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Motorcyclist injury risk as a function of real-life crash speed and other contributing factors

Chengkai Ding[a,*], Matteo Rizzi[b], Johan Strandroth[c], Ulrich Sander[d], Nils Lubbe[e]

[a] *Autoliv Vehicle Safety System Technical Center, Shanghai, China*
[b] *Swedish Transport Administration, Borlänge, Sweden*
[c] *VicRoads, Victoria State Government, Melbourne, Australia*
[d] *Veoneer Sweden, Vårgårda, Sweden*
[e] *Autoliv Research, Vårgårda, Sweden*

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ABSTRACT

The Vision Zero approach advocates for a road transport system designed with human injury tolerance and human fallibility as its basis. While biomechanical limits and the relationship between speed and injury outcome has been extensively investigated for car occupants and pedestrians, research analyzing this relationship for motorcyclists remains limited. The aim of this study was to address this issue by developing multivariate injury risk models for motorcyclists that estimate the relationship between speed and injury severity. For that purpose, motorcycle injury crashes from the German In-Depth Accident Study (GIDAS) database for the period 1999–2017 (n = 1037) were extracted. Different models were tested using logistic regression and backwards elimination of non-significant variables. The best fitting model in the current study included relative speed, type of crash opponent, impact location on the motorcycle and impact mechanism of the rider during the crash. A strong and significant relationship between relative speed and injury severity in motorcycle crashes was demonstrated. At 70 km/h, the risk for at least serious injuries in collisions with wide objects, crash barriers and narrow objects was 20%, 51%, and 64%, respectively. Further, it was found that head-on collisions between motorcycles and passenger cars, with both vehicles traveling at 60 km/h (a relative speed at 120 km/h), present 55% risk of at least serious injury to the motorcycle rider.

More research is needed to fully understand the boundary conditions needed to design a safe road transport system for motorcyclists. However, this study provides important insights into the relationship between speed and injury severity for riders in various crash situations. The results may be useful in the discussion of appropriate speed limits and in determining the benefits of countermeasures which aim to reduce crash speed.

1. Introduction

Road safety for Powered Two-Wheelers (PTW, i.e. motorcycles and mopeds) is a global concern. Estimated figures indicate that in 2010 there were more than one billion motor vehicles in the world (Ward's AutoWorld, 2011; Sperling and Gordon, 2009), of which approximately 300 million were PTW (OECD/ITF, 2015). It is also estimated that every year around 50 million PTW are produced globally, a figure comparable to the 65 million annual production volume of passenger cars (OECD/ITF, 2015). PTW, however, are not evenly spread across the world: around 77% are in Asia, 14% in Europe, 7% in North and Latin America, and only 2% in Africa and the Middle East (Rogers, 2008).

Globally, PTW account for nearly a quarter of all road traffic fatalities. The South-East Asian Region and Western Pacific Region stand out: as much as 34% of traffic fatalities involve PTW in these regions (WHO, 2015). During the period 2001–2011, PTW accounted for an increasing percentage of road fatalities in most OECD (Organization for Economic Cooperation and Development) countries; in 2011, this percentage ranged between 8% and 30% (OECD/ITF, 2015). In the European Union, 17% of all road fatalities in 2014 involved PTW users (EC, 2016).

Several studies have indicated that the human component is predominant in the causation of motorcycle crashes (Hurt et al., 1981; MAIDS, 2004). In MAIDS (2004), for instance, it was reported that in 50% of cases the main crash cause was human error by a passenger car driver. In most cases, such errors were considered to be due to the failure to observe the PTW. In a further 37% of cases, the main crash cause was determined to be a human error by the PTW rider. Human

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* Corresponding author.
E-mail address: chengkai.ding@outlook.com (C. Ding).

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error is a common cause of road crashes in general (Rumar, 1985; Tarrière et al., 1996) as well as crashes with other means of transportation, like trains or aircrafts (Wiegmann and Shappell, 2003; Dhillon, 2007).

Previous research has shown that the fatality rates for motorcyclists are 20 to 40 times higher than for car occupants per distance travelled (Blackman and Haworth, 2013). As Elvik (2009) states, today's road transport system is unfair to PTW users, as their risk for severe or fatal injury when involved in a crash is much higher than for other road users. However, during the last two decades several countries have adopted a road transport safety strategy called Vision Zero or the Safe System approach which has the long-term vision of eliminating fatal or impairing injuries within the road transport system. Its aim is primarily to eliminate severe injuries, rather than crashes, by aligning crash severity with the potential to protect from bodily harm. To achieve this, the road transport system needs to be designed based on human injury tolerance alongside the mental and physical limitations of human beings (Tingvall, 1997). Basically, this means that speed limit compliance and crash protection should be closely connected and work together in synergy – creating boundary conditions for each type of road user – where the set speed limit depends on the combined ability of the road and vehicles to handle the impact energy and to protect their users when a crash occurs. However, how to determine the speed limits of a safe transport system based on the boundary conditions for PTW riders is currently unknown.

Motorcyclists are considered to be vulnerable road users (VRUs) since the possibility of mitigating their injuries when involved in a serious crash is limited: one of the possible and most common countermeasures to reduce injury severity is the use of protective gear (i.e. helmets and protective clothing). Helmets have been shown to be effective in reducing serious and fatal head injuries by almost 50% (Liu et al., 2008; Ulleberg, 2003). However, the majority of fatal injuries are to the head, even among riders with helmets (DaCoTa, 2012; NHTSA, 2008). Other protective equipment has been proven to reduce injury risks in a crash. De Rome et al. (2012, 2011) have shown that motorcyclists are significantly less likely to be admitted to hospital if they crash while wearing motorcycle jackets, trousers or gloves. However, it has been argued that the extent to which clothing can prevent injuries in high-impact crashes is limited (De Rome et al., 2011), and protective clothing is thought to offer the greatest injury reductions in low-impact crashes (Hell and Lob, 1993; Noordzij et al., 2001; Otte et al., 2002). The crashworthiness of current motorcycles is also limited (DaCoTa, 2012), although there is evidence suggesting that some particular designs may provide some degree of protection to specific body regions in a motorcycle crash (Meredith et al., 2014; Rizzi, 2015). So far, only one motorcycle model has been commercialized with an airbag fitted to the fuel tank, and no empirical evidence of its effectiveness is available. Encouragingly, antilock brakes (ABS) have been shown to prevent crashes in the first place but also to lower the severity of the crashes that do occur, presumably due to reduced impact speed and improved stability (Rizzi et al., 2015). With regard to the road infrastructure, some road barriers may pose a particular risk for motorcyclists as they were originally developed to protect car occupants. For instance, research has indicated that motorcycle crashes with guardrails and trees are 7–15 times more likely to be fatal than hitting the ground, respectively (Daniello and Gabler, 2011). Also, crash posture (i.e. whether the motorcyclist is in an upright position or not during a crash) has been shown to affect injury risk in crashes against road barriers (Rizzi et al., 2012).

Several studies have investigated the influence of specific risk factors or countermeasures on injury severity among motorcyclists (e.g. Fredriksson and Sui, 2015, 2016). However, research showing an accurate relation between travelling speed (or change of velocity during a motorcycle crash) and injury outcome among motorcyclists remains sparse, although such a relationship has been extensively investigated for car occupants (Gabauer and Gabler, 2006; Hampton and Gabler, 2009; Kusano and Gabler, 2011; Richards and Cuerden, 2009; Viano and Parenteau, 2010; Weaver et al., 2015) and pedestrians (Kröyer et al., 2014; Rosén et al., 2011; Tefft, 2013).

One of the few studies that begins to address this issue for motorcyclists provides some data that "clearly indicates that as the impact speed increases, the frequency of serious, critical and maximum injuries increases", but without providing a mathematical function linking travelling speed and estimated injury outcome (MAIDS, 2009). Similar results were reported by two early studies, Hurt et al. (1981) and MAIDS (2004). Hurt et al. collected in-depth data of 900 police-reported motorcycle crashes in the Los Angeles urban area during the period 1976-1977. Approximately 2% of the motorcyclists were uninjured. Based on on-scene investigations, it was found that higher crash speeds were more likely to result in fatalities. More specifically, the frequency of fatalities within different ranges of crash speeds was as follows: 3% at less than 32 km/h, 7% at 33–48 km/h, 26% at 49–64 km/h, 28% at 65–80 km/h, and 37% at more than 81 km/h. These results were not stratified depending on helmet wear, crash configuration or collision partner. The MAIDS (2004) study was conducted between 1999 and 2000 in France, Germany, the Netherlands, Spain, and Italy. Research institutes and universities collected in-depth data from 523 motorcycle and 398 moped crashes within specified sampling areas using on-scene investigations. Approximately 2% of the riders were uninjured. The findings showed that the frequency of riders with a maximum injury severity MAIS of level 3 (seriously injured) or higher according to the Abbreviated Injury Scale (Gennarelli and Wodzin, 2006), expressed as MAIS3 +, increased with crash speed as follows: 13% at less than 30 km/h, 24% at 31–50 km/h, 45% at 51–60 km/h, and 50% at more than 60 km/h. As in Hurt et al. (1981), helmet wear, crash configuration and collision partner were not taken into account.

A more detailed analysis by Otte (2006) found that injury severity MAIS was also related to driver throw distance (moving distance of driver after first crash). Otte et al. (2012) highlight the relevance of particular impact situations and accident causes to severe VRU injuries based on accident and injury statistics. Building on this, Otte et al. (2015) conducted multivariate analysis to investigate influences of accident and human individual conditions on the overall injury severity of motorcyclists. However, the multi-variable logistic regression method in Otte's study included both relative speed (the magnitude of the vector difference between motorcycle speed and opponent speed) and driving speed of the motorcycle, which may cause co-linearity within the model, and the effect of both variables on injury risk may be underestimated.

