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Injury risk curves to guide safe speed limits on Swedish roads using German crash data supplemented with estimated non-injury crashes

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A R T I C L E I N F O

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A B S T R A C T

Vision Zero postulates that no one should be killed or seriously injured in road traffic; therefore, it is necessary to define evidence-based speed limits to mitigate impact severity. The overall aims to guide the definition of safe speeds limits by establishing relations between impact speed and the risk of at-least-moderate (MAIS2+) and at-least-severe (MAIS3+) injuries for car occupants in frontal and side crashes in Sweden. As Swedish in-depth data are unavailable, the first objective was to assess the applicability of German In-depth Accident Study (GIDAS) data to Sweden. The second was to create unconditional injury risk curves (risk of injury given involvement in any crash), rather than risk curves conditional on the GIDAS sampling criterion of suspected-injury crashes. Thirdly, we compared the unconditional and conditional risk curves to quantify the practical implications of this methodological choice. Finally, we provide an example to demonstrate how injury risk curves facilitate the definition of safe, evidence-based speed limits in Sweden. Characteristics important for the injury outcome were similar between GIDAS and Swedish data; therefore, the injury risk curves using German GIDAS data are applicable to Sweden. The regression models yielded the following results for unconditional injury risk curves: 10 % MAIS2+ at 25 km/h impact speed for frontal head-on crashes, 20 km/h for frontal car-to-object crashes, 55 km/h in far-side crashes, and 45 km/h in near-side crashes. A 10 % MAIS3+ risk was reached between 70 and 75 km/h for all crash types. Conditional injury risk curves gave substantially different results; the 10 % MAIS3+ risk in near-side crashes was 140 km/h, twice the unconditional value. For example, if a 10 % MAIS3+ risk was acceptable, treating remaining uncertainty conservatively, assuming compliance with speed limits and that Automated Emergency Braking takes 20 km/h of the travel speed before impact in longitudinal traffic, the safe speed limit for car occupants on most Swedish roads would be 80 km/h and 60 km/h in intersections.

1. Introduction

Following Sweden's adoption of Vision Zero in 1997, proclaiming that no one should be killed or seriously injured in road traffic, several governments world-wide have mandated a zero or near-zero road traffic casualty target by 2050 (Truong et al., 2022). The basis for Vision Zero is an understanding of, firstly, the crash violence a human can physiologically withstand in road traffic crashes and, secondly, the capabilities and limitations of humans using the road transport system. These essential premises are not expected to change suddenly, making them suitable for long-term planning (Larsson et al., 2010). Improvements are expected and encouraged in the design of safe vehicles and safe roads, accommodating human tolerance and error. The combined ability of vehicles and roads to prevent injuries is limited to some manageable crash violence, which needs to be controlled by ensuring travel speeds are safe. Continued advances in vehicle and road safety could at some point increase safe travel speeds and speed limits (Larsson et al., 2010).

The definition of serious injury for road safety targets can differ. The Abbreviated Injury Scale (AIS) is most used; it rates injuries from 0 to 6, i.e., from none to currently untreatable (Schmitt et al., 2014). For example, road safety targets can aim to limit injuries with an AIS of at least 2 (hereafter: MAIS2+) or 3 (MAIS3+)—or alternatively, injuries leading to 1 % or greater permanent medical disability (Tingvall et al., 2013; Larsson et al., 2010). While the definition of serious injury will influence what speed is considered safe, any definition requires knowledge of the relation between crash violence and injury outcome.

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What speed is safe also depends on vulnerability of the road users (Lubbe et al., 2022) and, for the same road user, between crash configurations (Doecke et al., 2020).

Road speed limits in Sweden are currently being reassessed with a focus on car occupants. Roads with a 90 km/h speed limit have been reduced to 80 km/h when cars can collide in head-on crashes (Trafikverket, 2021), since previous research has suggested that 80 km/h is the maximum speed at which two modern cars of the highest safety standard can mitigate the crash violence to a survivable level in a head-on crash (Trafikverket, 2016). The safe speed limit of 80 km/h for head-on crashes was already suggested by Eugensson et al. (2011) based on the assumption that active safety (such as Automated Emergency Braking) can reduce vehicle speed from 80 to 60 km/h prior to the collision and crashes at 60 km/h can be managed by crashworthiness and restraints (passive safety measures). Rizzi et al. (2023) confirmed the 80 km/h speed limit for head-on car crashes in their vision for 2030 cars, but suggested a speed limit of 50 km/h when heavy vehicles, such as trucks, mix with cars. At the same time, speed limits up to 120 km/h exist when a median barrier is available so head-on crashes cannot occur (Trafikverket, 2021). In side crashes (a car's front impacts another car's side), the maximum speed recommended by Eugensson et al. (2011) is 70 km/h, adding 15 km/h manageable by active safety to the 55 km/h manageable by passive safety. Rizzi et al. (2023) suggested 60 km/h is manageable by passive safety (with no reduction manageable by active safety).

A variety of studies have established mathematical relations between crash violence and the injury and fatality risks, so-called injury risk curves (IRCs), in frontal and side crashes. These IRCs guide decisions on safe speeds: once an acceptable risk level is agreed on, a corresponding tolerable crash violence can be ascertained. Measures of crash violence can be traffic-related (speed limit or driving speed), pre-impact-related (impact or closing velocity) or impact-related (Delta V, Energy Equivalent Speed, acceleration, intrusion). Impact-related measures are recommended for car occupant safety analyses (ISO, 2003) as they relate most closely. Most IRCs use Delta V (the change in a vehicle's velocity from immediately before the impact to immediately after) as a measure for crash violence. However, speed limits regulate not Delta V, but travel speed. A relation between travel speed and risk of serious injury (MAIS3+) for car occupants based on US data was established by Doecke et al. (2021): A 1 % car occupant injury risk was associated with an average of 63 km/h (travel speed) over all crash types, ranging from 17 km/h in head-on crashes to 91 km/h in rear-end crashes.

Only a few studies relate injury risk to impact speed (velocity of a vehicle's center of gravity immediately prior to impact) or closing speed (vector difference of impact velocities of two crash partners), which is needed to set limits to be managed by crashworthiness in Eugensson et al. (2011) and Rizzi et al. (2023). Lubbe et al. (2022) used the German In-Depth Accident Study (GIDAS) to establish MAIS2+, MAIS3+, and fatality risks based on the closing speed for car occupants impacted by another car's front, irrespective of crash configuration. A 10 % MAIS3+ injury risk for the car driver was reached at a closing speed of 112 km/h, equivalent to 56 km/h impact speed for each car in a head-on crash. Doecke et al. (2020) used US data (specifically, the National Automotive Sampling System-Crashworthiness Data System: NASS-CDS) to establish MAIS3+ risk for car occupants for front, side, rear-end, and head-on crashes as a function of impact speed. The 10 % risks were reached at 108 km/h for front, 71 km/h for side, 88 km/h for rear-end, and 53 km/h for head-on crashes. The authors did not separate side crashes into near-side and far-side. Further, they defined the head-on speed as half the closing speed, not as each vehicle's impact speed. Both Doecke et al. (2020) and Lubbe et al. (2022) concurred that a head-on collision at 60 km/h appears survivable, but bears some risk of serious injury.

Dean et al. (2023) used newer US data (the Crash Investigation Sampling System: CISS) and Event Data Recorder data to related both Delta V and impact speed to MAIS2+ injury risks for three crash configurations: car-to-car side crash, car-to-car head-on crash and car-to-barrier frontal crash. While Delta V was a significant predictor for injury outcome in all crash configurations, impact speed was a significant predictor only in head-on crashes. A 50 % MAIS2+ injury risk in head-on crashes was related to an impact speed of 62 km/h for occupants over 65 years old and 82 km/h for younger occupants. Meaningful IRCs as a function of impact speed for side crashes and barrier frontal crashes were not presented.

To date, IRCs as a function of impact speed based on Swedish data are lacking, and the applicability of US or German IRCs to Sweden is not obvious. Data from Sweden recorded in the Swedish Traffic Accident Data Acquisition (STRADA) do not have information on speeds other than speed limits; therefore, STRADA cannot be used to construct IRCs based on impact speed. Dean et al. (2023) responded to the need to set safe speeds for Sweden by comparing occupant age, occupant MAIS, vehicle curb weight, and vehicle model year of the US sample to Swedish STRADA data. The authors concluded that the crash occupant and vehicle populations in the US and Sweden are similar for the frontal crash modes; therefore, the relations between impact speed and MAIS2+ injury for head-on crashes in the US are applicable to Sweden. Unfortunately, a similar comparison between recent German GIDAS data and Swedish STRADA data to assess the applicability of German data is not available.

In-depth databases such as GIDAS do not record all crashes. There is typically a severity threshold below which data are not collected, or some other condition. For example, the US NASS-CDS and CISS record tow-away crashes; crashes leading to less damage are not recorded. GIDAS records only crashes with at least one suspected injury. Thus, IRCs based on these databases are conditional, meaning that they model an injury risk only for someone involved in a crash of the type that was sampled (Hautzinger et al., 2007). Unconditional IRCs, instead, model the risk of involvement in any type of crash, requiring knowledge of all crashes, including those that were not sampled (and therefore unavailable). For some applications, including limiting the injury severity of any type of crash given the impact speed, unconditional IRC are preferred. Conditional and unconditional IRCs were not expected to differ substantially (Ding et al., 2018); however, if the number of non-sampled crashes could be estimated, then any difference between them could also be estimated. There are ways to perform this estimation, as shown by Andricevic et al. (2018). The number of uninjured car occupants, given the objective Energy Equivalent Speed (a crash severity measure), was modeled, assuming an exponential distribution. Unconditional IRCs were then constructed on the expanded dataset with binary logistic regression.

In summary, there are some IRCs based on US data that can be used to indicate the speeds manageable by crashworthiness and set speed limits in Sweden. However, IRCs at MAIS2+ level for frontal car-to object, far-side, and near-side crashes are missing, and at the MAIS3+ level, a division in near- and far-side crashes is not available. More importantly, injury risk in head-on crashes is not reported as the impact speed of each car. Analysis of data from somewhere other than the US might confirm or contradict previous findings and contribute to a more generalizable body of knowledge.

The aim of this study is to provide evidence to enable setting speed limits to safe speeds in Sweden. To do so, we first investigated whether findings from the GIDAS can be applied to Sweden. We compared car model years, weights, occupant injury severity, and age in STRADA and GIDAS, for comparable sets of frontal and side crashes.

