.8%	37.3%	66.2%	52.0%
Type of roadway	Paved road	52.2%	84.0%	75.0%	94.7%
	Pedestrian or cyclist path	43.5%	9.3%	14.1%	2.7%
	Adjoining paved area or parking lot	0.0%	2.7%	6.3%	1.3%
	Other type of road (track or path)	4.3%	4.0%	4.7%	1.3%
Roadway condition	Dry	91.0%	90.4%	75.4%	83.3%
	Wet	6.7%	9.6%	24.6%	16.7%
	Snow/ice-covered	1.1%	0.0%	0.0%	0.0%
	Slippery (oil spillage, …)	1.1%	0.0%	0.0%	0.0%
Lighting condition	Daylight	90.1%	89.3%	56.9%	64.0%
	Darkness	8.8%	6.7%	35.4%	30.7%
	Dusk/dawn	1.1%	4.0%	7.7%	5.3%
Movement of bicyclist or pedestrian in relation to PTW movement	Moving in opposite direction	46.2%	20.0%	9.4%	1.4%
	Moving in same direction	17.6%	37.3%	20.3%	5.4%
	Approaching from left	4.4%	17.3%	29.7%	41.9%
	Approaching from right	17.6%	22.7%	32.8%	44.6%
	Fall w/o. collision (bicyclist)	14.3%	2.7%	-	-
	Standing, lying on ground (pedestrian)	-	-	7.8%	6.8%