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Safe speeds: fatality and injury risks of pedestrians, cyclists, motorcyclists, and car drivers impacting the front of another passenger car as a function of closing speed and age

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Abstract: As crash speed increases, so does the probability of injury. The vulnerability of different road users varies greatly, in part due to differences in their protective equipment. Therefore, for the same speed, their injury probabilities are different. The objective of this study is to define injury risk curves, mathematical relations between closing speed (the relative speed between two crash partners) and injury outcome, for different road users. These risk curves can be used to rank road user vulnerability and define safe speeds, i.e. speeds not exceeding tolerable injury probabilities. Crashes involving pedestrians, cyclists, motorcyclists, and car drivers impacting the front of another passenger car (i.e. frontal impacts from the other car's perspective) were extracted from the German in-depth accident study (GIDAS). The injuries were modelled as a function of closing speed and road user age using a weighted binary logistic regression. In accordance with the Abbreviated Injury Scale 2015 revision, three injury severities were modelled: at-least-moderate injury severities, at-least-serious injury severities, and fatal injuries. The constructed risk curves predicted injury outcomes with an average Area under the Curve ranging from 0.66 to 0.94 in cross-validation. A 10% risk of sustaining at-least-serious injuries corresponds to a closing speed of 29 km/h for pedestrians, 44 km/h for cyclists, 48 km/h for motorcyclists, and 112 km/h for car drivers. If a 10% risk of serious injury is acceptable, the closing speeds can be translated into safe speed limits of 25 km/h for cars with pedestrian encounters; 20 to 25 km/h for cyclists, motorcyclists, and cars when they encounter each other; and 55 km/h for cars in head-on impacts. These safe speeds align with current speed limits of 20 to 30 km/h in urban centers but bring into question the current practices of much higher speed limits on rural roads shared by bicycles, motorcycles, and cars. However, safe speed limits could be increased (maintaining a 10% serious injury risk) if road users have more protective equipment and Automated Emergency Braking reliably reduces impact speeds in all crash types.

Keywords: active travel, injury risk function, Safe System, speed limit, Vision Zero

1 Introduction

In sustainable city development, walking and cycling are promoted as environmentally friendly and healthful transport modes (*ECMT, 2004*). Further, compared to private car use and public transport, walking and cycling demand less space (*Pucher & Buehler, 2010*). Similarly, motorcycles also require less space and may have environmental benefits. Therefore, national governments encourage alternatives to cars and implement plans to support the increase in cycling and other active travel modes: for example, Germany aims for "*more, better and safer cycling*" in the national cycling plan (*BMDV, 2021*).

Pedestrians, cyclists, and motorcyclists, in contrast to car occupants, lack the crash protection of a metal cage and energy-absorbing crumple zones. Hence, these road users are often collectively referred to as Vulnerable Road Users (VRUs). Switching from cars to bicycles in today's transportation system will likely lead to an increase in road traffic casualties; cyclists have a ten-fold fatality risk (*ITF/OECD, 2019; Nilsson et al., 2017*) and a 29-fold injury risk compared to car occupants (*Nilsson et al., 2017*). Nevertheless, a net societal benefit is expected, as lives will be saved through better air quality and increased physical activity (*ITF/OECD, 2018; Götschi et al., 2015*). For example, in Sweden, around 100 VRUs die in road traffic annually, contrasted by almost 3,500 premature deaths prevented annually by walking and cycling as active travel modes (*Trafikverket, 2016*).

While passenger cars have become substantially better at protecting their occupants over the decades (*Forman et al., 2019; Kullgren et al., 2019*), VRUs appear not to have experienced comparable improvements. In the USA, the share of people dying inside vehicles (occupants of passenger cars, light trucks, large trucks, buses, and other vehicles) as a percent of all crash fatalities has declined from as high as 80% in 1996 to 66% in 2019. In consequence, the percentage of people dying outside vehicles (VRUs and other non-occupants) has increased from 20% in 1996 to as much as 34% in 2019 (*NHTSA, 2020*). Similarly, in the European Union, passenger car occupant fatalities have decreased more than VRU fatalities in crashes from 2007 to 2016 (*EC, 2018*).

To reduce the number of road traffic casualties among VRUs, both better infrastructure and traffic participant education have been suggested (*Pucher & Buehler, 2010*), as well as improved vehicle design (*Hu & Klinich, 2015; Strandroth et al., 2014*). However, such interventions require substantial engineering effort and long-term investment. Furthermore, interventions should address not only casualties, but road dangers more broadly; if cycling and walking are perceived as dangerous they might be replaced by car trips, which are perceived as safer. In that case, a reduction in fatalities may simply be the consequence of a shift in exposure, away from the desired goal of increased active travel (*Tight et al., 1998*).

A strong inverse correlation between volume and speed of traffic and levels of walking and cycling suggests that interventions reducing traffic speed and volume are likely to promote walking and bicycling—thus resulting in public health gains (*Jacobsen et al., 2009*). Therefore, traffic calming measures are recommended to reduce casualty numbers and increase the use of desirable active travel modes (*Tight et al., 1998*). Limiting the speed of motor vehicles, the overwhelming source of danger on the roads (*Tight et al., 1998*), would be a major contributor to the imperative that all road users should be free from harm (*Davis & Obree, 2020*).

To evaluate objective risks, one needs to have detailed, precise knowledge about the relation between speed and injury probability for different types of road users and crash modes. These mathematical relations can be visualized in a two-dimensional space as injury risk curves, which can facilitate speed limit decisions with consideration for different types of road users.

The speed can be defined either as the impact speed of the car, which is the speed of the car immediately prior to impact; or, considering both vehicles' speed, as the closing speed, which is the scalar of "*the vector difference between impact velocity and velocity of the centre of gravity of a vehicle/object struck immediately before impact*" (*ISO, 2020*). Speed limits do not necessarily equal impact speed as pre-impact braking manoeuvres may decrease impact speed compared to the speed limit. However, drivers (or automated systems) cannot be expected to apply brakes before impact without exception; for example, drivers did not brake in at least 30% of all car-to-pedestrian crashes recorded in the German in-depth accident study (GIDAS) (*Niewöhner et al., 2011*). It appears necessary to set speed limits at the tolerable impact speed until automated systems are proven to reduce impact speed in all possible crashes. Other measures characterizing impact severity exist, such as delta-v, the "*vector difference between impact velocity and separation velocity*" (*ISO, 2020*), which is particularly popular. However, its relation to travel speed is more complex.

The Safe System approach aims for an injury-free transport system for all road users (with a tolerance for human error), guiding speed limit decisions in relation to other traffic elements and interventions (*ITF/OECD, 2008*). Given the system state (the protection levels achievable through safe cars, safe roads, and safe road users), safe driving speeds can be conceptually defined as the speeds (in whichever way measured) at which humans will not be subjected to external forces exceeding their injury tolerance (*Larsson et al., 2010*).

The safe speed for the occupant of a car with the latest protection systems is higher than for a pedestrian, who has essentially no protective equipment. Clearly, what speed is safe depends on which road users interact. *Eugensson et al. (2011)* suggest a speed limit of 40 km/h where cars can encounter pedestrians, assuming that braking can reduce the impact speed by 10 km/h and that the impact energy at 30 km/h can be handled by energy-absorbing structures or other protective equipment, thus avoiding injuries. The *ITF/OECD (2018)* suggests a speed limit of 30 km/h for urban areas where VRUs and vehicles are both present. Similarly, the *ETSC (2020)* encourages a speed limit of 30 km/h for residential areas with pedestrians and cyclists. Notably, these studies make no distinction between cyclists and pedestrians and do not mention safe speeds for areas with motorcyclists.

Jurewicz et al. (2016) suggest operationalizing safe speed for a struck traffic participant as the striking impact vehicle speed which leads to a 10% probability of sustaining at least serious injury. Safe striking vehicle impact speeds for struck car occupants in head-on, side and rear-end impacts are calculated using simple mechanical assumptions from risk curves developed from the relations between delta-v (the velocity change during impact) and injury risk by *Bahouth et al. (2014)*. The proposed safe speeds are 30 km/h in head-on and side impacts, and 55 km/h in rear-end impacts. These impact speeds assume that the struck vehicle is stationary in rear-end crashes and that both vehicles have the same speed in head-on impacts. Similarly, based on risk curves from *Davis (2001)*, *Jurewicz et al. (2016)* suggest 20 km/h as safe speed for struck pedestrians. The proposed safe speeds are based on simplistic assumptions and dated field data which combine two different sources; therefore, as the authors suggest, "*require further research and refinement*" (*Jurewicz et al., 2016*).