Secondly, we estimated the underreporting of non-injury crashes and compensated for it to create unconditional IRCs (risk of injury given involvement in any type of crash). IRC dependent on car impact speed at MAIS2+ and MAIS3+ severity levels are established for front and side crashes. We differentiated frontal crashes into head-on and object crashes, side crashes into near and far side.

Thirdly, we quantified the differences between the conditional and unconditional IRCs to highlight practical implications.

Finally, we exemplify with an unconditional 10 % MAIS3+ risk how authorities can use these IRCs to set evidence-based speed limits in Sweden.

2. Data

2.1. GIDAS

GIDAS started in 1999 as a cooperative venture of the Federal Highway Research Institute (BASt) and the Research Association of Automotive Technology (FAT), with two sampling areas in and around Dresden and Hanover. Approximately 1,000 crashes per sampling area are recorded every year. The police report crashes to the GIDAS teams, who travel to the crash site for inspection if at least one person is reported injured. Up to 3,500 pieces of information per crash are coded, including speed information (Liers, 2018). The comprehensive information includes personal and vehicle data. All crashes in the GIDAS database are reconstructed after the data collection is completed. In the reconstruction, all events of a crash are stored in chronological order (including, for example, vehicle speed at impact and Delta V).

2.2. GIDAS sample for IRCs

We used the GIDAS data from the years 1999 to 2022. A crash event can consist of several participants and crashes. In this study, we excluded all events that included a rollover, filtered remaining crash events for the crash with the worst consequences for occupant injury, and assigned a crash type. Crash types were defined by crash partners, damage area, and principal direction of force.

- Car-to-car head-on crash: Two cars, each with frontal damage and a frontal direction of force (11, 12, and 1o'clock). To construct the IRCs, the impact speed and longitudinal Delta V are taken for each car. Note that this definition of impact speed differs from that of Doecke et al. (2020), who defined it as half the closing speed between the vehicles.
- Car-to-object frontal crash: One car and one object, the car with frontal damage and a frontal direction of force (11, 12, and 1o'clock). Impact speed and longitudinal Delta V are taken for the car.
- Car-to-car side crash: Two cars, one with frontal damage and a frontal direction of force (11, 12, and 1o'clock) and the other with side damage (left or right) and corresponding direction of force (2, 3, or 4 o'clock for the right side and 8, 9, or 10 o'clock for the left side). Impact speed is taken as that of the car with frontal damage (the striking car; causing injury in the car with side damage) and Delta V is the lateral component of the total Delta V of the car with side damage (the struck car). Most of the time, the striking and stuck vehicle both move. In a few cases, the target vehicle loses control and slides sideways into the front of a parked vehicle. We treat this as a side impact for the target vehicle at zero impact speed. Side crashes are later divided into near-side and far-side crashes; in near-side crashes the injured occupant is seated on the struck side, while in far-side crashes the injured occupant is seated on the non-struck side.

Other crash types present in GIDAS were not further considered in this study. For the selected crashes, we extracted data for belted front-row occupants who were 13 years old or older, with known sex and injury status, in cars equipped with a frontal airbag. While children in cars are generally well protected, misuse or non-use of Child Restraint Systems can substantially increase the risk of injury. Misuse can be hard to detect in retrospective crash data collection; therefore, we did not include children in our analysis. Cars are defined in Appendix A, Table A1.

Only crashes involving well-performing, modern cars were kept for further analysis. We supplemented the GIDAS dataset with Euro NCAP test results. Cars with a Euro NCAP Adult Occupant Protection score equal to or higher than 25 points were included; cars with lower scores were excluded. Cars present in GIDAS, but not assessed in Euro NCAP, with a model year earlier than 2013 were excluded based on the general assumption that they are not likely to be very crashworthy. Non-assessed car models with a model year after 2013 were included.

Poorly rated cars have higher injury risks (Lie and Tingvall, 2010), and not using the seatbelt substantially increases the risk (Kahane, 2015). Excluding unbelted and poorly rated cars in our sample reflects Sweden's ambition to ensure that all occupants are belted and use safe cars (99.5 % of car occupants should be belted and 90 % of sold new cars should have the highest Euro NCAP rating by 2030; Trafikverket, 2021).

We extracted data for 2,235 occupants in 1,739 cars. Male (51 %) and female (49 %) occupants are equally represented. The mean occupant age was 44 years, with an interquartile range of 22. A similar number of occupants experienced head-on and side crashes; fewer were involved in frontal crashes with objects. The injury severity distribution (according to the 2015 maximum known score on the AIS scale) is shown in Table 1. In some instances, the severity of one or several injuries is unknown, so the maximum AIS is unknown. For example, if no injury details (no AIS levels) at all are reported for an occupant, the maximum known AIS is 0 and the MAIS is unknown. Thus, if we had used the maximum injury severity, we would have had to deal with missing data. In our dataset, 112 out of 2,235 occupants had an unknown maximum AIS.

Impact speeds ranged from 1–108 km/h (median 33 km/h, mean 34.9 km/h, SD 17.8 km/h) in head-on car-to-car crashes, from 2–94 km/h (median 29 km/h, mean 31.6 km/h, SD 14.7 km/h) in frontal car-to-object crashes and from 0–150 km/h (median 40, mean 41.4 km/h, SD 19.4 km/h) in side crashes. Recall that a side impact at zero impact speed can happen when the target vehicle loses control and slides sideways into the front of a stationary vehicle.

2.3. GIDAS samples for comparison with STRADA

For the comparison between Germany and Sweden, we restricted our GIDAS sample to crashes occurring between 2017 and 2019. We included all cars on the road, not only well-performing, modern cars; therefore, we did not apply that filter from the previous section. Otherwise, the same filters were applied.

This filtering yielded 205 occupants in 163 cars in head-on crashes, 200 occupants in 150 cars in side crashes (including both near- and far-side), and 164 occupants in 144 frontal car-to-object crashes. We extracted the cars' curb weights and registration year as well as occupants' injury severity (according to AIS 2015) and age.

2.4. STRADA samples

The Swedish crash database STRADA contains traffic accidents from 1996 and onwards from all over Sweden. STRADA is built from two different sources, police, and emergency hospital data. The police recover information from the crash site and hospitals provide injury information. However, unlike in GIDAS, crashes are not reconstructed.

Table 1
Distribution of maximum known injury severities (according to the 2015 AIS scale).

	Car-to-car Head-on	Near-side	Far-side	Car-to-object Frontal
MAIS 0	119	70	109	76
MAIS 1	557	312	213	358
MAIS 2	126	47	29	118
MAIS 3	22	8	4	29
MAIS 4	6	0	2	9
MAIS 5	4	1	1	8
MAIS 6	2	3	0	2
Total	836	441	358	600

Therefore, information on vehicle speed at impact and Delta V is not available; only the speed limits are known.

We filtered STRADA data from 2017 to 2019 for cars in relevant crash types and occupant characteristics, to match the GIDAS sample: 13 years or older, belted, and seated in the front. For this sample, we extracted car weight and model year as well as the occupants' injury severity (according to the 2008 AIS) and exact age. We obtained 974 occupants in car-to-car head-on crashes, 2,082 occupants in turning and crossing crash types (the closest match to car-to-car side crashes in GIDAS), and 2,775 occupants in single-car crashes (the closest match to frontal car-to-object crashes in GIDAS).

3. Statistical modeling for unconditional IRCs

We followed a two-step procedure to estimate the IRCs. First, we specified a Bayesian exponential regression model to estimate the frequency of impact speed for property damage only (PDO) crashes, which are missing in GIDAS. This step created multiple complete versions of the PDO data by replacing the missing values with plausible data from the estimated distribution. Second, we specified a Bayesian ordered probit regression model to estimate the probability of injury severity given the impact speed. This was done using the datasets created in the first step through multiple imputation (Sterne et al., 2009). From the IRCs, we estimated the speed ranges (best estimates and a 95 %-prediction interval) associated with the probability of a specific injury outcome. Details on the computational implementation are provided in Appendix D. To enable comparison with previous studies on the topic, we also applied the analysis procedure using Delta V (instead of impact speed) as the predictor of injury severity; these results are reported in Appendix E.

3.1. Estimation of PDO crashes

A crash is reported in GIDAS only if at least one of the occupants was reported injured (Liers, 2018). As a result, lower injury-severity crashes are underreported. However, standard weighting procedures using national statistics (Hautzinger et al., 2004; Sander & Lubbe, 2018) can compensate for the underreporting of slight injury crashes. We applied weight factors *w* by crash type (seven categories), year (1999 to 2020), and injury severity (slight, severe, and fatal) as detailed in Appendix B, Table B1. Further, PDO crashes are also often missing, not only from GIDAS but also from national statistics, which are based on police reports. For many PDO crashes, the police are never called to the scene (Destatis, 2022). Therefore, weighting GIDAS towards national statistics does not compensate for missing PDO crashes. We applied a multiple imputation procedure to compensate for this bias (Sterne et al., 2009; van Buuren, 2018, paragraph 1.4).

In this procedure, we assumed that the rate of missing PDO crashes (i.e., MAIS = 0) at high impact speed in the crash configurations of interest would be extremely low or zero—a high impact speed crash is likely to lead to injuries to a least one of the occupants and would thus be included in GIDAS. Similarly, at low impact speed, we assumed the rate missing PDO crashes to be high. We therefore set a cut-off threshold *t* at the 75th percentile of the aggregate impact speed distribution for the specific crash configuration under analysis to separate *low* from *high* impact speed crashes. All crashes recorded at impact speeds above *t* were retained, and all PDO crashes recorded at impact speeds below *t* were discarded. The threshold *t* was a compromise to retain as many data points as possible while reducing the bias from a partially reported case count. The advantage of setting a threshold based on percentiles is that it is deterministic and can be programmatically applied to all the datasets. This approach resulted in a truncated distribution of PDO crashes with respect to impact speed (Step 1 in Fig. 1).

