



Short Communication

Characteristics of pedestrian head injuries observed from real world collision data



Guibing Li^a, Fang Wang^b, Dietmar Otte^c, Ciaran Simms^{d,*}

^a School of Mechanical Engineering, Hunan University of Science and Technology, Xiangtan, 411201, China

^b School of Mechanical and Automotive Engineering, Xiamen University of Technology, Xiamen 361024, China

^c Accident Research Unit, Medical University of Hannover, Hannover, 30625, Germany

^d Trinity Centre for Bioengineering, Trinity College Dublin, Ireland

ARTICLE INFO

Keywords:

Pedestrian head injury

Collision data

Injury risk

ABSTRACT

Head injury is one of the most common injury types in vehicle-to-pedestrian collisions, which leads to death and long-term disabilities. However, detailed analysis of pedestrian head injuries in real world collisions is scarce. Thus the current study used two samples of 120 cases and 184 cases extracted from 1060 pedestrian collision cases captured during 2000–2015 from the GIDAS (German In-Depth-Accident Study) database to investigate the detailed characteristics of AIS2+ pedestrian head injuries. Firstly, the interrelationship between different head injury types (skull fracture, focal brain injury, concussion and diffuse axonal injury (DAI)) was analysed using the sample of 120 cases which each had at least one AIS2+ head injury. Then the influences of impact speed, pedestrian age and car front shape parameters on the injury risk of skull fracture, focal brain injury and concussion were assessed using the logistic regression method, based on the sample of 184 AIS1+ cases where the primary head contact location was within the windscreen glass area. The results show that: skull fractures and focal brain injuries dominate for AIS3+ head injuries and are generally associated with each other; concussion is the most important injury type for AIS2 head injuries and usually occurs in isolation. Further, for head impacts to the windscreen glass area a higher bonnet leading edge helps to reduce concussion odds, and none of the selected car front shape parameters are significant for the odds of skull fracture and focal brain injury, and vehicle impact speed and pedestrian age are insignificant for concussion. These detailed characteristics of pedestrian head injuries provide a basis for future pedestrian head injury prevention strategies with skull fractures and focal brain injuries being the most important injuries to address.

1. Background

In vehicle-to-pedestrian collisions, head injuries are one of the most common injury types (Chen et al., 2009; Fildes et al., 2004; Neal-Sturgess et al., 2007; Li et al., 2016; Otte, 1999; Otte et al., 2012) and can lead to lifelong disability or death (Schmitt et al., 2010; Yang, 2005). Typical pedestrian head injuries in traffic collisions include scalp injuries, skull fractures and brain injuries, where brain injuries can be classified into focal brain injuries (mostly hematoma and contusions) and diffuse brain injuries (mostly diffuse axonal injury (DAI) and concussion) (Li et al., 2017a; Schmitt et al., 2010; Simms and Wood, 2009; Yang, 2005). Previous studies on head injury mechanisms have shown that skull fractures and focal brain injuries are usually caused by contact force and linear acceleration, while rotational dynamic response is the main source for diffuse brain injuries (Gennarelli et al., 1971, 1972, 1982; Margulies et al., 1990; Ommaya and Gennarelli, 1974).

Moreover, the pedestrian kinematics in vehicle collisions are variable and are affected by various factors such as impact boundary conditions and vehicle front design. Thus it is necessary to distinguish different injury types when developing head injury prevention strategies.

Analysis of real world collision data is usually the foundational step for pedestrian injury prevention. Many studies have attempted at understanding the detailed characteristics of pedestrian head injuries in real world collisions. Otte (1999), using 762 car-to-pedestrian cases from Germany, found that: most AIS2+ head injury cases had an impact speed higher than 40 km/h and contact was mostly with the windscreen area; for impacts lower than 40 km/h most head injuries are soft tissue lesions and concussion, and the proportions of skull fractures and brain injuries are lower than for cases above 40 km/h. Richards and Carroll (2012) reported that pedestrian age is significant for intracranial injuries but not significant for head fractures, based on information collected by hospitals in England. Arregui-Dalmases et al.

* Corresponding author.