A study from IRMRC (Injury Risk Management Research Centre) in the University of New South Wales focused on injury risk to motorcyclists in accidents that involved fixed roadside objects, with the aim of determining efficient strategies to improve motorcyclist safety (Bambach et al., 2011). The study was based on data from NASS-GES (The United States National Automotive Sampling System - General Estimates System), which was weighted to represent around 30,000 motorcycle accidents in the US. After investigating the associations between injury outcome and multiple variables, injury risk curves were developed by logistic regression. Due to the data limitations, the traveling speed of the motorcycle as estimated by police was included as one of predictors in the risk model, although the impact speed or delta-v (the magnitude of the vector difference between impact velocity and separation velocity, ISO 12353-1, 2002) of the motorcyclist may be more representative of crash energy. From the risk curve model, the study found that travel speed, age of the motorcyclist, whether speeding related or not, motorcycle model year, whether day or night, and location features were all associated with the fatality risk. A pre-crash travelling speed of 55 km/h was estimated to have a 10% fatality risk against a fixed object.

2. Objective of the study

Injury thresholds are essential in designing a safe transport system for all road users; to achieve this, more research is needed to understand the boundary conditions for powered two-wheelers. The aim of this study is to develop multivariate injury risk models for motorcyclists that estimate the relationship between speed and injury severity.

3. Methods and materials

3.1. Data sources

The German In-Depth Accident Study (GIDAS) database was used in the present study. GIDAS was initiated in 1999 as a joint research project by the German Federal Highway Research Institute (BASt) and the German Research Association for Automotive Technology (FAT). Details of accidents occurring in two areas of Germany, around Hannover and Dresden, are collected; the sample area contains both rural and urban traffic. Work shifts are equally distributed between night and day and at least one confirmed personal injury is required for inclusion in the database (Otte et al., 2003).

The distribution of accident location and injury severity in GIDAS shows a predominance of urban crashes with slight injury outcomes. Differences between the distribution of accidents in GIDAS and their distribution nationally could lead to bias in the study results such that they are not representative of real life scenarios. Therefore, weighting is needed to ensure the findings reflect the situation in Germany as accurately as possible. The data from the Federal Statistical Office in Germany, DESTATIS, includes all the police reported traffic accidents throughout Germany. The injury distribution of motorcyclists (include driver and passenger) from GIDAS, a subset of DESTATIS, and DESTATIS (2016) on L3e and L4e vehicles, that is “two-wheel vehicles without a sidecar (category L3e) or with a sidecar (category L4e), fitted with an engine having a cylinder capacity of more than 50 cm^3 if of the internal combustion type and/or having a maximum design speed of more than 45 km/h,” (2002/24/EC), is given in Table 1 below. Note that we used the combined L3e and L4e numbers for weighting, as only this combination was readily available in DESTATIS, while regression modelling was done on L3e only as the category of primary interest.

The normalized weighting factors for accident location and injury severity were calculated by dividing the proportion of each combination of accident location and injury outcome found in the national data by the corresponding proportion found in the GIDAS data. A weighting greater than 1 indicates the category was under-reported in GIDAS, and vice versa. Notably, as Table 1 indicates, accidents in rural areas are under-reported in GIDAS (1999–2017), especially for slight injury cases.

3.2. Data filtering

Accidents involving motorcycles were selected from GIDAS (1999–2017) (1. step below). In order to create a consistent dataset, this study chose to focus on the injury risk to the driver of the motorcycle only, and the sample was further restricted (2. to 7. step). The numbers in brackets indicate the sample size after each of the following steps:

1. Select L3e motorcycle involved cases (n = 3209);
2. Exclude cases where the crash event caused worst injury was not recorded (n = 2389);
3. Exclude motorcycles struck from behind (n = 2285);
4. Exclude VRUs, buses and trucks as crash opponents (n = 2090);
5. Exclude motorcyclists who were run over (n = 2075);
6. Exclude uninjured motorcyclists. National statistics do not include uninjured cases, therefore weighting for uninjured cases was not available. (n = 2049);
7. Exclude motorcyclists without helmets (n = 2009; i.e. 40 cases involving non-helmeted motorcyclists).

Table 1
Weighting calculation from GIDAS to DESTATIS.

Location	Injury severity	GIDAS		National		Weighting
		Freq.	Prop.	Freq.	Prop.	
urban	slight injury	1550	47.8%	12735	42.5%	0.89
urban	severe injury	775	23.9%	4290	14.3%	0.60
urban	fatal injury	37	1.1%	138	0.5%	0.40
rural	slight injury	349	10.8%	6809	22.7%	2.11
rural	severe injury	470	14.5%	5520	18.4%	1.27
rural	fatal injury	64	2.0%	494	1.6%	0.84

Table 2
Potential predictors for injury risk model.

Categories	Description	Abbreviation
Motorcycle	Weight	MC.W
	Length	MC.L
	Seat Height	MC.SH
	Handlebar to Seat distance	MC.HS
Driver	Weight	Driver.W
	Height	Driver.H
	Age	Driver.age
	Protection clothes (1 = yes, 0 = no)	Driver.P
Crash opponent	Type of opponent (passenger car, narrow object, wide object, crash barrier, ground)	OP.type
Crash mechanism*	Crash speed	VK
	Relative speed	Vr
	Relative speed in longitudinal or lateral direction according to motorcycle coordinate	Vr_x, Vr_y
	Delta-v caused worst injury	DV
	Delta-v in longitudinal or lateral direction according to motorcycle coordinate	DV_x, DV_y
	Driver impact on opponent with directional change (1 = yes, 0 = no)	Driver.impact
	Impact location on motorcycle (1 = front, 0 = side)	ImpactSide
Pre-crash status	Pre-crash status of motorcycle (1 = unstable, 0 = stable)	PreCrashStatus

* Crash event that caused worst injury during accident was considered.

3.3. Candidate variables for logistic regression modelling

Table 2 lists those variables considered likely to affect motorcyclist injury and therefore first selected as potential predictors in the multivariable logistic regression model. It should be noted that, in some crash types, low motorcycle impact speeds could have high injury risks due to high delta-v (for example, a head-on impact with an oncoming vehicle at high speed); conversely, there may be crash configurations in which high motorcycle impact speeds could have low injury risks (for example, a single-vehicle crash involving impact with the road surface only). This is illustrated simply in Fig. 1. Therefore, relative speed and delta-v were both included as potential predictors to reflect impact severity with other moving vehicles.

Wu et al. (2018) found that the parameters relating to the accident environment which have a significant influence on accident severity include accident location, accident time (day or night) and road condition. But the accident environment may influence the crash scenario, and thus influence the injury result. For example, brake reaction would be later if the accident happened at night with bad vision, and a higher crash speed would result. To avoid a correlation effect between environment and accident scenarios, only variables which have a straightforward influence on the injury result were selected in this study.

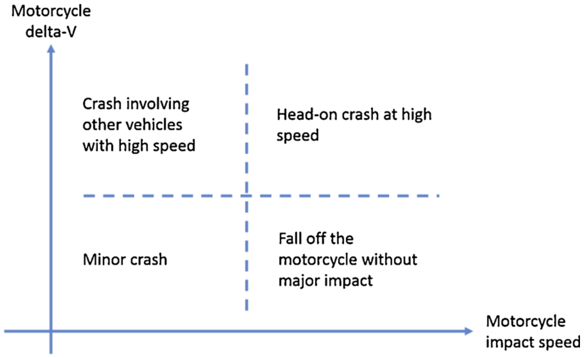

Fig. 1. Examples of motorcycle delta-v and impact speed in different crash types.

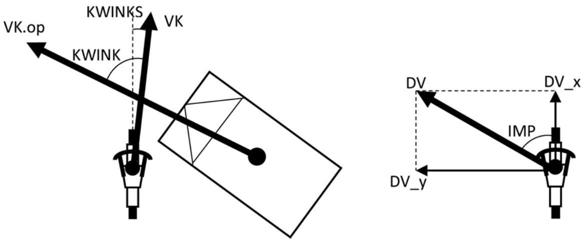

Fig. 2. Dynamic parameters.

3.3.1. Crash mechanism parameter calculation

GIDAS utilizes accident reconstructions, from which detailed crash mechanism parameters are calculated, such as immediate pre-crash speed (VK), delta-v (DV), collision angle (KWINK), slip angle (KWINKS), and impulse angle (IMP) (see Fig. 2). The collision angle is measured between the directions of the velocities of both vehicles. For all vehicle-to-object collisions, this is recorded as 0°. The slip angle defines the inclination of the vehicle's longitudinal axis in relation to the direction of motion of the center of gravity (center of gravity path). The impulse angle is the angle between the longitudinal axis of the vehicle in a forward direction and the direction of the delta-v. All measurement angles are recorded as mathematically positive in anti-clockwise direction.

The equations in Table 3 detail the calculation process for the relative speed of crash opponent and delta-v on the motorcycle according to the longitudinal and lateral direction of the motorcycle. These calculations are based on the assumption that the motorcycle was upright before crash and are therefore not calculable if the motorcycle was inclined or had fallen to the ground at the point of collision. Here, we label the variable 'PreCrashStatus' with "unstable" status if the motorcycle skidded before crashing, or if the current crash was not the first crash of the accident. Otherwise, it is labeled with "stable" status. A simple example is outlined below. Let's assume a motorcycle ($VK = 60\,\text{km/h}$) is to collide head-on with a passenger car ($VK.\,op = 60\,\text{km/h}$) with a KWINK of 180 °. The relative speed between the motorcycle and the passenger car is then 120 km/h.