We specified a Bayesian regression model to infer an exponential distribution on the truncated dataset (inspired by Andricevic et al., 2018). The model inferred the rate parameter λ of the exponential distribution, of which only the right tail is visible:

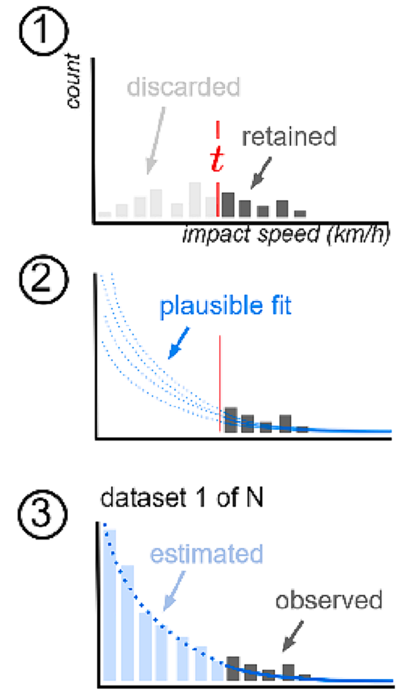

Fig. 1. Procedure to estimate the frequency of PDO crashes. First, we retained the cases above the 75th percentile of the aggregated impact speed distribution and discarded the ones below. Second, we fit a Bayesian exponential regression model on the truncated distribution, obtaining a distribution of plausible curves. Third, we sampled N = 50 of these plausible curves, creating a new PDO crash distribution with each one.

$$p(Impactspeed|\lambda, MAIS = 0) \sim Exp_{[t,\infty)}(\lambda) \quad (1)$$

Every case (an injured or non-injured occupant) extracted in GIDAS was weighted, $w \geq 0$ (e.g., a crash with a weight of 2 would count as two cases). The weight was incorporated into the model by scaling the likelihood contributions of each observation (weighted regression). The exponential distribution is memoryless, so the estimated λ on the truncated distribution also describes the distribution of impact speeds below t, $p(impact\ speed \mid impact\ speed > t) = p(impact\ speed)$ (see Step 2 in Fig. 1).

The outcome of Bayesian inference is a posterior probability distribution for λ which incorporates the uncertainty in the parameter estimation. The mean of this distribution is the expected, most likely value. Imputed values were sampled from this posterior distribution. Specifically, we sampled 50 values for λ to create several different plausible distributions of PDO crashes (see Step 3 in Fig. 1). The sampling size of 50 was a balance between sampling variability from the imputation process and computational cost (Sterne et al., 2009; van Buuren, 2018, para. 2.8). All plausible datasets were identical for the observed data above t but differed in the imputed values. For each plausible dataset, we estimated the missing count n^- of PDO crashes below t as:

$$n^- = n^+ * s/(1 - s) \quad (2)$$

where n^+ is the observed count (weighted) of cases above t; s is a scaling factor computed as the value of the cumulative density function (cdf) for an exponential distribution with a given λ and t. Thus $s = cdf_\lambda(t)$ is the probability of any value to be less or equal than t. Then, let n_{tot} be the total number of PDO crashes at any impact speed ≥ 0:

$$n_{tot} = n^+ + n^- \quad (3)$$

we set:

$$n^{-} = n_{tot} * s \tag{4}$$

By substituting (3) into (4) we obtain (2). Each estimated PDO case had $w = 1$.

Bayesian models require setting prior distributions. As we were uncertain about the specific missing values proportion, we placed vague priors to regularize the model (we used the default priors in the package *brms*; Bürkner, 2017; Bürkner, 2018). The plausible datasets accounted for all uncertainty in predicting the missing values by injecting appropriate variability into the multiple imputed values (Sterne et al., 2009). All 50 PDO datasets were used to estimate the IRC via multiple imputation.

3.2. Unconditional IRCs

The plausible PDO (i.e., MAIS = 0) cases from model (1), together with the observed injured cases (i.e., MAIS ≥ 1), were used to model the probability of a specific injury outcome based on impact speed (Step 1 in Fig. 2). While binary logistic regression is an established method in accident research (Schubert et al., 2023), probit ordinal regression (e.g., Wisch et al., 2017) may be a better choice, as the injury outcome in the MAIS scale is an ordinal factor (MAIS: $0 < 1 < \ldots < 6$).

Using a Bayesian ordered probit regression with equal variance (Bürkner & Vuorre, 2019), we defined four independent models—one for each crash configuration (car-to-car head-on crash, car-to-object crash, car-to-car near-side crash, and car-to-car far-side crash). Each model was specified in the same way:

$$p(MAIS = K|\mu,\tau) = \Phi([\tau_k - \mu_i]) - \Phi([\tau_{k-1} - \mu_i]) \tag{5}$$

$$\mu_i = \beta impact\_speed_i \tag{6}$$

with:

$$p(MAIS = 0|\mu,\tau) = \Phi([\tau_0 - \mu_i]) \tag{7}$$

$$p(MAIS = 6|\mu,\tau) = 1 - \Phi([\tau_5 - \mu_i]) \tag{8}$$

where Φ is the standard cumulative function (its inverse is known as the probit link function); τ is the set of K thresholds (latent variables) that separate the $K + 1$ ordered level of MAIS k=$\{0, 1, 2, 3, 4, 5, 6\}$; Φ is rescaled to accommodate $\mu \neq 0$ by a regression that depends on each observation i for impact speed and coefficients β. Thus, $\Phi([\tau_k - \mu_i])$ is the cumulative probability for the k^{th} MAIS level, and $\Phi([\tau_k - \mu_i]) - \Phi([\tau_{k-1} - \mu_i])$ is the probability for MAIS = k relative to the level below. The models' priors were vague to regularize the model (we used the default priors in the package *brms*; Bürkner, 2017; Bürkner, 2018).

Model (5) was fit on each of the 50 datasets from model (1) separately (Step 2 in Fig. 2). At the end, the posterior samples from the all the 50 models were pooled (Step 3 in Fig. 2). In this way, the IRCs combined the inherent uncertainty of PDO crashes and the uncertainty in the injury risk estimation to each dataset.

This modeling generated unconditional IRCs (i.e., risk of injury given involvement in any type of crash). Thereby, we addressed the constraints on prior research which used GIDAS data: due to the sampling threshold of suspected injury, the resulting IRCs were inherently conditional on the occurrence of a suspected-injury crash. To demonstrate the impact and relevance of this modeling approach, we also computed traditional (conditional) IRCs, using the same probit ordinal regression approach (i.e., taking weighted GIDAS data, but without estimating and

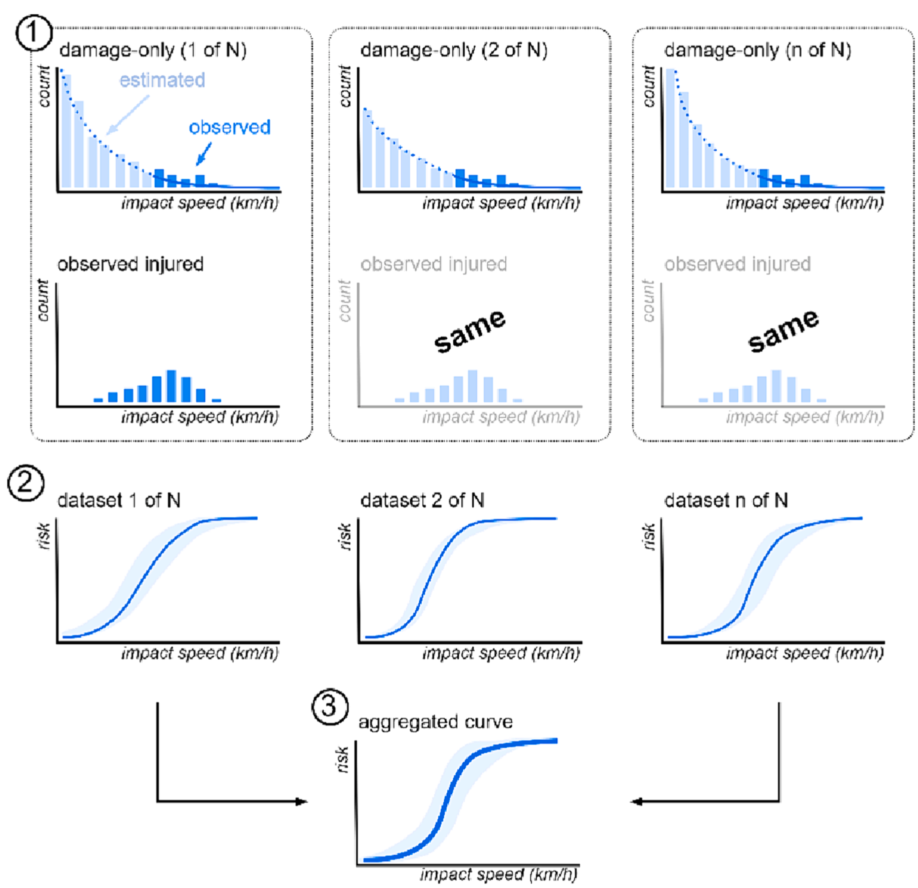

Fig. 2. Procedure to estimate the IRC using multiple imputation: first, combine each of the 50 plausible PDO crash datasets with the observed injured cases and repeat this step for each of the plausible PDO distributions; second, estimate the IRC (including uncertainty) from each of the 50 datasets; third, aggregate the results from each of the 50 IRCs (including uncertainty).

adding the missing PDO cases) and compared the unconditional and conditional IRCs.

3.3. Estimated speed range associated with a specific probability of injury outcome

Model (5), as is common for IRCs, yields the probability of injury at a specific speed, *p(injury | speed)*. However, policymakers would like to know the range of speeds associated with a specific target risk, *p(speed | injury)*, in order to set new speed limits accordingly. Instead of building additional models, we estimated *p(speed | injury)* directly from the posterior samples from model (5). That is, we extracted those samples associated with a specific injury risk within an interval of 10 %. For example, for a target of 10 % injury risk, we obtained the speed distribution of the samples associated with a risk probability in the interval 9.9 %–10.1 %.

4. Results

4.1. Generalizing from Germany to Sweden

German GIDAS data were compared to Swedish STRADA data. Factors known to affect injury risk (occupant age, car curb weight, car registration year) and injury outcome itself were extracted.

The data for head-on crashes are shown in Fig. 3a–d. In Germany, 51 % were male while more occupants were male in Sweden (57 %). In Germany, occupants are older. Median occupant age is 46 years in Germany and 45 years in Sweden. Frailty and thereby injury probability increases with age. A one-year increase in age is, however, not substantial: Lubbe et al. (2022) compute a 0.02 % difference in MAIS3+ risk for car occupants of 45 and 46 years at 50 km/h.