Accordingly, this study aims to construct comparable, up-to-date injury risk curves for different types of road users: the VRUs pedestrians, cyclists, and motorcyclists, as well as passenger car drivers. "Comparable" means that data preparation and explanatory variables for the different types are identical. With these risk curves, the study aims to provide a vulnerability ranking (injury probability at a given impact speed) for different road user types. The risk curves are then used to suggest appropriate speed limits for each type, so that cars will be travelling at safe speeds when they encounter other road users. Furthermore, we demonstrate how the risk curves can be used for Safe System design, prioritizing and combining interventions for impact speed reduction and injury mitigation.

2 Literature review

There is a substantial amount of literature relating impact speed to injury probability for pedestrians impacted by a passenger car. A literature review by *Rosén et al. (2011)* demonstrates how the early studies suffer from sampling bias: In-depth data samples typically contain more serious and fatal injuries than national data. Therefore, most injury risk curves from early studies overestimate the fatality risk at a given impact speed. A more recent literature review and meta-analysis by *Hussain et al. (2019)* includes 20 studies from 1980 to 2017 of pedestrians impacted by the front of motor vehicles. The studies indicate a 10% fatality risk at speeds ranging from approximately 20 to 60 km/h, with a best estimate of 37 km/h. Impact speed is typically given as car speed at impact, as the influence of the pedestrian speed on the relative impact speed is deemed to be negligible.

For car-to-bicycle crashes, with a cyclist impacting the front of a passenger car, *Rosén (2013)* and *Jeppsson & Lubbe (2020)* provide injury risk curves. Both studies are based on GIDAS data. Although different input data were used for training the logistic regression model (only cars with a registration year later than 1997 in *Jeppsson & Lubbe (2020)* and no such limitation in *Rosén (2013)*), they obtained similar results. The 10% fatality risk of cyclists corresponds to 60 km/h (*Jeppsson & Lubbe, 2020*) or 67 km/h (*Rosén, 2013*). In both studies, impact speed is given as car speed on impact, without taking bicycle speed into account. Even though the influence of the cyclist speed on the impact is not negligible (*Spitzhüttl & Liers, 2016*), *Jeppsson & Lubbe (2020)* found that car impact speed gives a slightly better model fit than closing speed.

Rosén (2013) notes that cyclists' injury risks are lower than pedestrian risks and stresses that further research is needed to understand the differences. *Nishimoto et al. (2015)* present injury risk curves for both cyclists and pedestrians on the same dataset (Japanese national road traffic accident data from 2000 to 2013), but the use of different sets of explanatory variables to model the risk of serious injury complicates a direct comparison. Nevertheless, the results indicate that pedestrians are more likely than cyclists to sustain serious injuries when impacted by a car at any given speed.

For motorcyclist crashes, *Ding et al. (2019)* provide injury risk curves based on the GIDAS data, linking injury and fatality outcome to impact speed and other factors. One of the modelled crash partners for motorcyclists is passenger cars. Impact speed is calculated as the closing speed between the motorcyclist and the car, as both can make substantial contributions. The 10% fatality risk is indicated at a closing speed of 114 km/h. Motorcyclists thus appear to be much less vulnerable than cyclists and pedestrians in impacts with cars, but different study populations and (as with cyclists) explanatory variables hinder accurate comparisons between the risk curves.

For car-to-car crashes, most injury risk curves relate injury outcome to delta-v (the velocity change during impact), rather than car impact speed or closing speed between two crash participants (*Bareiss & Gabler, 2020; Stigson et al., 2012; Gabauer & Gabler, 2006*). This choice of impact severity measure makes it difficult to compare the vulnerability of car occupants to the vulnerability of other road users at a given driving speed. One recent publication estimates injury probability given the closing speed between a car and its crash partner, using data from the US NASS-CDS (National Automotive Sampling System-Crashworthiness Data System), in combination with speed information from EDRs (Event Data Recorders) (*Doecke et al., 2020*). The 10% serious injury risk for car occupants occurs at closing speeds ranging from 71 to 108 km/h, depending on the crash scenario. Comparing these injury risks to the fatality risks for other road users, car occupants appear to be among the least vulnerable road user groups. However, differences in data used and explanatory variables in the construction of the regression models hinder accurate comparison once again.

Another consistently influential factor on injury outcome besides impact severity (measured as some form of impact speed) is age. Age is a prominent factor influencing biomechanical properties, with increasing age soft tissues and bones stiffen (*Schmitt et al., 2019*). Age has been identified as highly influential and was successfully modelled as co-variate for injury risk curves (*Bareiss & Gabler, 2020; Niebuhr & Junge, 2017; Stigson et al., 2012*). To compare vulnerability of road user types, explicitly modelling the effect of age, and thereby age differences, is necessary. Many other factors are also known or suspected to influence injury risks. However, some are difficult to obtain or to compare across different types of road users (e.g. skidding before impact). For the purpose of providing evidence for setting speed limits, however, generalizability trumps detail: the purpose is not to describe risks in very specific circumstances but for the entirety of traffic situations (*Doecke et al., 2020*). While *Doecke et al. (2020)* modelled impact configuration in addition to speed, and not occupant age, it appears feasible (as the information is often readily available) and beneficial for comparison and generalization to other populations to model age across road users.

3 Methods

3.1 Dataset and weighting

All data were retrieved from the German In-Depth Accident Study (GIDAS) database. This accident data collection project is supported by the Federal Highway Research Institute (BASt) and the German Association for Research in Automobile Technology (FAT). The GIDAS collects accidents from two investigation areas (Hannover and Dresden and their surroundings), selected since they are representative of traffic situations and street types in Germany. When there is a road crash with suspected injury to at least one road user, within the investigation area and shift time, then the team drives to the scene of the most current crash site to collect evidence (*Liers, 2018*; *Otte et al., 2003*). Every crash is reconstructed and approximately 3500 variables per case are estimated (*Liers, 2018*). For some information, like impact speed, an error tolerance is given. Moderate random error in the impact speed estimation was shown not to influence pedestrian injury risk curves substantially (*Rosén & Sander, 2010*).

Due to the higher selection probability for crashes with serious and fatal outcomes, GIDAS over-represents fatal and serious crashes (*Pfeiffer & Schmidt, 2006*). To overcome this bias in GIDAS, German national data were used to calculate weighting factors which adjust GIDAS to national data (*Hautzinger et al., 2004*). The weighting was applied at the accident level, based on the accident type—seven different types of conflict situations *(Destatis, 2019)*—and police-recorded injury severity (crashes with fatal, serious-injury, or slight-injury outcome) for each accident year. Accident years ranged from 1999 to 2020, corresponding to our GIDAS sample. The calculations are detailed in the appendix.

For car-to-cyclist and car-to-motorcyclist crashes, the worst impacts (in terms of injury outcome) with the front of the car are coded in GIDAS and were thus simply selected. For car-to-pedestrian crashes, the worst impact is not coded; instead the first of potentially multiple crashes for the car and the first and only crash for the pedestrian were selected. For car drivers, consistent with the approach for VRUs, only the worst impacts in which the striking car front impacted the struck car were selected. Impacts were not further differentiated as head-on, side, or rear-end, but treated as one group to provide overall car occupant risk. Car drivers were selected and modelled to represent car occupants for simplicity. Additionally, crashes in which roll-over occurred at any time, or VRUs were run over, were excluded.

3.2 Constructing Injury Risk Curves

Two explanatory variables known to substantially influence injury risk were considered: road user age and closing speed. Hence, two different models to predict injury risk have been evaluated: one considering closing speed only (our primary interest) and one considering both closing speed and road user age.

Closing speed is also sometimes referred to as relative speed. For example, two cars both travelling at 50 km/h colliding head-on have a closing speed of 100 km/h. Age is recorded in full years in GIDAS. Since children and adults are different in physiological structure (*Tarriere, 1995*) people 14 years old or younger were excluded. Cases with unknown age or relative speed were also excluded from the sample.

Predictions of three levels of injury severity were calculated, using the 2015 revision of Abbreviated Injury Scale, AIS (*AAAM, 2016*), and its maximal value, MAIS: MAIS2+F (at least moderate injury, an AIS code of 2 or higher; or a recorded fatality, irrespective of MAIS level), MAIS3+F (at least serious injury or fatality, irrespective of MAIS level) and, lastly, fatal injury outcome.

Logistic regression was used to quantify the injury risk. The dependent value (injury or non-injury at MAIS2+F, MAIS3+F, and fatal injury levels) is binary. The output of the model, the probability of sustaining injury at the given level, facilitates drawing the injury risk curve. The mathematical definition is as follows:

$$\mathrm{P}(\text{class} = 1|X_1, X_2 \dots X_n) = \frac{1}{1+e^{-z}}, \tag{1}$$

where $\mathrm{Z} = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \cdots + \beta_n X_n$ with $\beta_0, \beta_1, \beta_2 \dots \beta_n$ being the parameters that the logistic regression estimates from the data; and

$X_1, X_2 \dots X_n$ are the independent variables (closing speed or closing speed and age, depending on the model).