E-mail address: csimms@tcd.ie (C. Simms).

<https://doi.org/10.1016/j.aap.2019.05.007>

Received 2 September 2018; Received in revised form 15 April 2019; Accepted 6 May 2019

Available online 24 May 2019

0001-4575/ © 2019 Elsevier Ltd. All rights reserved.

(2010) analysed 10,341 pedestrian collision cases from eight European countries and suggested that the proportion of internal traumatic brain injuries is significantly higher than fractures to the head, more than half of presented head injuries could be related exclusively to rotational mechanisms, 12% were associated with translational ones, and the 26.4% were the result of both mechanisms combined. Badea-Romero and Lenard (2013) reviewed 205 accidents from the UK On-the-Spot study involving pedestrians and pedal cyclists and found that for the cases where the vulnerable road users either interacted with a flat-fronted vehicle, tumbled to the side or vaulted the roof, vehicle impacts are the main source of face or skull fracture or an intracranial injury not restricted to isolated loss of consciousness, while intracranial injuries only with loss of consciousness and superficial injuries to the face or scalp were more likely from ground contacts. Fredriksson et al. (2010) analysed 1030 GIDAS pedestrian cases from 1998 to 2008 and claimed that the most frequent injury mechanism for a pedestrian's head is 'head-to-windscreen area' and most AIS3+ head injuries resulting from this mechanism are to the brain (20 out of 39 cases) or combined brain and skull (15 out of 39 cases). However, these studies did not distinguish between focal brain injuries and diffuse brain injuries in detail for pedestrians. Furthermore, the interrelationship between different types of head injuries and the influence of vehicle front shape on pedestrian head injuries were not investigated in these studies. s

Therefore, the purpose of the current study is to investigate the interrelationship between different head injury types (skull fracture, focal brain injury, concussion and DAI) and the significant factors for these in car-to-pedestrian collisions. To achieve this goal, recent GIDAS data (captured during 2000–2015) and logistic regression approaches were employed to assess relationships between AIS2+ pedestrian head injuries and vehicle impact speed, pedestrian age and vehicle front shape parameters.

2. Methods

2.1. Collision data

Pedestrian collision data captured during 2000–2015 from the German In-depth Accident Study (GIDAS) were employed. For each case in the database, information on the vehicle model and impact speed, pedestrian gender, age and height, body region, severity level and source of injuries and pedestrian-to-vehicle contacts was recorded (Otte, 2005; Otte et al., 2003). All injuries were documented by the team and coded using the 2005 Abbreviated Injury Scale (AIS) system (Gennarelli and Wodzin, 2006). After the knowledge of the existing movement of the human body during and after the impact phase, each injury is finally assessed by experienced team members for their causation using traces and details of the whole reconstruction work. Based on all available evidence including matching of the vehicle damage pattern to the observed injuries (injury characteristics, medical report and x-rays and CT-scans), the team assigned each injury to the contact source. Furthermore, the kind of information and quality of coding of the causation is coded within the system. Cases with unknown, or doubtful assignment were excluded from this analysis. Nonetheless, an element of subjectivity remains in the assignment of injury sources, and given the recognised uncertainty in this approach (Shang et al., 2018), a benchmarking exercise would be of benefit in future.

The preliminary data filtration was conducted with the following inclusion criteria: 1) at least one AIS1+ injury was observed, 2) collisions involving passenger cars, 3) both pedestrian age and vehicle impact speed are available, 4) pedestrians hit only once by a vehicle's front. In total 1060 cases were selected from an original collision sample of 1258 cases as the analysis sample. Of these, one sub-sample of 120 cases which each had at least one AIS2+ head injury was employed for analysis of the interrelationship between different head injury types and a second sub-sample of 184 AIS1+ cases where the primary head contact location was within the windscreen glass area

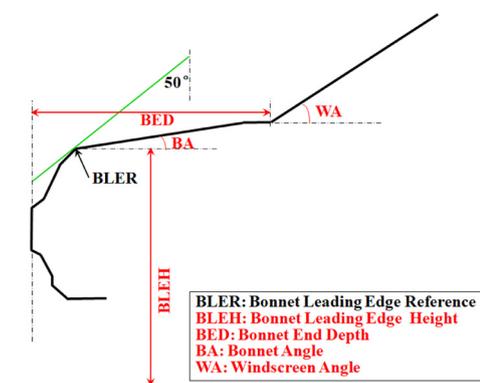


Fig. 1. Car front shape parameters defined in this study (measurements in red) (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

was used for investigation of the significant factors for different head injury types.