German occupants are in newer cars. Median car registration year differs by one. Newer cars typically have better crashworthiness and lower injury risks, but one year difference appears inconsequential (Kullgren et al., 2019).

German occupants are in lighter cars. Median curb weight differs by 205 kg. Mass differences in two-vehicle crashes lead to the lighter car experiencing a larger change of velocity, which is associated with a larger injury probability (Appendix E). Effects of mass imbalance can be calculated, but are somewhat complex (Kullgren et al., 2001). As Fig. 3c shows, mass distributions in Germany and Sweden are parallel lines, therefore there is little indication that Sweden suffers more from mass imbalances than Germany.

High-severity injuries are rare in both datasets. Differences in the injury severity distribution would more likely highlight a difference in data sampling than actual injury outcome of road traffic crashes. This can be consequential for conditional risk curves. As Fig. 3b shows, both Sweden and Germany have few uninjured (MAIS0) occupants, as they sample crashes with injury, therefore potentially benefitting similarly from imputation approaches to estimate unconditional IRCs. Similar trends for car-to-car side crashes and car-to-object crashes are demonstrated in Appendix C.

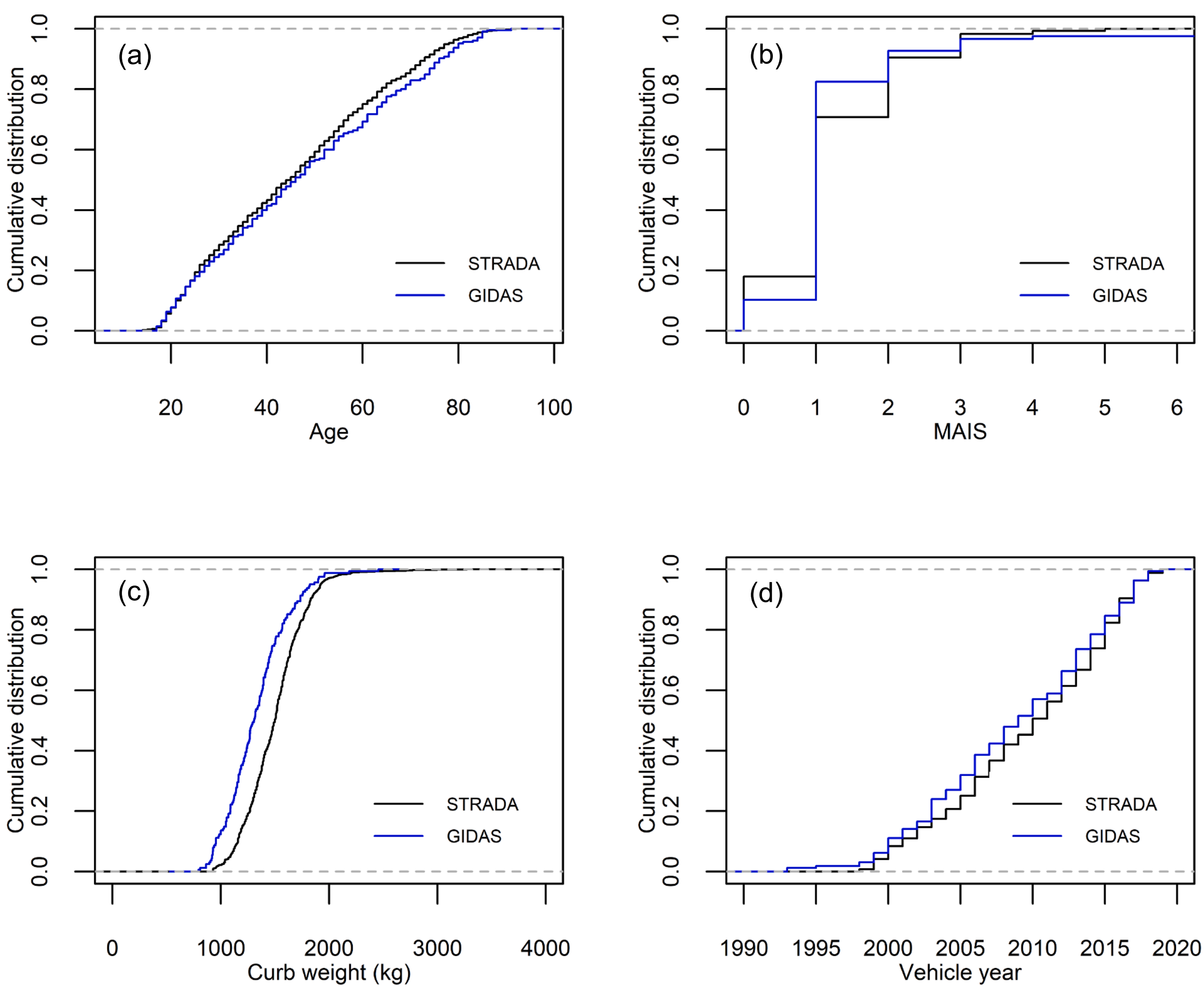

Fig. 3. Comparison between STRADA (black curve) and GIDAS (blue curve) in head-on crashes (a): Occupant ages (b): Injury severity (AIS 2008 for STRADA and AIS 2015 for GIDAS) (c): Car curb weight (d): Car model year in STRADA and car first registration year in GIDAS.

There appear to be no substantial differences between Germany and Sweden for these factors—or, at least, they are smaller than the differences between Sweden and the US as reported by Dean et al. (2023). Therefore, IRCs describing the relation between crash severity and car occupant injury using German GIDAS data should be reasonably accurate for Swedish car occupants as well.

4.2. Estimation of non-injury (damage only) crashes

The models showed good agreement with the observations that were retained. The distributions for PDO head-on and object crashes had generally lower λ than those for side crashes (near and far side; Table 2). That is, on average, head-on crashes occurred at higher (and more variable) impact speeds than side crashes (E[impact_speed] = $1/\lambda$, Var [impact_speed] = $1/\lambda^2$).

Note that the plausible exponential distributions are more narrowly centered around the best estimate for side crashes, especially far-side crashes (Fig. 4). This feature is the result of our modeling approach and data, which had few-to-no cases at high speeds, but was centered just above the cut-off threshold t at the 75th percentile of the aggregate impact-speed distribution.

4.3. IRCs

Unconditional injury risks (the risk of being injured in a crash, computed by imputing and adding damage-only crashes) in head-on collisions with another car are depicted in Fig. 5. Unconditional 10 % and 50 % MAIS2+ injury risks were reached at 25 km/h (95 % interval 15–35 km/h) and 95 km/h (95 % interval 80–120 km/h), respectively, while a 10 % MAIS3+ injury risk was reached at 75 km/h (95 % interval 65–90 km/h). Conditional injury risks (the risk of injury given involvement in a suspected-injury crash, computed straight from weighted GIDAS data) in suspected-injury crashes are depicted in Fig. 6. Conditional 10 % and 50 % MAIS2+ injury risks were reached at 5 km/h (95 % interval 0–15 km/h) and 160 km/h (95 % interval 120 – more than 200 km/h), respectively, while a 10 % MAIS3+ injury risk was reached at 120 km/h (95 % interval 85–180 km/h).

Unconditional injury risks in frontal car crashes with an object are depicted in Fig. 7. Unconditional 10 % and 50 % MAIS2+ injury risks were reached at 20 km/h (95 % interval 0–35 km/h) and 100 km/h (95 % interval 85–180 km/h), respectively. A 10 % MAIS3+ injury risk was reached at 70 km/h (95 % interval 55–100 km/h. Fig. 8 illustrates conditional injury risks in suspected-injury frontal crashes with an object. Conditional injury risk levels could not be computed as the curves are too flat.

Unconditional injury risks in far-side crashes are depicted in Fig. 9. Recall that the impact speed of the striking car (the one with frontal damage) is used to compute the injury risk in the struck car (the one with side damage). Unconditional 10 % and 50 % MAIS2+ injury risks were reached at 55 km/h (95 % interval 55–60 km/h) and 80 km/h (95 % interval 75–85 km/h), respectively, while 10 % MAIS3+ injury risk was reached at 75 km/h (95 % interval 65–80 km/h). Fig. 10 illustrates conditional injury risks in a suspected-injury, far-side crash. Conditional 10 % and 50 % MAIS2+ injury risks were reached at 50 km/h (95 % interval 30–70 km/h) and 160 km/h (95 % interval 120 – more than 200 km/h), respectively, while a 10 % MAIS3+ injury risk was reached at 120 km/h (95 % interval 90–190 km/h).

Unconditional injury risks in near-side crashes are depicted in Fig. 11. Unconditional 10 % and 50 % MAIS2+ injury risks were reached at 45 km/h (95 % interval 40–50 km/h) and 70 km/h (95 % interval 70–85 km/h), respectively. A 10 % MAIS3+ injury risk was reached at 70 km/h (95 % interval 65–80 km/h). Fig. 12 illustrates injury risk in a conditional, suspected-injury near-side crash. Conditional 10 % and 50 % MAIS2+ injury risks were reached at 25 km/h (95 % interval 0–50 km/h) and 160 km/h (95 % interval 120 – more than 200 km/h), respectively, while a 10 % MAIS3+ injury risk was reached at 140 km/h (95 % interval 95 – more than 200 km/h).

Unconditional IRCs with Delta V as a predictor are provided in Appendix E. While impact speed is more directly relatable to speed limits and therefore chosen for these analyses, Delta V is the more commonly used proxy for crash severity. The IRCs based on Delta V were steep and have narrow 95th percentile intervals, suggesting that Delta V is indeed a good predictor for injury outcome and that these IRCs may be useful in other analyses.

4.4. An example of using IRCs to set safe speeds

If a 10 % MAIS3+ risk were acceptable, our best estimate is that head-on crashes must not occur at speeds higher than 75 km/h, frontal car-to-object crashes at 70 km/h, near-side crashes at 70 km/h and far-side crashes must not occur at speeds higher than 75 km/h. In a conservative approach, one might choose not the best estimate, but the lower bound of the 95 % interval. The more uncertainty there is about the true value, the lower the speed limit could be to ensure it is safe despite uncertainty. For the 10 % MAIS3+ risk, the conservative value for all crash types was approximately 60 km/h for all crash types (65, 55, 65 and 65 km/h for head-on, frontal car-to-object, near-side and far-side). Assuming that Automated Emergency Braking can reduce impact speeds by 20 km/h from initial travel speed in frontal crashes and compliance with speed limits, a speed limit of 80 km/h can be set to ensure a maximum 10 % risk of MAIS3+ injuries, the safe speed in this example, on most roads. In intersections, where Automated Emergency Braking is not expected to reduce impact speeds, the speed limit can be set to 60 km/h.