Furthermore, 95% confidence intervals are calculated from the mean and standard deviation, assuming normal distribution. The function *glm()* in R is used to calculate the regression coefficients and confidence intervals in the weighted binary logistic regression.

3.3 Model evaluation

The dataset is unbalanced, as many more crashes lead to slight injury than to serious or even fatal injury. In this case, analyzing the receiver operating characteristic (ROC) curve is favored over other metrics such as accuracy (*He & Ma, 2013*).

The ROC curve illustrates the true positive rate versus the false positive rate with different thresholds. For each ROC curve, the area under the curve (AUC) is calculated. The AUC assesses the model’s ability to discriminate true cases from nontrue cases (*Kleinbaum et al., 2002*). The AUC value ranges from 0 to 1; the larger the AUC, the better the discrimination performance. An AUC value of 0.5 indicates that the model has no discrimination ability, while an AUC value of 1 indicates perfect discrimination ability.

The emphasis is on consistent and comparable models, so explanatory variables were kept to a minimum. For all VRUs and drivers across all injury severities, Model 1 used only closing velocity and Model 2 used closing velocity and age. A simple voting strategy was adopted to select the better model: for each road user within one specific injury, the model whose variable(s) had the higher average AUC got the vote. The model whose variable set had more votes was selected. P-values for regression coefficients were also calculated using the Wald-test but were not used for model selection.

All evaluations were carried out as five-fold cross validation with the AUC averaged to indicate model performance.

3.4 Application to Safe System design

The safe speed can be increased with different countermeasures, whose effects can be analyzed and described with the injury risk curves. The data can be re-analyzed and the injury risk curves can be re-drawn to see what would happen if different safety improvements were introduced.

To illustrate the effect of common safety measures on the model results, we equipped cars with Automated Emergency braking (AEB) and cyclists with protective equipment.

A magic helmet and a magic jacket were modelled: the term 'magic' denotes a theoretical concept (not to be confused with a statement on the realistic protective performance of helmets and jackets). The magic helmet decreased head injury by two levels on the AIS scale if no helmet was worn previously (AIS 0 is the lower bound); if a helmet was used or helmet use was unknown in the original sample, the magic helmet would have no effect. The magic helmet did not affect other body regions. For example, an un-helmeted cyclist sustaining both AIS2 head and thorax injures is an MAIS2+F case; when the magic helmet is added, the cyclist sustained an AIS0 head injury and an AIS2 thorax injury, so it is still an MAIS2+F case. New injury risk curves were calculated for the now-helmeted sample. Similarly, the magic jacket reduced thorax injuries by two levels on the AIS scale (AIS 0 was the lower bound). Wearing both the magic helmet and jacket reduced both head and thorax injuries simultaneously. In cases with a fatally injured cyclist, the magic helmet and/or jacket were modelled so as not to affect the injury outcome at all.

The effect of magic Automated Emergency Braking (AEB) was also added to the analysis. Assuming AEB reduces impact speed by 10 km/h in all cases, as indicated by *Eugensson et al. (2011)*, then the impact speed with AEB would be 10 km/h lower than without, so the x-axis was simply re-labeled. Any other assumed of proven impact speed reduction could be implemented and interpreted similarly.

4 Results

4.1 Data sample

In total, our data sample included 11,526 weighted cases (i.e. persons with known injury severity, age, and closing speed), distributed across injury severities and road users as shown in Table 1. The majority of cases were car drivers, and only 12 fatal motorcyclist cases were included.

Table 1. Data sample distribution over road users and injury severities

	Cyclist	Driver	Motorcyclist	Pedestrian
MAIS2+F (No / Yes)	*(1 772 / 705)*	*(6 528 / 855)*	*(236 / 188)*	*(593 / 649)*
MAIS3+F (No / Yes)	*(2 309 / 168)*	*(7 195 / 188)*	*(358 / 66)*	*(1 014 / 228)*
Fatal (No / Yes)	*(2 445 / 32)*	*(7 332 / 51)*	*(412 / 12)*	*(1 178 / 64)*

Closing speed is the key variable in the logistic regression model. For cyclists and pedestrians in our sample, most impacts occurred at closing speeds below 50 km/h, while for car drivers and motorcyclists the impacts occurred at a wide range of impact speeds (Figure 1).

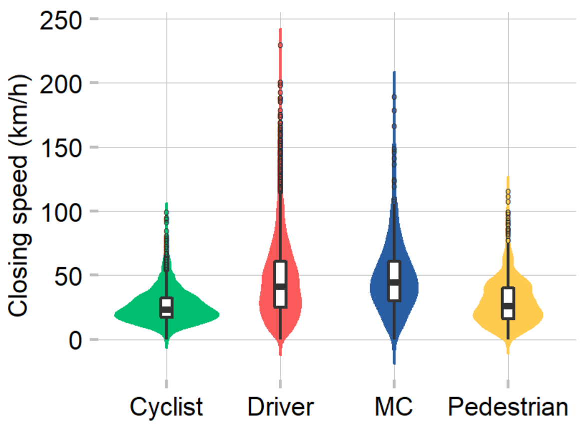

Figure 1. Closing speed distribution for road users. MC: motorcyclist. A boxplot (depicting the median as a solid line, Q1-Q3 as box whiskers up to 1.5 times the interquartile range, and potential outliers as points) is embedded in a violin plot (a visualization of the kernel density estimate, a smoothed version of the histogram).

Some, but not all, drivers reduced speed before impact. On average, speed reduction by the passenger car (the collision partner) was 6 km/h in pedestrian collisions, 3 km/h in cyclist collisions, 4 km/h in motorcycle collisions and 10 km/h in collisions with another passenger car.

Road user ages spanned a wide range for all road user types. The motorcyclists are, on average, the youngest road user group. Median ages are 39 years for cyclists and car drivers, 37 years for motorcyclists, and 46 years for pedestrians. The cyclist and pedestrian age distributions in Figure 2 are longer as they include more elderly road users.

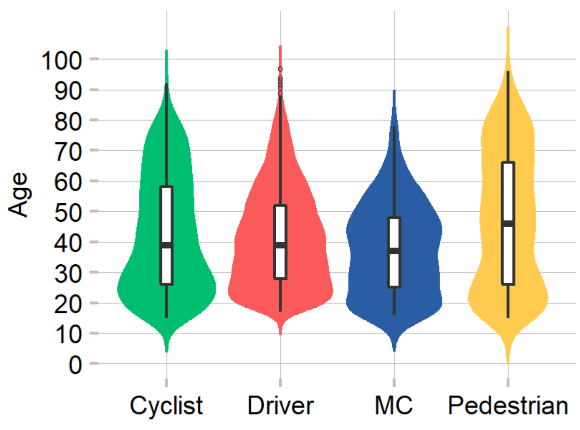

Figure 2. Age distribution for road users. MC: motorcyclist. A boxplot (depicting the median as a solid line, Q1-Q3 as box whiskers up to 1.5 times the interquartile range, and potential outliers as points) is embedded in a violin plot (a visualization of the kernel density estimate, a smoothed version of the histogram).

The availability and use of protective equipment may explain some differences in vulnerability across the road users. For cyclists and motorcyclists, protective equipment is defined as the helmet, whereas for car drivers it is defined as the seat belt. Pedestrians have no protective equipment. While approximately 90% of the car drivers and motorcyclists used protective equipment, only 8% of cyclists were known to have worn a helmet (Figure 3).

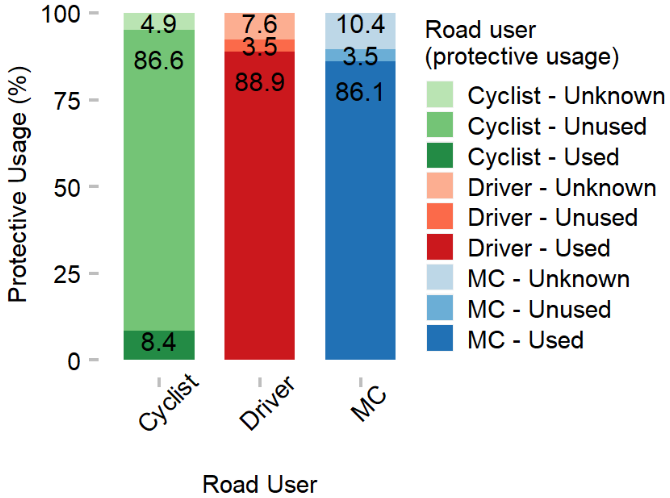

Figure 3. Use of protective equipment for cyclists, car drivers, and motorcyclists (MC)

4.2 Model selection

For the model selection, a five-fold cross validation was carried out and an averaged AUC value was calculated for both candidate models (Figure 4). Overall, the AUC increased with injury severity. There were no fundamental differences between the two models' performance; the AUC values are close to each other. For pedestrians, cyclists, and car drivers, Model 2, which combines closing speed and road user age, slightly outperformed Model 1 (which uses only closing speed) for all injury severities. On the other hand, for motorcyclists, Model 1 had slightly better scores for MAIS3+F and fatal crashes. Closing speed together with age was selected as the final model as the AUC was, on average, higher than for Model 1 and more votes were counted.