2.2. Statistical analysis

In this study the AIS2+ pedestrian skull fractures, focal brain injuries, concussion and DAI and the following predictors were considered: vehicle impact speed, pedestrian age and car front shape parameters (Fig. 1) of bonnet leading edge height (BLEH), bonnet end depth (BED), bonnet angle (BA) and windscreen angle (WA). These car front shape parameters were measured in our previous studies (Li et al., 2017b; Shang et al., 2017), where the bonnet leading edge reference was defined by EEVC WG17 protocol (EEVC, 2002).

All AIS2+ pedestrian head injuries in the sample were generally classified into one of four types: skull fracture, focal brain injury, concussion or DAI. The distributions of pedestrian collision cases as a function of head injury type and AIS level (AIS2+ and AIS3+) were then calculated, where cases with multi-type injuries (two or more injury types occurred together) and single-type injuries (only one injury type occurred) were distinguished. The Spearman's rank correlation coefficient with a 5% significance level was used to assess the correlation between different head injury types at the AIS2+ level, similar to a previous study (Zou et al., 2018). These analyses help to build a basic understanding on the interrelationship between different head injury types.

As applied in many previous studies on accident analysis (Badea-Romero et al., 2010; Huang et al., 2018; Kong and Yang, 2010; Li et al., 2017b, 2018; Nie et al., 2015; Shang et al., 2017; Zhang et al., 2008), logistic regression is an effective statistical method to determine whether predictor(s) that are continuous and/or categorical have a significant influence on a (binary) injury outcome. Logistic regression models a nonlinear association in a linear way by using a logarithmic transformation of the outcome variable (Hosmer and Lemeshow, 2004). However, there are a few caveats to using logistic regression model: there should be enough cases for each category (binary) in the dependent variable; collinearity between predictors in the independent variables can bring great interference to the model, which should be eliminated in advance; logistic regression cannot address missing values which should be appropriately handled before applying this approach. Furthermore, the logistic regression model itself does not perform statistical classification and the regression result is sensitive to the selection of predictors to some extent. Performing classifiers such as the classification trees to exclude predictors of less importance improves the predictive accuracy of logistic regression models when a large number of predictors are considered (Badea-Romero et al., 2010).

The focus of the current study is on the effects of vehicle front shape, thus the selection of predictors is firstly based on potential

vehicle shape parameters affecting pedestrian head injuries proposed in previous studies (Badea-Romero and Lenard, 2013; Li et al., 2017b). Impact speed and pedestrian age are also included as control predictors since they have an important influence on pedestrian head injuries (Kong and Yang, 2010; Li et al., 2017b; Richards and Carroll, 2012; Zhang et al., 2008). Therefore, logistic regression with impact speed, pedestrian age and car front shape parameters (Fig. 1) as predictors was employed to investigate the factors affecting the AIS2+ injury odds of a given head injury type. The logistic model and injury probabilities are:

$$\text{logit}(p) = \log\left(\frac{p}{1-p}\right) = \beta_0 + \beta_1 * x_1 + \dots + \beta_i * x_i \tag{1}$$

$$p = \frac{\exp(\beta_0 + \beta_1 * x_1 + \dots + \beta_i * x_i)}{1 + \exp(\beta_0 + \beta_1 * x_1 + \dots + \beta_i * x_i)} \tag{2}$$