5. Discussion

5.1. Comparison to previous work

The unconditional GIDAS-based 10 % MAIS3+ side crash injury risk at 75 km/h (for both near- and far-side) matches closely with the US NASS-CDS-based 10 % MAIS3+ side crash risk at 71 km/h from Doecke et al. (2020), as does the entire IRC (Fig. 13). One might expect the unconditional IRCs to be steeper, as the data even include an estimate for non-tow-away crashes at very low impact speeds, which are missing in the tow-away sample of Doecke et al. (2020). However, other differences in data preparation may offset these effects: for example, Doecke et al. (2020) excluded data if the vehicle impact speed estimate was based on vehicle maneuvering, and there may be additional differences in car characteristics and occupant protection offered. Nevertheless, the IRCs are nearly identical; therefore, the conclusions and implications for near-side crash protection derived from Doecke et al. (2020) still hold.

Table 2
Results from the procedure to estimate plausible PDO crash distributions. The posterior distribution for the rate parameter λ is summarized by the median and the 95% percentile interval.

Crash type	Observed (n)	Truncated at (km/h)	Retained (n)	λ
Head-on	114	44	29	0.05 [0.03 – 0.07]
Car-to-object	69	66	18	0.04 [0.02 – 0.06]
Far-side	106	39.5	27	0.12 [0.08 – 0.17]
Near-side	65	36	17	0.09 [0.05 – 0.13]

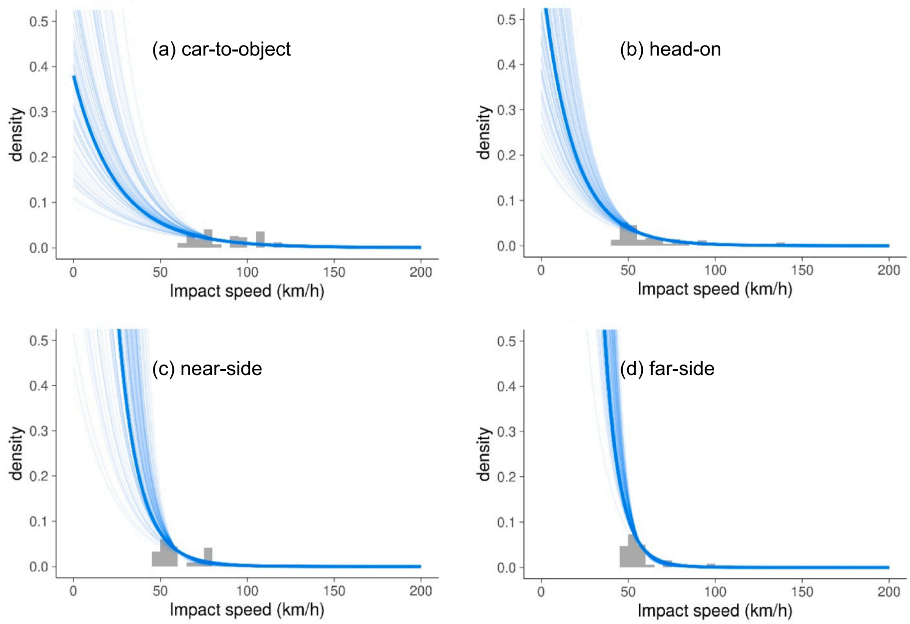

Fig. 4. Posterior predictive check for the PDO crashes model. Each panel shows the results for a specific crash type: (a): frontal car-to-object (b): car-to-car head-on (c): near-side (d): far-side. In each panel there are 100 plausible exponential distributions sampled from the posterior distribution for λ (thin blue lines) and the expected curve (defined by the average of the full posterior distribution for λ: thick blue line) on top of the observed (truncated and weighted) PDO crash distribution (gray histogram).

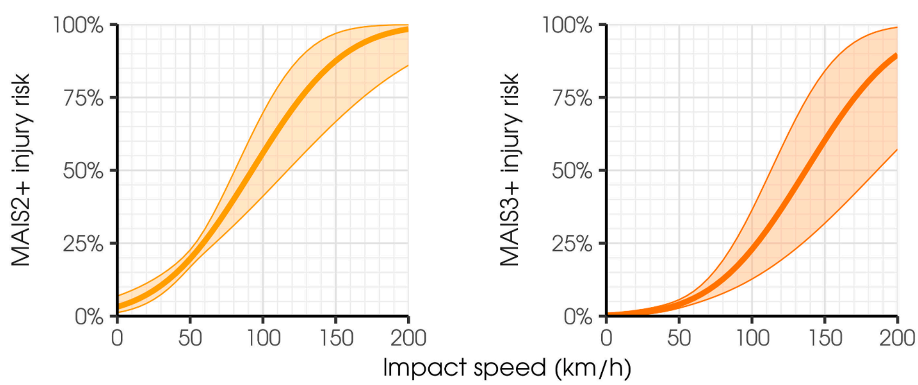

Fig. 5. Unconditional IRCs for head-on crashes. Each panel shows the expected IRC (thick line) and the 95 % percentile interval: MAIS2+ in left and MAIS3+ in right panel.

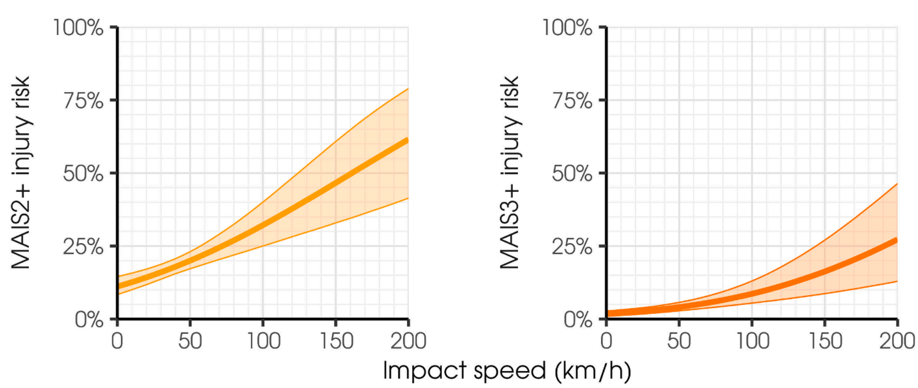

Fig. 6. Conditional IRCs for head-on crashes. Each panel shows the expected IRC (thick line) and the 95 % percentile interval: MAIS2+ in left and MAIS3+ in right panel.

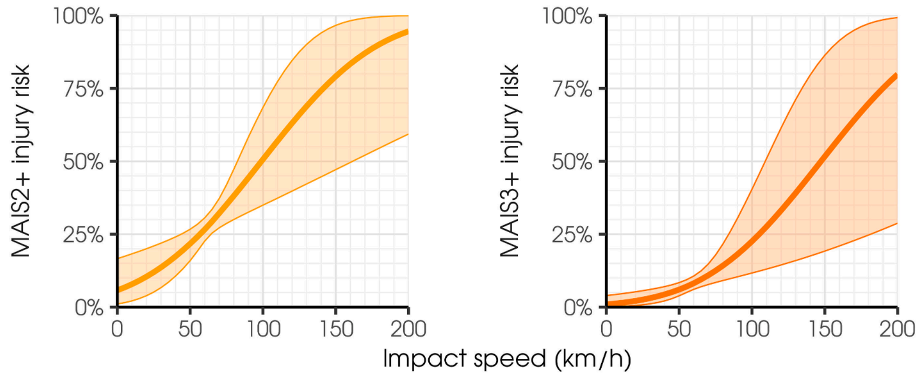

Fig. 7. Unconditional IRCs for frontal car-to-object crashes. Each panel shows the expected IRC (thick line) and the 95 % percentile interval: MAIS2+ in left and MAIS3+ in right panel.

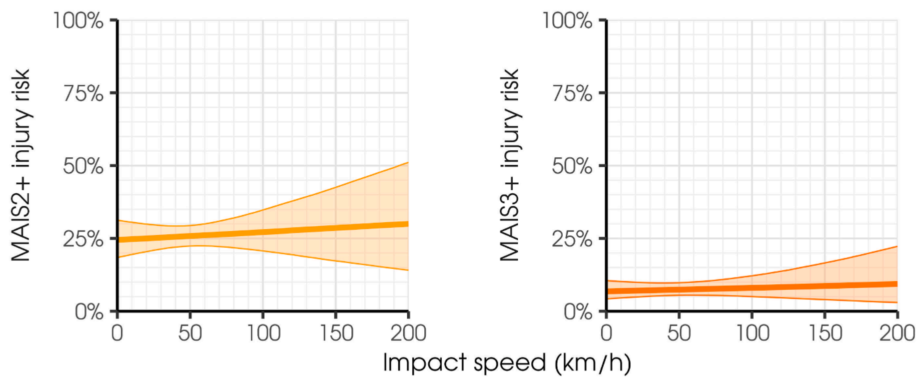

Fig. 8. Conditional IRCs for frontal car-to-object crashes. Each panel shows the expected IRC (thick line) for each cumulative MAIS level and the 95 % percentile interval: MAIS2+ in left and MAIS3+ in right panel.

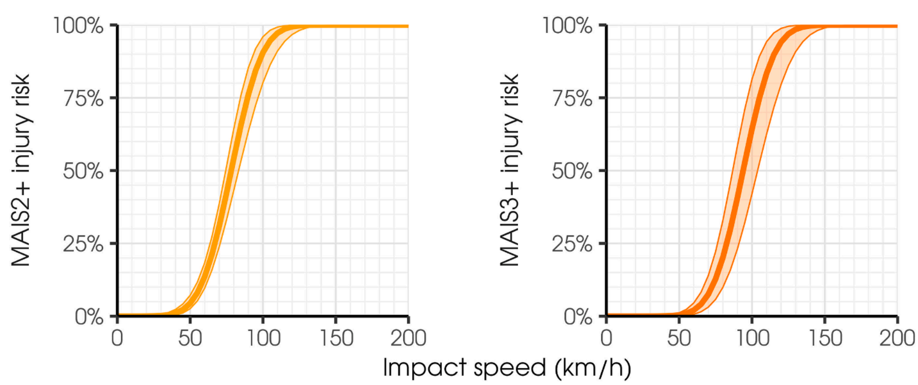

Fig. 9. Unconditional IRCs for far-side crashes. Each panel shows the expected IRC (thick line) and the 95th percentile interval: MAIS2+ in left and MAIS3+ in right panel.