3.3.2. Crash opponent type

Crash opponent type (variable 'OP.type') is recorded in the variable "KONOBJ" from GIDAS. All opponents other than passenger cars were summarized into four groups, as Table 4 shows.

3.3.3. Impact mechanism of motorcyclist

In a motorcycle accident, the rider is not restrained on the vehicle like occupants in a passenger car. Therefore, delta-v on the motorcycle may not reflect impact severity on motorcyclists. An additional variable named 'Driver.Impact' is involved to indicate impact mechanism on the motorcyclist.

Two groups were specified based on whether the motorcyclist impacted the opponent with directional change. Directional change in this situation usually indicates higher delta-v on the motorcyclist; examples include side impacts from a car and front impacts where the motorcyclist flies into the opponent. Conversely, impacts without directional change or non-impacts are usually comparatively minor; examples include the motorcycle scraping along the opponent or the rider separating from the motorcycle during or before the crash.

3.4. Data preparation

Further data preparation was applied to the sample data to exclude data errors, impute missing data in the above variables, and guarantee a completed dataset. In the final sample, missing values for the motorcyclist were imputed by mean value: age (12 missing) was imputed as 35.4 years old, weight (310 missing) was imputed as 82.1 kg, and height (300 missing) was imputed as 178.9 cm. For the missing data relating to the motorcycle, the knn (k-nearest neighbours, k = 5 in current study) algorithm was used for imputation of weight (373 missing), seat height (163 missing), handle bar to seat distance (234 missing), length (143 missing), and engine power (308 missing). In addition to the above parameters, the motorcycle type and driving speed were involved as input in knn algorithm. After this step, 1789 cases were left.

However, imputing missing values of crash-related variables would lead significant bias if the results are to reflect real-life situations, and therefore the 752 cases with missing values of crash related variables were omitted. These cases included 660 cases with worst impact being with the ground. As relative speed and delta-v could not be computed, ground impacts were analyzed separately. The final main data set consisted of 1037 crashes, which are listed in Appendix A grouped by key variables to illustrate the data structure.

Table 3
Dynamic parameter calculation.

Pre-crash	OP. type	Relative speed (x, y)	Delta-v (x, y)
Stable	Passenger car	$V1_y = VK \times \sin(KWINKS)$ $V1_x = VK \times \cos(KWINKS)$ $V2_y = VK.\,op \times \sin(KWINKS + KWINK)$ $V2_x = VK.\,op \times \cos(KWINKS + KWINK)$ $Vr_x = V2_x - V1_x$ $Vr_y = V2_y - V1_y$	$DV_y = DV \times \sin(IMP)$ $DV_x = DV \times \cos(IMP)$
	Object	$VK.\,op = 0$ $Vr_x = -VK \times \sin(KWINKS)$ $Vr_y = -VK \times \cos(KWINKS)$	$DV_y = DV \times \sin(IMP)$ $DV_x = DV \times \cos(IMP)$
Unstable	Passenger car	Partly available	Partly available
	Object	Partly available	Partly available
	Ground	Not available	Not available

Table 4
Crash opponent definitions for GIDAS codes.

Narrow object	guardrail post; guidepost; traffic sign pole; traffic light pole; streetlight pole; wooden mast; metal or concrete mast; tree, snapped by collision; tree (stable)
Wide object	wire-mesh fence; wooden fence; fence, partially bricked; wall; earth wall; house wall
Crash barrier	crash barrier; guardrail; crash barrier pillar; bridge balustrade
Ground	curbstone; rails; roadside ditch; ditch overpass; embankment downward slope; object on road; road surface; sidewalk/bicycle lane; other paved road; sand, gravel; grass, lawn; field; shrubbery

3.5. Correlation test

High correlation between variables can decrease the precision of the regression coefficient estimates and thereby impede the analysis of the contribution of primary variables to injury risk (Vittinghoff et al., 2005). Therefore, before the modeling process, a correlation test was performed. Kendall's rank correlation test was pair wise performed on variables relating to the motorcycle, motorcyclist and crash mechanism. For better observation, log transformations were performed on relative speed and delta-v to make the highly skewed distributions less skewed.

3.6. Logistic regression

Binary logistic regression is commonly used to analyze the influence of one or several predictor variables on a binary outcome similar to linear regression being used to analyze the influence on a continuous outcome (Vittinghoff et al., 2005). Extensions to outcomes with more than two outcome categories exist but were not applied in our study: Motorcyclist injury was binary and did either occur or not occur. The probability of injury P(x) is calculated from predictors ($x_0 \,..\, x_n$) in the following form:

$$P(x) = \frac{e^t}{e^t + 1} = \frac{1}{1 + e^{-t}}$$

where $t = \beta_0 + \beta_1 x_1 + \ldots + \beta_n x_n$.

The coefficients ($\beta_0 \,..\, \beta_n$) of potential variables were calculated based on the observed data to quantify the effect that the predictors have on injury outcome. Software R was used in this study, in which the package "stats" provided commands to do the logistic regression, and iteratively reweighted least squares (IWLS) was used as default model fitting method.

3.7. Backwards elimination

Backward elimination was used to further filter variables based on their significance in influencing motorcyclist injury. In this approach, the regression model includes all candidate variables. The chosen model fit criterion, the Akaike Information Criterion (AIC), is calculated at the first step, and then those variables which showed the most insignificant loss of model fit are iteratively deleted until no further variables can be deleted without a statistically significant loss of fit. After this backward elimination, a final model could be achieved with a simplified structure and acceptable loss of model fit.

3.8. Model evaluation

After logistic regression models had been built and coefficients had been examined, evaluation criteria were calculated to compare goodness of fit and predictive validation between models. To evaluate the goodness of fit, Residual deviation, AIC, and Pseudo R2 were used.

On the other hand, logistic regression models can work as binary classifiers based on specific injury risk thresholds. The true positive rate (TPR) and the false positive rate (FPR) of prediction could be changed by various threshold settings. The receiver operating characteristic (ROC) curve is created by plotting TPR against FPR. The area under ROC (AUC) is therefore a reflection of prediction effectiveness. However, in order to avoid over-fitting problems in the prediction evaluation, the classifier was built from a training set and the evaluation was conducted on a test set. The prediction performance differs between different training and test sets; to get a robust reflection of prediction performance, in the current study a 10 × 10-fold cross validation was conducted, and the median of AUCs was calculated.

For Residual deviation and AIC, the lower the value the better; for Pseudo R2 and AUC, the higher the value, the better. Based on these coefficients, in-sample error and extra-sample error can be compared between models.

4. Results

4.1. List of candidate models

Based on the pairwise correlation test (see in Appendix A), potential models were set to avoid correlated variables, as shown in Table 5. It should be noted that the rider's throw distance was not included in the analysis, because of the correlation found between throw distance and driving speed (Otte, 2006). Additionally, for the purpose of practical application, we chose speed rather than throw distance in risk models. Of the models, Model0 was an intercept-only model, which served as a baseline for other models to indicate the performance improvement when more independent variables were included. Model1 included only crash speed, VK, as a crash-mechanism related parameter to describe the crash severity, which was used in a previous study for impact on stationary objects (Bambach et al., 2011). Further models include more of the candidate variables which potentially influence injury outcome.

The eight candidate models (Table 5) were attempted in logistic regression which was followed by backward elimination. Via backward elimination, rest variables were identified which had no significant effect on injury outcome or model performance (AIC), particularly parameters related to the motorcycle and the driver. These non-significant variables were eliminated from the respective models.

4.2. Regression result and data visualization

Model performance was found to improve when moving from the baseline intercept Model0 to the collision speed only Model1, and again when moving to the more complex models. When considering different injury levels, Model2, which is a relative-speed based model, performed best according to each of the four evaluation criteria. Although a similar level of performance was found in Model6 and Model7, these are based on delta-v rather than relative speed, and thus considered more complex; Model2 was therefore taken forward. Detailed results for each injury risk model for the different levels of injury severity can be found in Appendix A, in Table A9 (MAIS2 + F, i.e. at least moderate injury on the Abbreviated Injury Scale, or fatal), Table A10 (MAIS3 + F, i.e. at least serious injury on the Abbreviated Injury Scale, or fatal) and Table A11 (Fatal).

Table 6 summarizes the parameters and evaluation results for the relative speed based model (Model2). Of the three risk categories, the MAIS3 + F risk was found to be most sensitive to crash status. Front impact, unstable pre-crash status and impact on driver positively influence MAIS3 + F injury risk. However, only pre-crash status showed significant influence on fatal risk; it may be that there were too few fatal cases in the sample for the influence of these factors to be evaluated.

Table 5
Candidate model list.

	Model0	Model1	Model2	Model3	Model4	Model5	Model6	Model7
Intercept	●	●	●	●	●	●	●	●
MC.SH		○	○	○	○	○	○	○
MC.HS		○	○	○	○	○	○	○
MC.L		○	○	○	○	○	○	○
Driver.H		○	○	○	○	○	○	○
Driver.age		○	○	○	○	○	○	○
Driver.P		○	○	○	○	○	○	○
VK		●					●	●
Vr			●					
Vr_x				●				
Vr_y				●				
ImpactSide		●	●	●				
DV					●		●	
DV_x						●		●
DV_y						●		●
OP.type		●	●	●	●	●	●	●
PreCrashStatus		●	●	●	●	●	●	●
Driver.Impact		●	●	●	●	●	●	●

○candidate variables with no significant effect on injury or excluded by backward elimination.
●final variables in models.