where p is the probability of a head injury type, β_i are the estimated coefficients based on the method of maximum likelihood (Dobson, 2002), and x_i are the predictors (speed, age and vehicle shape parameters). The Wald test was employed to determine whether a relationship between an injury type and a predictor is statistically significant based on the hypothesis that the coefficient (β_i) of the independent variable in the model is significantly different from zero. A p -value lower than 0.05 indicates that the corresponding predictor has a significant influence on the probability of a head injury type. To evaluate the goodness of fit of a logistic regression model, the overall percentage correct ((true positive + true negative)/sample size) was estimated for each model. The Odds Ratio (OR) was then applied to assess the effects of each predictor on the risk of a head injury type, which estimates the change in injury odds per unit increase in the corresponding predictor with other predictors being controlled. Thus an OR greater/less than 1 respectively indicates a rising/falling trend of injury odds when increasing the magnitude of a predictor. Confidence Intervals (CI) at the 95% level were also constructed.

To reduce the well-known effect of stiffness of head contact locations on injury outcome (Mizuno et al., 2001) and to keep enough cases with head injuries, the focus of the logistic regression model is therefore on accident cases where the primary head contact location was within the windscreen glass area (i.e. excluding the windscreen frame and A-pillars). This region is the main source for AIS2+ pedestrian head injuries in the GIDAS data (Li et al., 2017b). To build the logistic regression model, injury outcome at each AIS level (dependent variable) was defined as a binary variable and coded as 1/0 for the cases with/without a skull fracture, focal brain injury and concussion, respectively. Table 1 shows the information for the sample for logistic regression analysis, where the numbers for cases with/without (1/0) a selected injury were counted. The case for DAI was not considered in the logistic regression analysis due to lack of data (there are only 3 out of 184 cases with DAI). Only passenger car cases were included in the sample, to avoid outliers in the shape parameters due to substantial gaps in geometry between different vehicle types. No outlier was observed in impact speed and pedestrian age data. There is no missing data in the selected models due to the inclusion criteria for sampling. No statistical classification was performed to filter the predictors as only six parameters were considered in the logistic regression models. Preliminary analyses were conducted to check the multicollinearity between

Table 1
Windscreen collision data for injury risk estimation using the logistic regression model (the numbers 1 or 0 indicate injury/no injury, respectively).

Injury type	Predictor	No. of cases (total N = 184)
Skull fracture	Speed, Age, BLEH, BED, BA and	1 = 29, 0 = 155
Focal brain injury	WA	1 = 32, 0 = 152
Concussion		1 = 25, 0 = 159

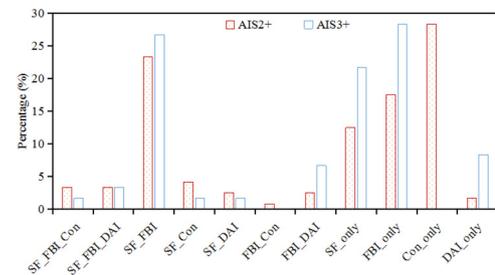


Fig. 2. Pedestrian collision case distribution as a function of head injury type and severity (SF = skull fracture, FBI = focal brain injury, Con = concussion and DAI = diffuse axonal injury).

predictors and the statistical significance of interaction terms between speed/age and shape parameters. The interaction terms between predictors are not included in the logistic models since serious multicollinearity problems arose in these cases and they were not statistically significant for pedestrian AIS2+ head injury outcome. No multicollinearity was observed between the predictors in Table 1.

3. Results

3.1. Interrelationship between different head injury types

Fig. 2 shows the distribution of pedestrian collision cases as a function of head injury type observed, where the proportions for multi-type injuries (e.g. SF_FBI represents skull fractures with focal brain injuries) and single-type injuries (e.g. SF_only means only skull fractures) were calculated. For cases with at least one AIS2+ head injury, the main injury types are concussion only (28%) and skull fracture combined with focal brain injuries (23%), followed by the injury types of focal brain injury only (18%) and skull fracture only (13%). For cases with at least one AIS3+ head injury, focal brain injury only (28%), skull fracture combined with focal brain injuries (27%) and skull fracture only (22%) are the top three important injury types. Table 2 shows the Spearman's rank correlation coefficients between different head injury types at the AIS2+ level. The correlation skull fracture and focal brain injury is statistically significant and a positive coefficient is observed, which indicates that skull fractures usually occurred together with focal brain injuries. On the other hand, correlations between concussion and all other head injury types are statistically significant but with minus coefficients. This implies that other head injuries were not frequent when concussion occurred.