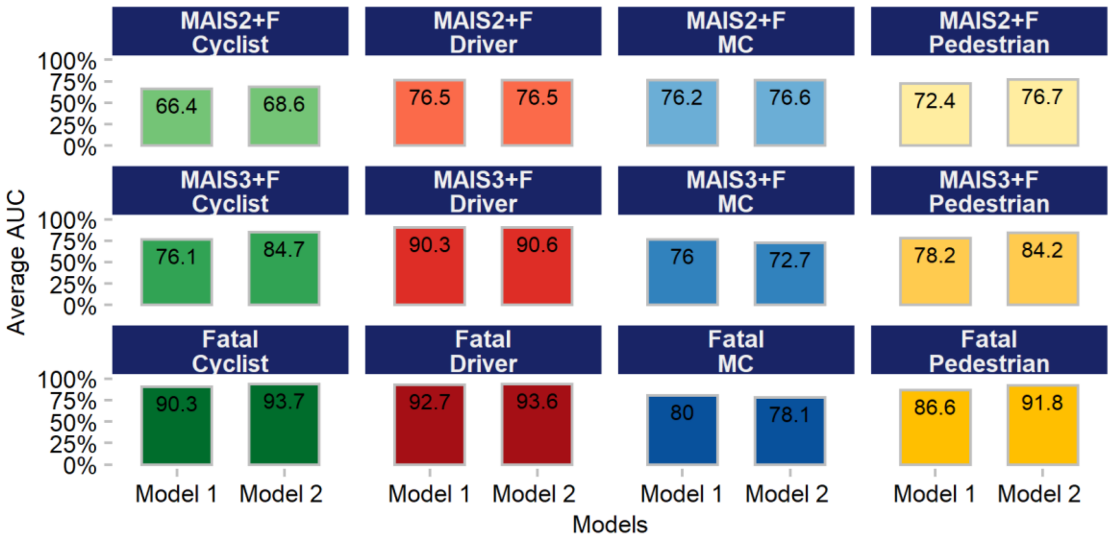

Figure 4. Candidate model performance measured by AUC. Model 1 consists of only closing speed and Model 2 consists of the combination of closing speed and road user age.

4.3 Injury risk curves

Regression coefficients for the injury risk curves of the different road users at all three injury severities are given in Table 2–Table 5. The regression coefficients describe the logarithmic odds of sustaining injury with a unit increase in the explanatory variable(s). All regression coefficients concerning closing speed were positive and significant, demonstrating that increased closing speed increases injury risk, no matter which road user type or injury severity level is considered. Furthermore, increased age is associated with increased injury risk.

Injury risk curves constructed from the regression coefficients from Table 2–Table 5 with the road user age consistently set to 65 years, together with their 95% confidence intervals, are shown in Figure 5–Figure 7. The age of 65 years was chosen as the border between mid-aged and older road users (*Wisch et al., 2017b*); risk curves for any other age can easily be calculated with the coefficients given in Table 2–Table 5.

Table 2. Pedestrian injury risk models: Logistic regression coefficient estimates according to Equation (1)

Pedestrian		Estimate (β_i)	Std. Error	p-value
	Intercept	*-3.041*	*0.225*	*<0.05*
MAIS2+F	*Closing speed*	*0.062*	*0.005*	*<0.05*
	Age	*0.027*	*0.003*	*<0.05*
	Intercept	*-6.190*	*0.387*	*<0.05*
MAIS3+F	*Closing speed*	*0.078*	*0.006*	*<0.05*
	Age	*0.038*	*0.004*	*<0.05*
	Intercept	*-10.204*	*0.987*	*<0.05*
Fatal	*Closing speed*	*0.099*	*0.011*	*<0.05*
	Age	*0.053*	*0.010*	*<0.05*

Table 3. Cyclist injury risk models: Logistic regression coefficient estimates according to Equation (1)

Cyclist		Estimate	Std. Error	p-value
	Intercept	*-3.231*	*0.172*	*<0.05*
MAIS2+F	*Closing speed*	*0.052*	*0.004*	*<0.05*
	Age	*0.019*	*0.003*	*<0.05*
	Intercept	*-7.467*	*0.390*	*<0.05*
MAIS3+F	*Closing speed*	*0.079*	*0.006*	*<0.05*
	Age	*0.047*	*0.005*	*<0.05*
	Intercept	*-10.674*	*0.904*	*<0.05*
Fatal	*Closing speed*	*0.100*	*0.011*	*<0.05*
	Age	*0.053*	*0.011*	*<0.05*

Table 4. Motorcyclist injury risk models: Logistic regression coefficient estimates according to Equation (1)

Motorcyclist		Estimate	Std. Error	p-value
	Intercept	*-2.965*	*0.421*	*<0.05*
MAIS2+F	*Closing speed*	*0.047*	*0.006*	*<0.05*
	Age	*0.010*	*0.008*	*0.177*
	Intercept	*-4.555*	*0.592*	*<0.05*
MAIS3+F	*Closing speed*	*0.040*	*0.006*	*<0.05*
	Age	*0.011*	*0.011*	*0.299*
	Intercept	*-7.494*	*1.458*	*<0.05*
Fatal	*Closing speed*	*0.047*	*0.009*	*<0.05*
	Age	*0.014*	*0.027*	*0.606*

Table 5. Car driver injury risk models: Logistic regression coefficient estimates according to Equation (1)

Car driver		Estimate	Std. Error	p-value
	Intercept	*-4.255*	*0.139*	*<0.05*
MAIS2+F	*Closing speed*	*0.030*	*0.001*	*<0.05*
	Age	*0.010*	*0.002*	*<0.05*
	Intercept	*-7.654*	*0.345*	*<0.05*
MAIS3+F	*Closing speed*	*0.041*	*0.002*	*<0.05*
	Age	*0.021*	*0.005*	*<0.05*
	Intercept	*-9.645*	*0.720*	*<0.05*
Fatal	*Closing speed*	*0.044*	*0.004*	*<0.05*
	Age	*0.021*	*0.010*	*<0.05*

The MAIS2+F curve is positioned highest, followed by the MAIS3+F curve and the fatal curve, which indicates that at the same closing speed an MAIS2+F injury is most likely. Furthermore, pedestrian and cyclist injury curves reach 100% injury probability at all levels within the depicted closing speed range (0–150 km/h): the fatality risk curves for these two road user groups appear more sensitive to impact speed, thereby indicating higher vulnerability. In contrast, the fatality risk curves for motorcyclists and drivers remain at low probabilities even at higher speeds, indicating less dependency on (and lower vulnerability to) impact speed. Furthermore, the motorcyclist injury risk curves have the widest confidence intervals, reflecting the lowest number of cases—and perhaps indicating the least strong (albeit statistically significant) relation between closing speed and injury outcome.

Pedestrian and cyclist injury risks are almost identical for MAIS3+F and fatal injuries but more separated for MAIS2+F injuries. The small risk surplus of pedestrians can likely be attributed to the protective equipment occasionally used by cyclists but never by pedestrians. It might also be attributed to differences in diet and exercise, or general fitness. The larger surplus at MAIS2+F might relate to impact kinematics; in car to pedestrian impacts the pedestrian must be impacted directly while in car to cyclist impacts, the impact might be between the car and the bicycle with the bicyclists falling to the ground, potentially a less violent impact. Detailed injury data (see appendix) provided evidence for this hypothesis as pedestrians sustained more lower extremity injuries from car impacts—typically the first point of impact in car to pedestrian crashes. As often observed with risk curves developed by logistic regression, the MAIS2+F risk at zero speed is not zero. This may reflect a reality: injuries sustained from falling to the ground at near zero impact speed. Further, it appears of little practical concern, one can simply define zero injury risk at zero speed and introduce a discontinuity to the curve (*Schramm, 2011*).