Further comparison with Doecke et al.'s results is not possible, as frontal car-to-object crashes were not included and the impact speed for head-on crashes was defined differently (as half the closing speed).

The unconditional MAIS2+ IRCs in head-on crashes can be compared to the US CISS IRC from Dean et al. (2023) for occupants under 65 years, as our mean age is 44 years. Again, our unconditional curves are less steep (Fig. 14), despite the fact that, as in Doecke et al.'s sample, CISS only sampled tow-away crashes. Dean et al. (2023) indicated a head-on impact speed of 82 km/h leads to a 50 % (±31 %) MAIS2+ risk for occupants younger than 65 years, while we suggest a 50 % MAIS2+ injury risk at 95 km/h (95 % interval 80–120 km/h). The IRCs are close to each other, and implications based on lower bounds (i.e., conservative estimates) can be drawn from either one.

Head-on crashes were the only crash type in which impact speed was a significant predictor for injury outcome in Dean et al. (2023). We do not compare other crash types here, but there is a comparison to our Delta V IRCs in Appendix E.

The unconditional GIDAS-based IRCs are no steeper than the comparable US IRCs, although they are substantially steeper than the conditional GIDAS curves. This similarity may be an indication that the estimation and addition of non-injury cases to GIDAS was not excessive—instead, adding only a conservative count.

5.2. Unconditional versus conditional IRCs—does it matter?

In Figs. 5 to 12, we depict both unconditional and conditional IRCs.

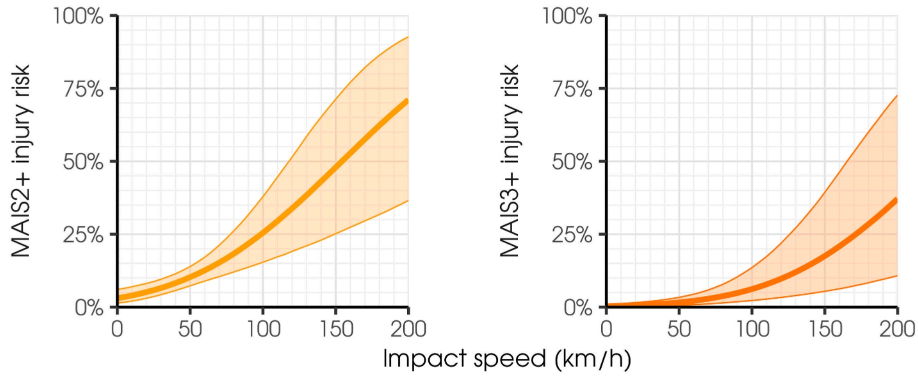

Fig. 10. Conditional IRCs for far-side crashes. Each panel shows the expected IRC (thick line) and the 95th percentile interval: MAIS2+ in left and MAIS3+ in right panel.

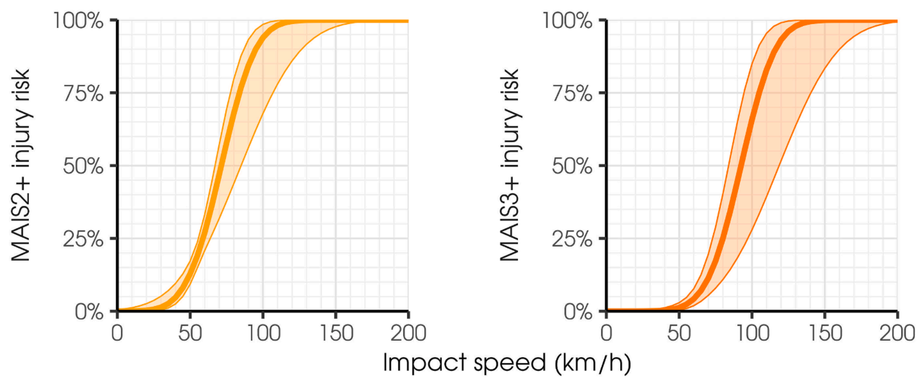

Fig. 11. Unconditional IRCs for near-side crashes. Each panel shows the expected IRC (thick line) and the 95th percentile interval: MAIS2+ in left and MAIS3+ in right panel.

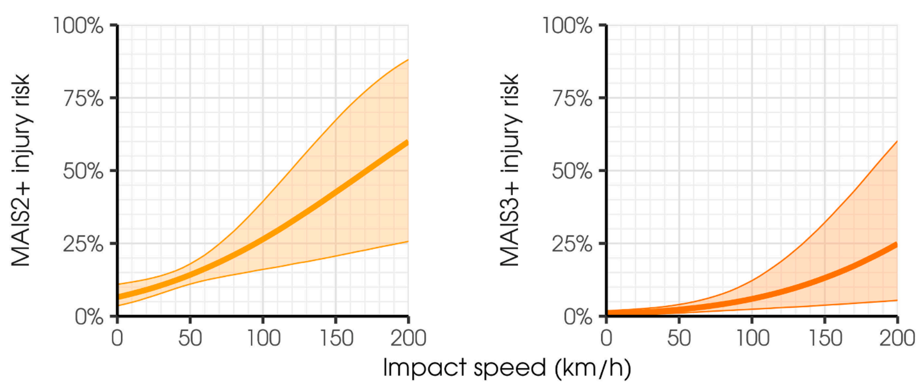

Fig. 12. Conditional IRCs for near-side crashes. Each panel shows the expected IRC (thick line) for each cumulative MAIS level and the 95th percentile interval: MAIS2+ in left and MAIS3+ in right panel.

The former depict the risk of injury in any crash, based on GIDAS injury data and our estimate of non-injury cases; the latter depict the risk using only the crashes from GIDAS data, which involve at least one suspected injury (therefore, risk of injury given involvement in a suspected-injury crash).

Andricevic et al. (2018) already stated that the GIDAS sampling bias leads to an overestimation of the injury risk for low-severity crashes. The authors compensated for the bias by adding low-severity, property PDO cases to the dataset; they used a logic similar to the one used in this work, but a different modeling approach. However, they did not report the numerical effects and the importance of the compensation.

Ding et al. (2018) suspected that the difference between conditional and unconditional risks is particularly notable for risk estimates for low speeds, which result primarily in non-injury crashes, but that the difference has only marginal effects on risk estimates for higher speeds.

As expected, injury risks at zero impact speed were closer to zero with the unconditional IRCs—if they were not zero already with the conditional curves (Figs. 5–12). The common property of regression models (that they need not pass through zero) is often criticized and adding uninjured data points at the lower velocity range brings the regression line closer to passing though zero.

Unconditional IRCs are steeper, i.e., risk increases faster from lower speeds. In fact, for frontal car-to-object crashes, conditional IRCs are so flat that they essentially do not depict a relation between impact speed and injury risk, while unconditional curves show a clear relation (Fig. 7). In all crash types, the speed associated with a 50 % MAIS2+ injury risk is

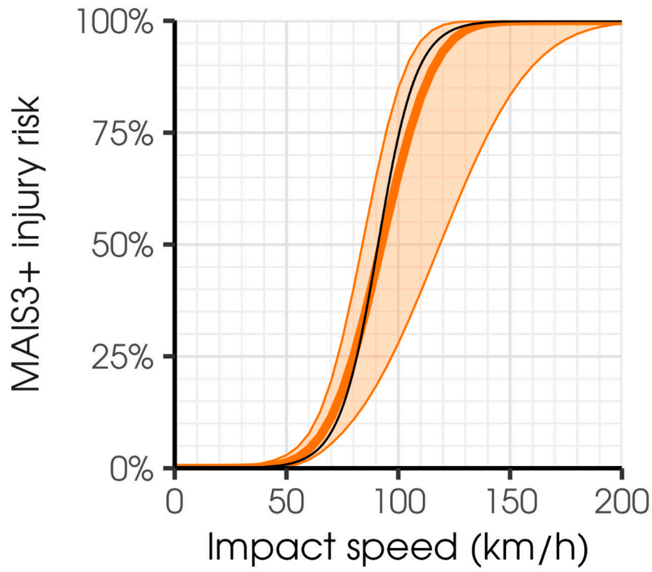

Fig. 13. Our near-side MAIS3+ injury risk (thick line with shaded area indicating 95th percentile interval, identical to the right panel of Fig. 11) compared to Doecke et al.'s (2020) side-crash risk (including both near- and far-side crashes) depicted as thin line.

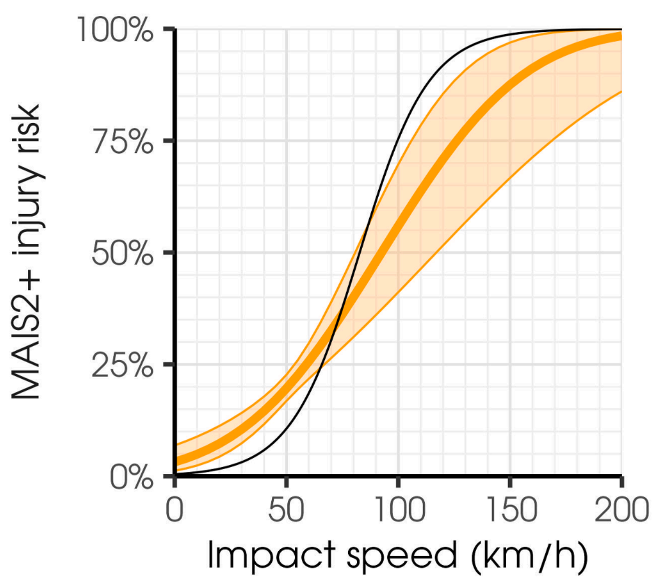

Fig. 14. Our head-on MAIS2+ IRC (thick line with shaded area indicated 95th percentile interval) compared to the IRC for occupants < 65 years from Dean et al. (2023), shown as a thin solid line.

substantially lower for the unconditional IRCs while the 10 % is slightly higher (Table 3 and Figs. 5–12). We note that a sampling bias for more severe cases affects risk estimates at high probabilities as well as low probabilities.