3.2. Effects of predictors on pedestrian head injury risk

Table 3 shows the logistic regression results for different head injury types, including significance level (p-value), mean and 95% CI of the OR, and coefficients for predictors and the overall percentage correct (%C). The high percentage correct values ($\geq 84\%$ for all models) indicate that all logistic models show good prediction for the data in the corresponding sample. For skull fracture and focal brain injury, the p-values of impact speed and pedestrian age are < 0.05 (bold) and the

Table 2
Spearman's rank correlation coefficients between different head injury types at the AIS2+ level (superscript * means statistical significance and no superscript indicates no statistical significance).

	Skull fracture	Focal brain injury	Concussion	DAI
Skull fracture	\	0.20*	-0.44*	0.06
Focal brain injury	0.20*	\	-0.60*	0.05
Concussion	-0.44*	-0.60*	\	-0.25*
DAI	0.06	0.05	-0.25*	\

Table 3
Logistic regression analysis results for different head injury types (p-values in bold indicate statistically significant).

Injury type	Predictor	OR (95% CI)	β	p-value	%C
Skull fracture	Speed	1.035 (1.010-1.061)	0.035	0.006	84
	Age	1.019 (1.001-1.038)	0.019	0.046	
	BLEH	1.002 (0.990-1.013)	0.002	0.780	
	BED	0.999 (0.994-1.003)	-0.001	0.497	
	BA	0.965 (0.822-1.133)	-0.036	0.663	
	WA	0.950 (0.826-1.093)	-0.051	0.474	
Focal brain injury	Speed	1.040 (1.014-1.067)	0.039	0.002	85
	Age	1.025 (1.007-1.045)	0.025	0.008	
	BLEH	1.001 (0.989-1.011)	0.001	0.997	
	BED	1.001 (0.996-1.005)	0.001	0.745	
	BA	0.996 (0.836-1.187)	-0.004	0.967	
	WA	0.901 (0.764-1.063)	-0.104	0.218	
Concussion	Speed	0.995 (0.965-1.027)	-0.005	0.771	86
	Age	1.004 (0.986-1.022)	0.004	0.674	
	BLEH	0.983 (0.971-0.996)	-0.017	0.011	
	BED	1.001 (0.998-1.003)	0.001	0.960	
	BA	0.915 (0.782-1.071)	-0.089	0.269	
	WA	1.055 (0.915-1.217)	0.054	0.462	

ORs for both speed and age are > 1 , but the p-values for all selected shape parameters are > 0.05 . For the concussion case, the p-value of BLEH is < 0.05 (bold) and with an OR < 1 , but the p-values for both impact speed and pedestrian age are > 0.05 .

4. Discussion

This study presents a detailed analysis of different types of pedestrian head injuries based on recent pedestrian collision data. The results show that 77% of AIS 3+ cases are either skull fracture with focal brain injury, skull fracture only or focal brain injury only, and skull fractures and focal brain injuries are usually associated with each other for both AIS2+ and AIS3+ cases (Fig. 2). Correlation analysis also indicates that skull fractures have a strong positive correlation with focal brain injuries, see Table 2. These findings suggest that the prevention of focal brain injuries and skull fractures should remain the main focus in vehicle safety design for pedestrian protection. This might be achieved by softening the contact stiffness of vehicle front structures to reduce head linear acceleration and impact force since they are regarded as the main mechanisms for focal brain injuries and skull fractures (Gennarelli et al., 1971,1972; Ommaya and Gennarelli, 1974; Schmitt et al., 2010; Yang, 2005). Moreover, the logistic regression analyses show that car shape parameters are not statistically significant for focal brain injuries and skull fractures (p-values > 0.05 , see Table 3), even though this is not in line with the finding from a previous study where bonnet length is a significant predictor for AIS3+ head injury risk (Zhang et al., 2008). But this difference is probably due to the fact that in the study of Zhang et al. (2008) the logistic regression model was built based on a sample without control of head contact location, where a shorter bonnet would be more likely to have a head contact on the windshield frame and hence an increased injury risk. Accordingly, the subsystem impactor tests used in current pedestrian safety regulations focusing on vehicle stiffness are logically efficient for head injury prevention and have shown a positive effect on reducing pedestrian head injuries in collisions (Li et al., 2018).