A vulnerability ranking can be derived from the injury risk curves: the lowest curve indicates the lowest vulnerability. The ranking, from lowest to highest vulnerability, is: drivers, motorcyclists, cyclists, and finally pedestrians.

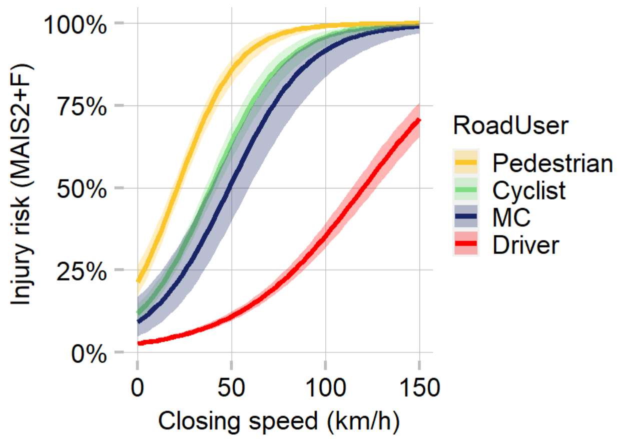

Figure 5. MAIS2+F injury risk curves with confidence levels, for different road users at 65 years of age

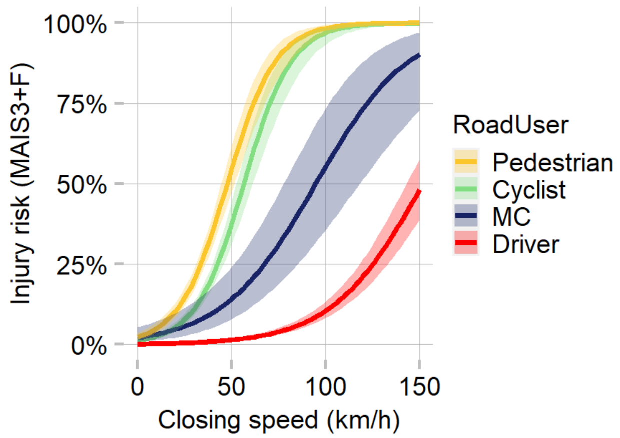

Figure 6. MAIS3+F injury risk curves with confidence levels, for different road users at 65 years of age

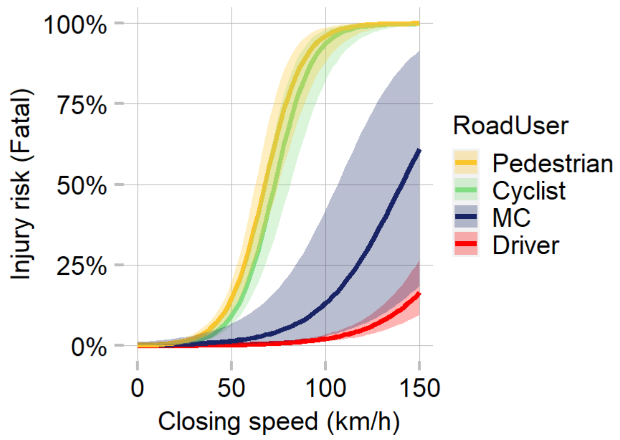

Figure 7. Fatal injury risk curves with confidence levels, for different road users at 65 years of age

4.4 Application to Safe System design

As indicated by the Recommendations of the Academic Expert Group for the 3rd Global Ministerial Conference on Road Safety (*Academic Expert Group, 2019*), a speed corresponding to 10% MAIS3+F injury risk may be considered a safe speed. The corresponding closing speed for the road users is calculated taking their median age, not to rank vulnerability for a specific age (65 years in the previous section), but to indicate risk on the road, given the observed age distribution of each road user group in the data. A 10% MAIS3+F injury risk corresponds to a closing speed of 29 km/h for pedestrians, 44 km/h for cyclists, 48 km/h for motorcyclists, and 112 km/h for car drivers. It is straightforward to read alternative safe speeds from the risk curves, should one select a different injury severity level (MAIS2+F or Fatal), risk percentage (other than 10%) or age (other than 46 years for pedestrians, 39 years for cyclists and car drivers, and 37 years for motorcyclists).

Injury risk can be reduced, or the safe speed can be increased, with different countermeasures. The effects can be analysed and described with the injury risk curves. The effect of protective equipment (magic helmets and jackets for cyclists and AEB for cars) was modelled and quantified to demonstrate how much safe speeds can change when protective measures are introduced.

Recall from Figure 3 that most of the cyclists did not wear a helmet; adding protective equipment in a what-if analysis and re-drawing injury risk curves should lead to some risk reductions.

Figure 8 shows the effects of the protective equipment on MAIS2+F injury risk. There is little effect at low speeds, but as closing speed increases, the gap between the curves (the risk reduction) grows larger before finally becoming small again. The magic helmet and jacket have little effect at low speeds because the majority of head and thorax injuries are already less than AIS2. At high speeds, most injuries are already at AIS4 or higher, again limiting the equipment's effect. Overall, the magic helmet reduces injury risk more than the magic jacket: assuming a 25% risk of at least moderate injuries (MAIS2+F) is acceptable, the safe closing speed could be increased from 27 to 38 km/h with the magic helmet, to 30 km/h with the magic jacket, and to 44 km/h with both. The safe speed with the magic helmet, magic jacket, and AEB together would then increase from 27 to 54 km/h.

More potential countermeasures can be added to the analysis, thereby allowing a direct estimate of how different interventions affect (and potentially increase) the safe speed, as long as their effects can be described reasonably simply and accurately.

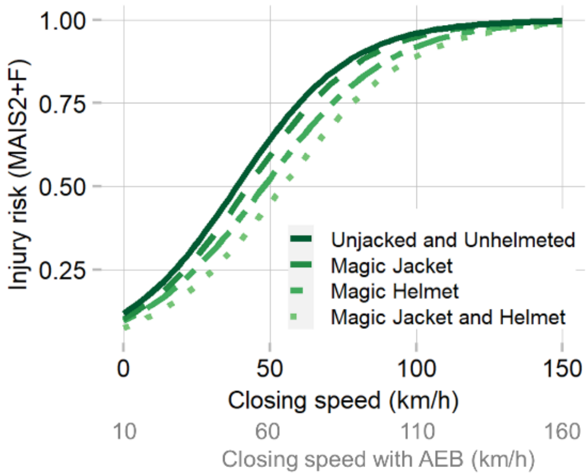

Figure 8. The injury risk-reducing effect of protective equipment for cyclists

5 Discussion

In the Safe System approach, the speed limit is a key component. Given the state of protection provided by safe cars, safe roads, and safe road users, one can determine safe speeds. In our study, we used German data from 1999-2020 to define the state and calculate safe closing speeds (with 10% MAIS3+F injury risk). Both the injury severity level and the risk percentage were arbitrarily set in this study and are expected to be set by the public and policy makers. The risk curves presented facilitate safe speed determination at other severity and risk levels. Nevertheless, assuming a 10% MAIS3+F risk is acceptable, then the corresponding safe closing speeds are 29 km/h for pedestrians, 44 km/h for cyclists, 48 km/h for motorcyclists, and 112 km/h for car drivers.

To interpret these speeds, one should recall that they are closing speeds and consider the speeds of the different road users. The worst-case scenario would be a straight head-on impact. A pedestrian might walk at 5 km/h into a car front, leaving 25 km/h or less as the safe travelling speed for the car when pedestrians might be encountered, in agreement with previous suggestions (*ETSC, 2020; ITF/OECD, 2018; Jurewicz et al., 2016*). A cyclist easily travels at 15 km/h or more, leaving 30 km/h or less for the car. If both vehicles are treated as equal, a speed limit of 20 km/h is indicated—similar to the limit for pedestrian encounters. Both speeds seem generally in line with the current practice of speed limits of 20 to 30 km/h in urban areas where cars and pedestrians or cyclists mix. However, on rural roads, where bicycles and cars share the same space, these speeds are often substantially exceeded, resulting in overtaking maneuvers (*Dozza et al., 2016*) and, if they fail, in crashes between cars and cyclists with high injury risks (*Isaksson-Hellman & Werneke, 2017; Wisch et al., 2017a*). Substantial investment to counter current casualties and encourage participation in active travel appears necessary. High-risk rural roads may be redesigned with separate cycling provisions, or car speeds may be reduced to 20 km/h, or cars may be prohibited from using these roads altogether.