Fig. 3 presents these three injury risk models visualized as risk curves for each opponent type. The curve indicates the injury risk for a motorcycle driver who impacts an opponent with directional change, and whose motorcycle was controlled and stable before the crash. Injuries caused by ground impact are not shown on these plots due to the missing relative speed in such cases. The colored area around curve indicates the 95% confidence area. Overall, the results show that, for a given relative speed, motorcycle impacts with narrow objects (e.g. trees or poles) or crash barriers have significantly higher risk than impacts with wide objects (e.g. walls). For instance, at 70 km/h the risk for MAIS 3+ or fatal injury in collisions under stable pre-crash status with wide objects, crash barriers and narrow objects is 20%, 51% and 64%, respectively. With regard to head-on collisions between motorcycles and passenger cars both travelling at 70 km/h (i.e. with a relative speed of 140 km/h), the risk for MAIS 3+ or fatal injuries was found to be 70%. These results imply that at speeds above 43 km/h, an impact with a crash barrier poses a lower risk for MAIS 3+ or fatal injuries than a head-on collision with a car travelling at the same speed as the motorcycle.

It was also found that the fatal risk in a head-on collision between a motorcycle at 60 km/h and a car at the same speed poses approximately a 10% fatality risk for a helmeted motorcycle rider. However, it is important to note that the 95% confidence intervals for fatalities were quite large (see Fig. 3).

The relative crash speed of sample cases varied by impact opponent: excluding the lowest and highest five values, the relative crash speed of impacts with passenger cars ranged from 4 to 167 km/h, with narrow objects from 30 to 78 km/h, with wide objects from 42 to 52 km/h, and with crash barriers from 20 to 85 km/h. The same situation is found for relative speed distribution (Fig. 4), with few object impact cases at speed less than 20 km/h. It should be noted that, given these speed distributions, model regressions were based on the above speed ranges, and extension out of these ranges is predicted by result models. This is the reason why the injury risk of a zero-speed crash comes up as higher than zero. Furthermore, only injured riders were included in this study, which means that we present conditional road user risk curves, which is the probability of injury at a certain severity given that the motorcyclist was injured. This is only a subset of all motorcycle-involving collisions and the conditional road user injury risk exceeds the unconditional injury risk of a motorcyclist sustaining a certain injury severity (Hautzinger et al., 2007). However, the effect is most pronounced at low speeds where non-injury collisions occur and is not expected to affect the results at higher speeds substantially.

As mentioned in data selection, the 660 cases in which the worst impact was with the ground were excluded due to the missing value of relative speed. However, an absolute crash speed based risk model for ground impacts can be constructed based on these cases. Fig. 5 shows a visualization of these models with risk curves for the three injury levels.

Table 6
Relative speed based injury risk models.

	MAIS2 + F	MAIS3 + F	Fatal
Estimated coefficients (Standard error)			
(Intercept)	−2.256 (0.188)***	−3.952 (0.279)***	−7.175 (0.778)***
Relative speed	0.033 (0.003)***	0.025 (0.003)***	0.035 (0.005)***
Impact on front (1) or side (0)	0.158 (0.151)	0.677 (0.22)**	0.28 (0.522)
Opponent: Passenger car	0	0	0
Opponent: Narrow object	1.801 (0.359)***	1.575 (0.341)***	1.05 (0.766)
Opponent: Wide object	−0.608 (0.572)	−0.386 (0.814)	−0.019 (1.655)
Opponent: Crash barriers	1.094 (0.311)***	1.013 (0.359)**	0.857 (0.738)
UnsTable (1) or stable (0) status	−0.032 (0.243)	0.495 (0.29).	1.827 (0.641)**
Impact on driver (1) or not (0)	0.047 (0.154)	0.529 (0.208)*	0.71 (0.542)
Evaluation criteria			
Resid.Dev	1166.57	717.02	149.94
AIC	880.7	445.6	137.1
Pseudo R2	0.1745	0.2322	0.3765
cvAUC(median)	0.7263	0.7607	0.9109

*‘***’: $0 < p < 0.001$, ‘**’: $0.001 < p < 0.01$, ‘*’:$0.01 < p < 0.05$, ‘.’:$0.05 < p < 0.1$.*

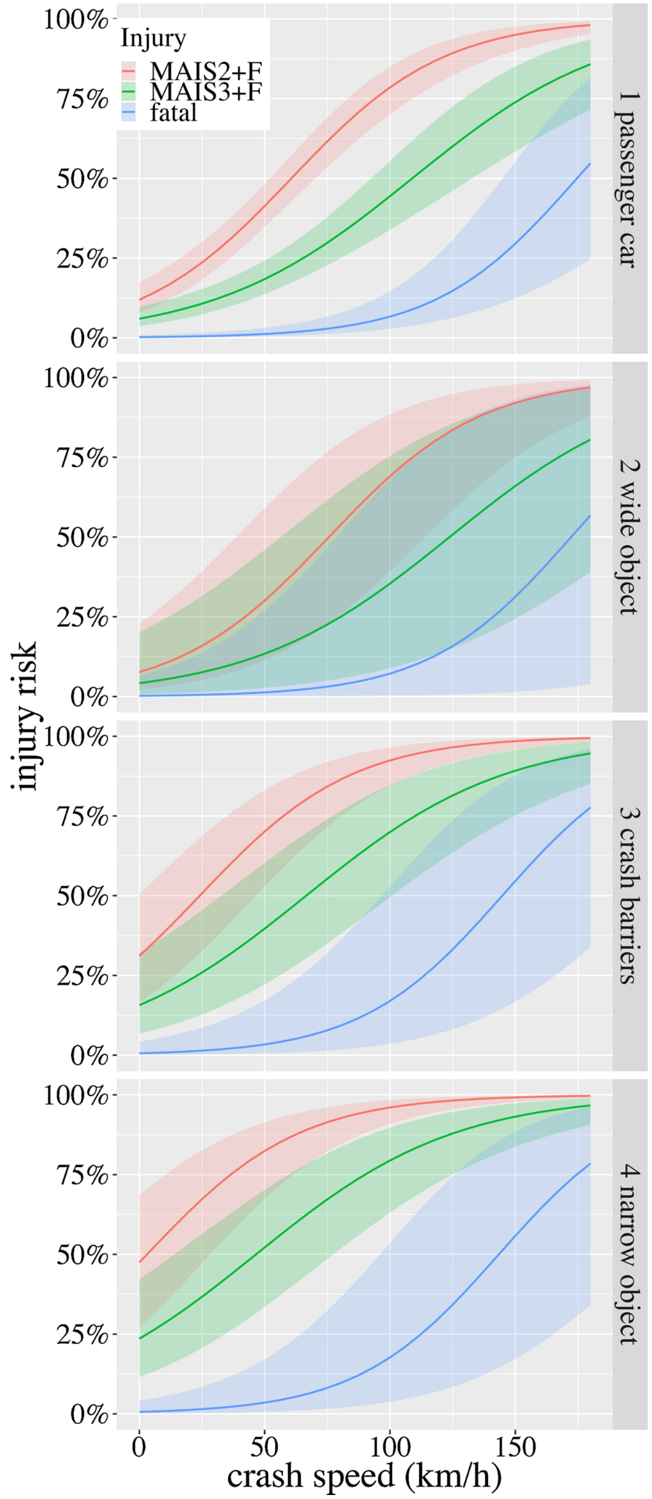

Fig. 3. Injury risk curves for different crash opponents.

Table 7 provides the detailed model parameters. For a given driving speed, ground impact shows lower injury risk than impact with other stationary opponents. When impacting the ground at 70 km/h, the estimated risks for fatality, MAIS 3 + F, and MAIS 2 + F were 1%, 12%, and 43%, respectively.

5. Discussion and implications

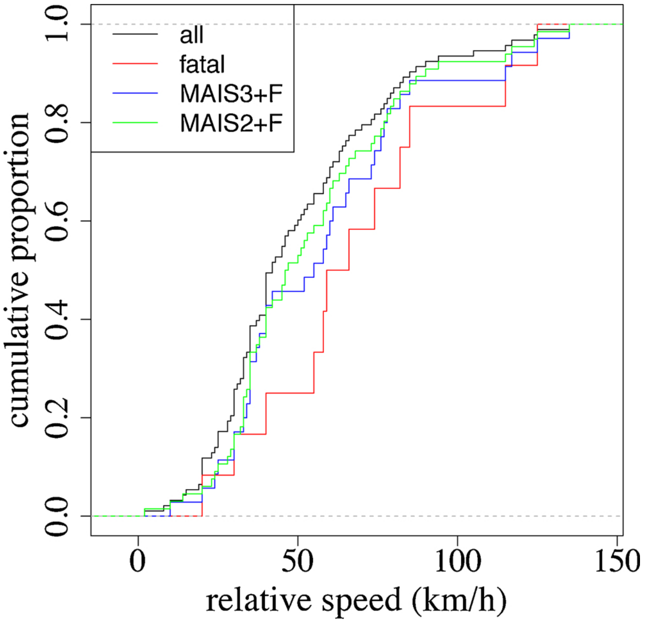

Fig. 4. Relative speed distribution for object impact cases.