In contrast, diffuse brain injuries (concussion and DAI) are less common for AIS3+ injury cases, where the DAI only injury type only accounts for 8% (Fig. 2). However, the proportion of collisions with concussion only injury (28%) is higher than all other injury types for the AIS2+ injury case and concussions usually occur alone (not accompanied by skull fractures and focal brain injuries), see Fig. 2 and Table 2. This finding implies that future vehicle safety design, where AIS2+ head injuries may be the primary concerns with softer front structure and better speed control system being employed to reduce

skull fractures and focal brain injuries, should also pay attention to concussions, as distinct from skull fractures and focal brain injuries. Furthermore, the logistic regression results indicate that increasing bonnet leading edge height by 1 cm may lead to an average 17% (CI: 4%–29%) reduction in concussion odds when fixing the head primary contact location within the windscreen area (Table 3). This is mainly because a higher bonnet leading edge height reduces rotation to the upper body and head, and hence reducing concussion risk (Gennarelli et al., 1971, 1982; Margulies et al., 1990; Schmitt et al., 2010; Yang, 2005). However, raising the bonnet leading edge height may affect head impact location and pedestrian kinematics in both primary and secondary impact, thus influencing head injuries in other aspects (Crocetta et al., 2015; Li et al., 2017c; Shi et al., 2019). Moreover, raising the bonnet leading edge height generally has negative implications for femur and pelvis risk (Matsui et al., 1999; Li et al., 2017b,2018). Therefore, the effect of bonnet leading edge height on concussion observed in the current study is based on the particular condition of the data sample, and further analysis is needed to verify this considering brain injuries from other impact mechanisms.

The logistic regression results not surprisingly indicate that increasing impact speed and pedestrian age leads to significantly higher odds of skull fracture and focal brain injury (p-value < 0.05 and OR > 1 , see Table 3). The results also show that both the vehicle impact speed and pedestrian age are insignificant for concussion odds (p-value > 0.05 , see Table 3). These differences between concussion and skull fracture/focal brain injury likely reflect the different injury mechanisms (Schmitt et al., 2010; Yang, 2005). However, the influence of age on head injury in different types is still controversial considering inconsistent remarks from previous studies (Andelic et al., 2008; Bauzá et al., 2008; Mallory, 2010; Richards and Carroll, 2012;) and further analysis is needed to understand the underlying reasons.

5. Conclusions

This study analysed pedestrian head injury characteristics in recent real world collisions with skull fracture, focal brain injury, concussion and DAI being distinguished. The vehicle-to-pedestrian collision data show that skull fractures and focal brain injuries dominate for AIS3+ head injuries and are generally associated with each other, while concussion is the most important injury type for AIS2+ head injuries and this usually occurs in isolation. Logistic regression results indicate that when head impacts are fixed at the windscreen area a higher bonnet leading edge helps to reduce concussion odds, none of the selected car front shape parameters is significant for the odds of skull fracture and focal brain injury, and vehicle impact speed and pedestrian age are not statistically significant for concussion.

Acknowledgments

This work was supported by the National Natural Science Foundation of China (Grant Nos. 51805162 and 51605407) and Natural Science Foundation of Hunan Province, China (Grant No. 2018JJ3532).