Correcting for sampling bias and non-injury cases in the model resulted in noticeably different IRCs. For example, if a 10 % MAIS3+ risk in near-side crashes is defined as safe, the best estimates for a corresponding speed limit recommendation differ by as much as a factor of two: 70 km/h based on unconditional IRCs and 140 km/h based on conditional IRCs. It seems clear that the former more accurately reflects reality.

We believe a modeling approach that includes compensation for sampling bias and non-injury cases is needed. This type of model may also facilitate the comparative analysis of different data sources. For example, GIDAS and US CISS differ in that the former samples crashes with a suspected injury while the latter samples crashes involving at least one towed passenger vehicle; therefore, US CISS is likely to contain more crashes without occupant injury. Compensating for differences in the non-injury crash data collected would improve the validity of comparisons between datasets (and thus countries).

This approach accounts for non-reported non-injury crashes, demonstrating the importance of including these cases for the practical application of recommending speed limits (given an acceptable injury probability). While this approach is an important preliminary step, it is not the only one possible, nor is it necessarily the most efficient or accurate; other modeling approaches may, in fact, ultimately be preferred. The cut-of threshold of 75 % is arbitrary; an exponential function is not the only plausible modeling approach.

Another approach would be to estimate non-injury crashes from real sources, like the naturalistic driving study SHRP2 or insurance claims. Additionally, authorities could modernize and expand data collection schemes to eliminate the collection bias. While it is perhaps neither necessary nor realistic for the police to attend to PDO crashes, telematic solutions could provide some additional basic national statistics if they are appropriately mandated and managed. We suggest that automated low severity crash data collection is an important area for further work; contemporary work should be interpreted with these results as background.

As noted in section 2.2, we use the maximum known AIS score to define injury severity. We are not using the maximum AIS injury severity as it is unknown in some cases. Thereby, we avoid introducing bias in case the maximum AIS injury severity information is not missing at random, but likely underestimate true severity in some cases. Ideally, we would like to treat the cases with a given maximum known AIS score but unknown maximum AIS injury severity as censored, but, to our best knowledge, current statistic packages in R do not compute regression with censored data.

5.3. Implications for safe speed limits in Sweden

We exemplify how to set safe speeds using a 10 % MAIS3+ risk as acceptable threshold and set it in context. The MAIS3+ level was chosen as it matches the European Commission's definition of serious injury for their reduction target; a 10 % level was chosen to stay away from the very tail of the injury risk functions as tails tend to be less reliable. However, we agree with Doecke et al. (2020) and their discussion on the question of acceptable risk: a target much closer to zero risk is required when aiming for zero fatalities and serious injuries.

Head-on crashes between cars were thought to be tolerable at an impact speed of 60 km/h (Eugensson et al., 2011; Rizzi et al., 2023). However, our IRC indicates a 10 % MAIS2+ injury risk at speeds as low as 25 km/h (95 % interval 15–35 km/h) and a 10 % MAIS3+ injury risk as high as 75 km/h (65–90 km/h). Going with the lower bound of the 95 % interval for a 10 % MAIS3+ injury risk, 65 km/h, and assuming that approximately 20 km/h may be addressable with pre-crash braking, a speed limit of 80 km/h on undivided roads appears reasonable, confirming earlier suggestions by Eugensson et al. (2011) and Rizzi et al. (2023). The lower bound of the 10 % MAIS3+ front-object injury risk is lower: 55 km/h, suggesting that also divided roads where roadside object collisions can occur should be limited to 80 km/h.

In intersections and crossings, where side crashes are most likely, a 10 % MAIS2+ risk was reached at impact speeds of 45 km/h (near side; 95 % interval 40–50 km/h) and 55 km/h (far side; 95 % interval 55–60 km/h). MAIS3+ risks of 10 % were reached at 75 km/h (far side; 95 % interval 65–80 km/h) and 70 km/h (near side; 95 % interval 65–80 km/h). The lower bounds of these 10 % MAIS3+ risks suggests that an impact speed of 65 km/h may be tolerable, which is slightly higher than the 55 km/h suggested by Eugensson et al. (2011) and the 60 km/h suggested by Rizzi et al. (2023). As Automated Emergency Braking is not expected to reliably reduce speeds in side crashes, these results indicate

Table 3
Impact speeds corresponding to risk levels in crash types for conditional and unconditional IRCs.

	Risk	Corresponding impact speed with conditional IRCs (km/h)	Corresponding impact speed with unconditional IRCs (km/h)
Head-on	10 % MAIS2+	5	25
	50 % MAIS2+	160	95
	10 % MAIS3+	120	75
Front-object	10 % MAIS2+	Not computable	20
	50 % MAIS2+	Not computable	100
	10 % MAIS3+	Not computable	70
Far-side	10 % MAIS2+	50	55
	50 % MAIS2+	160	80
	10 % MAIS3+	120	75
Near-side	10 % MAIS2+	25	45
	50 % MAIS2+	160	70
	10 % MAIS3+	140	70

that a lower speed limit than for longitudinal traffic roads is needed: 60 km/h for intersections (assuming compliance with speed limits).

The suggested speed limit is higher than the impact speed associated with a 10 % MAIS3+ risk (the example for safe speed) by the speed reduction assumed feasible for AEB. We apply the crude estimates from Rizzi et al. (2023): 20 km/h in frontal crashes and no reduction in side crashes. These estimates could be refined by modeling and simulating AEB effect on vehicle dynamics in the last seconds before a crash (Ferson et al., 2023). This, in turn, would require accurate data on travelling speeds and other pre-crash information (Olleja et al., 2023) as well as accurate AEB models including sensing, logic, and actuation.

The safe speed in a safe system approach depends on vehicles, infrastructure and road user behavior in the system. The proposed speed limits reflect the current situation. If future infrastructure design or vehicle systems (such as median and side barriers or wide safety zones at the roadside, or effective in-vehicle lane support across the whole vehicle fleet) can assure additional safety to eliminate crash or injury risks, speeds can be higher. Infrastructure can also directly influence driving speeds; instead of setting a speed limit for intersections, re-designing to a round-about inherently will reduce speeds and thereby crash severity. Assessing safe speeds should therefore be a reoccurring activity.

We restricted the analysis to crashes between cars and frontal crashes of cars with objects. Clearly, in most road traffic, there are also encounters between cars and trucks, which at the same impact speeds lead to much higher Delta Vs for cars and a concomitant higher injury probability for car occupants. If cars and trucks continue to mix, our recommended speed limits do not hold: they must be lower, or substantial improvements to crashworthiness and restraints must be made (Mroz et al., 2023; Östling et al., 2023). While safe speeds can be guided by the Delta V IRCs in Appendix E, future work is called for in order to relate injury to speeds in car-to-truck crashes.

Similarly, we did not analyze crashes between cars and vulnerable road users, who are less protected than car occupants and thus have a higher injury risk for a given impact speed (Lubbe et al., 2022). If cars and vulnerable road users continue to mix, speeds need to be limited to the injury tolerance of vulnerable road users—a lower speed than the recommendations for car-only crashes.

We did not explicitly model the effect of age; that is, injury risks presented are for the mean age of our samples (approximately 44 years old). Injury probability increases with age (Lubbe et al., 2022; Forman et al., 2019); therefore, elderly people will have substantially higher injury risks. (Safe speeds for 80-year-olds would be substantially lower.) The current road transport system with its travelling speeds does not guarantee safety for car occupants of very advanced age despite calls for greater attention. For example, "occupant's elevated age (>=70 years old)" is an "occupant specific factor" that explains why people die (Firey et al., 2023). Technological solutions are preferred. In their absence, an age limit for car occupants in addition to a speed limit or substantially lower speed limits than suggested here (to remain inclusive and protective of all equally) may be preferred over the status quo.

AIS scales in the comparison between Germany (GIDAS, AIS 2015) and Sweden (STRADA, AIS 2008) differ. Therefore, there are likely more AIS2 and AIS3 injuries reported in GIDAS as there would be had the 2008 scale been used (Unger et al., 2020). This might explain some of the differences we see in the MAIS distributions.

6. Conclusion

This study investigated safe speed limits for car occupants on Swedish roads accounting for non-reported non-injury crashes and demonstrated the importance of including these cases for the practical application of recommending speed limits.

Comparing German GIDAS and Swedish STRADA data, we found the characteristics important for the injury outcome (car model year, car weight, occupant injury severity, and occupant age) to be similar. Therefore, our findings, which are based on German data, can be generalized to Sweden.

We used Bayesian modeling to compensate for the sampling bias, since neither GIDAS nor national statistics collect complete data on PDO crashes. The compensation substantially affected the resulting IRCs, illustrated by a twofold difference between unconditional risk and conditional risk in this study. The ability to compensate for sampling bias and represent unconditional risk more accurately are imperative to obtain accurate safe speeds and provide evidence-based guidelines for speed limits. Further, the method allows datasets with different collection constraints to be considered together. Including or modeling unreported crashes remains an important area for further work.

If a 10 % MAIS3+ risk was acceptable, treating uncertainty conservatively by taking the lower bound of the 95 % interval, assuming compliance with speed limits and that Automated Emergency Braking can reduce impact speeds by 20 km/h from initial travel speed in longitudinal traffic, the safe speed limit for car occupants on most Swedish roads would be 80 km/h and 60 km/h in intersections. However, most roads are not used by car drivers alone, but shared with other road users. Mixing cars with heavy trucks or vulnerable road users lowers permissible speeds.

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CRediT authorship contribution statement

Nils Lubbe: Conceptualization, Methodology, Resources, Validation, Writing – original draft, Writing – review & editing. **Hanna Jeppsson:** Data curation, Formal analysis, Writing – original draft. **Simon Sternlund:** Data curation, Resources, Writing – review & editing.

Alberto Morando: Formal analysis, Methodology, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: N. Lubbe, H. Jeppsson and A. Morando are employed at Autoliv Research, located in Vårgårda, Sweden. Autoliv Research is part of Autoliv (www.autoliv.com), a company that develops, manufactures, and sells (for example) protective safety systems to car manufacturers. Results from this study may impact how Autoliv chooses to develop their products.

Data availability

The authors do not have permission to share data.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.aap.2024.107586.