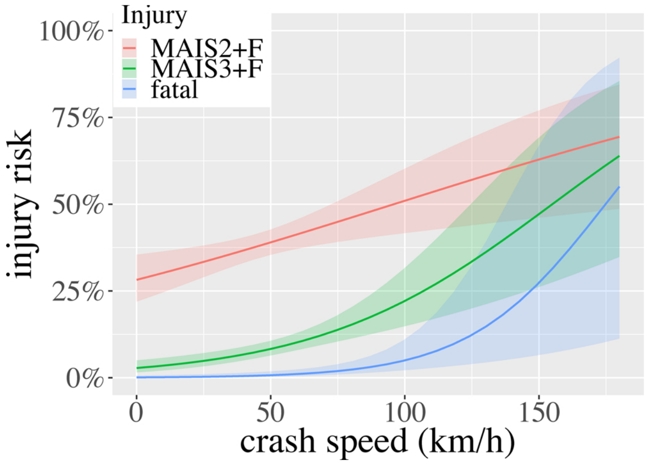

Fig. 5. Injury risk curves for ground impact cases.

Table 7
Crash speed based injury risk models for ground impact.

	MAIS2 + F	MAIS3 + F	Fatal
Estimated coefficients (Standard error)			
(Intercept)	−0.934 (0.171)***	−3.546 (0.308)***	−6.880 (0.911)***
Crash speed	0.010 (0.003)**	0.023 (0.005)***	0.039 (0.011)***

‘***’: $0 < p < 0.001$ ‘**’: $0.001 < p < 0.01$ ‘*’:$0.01 < p < 0.05$ ‘.’ $0.05 < p < 0.1$.

In order to facilitate a meaningful transition into a safe road transport system for PTW, injury thresholds for motorcycle riders are needed. This study investigated those thresholds by deriving risk curves for motorcycle riders that illustrate the relationship between relative speed or crash speed and injury severity in various crash situations, additionally, broken down by opponent type.

Relative speed was found to be the best proxy for crash severity, which is in line with previous research investigating the statistical relationship between relative speed and injury outcome (Otte, 2006; Otte et al., 2015). Similar to Otte et al. (2015), this study used multi-variable logistic regression to calculate injury risk, although impact severity was represented only by non-collinear variables to prevent correlation which may harm model parameter estimation. However, injury risk curves were not developed in Otte (2006) and Otte et al. (2015) which makes a full comparison with the present results difficult.

MAIDS (2004) and Hurt et al. (1981) also showed that speed had a significant correlation with injury severity. However, in these studies, no controls were made for factors like helmet wear, crash configuration or collision partner. Hurt et al. (1981) reported that an impact speed over 81 km/h resulted in a fatality risk of 37%, which is within the confidence limits of the curve representing crashes with narrow objects in this study (Fig. 3). MAIDS (2004) reported a 50% risk of MAIS3+ injuries at 60 km/h impact speed which is also similar to the risk for crashes with narrow objects (Fig. 3).

Further comparison of the present results can be made with Li et al. (2013) and Bambach et al. (2011). Interestingly, Li et al. (2013) reported a 50% risk of MAIS 2+ at 58 km/h relative collision speed with a passenger car. This result was very similar to those shown in Fig. 3, even though confidence limits were not shown in Li et al. (2013). Based on the traveling speed of the motorcycle as estimated by police, Bambach et al. (2011) reported a 10% fatality risk against a fixed object at a pre-crash travelling speed of 55 km/h, which is well within the confidence limits of the fatality risk curves shown in Fig. 3. Results from other studies should though be compared with caution, especially for vehicle-to-vehicle collisions, as most of them used impact speed and not relative speed. However, it can be concluded that the results from this study in terms of how injury risk increases with crash speed are in alignment with previous research.

Additionally, the present paper showed significant differences for different injury outcomes. For instance, in a collision with a narrow object at 70 km/h the calculated risks for fatality, MAIS 3 + F, and MAIS 2 + F were 7%, 64%, and 90%, respectively. This may be an important finding since non-fatal severe injuries also need to be addressed within the Safe System approach. It is therefore recommended that future research in this area should also include non-fatal severe injuries.

Lastly, this study showed that different opponent types present different risks for motorcyclists. Impacts with narrow objects and crash barriers showed significant higher risks than impacts with passenger cars at same relative speed. Similar results have been reported by Gabler (2007), who showed that the fatality risk for motorcycle-guardrail collisions is 3 times higher than for motorcycle-car collisions, and by Bambach et al. (2011), who found trees and poles to be a greater fatality risk for motorcyclists than roadside barriers.

Furthermore, the present study showed that ground impact had much lower injury risks than barrier impacts at same crash speed. Since ditch is regarded as ground in opponent definition, it could be evidence that a crash barrier is more harmful than a ditch behind it. These findings are supported by previous research indicating that motorcycle crashes with guardrails are seven times more likely to be fatal than hitting the ground (Daniello and Gabler, 2011).

5.1. Study limitations

The risk models presented in this study are limited to the situations represented in the sample after data filtering, which restricted the sample to front and side motorcycle impacts with passenger cars or fixed objects, in which the rider was injured, wearing a helmet, and was not run over. In other scenarios or with other rider characteristics, injury risks are likely to be higher or lower than those suggested by the results presented here.

Although weighting factors were applied in the current study, some bias in the sample data is hard to avoid completely. Furthermore, although GIDAS has been set up to offer a representative sample for Germany, and although it is reasonable to assume that the results of this study are broadly applicable throughout Europe, caution should be taken when applying the results in a different context in other parts of the world.

Additionally, it should be noted that the number of cases was limited, particularly for fatal crashes. Although more than 1000 cases were selected for this study, this is still insufficient to model some specific situations. For example, relatively few crashes with objects were available. Severe and fatal injury cases were also much rarer than slight injury cases. The effect of such imbalanced data structure is reflected in the results in Fig. 3: confidence intervals for the risk of slight injury from impacts with passenger cars are smaller than those for risk of severe injury from impacts with other crash opponents. To get a more robust risk estimation, more cases with severe injury resulting from impacts with objects are needed.

It should also be noted that all types of crash barriers were grouped in the present study (see Table 4). While previous research has reported differences in injury risks for motorcyclists in collisions with different types of road barriers (Gabler, 2007), the present material was too limited to perform such analysis. Because of the same issue it was not possible to assess the possible influence of Motorcyclist Protective Systems (MPS) on injury risk. This aspect should be addressed in the future, also to validate barrier testing procedures according to the European Technical Specification CEN/TS 1317-8.

A similar limitation was that all types of passenger cars were grouped for analysis - ideally, these could have been classified according to the type of vehicle. While this was beyond the aims of the present paper, future research should study the influence of mass compatibility and vehicle front-end design implementing, for example, VRU airbags (Fredriksson et al., 2014) on the injury risk for motorcyclists.

Other limitations, such as using fixed parameters in the regression model and thereby not accounting for potential unobserved heterogeneity (Savolainen et al., 2011) were deemed to be of minor importance.

5.2. Implications of results

The present findings have several important implications. As mentioned above, according to the Safe System approach, speed limit compliance and crash protection are closely connected. For instance, the present paper suggests that a head-on collision between a motorcycle at 60 km/h and another vehicle at the same speed poses approximately a 10% fatality risk for a helmeted motorcycle rider. This suggests that on rural roads, the current combination of speed limits and the limited crash protection offered by motorcycles and protective gear implies unacceptable risks of serious injury for motorcyclists. In other words, it could be argued that today's infrastructure and motorcycle design should be based on a maximum speed limit of 60 km/h in order to prevent serious injuries among motorcyclists. However, it is quite likely that the acceptance of such an intervention would be very low and may even be considered draconian. It is therefore important to develop integrated rider protection systems so that speed limits with higher user acceptability can be set. Clearly, the only way to sustain the same fatality risk (say 10%) at higher speed limits would be to improve motorcycle crashworthiness and link that to the infrastructure. Taking this further, if systems are developed which can reliably reduce speed prior to a collision (such as Autonomous Emergency Braking (AEB)), the designated speed limit could be even higher, without necessarily posing an increase in injury risks. While AEB systems in passenger cars have been proven effective in real-life crashes (Fildes et al., 2015), the development of similar technologies for motorcycles, Motorcycle Autonomous Emergency Braking (MAEB), is still ongoing, although with promising results (Savino et al., 2014).

5.3. Conclusion

To conclude, injury thresholds are essential in designing a safe transport system for all road users; to achieve this, more research is needed to fully understand the boundary conditions for powered two-wheelers. This study contributes by providing some important insights into the relationship between crash speed, injury severity, and impact mechanism for motorcyclists. The results may be useful in the discussion of appropriate speed limits and to understand the benefits of countermeasures which aim to reduce crash speed in comparison to in-crash protection.

Appendix A

Exploration of sample data

1037 motorcycles involved in 1032 accidents between 1999 and 2017 were selected as sample data for the current study. A statistical analysis of these data is provided here for better understanding. In the GIDAS database, accident type is recorded by the variable "UART" for each case. Table A1 gives the accident scenario distribution, in which collision between motorcycle and a turning or crossing vehicle is dominate.

Motorcycles were categorized into 8 groups. "Standard" and "supersport" are the most common motorcycle types involved in accidents (Table A2).

Additional descriptive statistics are given in Tables A3 and A4 below.

Table A5 shows the distribution of crash opponents causing the worst injury to the driver, including cases with missing relative speed. In this sample, passenger cars are the most frequent crash opponent (55.9%), followed by ground impact (36.9%).