References

- Andelic, N., Sigurdardottir, S., Brunborg, C., Roe, C., 2008. Incidence of hospital-treated traumatic brain injury in the Oslo population. *Neuroepidemiology* 30 (2), 120–128.
- Arregui-Dalmases, C., Lopez-Valdes, F.J., Segui-Gomez, M., 2010. Pedestrian injuries in eight European countries: an analysis of hospital discharge data. *Accid. Anal. Prev.* 42 (4), 1164–1171.
- Badea-Romero, A., Lenard, J., 2013. Source of head injury for pedestrians and pedal cyclists: striking vehicle or road? *Accid. Anal. Prev.* 50, 1140–1150.
- Badea-Romero, A., Furones, A., Páez, F.J., González, C., 2010. Multivariate modeling of pedestrian fatality risk through on the spot accident investigation. *Int. J. Auto. Tech-Kor.* 11, 711–720.
- Bauzá, G., LaMorte, W., Burke, P., Hirsch, E., 2008. High mortality in elderly drivers is associated with distinct injury patterns: analysis of 187,869 injured drivers. *J. Trauma.* 64 (2), 304–310.
- Chen, H., Fu, L., Cheng, H., 2009. A comparative study between China and IHRA for the

- vehicle-pedestrian impacts. SAE Technical Paper No. 2009-01-1205.
- Crocetta, G., Piantini, S., Pierinia, M., Simms, C., 2015. The influence of vehicle front-end design on pedestrian ground impact. *Accid. Anal. Prev.* 79, 56–69.
- Dobson, A., 2002. *An Introduction to Generalized Linear Models*. Chapman & Hall/CRC.
- EEVC, 2002. Improved Test Methods to Evaluate Pedestrian Protection Affordable by Passenger Cars, Technical Report. European Enhanced Vehicle-Safety Committee, Working Group17 Report. December 1998 with September 2002 updates. .
- Fildes, B., Gabler, H., Otte, D., Linder, A., Sparke, L., 2004. Pedestrian impact priorities using real-world crash data and harm. Proceedings of the International Research Council on Biomechanics of Injury (IRCOBI) Conference.
- Fredriksson, R., Rosén, E., Kullgren, A., 2010. Priorities of pedestrian protection a real-life study of severe injuries and car sources. *Accid. Anal. Prev.* 42 (6), 1672–1681.
- Gennarelli, T., Ommaya, A., Thibault, L., 1971. Comparison of translational and rotational head motions in experimental cerebral concussion. SAE Technical Paper No. 710882.
- Gennarelli, T., Thibault, L., Ommaya, A., 1972. Pathophysiologic responses to rotational and translational accelerations of the head. SAE Technical Paper No. 720970.
- Gennarelli, T., Thibault, L., Adams, J., Graham, D., Thompson, C., Marcincin, R., 1982. Diffuse axonal injury and traumatic coma in the primate. *Ann. Neurol.* 12 (6), 564–574.
- Hosmer Jr, D., Lemeshow, S., 2004. *Applied Logistic Regression*. John Wiley & Sons.
- Huang, J., Peng, Y., Yang, J., Otte, D., Wang, B., 2018. A study on correlation of pedestrian head injuries with physical parameters using in-depth traffic accident data and mathematical models. *Accid. Anal. Prev.* 119, 91–103.
- Kong, C., Yang, J., 2010. Logistic regression analysis of pedestrian casualty risk in passenger vehicle collisions in China. *Accid. Anal. Prev.* 42 (4), 987–993.
- Li, G., Otte, D., Yang, J., Simms, C., 2016. Pedestrian injury trends evaluated by comparison of the PCDS and GIDAS databases. Proceedings of the International Research Council on Biomechanics of Injury (IRCOBI) Conference.
- Li, F., Li, H., Xiao, Z., Lu, R., Zhang, Z., Zhu, H., Ren, L., 2017a. A review on injury mechanism of intracerebral hemorrhage in vehicle collisions. *Curr. Pharm. Design* 23, 1–16.
- Li, G., Lyons, M., Wang, B., Yang, J., Otte, D., Simms, C., 2017b. The influence of passenger car front shape on pedestrian injury risk observed from German in-depth accident data. *Accid. Anal. Prev.* 101, 11–21.
- Li, G., Yang, J., Simms, C., 2017c. Safer passenger car front shapes for pedestrians: a computational approach to reduce overall pedestrian injury risk in realistic impact scenarios. *Accid. Anal. Prev.* 100, 97–110.