References

Andricevic, N., Junge, M., Krampe, J., 2018. Injury risk functions for frontal oblique collisions. Traffic Inj. Prev. 19 (5), 518–522. https://doi.org/10.1080/15389588.2018.1442926.
Bürkner, P., 2017. brms: An R package for Bayesian multilevel models using Stan. J. Stat. Softw. 80 (1), 1–28. https://doi.org/10.18637/jss.v080.i01.
Bürkner, P., 2018. Advanced Bayesian Multilevel Modeling with the R Package brms. R J. 10 (1), 395–411. https://doi.org/10.32614/RJ-2018-017.
Bürkner, P., Vuorre, M., 2019. Ordinal Regression Models in Psychology: A Tutorial. Adv. Meth. Pract. Psychol. Sci. 2 (1), 77–101. https://doi.org/10.1177/2515245918823199.
Dean, M.E., Lubbe, N., Fredriksson, R., Sternlund, S., Gabler, H.C., 2023. Assessing the applicability of impact speed injury risk curves based on US data to defining safe speeds in the US and Sweden. Accid. Anal. Prev. 190, 107151 https://doi.org/10.1016/j.aap.2023.107151.
Destatis (2022). Statistisches Bundesamt (Destatis), Fachserie 8 Reihe 7, 2021 Verkehrsunfälle 2021 Available at: https://www.destatis.de/DE/Themen/Gesellschaft-Umwelt/Verkehrsunfaelle/Publikationen/Downloads-Verkehrsunfaelle/verkehrsunfaelle-jahr-2080700217004.pdf.
Ding, C., Rizzi, M., Strandroth, J., Sander, U., Lubbe, N., 2018. Motorcyclist injury risk as a function of real-life crash speed and other contributing factors. Accid. Anal. Prev. 123, 374–386. https://doi.org/10.1016/j.aap.2018.12.010.
Doecke, S.D., Baldock, M.R.J., Kloeden, C.N., Dutschke, J.K., 2020. Impact speed and the risk of serious injury in vehicle crashes. Accid. Anal. Prev. 144, 105629 https://doi.org/10.1016/j.aap.2020.105629.
Doecke, S.D., Dutschke, J.K., Baldock, M.R.J., Kloeden, C.N., 2021. Travel speed and the risk of serious injury in vehicle crashes. Accid. Anal. Prev. 161, 106359 https://doi.org/10.1016/j.aap.2021.106359.
Eugensson, A., Ivarsson, J., Lie, A., Tingvall, C., 2011. Cars Are Driven on Roads, Joint Visions and Modern Technologies Stress the Need for Co-Operation. Proceedings of the 22nd International Technical Conference on the Enhanced Safety of Vehicles (ESV) Washington, D.C..
Ferson N, Bergamini S, Mallada JL, Breitlauch P, Ishikawa T (2023). Development and validation of a simulation toolchain for the assessment of the injury reduction performance of active safety systems. *Proceedings of 7th International Symposium on Future Active Safety Technology toward zero traffic accidents* Kanazawa.
Firey LML, Rudd RW, Lockerby J, Craig MJ (2023). Identification of Influential Factors Among Fatalities of Restrained First-Row Occupants in Recent Frontal Crashes. *Proceedings of the International Research Council on the Biomechanics of Injury (IRCOBI)* Cambridge.
Forman, J., Poplin, G.S., Shaw, C.G., McMurry, T.L., Schmidt, K., Ash, J., Sunnevang, C., 2019. Automobile injury trends in the contemporary fleet: Belted occupants in frontal collisions. Traffic Inj. Prev. 20 (6), 607–612. https://doi.org/10.1080/15389588.2019.1630825.
Hautzinger, H., Pfeiffer, M., & Schmidt, J. (2004). Expansion of GIDAS Sample Data to the Regional Level: Statistical Methodology and Practical Experiences. Proceedings of *1st Expert Symposium on Accident Research (ESAR)* Hannover.
Hautzinger, H., Pastor, C., Pfeiffer, M., & Schmidt, J. (2007). Analysis Methods for Accident and Injury Risk Studies. Deliverable 7.3 of Project No. 027763 – TRACE.
ISO (2003). ISO 12353-2:2003 Road vehicles — Traffic accident analysis — Part 2: Guidelines for the use of impact severity measures.
Kahane, C.J., 2015. Lives saved by vehicle safety technologies and associated Federal Motor Vehicle Safety Standards, 1960 to 2012 – Passenger cars and LTVs – With reviews of 26 FMVSS and the effectiveness of their associated safety technologies in reducing fatalities, injuries, and crashes. National Highway Traffic Safety Administration, Washington, DC (Report No. DOT HS 812 069).
Kullgren A, Lie A, Tingvall C (2001). Mass data evaluation of the importance of structural and mass related aggressivity. *Proceedings of the 17th International Technical Conference on the Enhanced Safety of Vehicles (ESV)* Amsterdam.
Kullgren A, Axelsson A, Stigson H, Ydenius A (2019). Developments in car crash safety and comparisons between results from Euro NCAP tests and real-world crashes. *Proceedings of the 26th International Technical Conference on the Enhanced Safety of Vehicles (ESV)* Eindhoven.
Larsson, P., Dekker, S.W.A., Tingvall, C., 2010. The need for a systems theory approach to road safety. Saf. Sci. 48, 1167–1174. https://doi.org/10.1016/j.ssci.2009.10.006.
Lie, A., Tingvall, C., 2010. How Do Euro NCAP Results Correlate with Real-Life Injury Risks? A Paired Comparison Study of Car-to-Car Crashes. Traffic Inj. Prev. 3 (4), 288–293. https://doi.org/10.1080/15389580214632.
Liers, H. (2018). Traffic Accident Research in Germany and the German In-Depth Accident Study (GIDAS). ACMA-SIAM-VDA Conference on Safer & Sustainable Road Transportation, New Delhi. Available at: https://www.vufo.de/wp-content/uploads/2021/02/181120_SIAM_ACMA_VDA_Conference_Liers_GIDASPresentation.pdf.
Lubbe, N., Wu, Y., Jeppsson, H., 2022. 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. Traffic Safety Res. 2, 000006. https://doi.org/10.55329/vfma7555.
Mroz, K., Östling, M., & Lubbe, N. (2023). Passenger Cars in Head-on Crashes with Heavy Goods Vehicles: For what Severity Should Future Car Restraint Systems Be Designed? *Proceedings of the 27th International Technical Conference on the Enhanced Safety of Vehicles (ESV)* Yokohama.
Olleja, P., Bärgman, J., Lubbe, N., 2023. Can non-crash naturalistic driving data be an alternative to crash data for use in virtual assessment of the safety performance of automated emergency braking systems? J. Saf. Res. 83.
Östling, M., Eriksson, L., Dahlgren, M., & Forman, J. (2023). Frontal Head-On Car-to-Heavy Goods Vehicle Crashes Effect on the Restraint System. *Proceedings of the 27th International Technical Conference on the Enhanced Safety of Vehicles (ESV)* Yokohama.
Rizzi, M., Boström, O., Fredriksson, R., Kullgren, A., Lubbe, N., Strandroth, J., & Tingvall, C. (2023). Proposed Speed Limits for the 2030 Motor Vehicle. *Proceedings of the 27th International Technical Conference on the Enhanced Safety of Vehicles (ESV)* Yokohama.
Sander, U., Lubbe, N., 2018. Market penetration of intersection AEB: Characterizing avoided and residual straight crossing path accidents. Accid. Anal. Prev. 115, 178–188. https://doi.org/10.1016/j.aap.2018.03.025.
Schmitt, K.-U., Niederer, P.F., Cronin, D.S., Muser, M.H., Walz, F., 2014. Trauma Biomechanics: An Introduction to Injury Biomechanics, (4th ed.),. Springer.
Schubert, A., Babisch, S., Scanlon, J.M., Campolettano, E.T., Roessler, R., Unger, T., McMurry, T.L., 2023. Passenger and heavy vehicle collisions with pedestrians: Assessment of injury mechanisms and risk. Accid. Anal. Prev. 190, 107139 https://doi.org/10.1016/j.aap.2023.107139.
Sterne, J.A.C., White, I.R., Carlin, J.B., Spratt, M., Royston, P., Kenward, M.G., Wood, A. M., Carpenter, J.R., 2009. Multiple imputation for missing data in epidemiological and clinical research: Potential and pitfalls. BMJ 338, b2393. https://doi.org/10.1136/bmj.b2393.
Tingvall, C., Ifver, J., Krafft, M., Kullgren, A., Lie, A., Rizzi, M., Sternlund, S., Stigson, H., & Strandroth, J. (2013). The Consequences of Adopting a MAIS 3 Injury Target for Road Safety in the EU: a Comparison with Targets Based on Fatalities and Long-term Consequences. *Proceedings of the International Research Council on the Biomechanics of Injury (IRCOBI)* Gothenburg.
Trafikverket (2016) Åtgärder för systematisk anpassning av hastighetsgränserna till vägarnas trafiksäkerhetsstandard. Available at: https://www.trafikverket.se/contentassets/d54ed63f49f94ad3b0d304b191858c02/nationell_rapport_hastighetsanalys.pdf.
Trafikverket (2021). Analys av trafiksäkerhetsutvecklingen 2020. Målstyrning av trafiksäkerhetsarbetet mot etappmålen 2020. Available at: https://urn.kb.se/resolve?urn=urn%3Anbn%3Ase%3Atrafikverket%3Adiva-5062.
Truong, J., Strandroth, J., Logan, D.B., Job, R.F.S., Newstead, S., 2022. Utilising Human Crash Tolerance to Design an Interim and Ultimate Safe System for Road Safety. Sustainability 14, 3491. https://doi.org/10.3390/su14063491.
Unger T, Liers H, Schuster R, Kleber C (2020). Impact of the New Diagnostic Dictionary (AIS 2015) for Traffic Accident Research. *Proceedings of the International Research Council on the Biomechanics of Injury (IRCOBI)* Munich (conference postponed).
van Buuren, S., 2018. Flexible Imputation of Missing Data, 2nd ed. Chapman and Hall/CRC.
Wisch, M., Lerner, M., Vukovic, E., Hynd, D., Fiorentino, A., & Fornells, A. (2017). Injury Patterns of Older Car Occupants, Older Pedestrians or Cyclists in Road Traffic Crashes with Passenger Cars in Europe – Results from SENIORS. *Proceedings of the International Research Council on the Biomechanics of Injury (IRCOBI)* Antwerp.