Result of correlation test and logistic regression

The correlation analysis was performed on motorcycle parameters, driver parameters and crash mechanism parameters separately. The following tables show the Kendall rank correlation coefficients between variables in each group. Coefficients higher than 0.3 indicate that the two variables are at least medium correlated (Kendall, 1955). "Weight of motorcycle" was excluded in model due to its correlation with "handlebar to seat distance" and "length of motorcycle" (Table A6). For driver related parameters (Table A7), "weight" was excluded due to its correlation with "height". For crash mechanism related parameters (Table A8), some parameters showed obvious correlations with each other, due to some parameters being calculated from other parameters, such as "Vr_x" being a component of "Vr" in the longitudinal direction of the motorcycle. Such correlations could be avoided according to the Kendall coefficients. Finally, different combinations of low correlated variables (Kendall rank correlation coefficients < 0.3) were included in different models as shown in Table 5.

Table A1
Motorcycle accident scenario distribution (weighted).

Label	Freq.	Proportion (%)
0 - Accident of another kind	23	2.23
1 - Collision with another vehicle which starts, stops or is stationary	40	3.88
2 - Collision with another vehicle moving ahead or waiting	137	13.28
3 - Collision with another vehicle moving laterally in the same direction	99	9.59
4 - Collision with another oncoming vehicle	53	5.14
5 - Collision with another vehicle which turns into or crosses a road	597	57.85
6 - Collision between vehicle and pedestrian	0	0
7 - Collision with an obstacle in the carriageway	0	0
8 - Leaving the carriageway to the right (drive off the road)	48	4.65
9 - Leaving the carriageway to the left (drive off the road)	35	3.39
Sum	1032	100

Table A2
Motorcycle category distribution (weighted).

Label	Freq.	Proportion (%)
cross/enduro/trial/supermoto	49.2	4.75
custom	108.4	10.46
dual purpose	93.0	8.97
scooter	95.5	9.21
sports/sport touring	76.1	7.33
standard	308.6	29.76
supersport	215.9	20.82
touring	16.5	1.59
unknown	73.8	7.12
Sum	1037.0	100.00

Table A3
Descriptive statistics of discrete variables (weighted).

Category	Variables	Labels	Freq.	Ratio (%)
Motorcyclist	Injury severity	Unfatal (MAIS1)	659.6	63.6
		Unfatal (MAIS2,2+)	355.6	34.3
		Fatal	21.8	2.1
	Protection clothes	With protection	592.2	57.1
		Without protection	444.8	42.9
Crash mechanism	Pre-crash status of motorcycle	Stable	901.25	86.9
		Unstable	135.75	13.1
	Driver impact on opponent with direction change	Yes	690.51	66.6
		No	346.49	33.4

Table A4
Descriptive statistics of continuous variables (weighted).

Category	Variables	Min	Median	Mean	Max.
Motorcycle	Curb weight (kg)	64	199	193.7	400
	Seat height (cm)	48	81	80.9	116
	Handle bar to bench distance (cm)	11	72	70	126
	Length (cm)	127	208	208	280
Motorcyclist	Age (year)	15	32	34.33	78
	Weight (kg)	50	82	82.03	143
	Height (cm)	143	178.9	179.2	201
Crash mechanism on motorcycle	Crash speed (km/h)	0	40	43.1	146
	Longitudinal relative speed (km/h)	0	35.4	40.4	220
	Lateral relative speed (km/h)	0	6.5	9.1	115
	Longitudinal delta v (km/h)	0	13.9	19.3	157
	Lateral delta v (km/h)	0	5.5	7.6	71.7

Table A5
Crash opponent distribution.

Label	Freq.	Proportion (%)
Passenger car	1000	55.9
Ground	660	36.9
Narrow object	54	3.0
Wide object	20	1.1
Crash barrier	55	3.1
Sum	1789	100

Table A6
Motorcycle's parameter correlation analysis.

	MC.W	MC.SH	MC.HS	MC.L	VK
Motorcycle width (MC.W)	1	-0.13	0.32	0.31	0.06
Seat height (MC.SH)	-0.13	1	-0.05	-0.06	0.04
Handlebar to Seat distance (MC.HS)	0.32	-0.05	1	0.1	0.09
Motorcycle length (MC.L)	0.31	-0.06	0.1	1	-0.03
Crash speed (VK)	0.06	0.04	0.09	-0.03	1

Table A7
Driver parameter correlation analysis.

	Age	Weight	Height
Age	1	0.2	-0.07
Weight	0.2	1	0.3
Height	-0.07	0.3	1

Table A8
Crash mechanism parameter correlation analysis.

	VK	Vr	Vr_x	Vr_y	DV	DV_x	DV_y	Imp*	Side*	Pre*
VK	1	0.52	0.54	0.03	0.23	0.21	0.14	0.07	0.03	-0.04
Vr	0.52	1	0.9	0.23	0.44	0.37	0.28	0.09	0.12	-0.02
Vr_x	0.54	0.9	1	0.12	0.4	0.38	0.21	0.09	0.15	-0.04
Vr_y	0.03	0.23	0.12	1	0.25	0.15	0.4	0.1	-0.06	-0.02
DV	0.23	0.44	0.4	0.25	1	0.84	0.34	0.08	0.28	-0.05
DV_x	0.21	0.37	0.38	0.15	0.84	1	0.18	0.05	0.37	-0.07
DV_y	0.14	0.28	0.21	0.4	0.34	0.18	1	0.19	-0.16	-0.05
Imp	0.07	0.09	0.09	0.1	0.08	0.05	0.19	1	-0.11	-0.13
Side	0.03	0.12	0.15	-0.06	0.28	0.37	-0.16	-0.11	1	0.03
Pre	-0.04	-0.02	-0.04	-0.02	-0.05	-0.07	-0.05	-0.13	0.03	1

*Imp: driver impact on opponent (1 = yes, 0 = no); Side: Crash position (1 = front, 0 = side); Pre: Pre-crash status (1 = unstable, 0 = stable).

Table A9
MAIS2 + F injury risk models.

	Model0	Model1	Model2	Model3	Model4	Model5	Model6	Model7
Estimated coefficients (Standard error)								
Intercept	NA	−2.126 (0.194)***	−2.256 (0.188)***	−2.244 (0.192)***	−1.696 (0.142)***	−1.735 (0.145)***	−2.36 (0.188)***	−2.391 (0.19)***
Crash speed	NA	0.025 (0.003)***	NA	NA	NA	NA	0.019 (0.003)***	0.019 (0.003)***
Relative speed	NA	NA	0.033 (0.003)***	NA	NA	NA	NA	NA
Longitudinal relative speed	NA	NA	NA	0.03 (0.003)***	NA	NA	NA	NA
Lateral relative speed	NA	NA	NA	0.017 (0.007)*	NA	NA	NA	NA
Impact on front (1) or side (0)	NA	0.378 (0.146)**	0.158 (0.151)	0.165 (0.153)	NA	NA	NA	NA
Delta-v	NA	NA	NA	NA	0.038 (0.004)***	NA	0.031 (0.004)***	NA
Longitudinal delta-v	NA	NA	NA	NA	NA	0.035 (0.004)***	NA	0.028 (0.004)***
Lateral delta-v	NA	NA	NA	NA	NA	0.026 (0.009)**	NA	0.025 (0.009)**
Opponent: Passenger car	NA	0	0	0	0	0	0	0
Opponent: Narrow object	NA	1.84 (0.356)***	1.801 (0.359)***	1.916 (0.36)***	2.353 (0.356)***	2.381 (0.356)***	2.171 (0.359)***	2.191 (0.36)***
Opponent: Wide object	NA	−0.529 (0.566)	−0.608 (0.572)	−0.585 (0.572)	0.401 (0.569)	0.444 (0.569)	0.11 (0.574)	0.157 (0.573)
Opponent: Crash barriers	NA	1.158 (0.305)***	1.094 (0.311)***	1.17 (0.313)***	1.603 (0.299)***	1.659 (0.302)***	1.402 (0.308)***	1.45 (0.312)***
Unstable (1) or stable (0) status	NA	−0.011 (0.238)	−0.032 (0.243)	−0.047 (0.247)	−0.196 (0.239)	−0.179 (0.24)	−0.104 (0.245)	−0.098 (0.247)
Impact on driver (1) or not (0)	NA	0.185 (0.149)	0.047 (0.154)	0.045 (0.154)	0.147 (0.15)	0.122 (0.153)	0.111 (0.153)	0.08 (0.155)
Evaluation criteria								
Resid.Dev	1359.82	1219.89	1166.57	1170.62	1208.53	1203.92	1171.03	1167.55
AIC	1049	915.8	880.7	887.9	922.1	918.8	882.3	880.5
Pseudo R^2	0	0.141	0.1745	0.1695	0.133	0.1381	0.173	0.1767
cvAUC (median)		0.6802	0.7263	0.7256	0.6988	0.708	0.7221	0.7232

'***': $0 < p < 0.001$, '**': $0.001 < p < 0.01$, '*':$0.01 < p < 0.05$, '.': $0.05 < p < 0.1$.

Table A10
MAIS3 + F injury risk models.