- Li, G., Wang, F., Otte, D., Cai, Z., Simms, C., 2018. Have pedestrian subsystem tests improved passenger car front shape? *Accid. Anal. Prev.* 115, 143–150.
- Mallory, A., 2010. Head injury and aging: the importance of bleeding injuries. *The 54th Annals of Advances in Automotive Medicine (AAAM)* 54, 51–60.
- Margulies, S., Thibault, L., Gennarelli, T., 1990. Physical model simulations of brain injury in the primate. *J. Biomech.* 23, 823–836.
- Matsui, Y., Ishikawa, H., Sasaki, A., 1999. Pedestrian injuries induced by the bonnet leading edge in current car-pedestrian accidents. SAE Technical Paper No. 1999-01-0713.
- Mizuno, K., Yonezawa, H., Kajzer, J., 2001. Pedestrian head form impact tests for various vehicle locations. Proceedings of the 17th International Technical Conference on the Enhanced Safety of Vehicles (ESV) Paper No. 278.
- Neal-Sturgess, C., Carter, E., Hardy, R., Cuerden, R., Guerra, L., Yang, J., 2007. APROSYS European in-depth pedestrian database. Proceedings of the 20th International Technical Conference on the Enhanced Safety of Vehicles (ESV) Paper No. 07-0267.
- Nie, J., Li, G., Yang, J., 2015. A study of fatality risk and head dynamic response of cyclist and pedestrian based on passenger car accident data analysis and simulations. *Traffic Inj. Prev.* 16 (1), 76–83.
- Ommaya, A., Gennarelli, A., 1974. Cerebral concussion and traumatic unconsciousness: correlation of experimental and clinical observations on blunt head injuries. *Brain* 97, 633–654.
- Otte, D., 1999. Severity and mechanism of head impacts in car-to-pedestrian accidents. Proceedings of the International Research Council on Biomechanics of Injury (IRCOBI) Conference.
- Otte, D., 2005. 3-D laser systems for scaled accident sketches and documentation of traces after traffic accidents as basis of biomechanical analysis. Proceedings of the International Research Council on Biomechanics of Injury (IRCOBI) Conference.
- Otte, D., Krettek, C., Brunner, H., Zwipp, H., 2003. Scientific approach and methodology of a new in-depth investigation study in Germany called GIDAS. Proceedings of the 18th International Technical Conference on the Enhanced Safety of Vehicles (ESV) 168 Paper No.
- Otte, D., Jänsch, M., Haasper, C., 2012. Injury protection and accident causation parameters for vulnerable road users based on German in-depth accident study GIDAS. *Accid. Anal. Prev.* 44 (1), 149.
- Richards, D., Carroll, J., 2012. Relationship between types of head injury and age of pedestrian. *Accid. Anal. Prev.* 47 (4), 16–23.
- Schmitt, K., Niederer, P., Muser, M., Walz, F., 2010. *Trauma Biomechanics*, third edition. Springer.
- Shang, S., Otte, D., Li, G., Simms, C., 2017. Detailed assessment of pedestrian ground contact injuries observed from in-depth accident data. *Accid. Anal. Prev.* 110, 9–17.
- Shi, L., Han, Y., Huang, H., He, W., Wang, F., Wang, B., 2019. Effects of vehicle front-end safety countermeasures on pedestrian head injury risk during ground impact. *Proc. IMechE Part D: J. Automob. Eng.* <https://doi.org/10.1177/0954407019828845>.
- Simms, C., Wood, D., 2009. *Pedestrian and Cyclist Impact*. Springer.
- Yang, J., 2005. Review of injury biomechanics in car-pedestrian collisions. *Int. J. Veh. Saf.* 1 (1/2/3), 100–117.
- Zhang, G., Cao, L., Hu, J., Yang, K., 2008. A field data analysis of risk factors affecting the injury risks in vehicle-to-pedestrian crashes. *The 52nd Annals of Advances in Automotive Medicine (AAAM)* 52, 199–214.
- Zou, T., Yi, L., Cai, M., Hu, L., Li, Y., 2018. Injury source and correlation analysis of riders in car-electric bicycle accidents. *Appl. Bionics Biomech.* 3676858, 1–15.