In traffic situations where cars and motorcyclists can encounter each other, the safe driving speed is similar to that for cyclists, 20 to 25 km/h. This speed is substantially lower than current practice, where cars and motorcyclists can encounter each other in head-on impacts on rural roads with speed limits of 70 or 100 km/h in many countries. A speed limit of 25 km/h on most rural roads would be a substantial change, increasing travel time for motorcyclists and cars (and to a lesser extent for cyclists). However, other substantial changes to the transport system could increase the safe speed. A simple but drastic approach would be to prohibit motorcycles or cars altogether. Perhaps less drastic, but requiring tremendous effort, would be to separate motorcyclists and cars, i.e., building protected motorcycle-only roads. Finally, another option would be to substantially increase vehicle safety: implementing AEB and other assistance systems on both cars and motorcycles, more advanced in-crash protection such as airbags or safety cells and belts on motorcycles (concepts which were introduced but never widely adapted), and other yet-to-be-invented protective equipment for motorcyclists.

Where cars can encounter other cars, the safe speed limit is 55 km/h, half the closing speed of 112 km/h. This speed is substantially higher than the 30 km/h suggested by *Jurewicz et al. (2016)* for head-on and side impacts, but matches their recommendation for rear impacts. Further, the speed is in accordance with the 55–60 km/h impact speed at which passive safety systems can provide protection for side and head-on impacts, as suggested by *Eugensson et al. (2011)*. If we assume that all cars are equipped with a perfectly effective AEB system that reduces impact speeds by 20 km/h, the speed limit could be increased by that amount (*Eugensson et al., 2011*), for a safe speed of 75 km/h. If yet higher speeds are to be pursued, it appears necessary to prevent encounters.

5.1 Comparison to previous literature

The risk levels indicated in this study are not identical to previous research; neither are they contradictory, as differences are explainable and within the margins of error. As noted, to facilitate comparison with risk curves which did not explicitly model age as an explanatory variable, we used the median age of each road user group to obtain risks as seen in the field.

This study indicates a 10% pedestrian fatality risk at 56 km/h closing speed, which is within the range of 20–60 km/h stated by *Hussain et al. (2019)* (albeit at its higher end) and closely matches *Rosén & Sander (2009)* which used crashes from 1999–2007 from the same GIDAS data and reported an impact speed of 52 km/h at 10% fatality risk. Comparing their results with ours in more detail, our study indicates fatality risks at median age of 0.8% at 30 km/h, 5.8% at 50 km/h, 31.1% at 70 km/h, and 89.9% at 100 km/h—while they note 1.5%, 8.3%, 35.4%, and 89.1% at the same impact (i.e., car) speeds. The differences are well within the margin of error, and may in fact be due to differences in speed definitions, since closing speed is typically slightly higher than car impact speeds for the same crash. The use of newer data, and perhaps newer cars protecting pedestrians better, appears to have only a marginal influence on the results.

Table 6. Comparison of cyclist fatality risks to previous studies

	30 km/h	50 km/h	70 km/h	100 km/h
Current study	*0.4%*	*2.6%*	*16.1%*	*79.2%*
Jeppsson and Lubbe (2020)	*0.4%*	*3.6%*	*26.4%*	*91.4%*
Rosén (2013)	*0.3%*	*2.0%*	*12.6%*	*73.1%*

For cyclist fatality risk, the current study's results are similar to those of *Rosén (2013)*, see Table 6, despite the use of a different definition for speed. In the current study, the closing speed between the cyclist and the car is used, whereas *Rosén (2013)* chose the opponent car impact speed. Compared to another, more recent study which also used GIDAS data (*Jeppsson &*

Lubbe, 2020), our study indicates less speed dependence (the curve is less steep), but again the differences are well within the margin of error.

For motorcyclist injury risks, our results are in line with those of Ding et al. (2019) as shown in Table 7. In the current study, fatality risks are 0.4% (30 km/h), 1.0% (50 km/h), 2.4% (70 km/h), and 9.2% (100 km/h). Differences are within the (large) margin of error and may be the result of different filtering and exclusion criteria. The current study considered only car front impacts, while Ding et al. (2019) included all motorcycle-to-car crashes.

Table 7. Comparison of motorcyclist fatality and MAIS3+F risks to previous studies

	30 km/h	50 km/h	70 km/h	100 km/h
Current study fatality risk	*0.4%*	*1.0%*	*2.4%*	*9.2%*
Ding et al. (2019) fatality risk	*0.6%*	*1.2%*	*2.3%*	*6.4%*
Current study MAIS3+F risk	*5.1%*	*10.7%*	*21.1%*	*47.3%*
Ding et al. (2019) MAIS3+F risk	*12.0%*	*18.3%*	*27.0%*	*43.9%*

The car driver injury risks we report can be compared to the results for MAIS3+ injury risks in Doecke et al. (2020), which are based on US data. The 10% risks for front, side, and rear-end impacts are estimated to be reached at closing speeds of 71, 108, and 88 km/h, respectively. The side impact speed risk corresponds to the present study's 10% MAIS3+F risk, with a closing speed of 112 km/h, although the latter was not separated by crash type. Impact speeds for the other impact types are higher in the current study, but these results are not contradictory, given that different datasets and groupings were used.

5.2 Limitations and future work

The first aim was to rank road users by vulnerability; the scenario of being impacted by a car front was selected for all road user groups. This is the most common scenario, but not the only one. Injury risks for other scenarios, like a motorcyclist impacting the side of a car, might be different from the risks presented in this study, so additional scenarios would need to be considered to generalize the results. It would also be relevant to further detail the analyses into different crash scenarios, like head-on or side impacts, for the different road user types. For example, Bahrololoom et al. (2020) give cyclists injury risk and Doecke et al. (2020) car occupant risks by crash type; however, the influence of crash type appears to differ between road users and defining crash types consistently across road users is not trivial.

Furthermore, a car-centric perspective was chosen, as cars are the most common crash partner for VRUs; but they are not the only one. The injury risk of two motorcyclists encountering each other may be higher or lower than a car and a motorcyclist encountering each other, for example. Constructing risk curves and estimating safe speeds for other types of encounters not studied here, such as those including trucks and buses, are important future goals.

Initial exploratory data analysis considered the effect of vehicle age and sex on injury risk but did not reveal substantial and consistent influence. GIDAS data from 1999-2020 was used; the data includes older vehicle designs, and modern cars and motorcycles may offer better protection. However, these effects could not be modelled across road users with the limited sample size available. The results of this study should be re-evaluated with newer data in the future. Sex and other factors can be important to consider when broad comparisons between road user types are not the focus but the influence of a larger number of factors on a more homogenous road user group.

GIDAS only samples crashes with suspected injury of at least one participant; damage-only crashes are not sampled. Therefore, the risk curves are conditional, in the sense that the probability of injury is conditional on involvement in an injury-causing crash. However, the injury risk is expected to be very similar to the injury risk given the involvement in any type of crash when considering high injury severities and high speeds, as most of the data nonetheless describes uninjured participants (recall Table 1). The intercept of the MAIS2+ risk curves would probably decrease if damage-only crashes were available or estimated and more data with no injury at low speeds were included.

Modelling age as explicit variable allows to extrapolate to different populations; as injury risks consistently and substantially increased with age, older populations are at higher risk. Children of 14 years and less were deliberately excluded from analysis to facilitate comparisons between road users. Still, children are at risk of being impacted by passenger cars, particularly as pedestrians, and need to be protected. In exploratory analysis, we modelled pedestrian injury risk including all ages and found results not to differ substantially, that is, there was still a strong trend of increased risks with age. Therefore, safe speeds for the average age are also safe speeds for child pedestrians, at least according to our model. However, statistical methods allowing for non-linear relations (*Forman & McMurry, 2018*) may reveal more complex relations with age. Such modelling was beyond the scope of the present study.

It is not obvious how to apply the relation between age, closing speed and injury risk to other countries where car designs, the use of protective equipment, infrastructure, and road user behavior differ. It appears necessary to compare injury risk curves constructed independently from data samples from different countries in order to better assess generalizability.

6 Conclusion

Pedestrians were most likely to sustain injuries at any severity level, followed by cyclists, motorcyclists, and car drivers, when impacted by a car front with the same closing speed. This vulnerability ranking aligns with current protection levels: car occupants have metal cages, crumple zones, seatbelts and airbags; motorcyclists have helmets and protective clothing; cyclists have sparsely used helmets; and pedestrians typically have no protective equipment at all.

From the developed risk curves, assuming a 10% MAIS3+F risk as acceptable, safe closing speeds can be obtained: 29 km/h for pedestrians, 44 km/h for cyclists, 48 km/h for motorcyclists, and 112 km/h for car drivers. These closing speeds can be translated into driving speed limits of 25 km/h for cars with pedestrian encounters, 20 to 25 km/h for both cyclists and cars (as well as motorcyclists and cars if they can encounter each other), and 55 km/h when head-on impacts between passenger cars are possible. While these safe speeds align with current practices of 20 to 30 km/h in urban centers, rural roads shared by bicycles, motorcycles, and cars appear in need of substantial intervention and redesign.