	Model0	Model1	Model2	Model3	Model4	Model5	Model6	Model7
Estimated coefficients (Standard error)								
Intercept	NA	−3.865 (0.285)***	−3.952 (0.279)***	−4.075 (0.294)***	−3.383 (0.217)***	−3.395 (0.223)***	−3.86 (0.264)***	−3.864 (0.27)***
Crash speed	NA	0.021 (0.003)***	NA	NA	NA	NA	0.014 (0.004)***	0.014 (0.004)***
Relative speed	NA	NA	0.025 (0.003)***	NA	NA	NA	NA	NA
Longitudinal relative speed	NA	NA	NA	0.023 (0.003)***	NA	NA	NA	NA
Lateral relative speed	NA	NA	NA	0.025 (0.008)**	NA	NA	NA	NA
Impact on front (1) or side (0)	NA	0.798 (0.213)***	0.677 (0.22)**	0.703 (0.221)**	NA	NA	NA	NA
Delta-v	NA	NA	NA	NA	0.039 (0.005)***	NA	0.033 (0.005)***	NA
Longitudinal delta-v	NA	NA	NA	NA	NA	0.039 (0.005)***	NA	0.033 (0.005)***
Lateral delta-v	NA	NA	NA	NA	NA	0.014 (0.011)	NA	0.012 (0.012)
Opponent: Passenger car	NA	0	0	0	0	0	0	0
Opponent: Narrow object	NA	1.566 (0.339)***	1.575 (0.341)***	1.751 (0.346)***	2.117 (0.349)***	2.161 (0.35)***	1.955 (0.354)***	2.001 (0.354)***
Opponent: Wide object	NA	−0.405 (0.814)	−0.386 (0.814)	−0.313 (0.816)	0.66 (0.826)	0.672 (0.83)	0.44 (0.828)	0.464 (0.832)
Opponent: Crash barriers	NA	1.03 (0.356)**	1.013 (0.359)**	1.157 (0.369)**	1.555 (0.35)***	1.635 (0.352)***	1.358 (0.359)***	1.432 (0.361)***
UnsTable (1) or stable (0) status	NA	0.493 (0.288).	0.495 (0.29).	0.384 (0.302)	0.296 (0.29)	0.348 (0.29)	0.381 (0.294)	0.417 (0.295)
Impact on driver (1) or not (0)	NA	0.633 (0.203)**	0.529 (0.208)*	0.518 (0.208)*	0.521 (0.205)*	0.537 (0.208)**	0.502 (0.207)*	0.513 (0.21)*
Evaluation criteria								
Resid.Dev	843.68	744.65	717.02	716.45	727.12	722.92	714.43	711.07
AIC	560.9	467	445.6	447.7	455.3	452.6	440.4	438.8
Pseudo R^2	0	0.1938	0.2322	0.232	0.2112	0.2197	0.2415	0.2481
cvAUC (median)		0.7187	0.7607	0.7579	0.7481	0.74	0.7571	0.7505

'***': 0 < p < 0.001, '**': 0.001 < p < 0.01, '*':0.01 < p < 0.05, '.': 0.05 < p < 0.1.

Table A11
Fatal injury risk models.

	Model0	Model1	Model2	Model3	Model4	Model5	Model6	Model7
Estimated coefficients (Standard error)								
Intercept	NA	−7.171 (0.769)***	−7.175 (0.778)***	−7.358 (0.802)***	−6.5 (0.611)***	−6.562 (0.638)***	−7.839 (0.828)***	−7.953 (0.868)***
Crash speed	NA	0.038 (0.007)***	NA	NA	NA	NA	0.03 (0.008)***	0.03 (0.008)***
Relative speed	NA	NA	0.035 (0.005)***	NA	NA	NA	NA	NA
Longitudinal relative speed	NA	NA	NA	0.033 (0.006)***	NA	NA	NA	NA
Lateral relative speed	NA	NA	NA	0.037 (0.013)**	NA	NA	NA	NA
Impact on front (1) or side (0)	NA	0.246 (0.499)	0.28 (0.522)	0.287 (0.53)	NA	NA	NA	NA
Delta-v	NA	NA	NA	NA	0.048 (0.008)***	NA	0.035 (0.009)***	NA
Longitudinal delta-v	NA	NA	NA	NA	NA	0.045 (0.008)***	NA	0.032 (0.009)***
Lateral delta-v	NA	NA	NA	NA	NA	0.033 (0.024)	NA	0.031 (0.024)
Opponent: Passenger car	NA	0	0	0	0	0	0	0
Opponent: Narrow object	NA	0.781 (0.763)	1.05 (0.766)	1.307 (0.775).	1.668 (0.799)*	1.695 (0.796)*	1.223 (0.815)	1.23 (0.818)
Opponent: Wide object	NA	−0.232 (1.661)	−0.019 (1.655)	0.083 (1.662)	1.138 (1.736)	1.228 (1.741)	0.707 (1.723)	0.826 (1.728)
Opponent: Crash barriers	NA	0.631 (0.743)	0.857 (0.738)	1.005 (0.777)	1.906 (0.73)**	1.971 (0.728)**	1.39 (0.78).	1.398 (0.779).
Unstable (1) or stable (0) status	NA	1.803 (0.632)**	1.827 (0.641)**	1.582 (0.676)*	1.448 (0.632)*	1.447 (0.628)*	1.839 (0.671)**	1.812 (0.667)**
Impact on driver (1) or not (0)	NA	1 (0.514).	0.71 (0.542)	0.718 (0.542)	0.774 (0.497)	0.73 (0.495)	0.875 (0.527).	0.83 (0.526)
Evaluation criteria								
Resid.Dev	211.88	164.49	149.94	150.85	160.91	160.92	148.66	148.61
AIC	195.1	156.5	137.1	139.1	149.5	150.9	138.4	139.8
Pseudo R^2	0	0.275	0.3765	0.3765	0.3015	0.3042	0.3698	0.373
cvAUC(median)		0.8713	0.9109	0.8889	0.8491	0.8581	0.8951	0.8841

'***': 0 < p < 0.001, '**': 0.001 < p < 0.01, '*':0.01 < p < 0.05, '.': 0.05 < p < 0.

References

Bambach, M., Grzebieta, P.R., Olivier, J., Mcintosh, A.P.A., 2011. Motorcycle Crashes into Roadside Barriers Stage 3: Survivability Analysis. Prepared by February. pp. 1–25.

Blackman, R.A., Haworth, N.L., 2013. Comparison of moped, scooter and motorcycle crash risk and crash severity. Accid. Anal. Prev. https://doi.org/10.1016/j.aap.2013.03.026.

DaCoTA, Road Safety Data, Collection, Transfer and Analysis, 2012. Vehicle Safety. Deliverable 4.8u of the EC FP7 Project DaCoTA. Available at:. (Accessed 19 December 2017). http://safetyknowsys.swov.nl/Safety_issues/pdf/Vehicle%20Safety.pdf.

Daniello, A., Gabler, H.C., 2011. Fatality risk in motorcycle collisions with roadside objects in the United States. Accid. Anal. Prev. https://doi.org/10.1016/j.aap.2010.12.027.

De Rome, L., Ivers, R., Fitzharris, M., Du, W., Haworth, N., Heritier, S., Richardson, D., 2011. Motorcycle protective clothing: protection from injury or just the weather? Accid. Anal. Prev. https://doi.org/10.1016/j.aap.2011.04.027.

De Rome, L., Ivers, R., Fitzharris, M., Haworth, N., Heritier, S., Richardson, D., 2012. Effectiveness of motorcycle protective clothing: riders' health outcomes in the six months following a crash. Injury. https://doi.org/10.1016/j.injury.2011.10.025.

DESTATIS, 2016. Kraftrad- und Fahrradunfälle in Straßenverkehr 2015. Table 1.9.

available at:. (Accessed 19 October 2018). https://www.destatis.de/DE/Publikationen/Thematisch/TransportVerkehr/Verkehrsunfaelle/UnfaelleZweirad5462408157004.pdf?__blob=publicationFile.

Dhillon, B.S., 2007. Human Error in Railways. Human Reliability and Error in Transportation Systems. In Springer Series in Reliability Engineering. Springer, London, UK, pp. 77–90 978-1-84628-811-1.

Directive 2002/24/EC of the European Parliament and of the Council of 18 March 2002 relating to the type-approval of two or three-wheel motor vehicles and repealing Council Directive 92/61/EEC, Official Journal L 124, 09/05/2002 P. 0001 – 0044.

EC, Traffic Safety Basic Facts, 2016. Motorcycles & Mopeds. Available at:. (Accessed 22 March 2018). https://ec.europa.eu/transport/road_safety/sites/roadsafety/files/pdf/statistics/dacota/bfs2016_motomoped.pdf.

Elvik, R., 2009. Benefits and fairness: are the high risks faced by motorcyclists fair? In: van Elslande, P. (Ed.), Les Deux-Roues Motorisés: Nouvelles Connaissances et Besoins de Recherche. INRETS, Marseille, France p. 17.

Fildes, B., Keall, M., Bos, N., Lie, A., Page, Y., Pastor, C., Pennisi, L., Rizzi, M., Thomas, P., Tingvall, C., 2015. Effectiveness of low speed autonomous emergency braking in real-world rear-end crashes. Accid. Anal. Prev. https://doi.org/10.1016/j.aap.2015.03.029.

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 the 2015 International IRCOBI Conference Lyon.

Fredriksson, R., Sui, B., 2016. Powered two-wheeler accidents in Germany with severe injury outcome - accident scenarios, injury sources and potential countermeasures. Proceedings of the 2016 International IRCOBI Conference.

Fredriksson, R., Dahlgren, M., van Schijndel, M., de Hair, S., van Montfort, S., 2014. A real-life based evaluation method of deployable vulnerable road user protection systems. Traffic Inj. Prev. 15 (sup1), S183–S189. https://doi.org/10.1080/15389588.2014.928930.

Gabauer, D., Gabler, H.C., 2006. Correlating Delta-V to occupant injury using event data recorders. Annu. Proceeds/Association Adv. Automot. 57, 1.

Gabler, H.C., 2007. The risk of fatality in motorcycle crashes with roadside barriers. Proceedings of the 20th ESV Conference; Lyon, France; Paper Number 07-0474.

Gennarelli, T.A., Wodzin, E., 2006. AIS 2005: a contemporary injury scale. Injury 37 (12), 1083–1091. https://doi.org/10.1016/j.injury.2006.07.009.

Hampton, C.E., Gabler, H.C., 2009. Influence of the Missing Vehicle and CDC Only Delta-v Reconstruction Algorithms for Prediction of Occupant Injury Risk. Biomedical Sciences Instrumentation.

Hautzinger, H., Pastor, C., Pfeiffer, M., Schmidt, J., 2007. Analysis Methods for Accident and Injury Risk Studies. Deliverable 7.3 of TRACE Project. available from:. http://www.trace-project.org/publication/archives/trace-wp7-d7-3.pdf.

Hell, W., Lob, G., 1993. Typical injury patterns of motorcyclists in different crash types - effectiveness and improvements of countermeasures. 37th Annual Proceedings of the Association for the Advancement of Automotive Medicine.

Hurt, H.J., Ouellet, J., Thom, D., 1981. Motorcycle Accident Cause Factors and Identification of Countermeasures: Volume 1 Technical Report. January Contract No. DOT HS-5-01160, 425 pgs. .

ISO 12353-1, 2002. Road Vehicles – Traffic Accident Analysis – Part 1: Vocabulary.

Kröyer, H.R.G., Jonsson, T., Várhelyi, A., 2014. Relative fatality risk curve to describe the effect of change in the impact speed on fatality risk of pedestrians struck by a motor vehicle. Accid. Anal. Prev. 62, 143–152. https://doi.org/10.1016/j.aap.2013.09.007.

Kusano, K.D., Gabler, H.C., 2011. Injury mitigation in the collision partners of pre-collision system equipped vehicles in rear-end collisions. IEEE Conf. Intell. Transp. Syst. Proceedings. https://doi.org/10.1109/ITSC.2011.6082848.

Li, L., Yang, J., Otte, D., Xuenong, Z., Chao, Z., Xiaoping, Y., Weiqiang, L., 2013. A study on motor scooter accidents in China and Germany. Proceedings of the 5th Conference on Measuring Technology and Mechatronics Automation.

Liu, B.C., Ivers, R., Norton, R., Boufous, S., Blows, S., Lo, S.K., 2008. Helmets for preventing injury in motorcycle riders. Cochrane Database Syst. Rev. https://doi.org/10.1002/14651858.CD004333.pub3.

MAIDS, 2004. In-Depth Investigation of Accidents Involving PTW. Final Report 1.3. ACEM, Motorcycle Industry in Europe. Brussels, Belgium.

MAIDS, 2009. In-Depth Investigation of Accidents Involving PTW. Final Report 2.0. ACEM, Motorcycle Industry in Europe. Brussels, Belgium.

Meredith, L., Baldock, M., Fitzharris, M., Brown, J., 2014. Pelvic injury mechanisms among motorcyclists. The 2014 International IRCOBI Conference.

NHTSA, National Highway Traffic Safety Administration, 2008. Lower-Extremity Injuries in Motorcycle Crashes, DOT HS 810 982. Washington DC. .

Noordzij, C., Forke, E., Brendicke, R., Chinn, P., 2001. Integration of Needs of Moped and Motorcycle Riders into Safety Measures, Review and Statistical Analysis in the Framework of the European Research Project PROMISING, Workpackage 3. Leidschendam, the Netherlands.

OECD/ITF, 2015. Improving Safety for Motorcycle, Scooter and Moped Riders. OECD Publishing, Paris, France. https://doi.org/10.1787/9789282107942-en.

Otte, D., 2006. Technical parameters for determination of impact speed for motorcycle accidents and the importance of relative speed on injury severity. Engineering 724, 1–6. https://doi.org/10.4271/2006-01-1562.

Otte, D., Schroeder, G., Richter, M., 2002. Possibilities for load reductions using garment leg protectors for motorcyclists – a technical, medical and biomechanical approach. Annu. Proc. Assoc. Adv. Automot. Med.

Otte, D., Krettek, C., Brunner, H., Zwipp, H., 2003. Scientific approach and methodology of a new in-depth- investigation study in Germany so called GIDAS. Proceeding of the International Technical Conference on the Enhanced Safety of Vehicles.

Otte, D., Jänsch, M., Haasper, C., 2012. Injury protection and accident causation parameters for vulnerable road users based on German in-depth accident study GIDAS. Accid. Anal. Prev. 44 (1), 149–153. https://doi.org/10.1016/j.aap.2010.12.006.

Otte, D., Facius, T., Wiese, B., 2015. Accident Characteristics and Influence Parameters of Severe Motorcycle Accidents in Germany SAE. https://doi.org/10.4271/2015-01-1466.Copyright.

Richards, D., Cuerden, R., 2009. The Relationship between Speed and Car Driver Injury Severity (Road Safety Web Publication No.9). Transport April. .

Rizzi, M., 2015. Can a boxer engine reduce leg injuries among motorcyclists? Analysis of injury distributions in crashes involving different motorcycles fitted with antilock brakes (ABS). Traff. Inj. Prev. 16 (7), 739–746. https://doi.org/10.1080/15389588.2015.1007224.

Rizzi, M., Strandroth, J., Sternlund, S., Tingvall, C., Fildes, B., 2012. Motorcycle crashes into road barriers: the role of stability and different types of barriers for injury outcome. 2012 IRCOBI Conference Proceedings - International Research Council on the Biomechanics of Injury.

Rizzi, M., Kullgren, A., Tingvall, C., 2015. The combined benefits of motorcycle antilock braking systems (ABS) in preventing crashes and reducing crash severity. Traffic Inj. Prev. 17 (3), 297–303. https://doi.org/10.1080/15389588.2015.1061660.

Rogers, N., 2008. Trends in Motorcycle Fleets Worldwide. Presentation to Joint OECD/ITF Workshop on Motorcycling Safety.

Rosén, E., Stigson, H., Sander, U., 2011. Literature review of pedestrian fatality risk as a function of car impact speed. Accid. Anal. Prev. https://doi.org/10.1016/j.aap.2010.04.003.

Rumar, K., 1985. The role of perceptual and cognitive filters in observed behavior. In: Evans, L., Schwing, R.C. (Eds.), Human Behavior and Traffic Safety. Plenum Press, New York, pp. 151–165.

Savino, G., Rizzi, M., Brown, J., Piantini, S., Meredith, L., Albanese, B., Pierini, M., Fitzharris, M., 2014. Further Development of Motorcycle Autonomous Emergency Braking (MAEB), What Can In-Depth Studies Tell Us? A Multinational Study. Traff. Inj. Prev. https://doi.org/10.1080/15389588.2014.926009.

Savolainen, P.T., Mannering, F.L., Lord, D., Quddus, M.A., 2011. The statistical analysis of highway crash-injury severities: a review and assessment of methodological alternatives. Accid. Anal. Prev. 43, 1666–1676. https://doi.org/10.1016/j.aap.2011.03.025.

Sperling, D., Gordon, D., 2009. Two Billion Cars: Driving Toward Sustainability. Oxford University Press, New York.

Tarrière, C., Brutel, G., Perron, T., Chenisbest, B., Thomas, C., Driscoll, R., 1996. European accident causation survey. Proceedings of the International Conference Active and Passive Automobile Safety 205–214.

Tefft, B.C., 2013. Impact speed and a pedestrian's risk of severe injury or death. Accid. Anal. Prev. 50, 871–878. https://doi.org/10.1016/j.aap.2012.07.022.

Tingvall, C., 1997. The "Vision Zero" - a Road Transport System Free from Health Losses. Transp. Traffic Saf. Heal. New Mobil.

Ulleberg, P., 2003. Motorcykelsäkerhet – en litteraturstudie och meta-analys Förord. Transport.

Viano, D.C., Parenteau, C.S., 2010. Injury risks in frontal crashes by delta V and body region with focus on head injuries in low-speed collisions. Traff. Inj. Prev. 11 (4), 382–390. https://doi.org/10.1080/15389581003751623.

Vittinghoff, E., Glidden, D.V., Shiboski, S.C., McCulloch, C.E., 2005. Regression Methods in Biostatistics: Linear, Logistic, Survival, and Repeated Measures Models. Springer-Verlag, New York. https://doi.org/10.1007/978-0-387-27255-9.

Ward's AutoWorld, 2011. World Vehicle Population Tops 1 Billion Units. Available at:. (Accessed 19 December 2017). http://wardsauto.com/news-analysis/world-vehicle-population-tops-1-billion-units.

Weaver, A.A., Talton, J.W., Barnard, R.T., Schoell, S.L., Swett, K.R., Stitzel, J.D., 2015. Estimated injury risk for specific injuries and body regions in frontal motor vehicle crashes. Traff. Inj. Prev. 16, 108–116. https://doi.org/10.1080/15389588.2015.1012664.

WHO, World Health Organization, 2015. Global Status Report on Road Safety 2015. Geneva, Switzerland. Available at:. (Accessed 19 December 2017). http://apps.who.int/iris/bitstream/10665/189242/1/9789241565066_eng.pdf?ua=1.

Wiegmann, D.A., Shappell, S.A., 2003. A Human Error Approach to Aviation Accident Analysis: The Human Factors Analysis and Classification System. Ashgate Publishing, Ltd., Burlington, VT.

Wu, K.-F., Sasidharan, L., Thor, C.P., Chen, S.-Y., 2018. Crash sequence based risk matrix for motorcycle crashes. Accid. Anal. Prev. 117, 21–31. https://doi.org/10.1016/j.aap.2018.03.0. January 2017.