If all cars were equipped with perfectly effective AEB, or road users had better protective equipment, the driving speed limit could increase accordingly.

CRediT contribution statement

Nils Lubbe: Conceptualization, Methodology, Writing - Original Draft, Writing - Review & Editing. **Yi Wu:** Methodology, Investigation, Data curation; Formal analysis; Writing - Original Draft. **Hanna Jeppsson:** Investigation, Data curation; Formal analysis; Validation, Writing - Review & Editing.

Declaration of competing interests

Nils Lubbe and Hanna Jeppsson work at Autoliv Research, located in Vårgårda, Sweden. Yi Wu worked at Autoliv Vehicle Safety System Technical Center located in Shanghai, China. Both legal entities are part of Autoliv Inc. (*www.autoliv.com*), a company that develops, manufactures and sells for example protective safety systems to car manufacturers. Autoliv is a tier 1 supplier. Results from this study may impact how Autoliv choose to develop their products. The study was funded by Autoliv.

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Appendix

Data weighting

To make the GIDAS data representative for Germany as a whole weight factors were derived and used to adjust the data samples. From *Destatis (2019)* seven different conflict situations (UTYP 1 to 7), three injury severity levels (fatalities, seriously injured, slightly injured) as well as accident year (1999-2020) were extracted for road traffic crashes.

The raw weight factors are calculated using Equation (A1), which means that for each year 21 different weight factors (7 conflict situations times 3 injury severities) were calculated. Weight factors were normalized so that the weighted GIDAS sample size equals the unweighted sample size Equation (A2). The weight factors illustrate over- or under-representation of the database. If the raw weight factor is less than one—over-representation, and larger than one—under-representation.

$$Raw\ weight\ factor_{[severity]} = \left(\frac{Frequency\ National_{[severity]}}{Frequency\ National_{[all]}}\right) \Big/ \left(\frac{Frequency\ Database_{[severity]}}{Frequency\ Database_{[all]}}\right) \tag{A1}$$

$$Normalized\ weight\ factor_{[severity]} = Raw\ weight\ factor_{[severity]} \cdot \frac{number\ of\ rows_{[dataset]}}{sum_{[Raw\ weight\ factor]}} \tag{A2}$$

The weight factors used in the study are given in Table A1 and the scale factor for each road user is given in Table A2.

Table A1. Weight factors for crashes recorded in GIDAS by conflict situation (UTYP), year and injury severity to correct sampling bias against German national data. An empty cell means that no such crash was present in the database.

		UTYP 1: Driving accident	UTYP 2: Accident caused by turning of the road	UTYP 3: Accident caused by turning into a road or by crossing it	UTYP 4: Accident caused by crossing the road	UTYP 5: Accident involving stationary vehicles	UTYP 6: Accident between vehicles moving along in carriageway	UTYP 7: Other accident
	Slight	*1.179297*	*1.134536*	*0.88213*	*0.792441*	*1.204004*	*1.292566*	*2.120759*
1999	*Serious*	*0.80696*	*1.110546*	*0.673929*	*0.499978*	*0.716679*	*0.651913*	*1.300296*
	Fatal	*0.766223*	*0.289576*	*0.719242*	*0.287867*		*0.627842*	*0.268709*
	Slight	*0.908837*	*1.284115*	*0.877938*	*0.872589*	*2.255049*	*1.454243*	*1.353416*
2000	*Serious*	*0.73565*	*0.880815*	*0.634036*	*0.53537*	*1.337471*	*0.927147*	*1.126605*
	Fatal	*0.573259*	*1.707081*	*0.683348*	*0.689021*	*0.25271*	*0.825175*	*0.674581*
	Slight	*1.20134*	*1.013197*	*0.935591*	*0.689074*	*0.974458*	*1.377433*	*1.610523*
2001	*Serious*	*0.876154*	*0.767665*	*0.739343*	*0.480098*	*0.703944*	*0.689952*	*1.804405*
	Fatal	*0.405643*	*0.896295*	*0.765376*	*0.275267*		*0.486881*	*0.416497*
	Slight	*1.221908*	*0.988905*	*0.93602*	*0.707983*	*0.79579*	*1.554762*	*1.849401*
2002	*Serious*	*0.865905*	*0.910313*	*0.536676*	*0.481074*	*0.438849*	*0.785697*	*1.299095*
	Fatal	*0.355174*	*0.361736*	*0.555188*	*0.325112*	*0.171289*	*0.479685*	*0.655858*
	Slight	*1.259866*	*1.029762*	*0.832277*	*0.805105*	*0.899012*	*1.419029*	*1.611185*
2003	*Serious*	*0.901802*	*0.681436*	*0.687595*	*0.466023*	*1.13641*	*0.789197*	*1.293294*
	Fatal	*0.725666*	*0.221272*	*0.406261*	*0.462297*	*0.17147*	*0.550172*	*0.761529*

Table A1 (*cont.*)

		UTYP 1: Driving accident	UTYP 2: Accident caused by turning of the road	UTYP 3: Accident caused by turning into a road or by crossing it	UTYP 4: Accident caused by crossing the road	UTYP 5: Accident involving stationary vehicles	UTYP 6: Accident between vehicles moving along in carriageway	UTYP 7: Other accident
	Slight	*1.027576*	*1.207749*	*0.855925*	*0.77692*	*1.97488*	*1.328147*	*1.40838*
2004	*Serious*	*0.817985*	*1.099931*	*0.621793*	*0.512483*	*1.092094*	*0.9118*	*1.055188*
	Fatal	*0.623822*	*0.815683*	*1.650336*	*0.390227*		*0.516361*	*0.532227*
	Slight	*1.210102*	*0.88782*	*0.900232*	*0.756592*	*1.049644*	*1.447672*	*1.248287*
2005	*Serious*	*0.875623*	*0.940039*	*0.642098*	*0.590258*	*1.273725*	*0.799223*	*1.033107*
	Fatal	*0.588003*	*1.786753*	*1.763165*	*0.4052*	*0.082556*	*1.200604*	*0.66045*
	Slight	*1.078214*	*1.077838*	*0.801573*	*0.946167*	*1.086879*	*1.182159*	*1.918269*
2006	*Serious*	*0.852981*	*0.764846*	*0.707791*	*0.575907*	*3.753136*	*0.937604*	*1.140455*
	Fatal	*1.4325*	*0.452062*	*1.630913*	*0.323663*		*0.784101*	*0.779117*
	Slight	*1.22373*	*0.856999*	*0.884566*	*0.91586*	*0.993554*	*1.201489*	*1.771861*
2007	*Serious*	*0.811512*	*0.843801*	*0.723446*	*0.510172*	*1.235203*	*0.890555*	*1.298584*
	Fatal	*0.987252*	*0.270532*	*3.19439*	*0.396926*	*0.184847*	*1.400795*	*1.189954*
	Slight	*1.188195*	*0.967527*	*0.861602*	*0.791674*	*0.922759*	*1.31481*	*1.583992*
2008	*Serious*	*0.982909*	*0.636821*	*0.729732*	*0.427437*	*0.568709*	*0.904697*	*1.069676*
	Fatal	*0.97636*	*1.500246*	*1.578259*	*0.636104*		*1.044171*	*0.798131*
	Slight	*1.088391*	*0.905681*	*0.862393*	*0.829389*	*0.677446*	*1.417157*	*1.341866*
2009	*Serious*	*1.1219*	*1.035501*	*0.641304*	*0.525002*	*0.604229*	*0.968142*	*1.003629*
	Fatal	*0.789839*	*0.77512*		*1.319975*		*1.268084*	*0.799985*
	Slight	*1.104139*	*0.966647*	*0.827569*	*0.7535*	*0.857182*	*1.269039*	*1.411568*
2010	*Serious*	*1.095688*	*0.745085*	*0.668612*	*0.524408*	*0.778259*	*1.245855*	*1.078097*
	Fatal	*1.740783*	*1.364815*	*2.736067*	*0.399144*		*1.190994*	*1.007517*
	Slight	*0.94042*	*0.870604*	*0.851816*	*0.909215*	*1.070583*	*1.428596*	*1.265375*
2011	*Serious*	*1.023516*	*1.123306*	*0.713434*	*0.667793*	*0.674729*	*0.921033*	*0.977423*
	Fatal	*1.823085*		*1.438449*	*0.818374*		*2.536958*	*0.564993*
	Slight	*1.093293*	*0.998742*	*0.818789*	*0.672281*	*0.815088*	*1.274036*	*1.717092*
2012	*Serious*	*0.964399*	*0.67448*	*0.691136*	*0.678516*	*0.731305*	*0.963176*	*1.708074*
	Fatal	*1.804634*		*2.563702*	*0.345568*	*0.1654*	*0.764976*	
	Slight	*1.253049*	*0.90237*	*0.866078*	*0.739762*	*0.809952*	*1.223787*	*1.497137*
2013	*Serious*	*0.952867*	*0.606103*	*0.887716*	*0.447367*	*1.012363*	*1.299441*	*1.302993*
	Fatal	*0.773592*	*0.45753*	*2.260738*	*0.316752*		*0.904295*	*0.406187*
	Slight	*1.186226*	*0.921238*	*0.827562*	*0.910235*	*0.713753*	*1.307922*	*1.544035*
2014	*Serious*	*1.053917*	*0.618939*	*0.754777*	*0.556964*	*1.253492*	*0.967208*	*1.169926*
	Fatal	*0.730139*	*0.231232*	*0.617898*	*0.33918*		*1.085377*	*0.696057*
	Slight	*1.160608*	*0.87247*	*0.862273*	*0.696543*	*0.613075*	*1.292036*	*1.406306*
2015	*Serious*	*0.901027*	*0.806056*	*0.870761*	*0.53978*	*1.06608*	*1.250742*	*1.33316*
	Fatal	*0.764755*			*0.581655*		*0.925829*	*1.225261*

Table A1 (*cont.*)

		UTYP 1: Driving accident	UTYP 2: Accident caused by turning of the road	UTYP 3: Accident caused by turning into a road or by crossing it	UTYP 4: Accident caused by crossing the road	UTYP 5: Accident involving stationary vehicles	UTYP 6: Accident between vehicles moving along in carriageway	UTYP 7: Other accident
	Slight	*1.088638*	*0.813212*	*0.894394*	*0.755084*	*0.737908*	*1.501563*	*1.18697*
2016	*Serious*	*0.852291*	*0.92917*	*0.683567*	*0.606003*	*0.71549*	*1.213917*	*1.372357*
	Fatal	*0.697753*	*0.291006*	*1.22024*	*1.071431*		*0.611774*	*0.632717*
	Slight	*0.767701*	*1.005422*	*0.915242*	*0.883687*	*0.805818*	*1.603123*	*1.12018*
2017	*Serious*	*0.730793*	*1.145383*	*0.724777*	*0.84992*	*1.002821*	*1.332193*	*0.880975*
	Fatal	*1.084053*	*1.686304*	*0.692851*	*0.526054*		*1.029379*	*0.480963*
	Slight	*0.906683*	*1.074557*	*0.968061*	*1.06509*	*0.958587*	*1.324206*	*0.909894*
2018	*Serious*	*1.04974*	*1.071582*	*0.645141*	*0.929818*	*0.832596*	*1.018379*	*0.709884*
	Fatal	*0.819491*	*0.603889*	*0.476687*	*0.357194*		*0.46967*	*1.283586*
	Slight	*1.09426*	*0.956041*	*0.93156*	*0.700802*	*0.617997*	*1.350226*	*0.791455*
2019	*Serious*	*1.283987*	*0.846507*	*0.760885*	*0.827501*	*1.547566*	*1.244737*	*0.759073*
	Fatal	*1.271128*	*0.514246*		*1.303721*		*1.266702*	*0.813619*
	Slight	*0.519033*	*3.609033*	*0.711438*		*0.805075*	*7.057276*	*1.058156*
2020	*Serious*	*0.8464*		*0.192797*				*0.378541*
	Fatal							

Table A2: Sample size, sum of weight factor and scale factor divided by the different road users

Road user	Sample size	Sum weight factors	Scale factor
Pedestrian	*1224*	*946.0*	*0.7616*
Cyclist	*2477*	*2161.1*	*0.8725*
Motorcyclist	*424*	*396.8*	*0.9358*
Car driver	*7383*	*8030.7*	*1.0877*

Detailed injury data

Injured body regions are compared between cyclists and pedestrians. In the Tables A3-A6, the percentage of people sustaining at least one injury of at least the severity studied in the different body regions are listed by injury severity. For example, 50.1% of the MAIS2+ injured cyclists had at least one AIS2+ injury to the head, while more MAIS2+ injured pedestrian (57.8%) had at least one AIS2+ injury to the head. We have computed the numbers for all injuries, and for only those coded to originate from the car impact (excluding, for example, ground impact). It can be observed that pedestrians have, on average, more injured body regions and sustain more lower extremity injuries.

Table A3. Proportion of MAIS2+ injured cyclists and pedestrians sustaining MAIS2+ injuries in the listed body regions

Body region	Cyclist, % (N=705)	Pedestrians, % (N=649)
Reg1 – Head w/o face	*50.1*	*57.8*
Reg2 – face	*5.8*	*8.3*
Reg3 – neck w/o spine	*0.4*	*0.9*
Reg4 – thorax w/o shoulder	*12.6*	*18.3*
Reg5 – abdomen	*3.7*	*6.3*
Reg6 – spine	*6.8*	*10.3*
Reg7 – upper extremities	*26.7*	*25.3*
Reg8 – lower extremities	*35.2*	*57.8*

Table A4. Proportion of MAIS3+ injured cyclists and pedestrians sustaining MAIS3+ injuries in the listed body regions

Body region	Cyclist, % (N=168)	Pedestrians, % (N=228)
Reg1 – Head w/o face	*40.5*	*42.9*
Reg2 – face	*3.0*	*2.2*
Reg3 – neck w/o spine	*1.2*	*1.3*
Reg4 – thorax w/o shoulder	*36.3*	*42.5*
Reg5 – abdomen	*5.4*	*7.0*
Reg6 – spine	*7.7*	*9.6*
Reg7 – upper extremities	*7.1*	*7.5*
Reg8 – lower extremities	*34.5*	*54.8*

Table A5. Proportion of fatally injured cyclists and pedestrians sustaining fatal injuries in the listed body regions

Body region	Cyclist, % (N=32)	Pedestrians, % (N=64)
Reg1 – Head w/o face	*78.1*	*70.3*
Reg2 – face	*25.0*	*23.4*
Reg3 – neck w/o spine	*25*	*56.3*
Reg4 – thorax w/o shoulder	*6.3*	*9.4*
Reg5 – abdomen	*0*	*6.3*
Reg6 – spine	*6.3*	*3.1*
Reg7 – upper extremities	*28.1*	*32.8*
Reg8 – lower extremities	*3.1*	*1.6*

Table A6. Proportion of MAIS2+ injured cyclists and pedestrians sustaining MAIS2+ injuries from impact with the car in the listed body regions

Body region	Cyclist, % (N=498)	Pedestrians, % (N=573)
Reg1 – Head w/o face	*34.1*	*43.6*
Reg2 – face	*4.0*	*6.8*
Reg3 – neck w/o spine	*0.8*	*0.7*
Reg4 – thorax w/o shoulder	*14.3*	*17.3*
Reg5 – abdomen	*3.6*	*6.5*
Reg6 – spine	*6.4*	*8.7*
Reg7 – upper extremities	*17.9*	*19.0*
Reg8 – lower extremities	*35.5*	*59.7*

Table A7. Proportion of MAIS3+ injured cyclists and pedestrians sustaining MAIS3+ injuries from impact with the car in the listed body regions

Body region	Cyclist, % (N=134)	Pedestrians, % (N=206)
Reg1 – Head w/o face	*39.6*	*37.4*
Reg2 – face	*3.0*	*2.4*
Reg3 – neck w/o spine	*1.5*	*0.5*
Reg4 – thorax w/o shoulder	*35.8*	*38.8*
Reg5 – abdomen	*4.5*	*8.3*
Reg6 – spine	*7.5*	*6.3*
Reg7 – upper extremities	*4.5*	*3.9*
Reg8 – lower extremities	*31.3*	*54.9*

Table A8. Proportion of fatally injured cyclists and pedestrians sustaining fatal injuries from impact with the car in the listed body regions

Body region	Cyclist, % (N=29)	Pedestrians, % (N=60)
Reg1 – Head w/o face	*75.9*	*70.0*
Reg2 – face	*27.6*	*25.0*
Reg3 – neck w/o spine	*24.1*	*60.0*
Reg4 – thorax w/o shoulder	*6.9*	*10.0*
Reg5 – abdomen	*0*	*6.7*
Reg6 – spine	*6.9*	*3.3*
Reg7 – upper extremities	*31.0*	*35.0*
Reg8 – lower extremities	*3.4*	*1.7*