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# Influences of impact scenarios and vehicle front-end design on head injury risk of motorcyclist

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## Abstract

Motorcycle to vehicle collision is one of the most common accidents in the world and usually leads to serious or fatal head injuries to motorcyclists. This study aims to investigate the influences of impact scenarios and vehicle front-end design parameters on head injury risk of the motorcyclist. Five general vehicle types and different impact scenarios were selected for a parametric analysis. Impact scenarios were set according to ISO 13232 regulation considering impact angles and impact speeds. Five vehicle types of Sedan, MPV (Multi-Purpose Vehicle), SUV (Sport Utility Vehicle), EV (Electric Vehicle) and 1-Box vehicle were included.  $HIC_{15}$  (Head Injury Criterion), head angular acceleration and  $CSDM$  (Cumulative Strain Damage Measure) were calculated to evaluate head injury risk of the motorcyclist. The results show that the critical impact speed for  $HIC_{15}$  and head angular acceleration was around 15 m/s, while the critical speed for  $CSDM$  was approximately 10 m/s. Impact angle of  $45^\circ$  show extremely high injury risk to the motorcyclist head. Bonnet leading edge height and its combination with other parameter presented high influences on motorcyclist head injuries, and the increasing the bonnet leading edge height can potentially reduce head injury risk of motorcyclists. In summary, the present research results provide some theoretic bases for determining the test speed in motorcycle-vehicle crash regulation and design consideration for typical vehicle front end shape.

**Keywords:** Impact, Motorcyclist, Head injury, Vehicle front end shape, Multi-body system

## 1 Introduction

About 1.25 million people are killed on the roads every year, which leads to an economical loss of more than 50 billion dollars in each year (WHO, 2016). Among the lives lost to road traffic accidents, motorcyclists account for 14.6% of total road-user fatalities in European Union, 12.1% in Australia, 9.4% in the USA and 9.2% of total traffic deaths in Japan (WHO, 2016). Head injury is one of the most common injuries occurred in motorcyclist accidents and is estimated to be the cause of death in more than 50% of the motorcyclist fatalities (Chevalier et al., 2018; Macleod et al., 2010; Raslavičius et al., 2017). And one-third of these victims present solo head injuries (Macleod et al., 2010). The epidemiological investigation also shows that most of motorcyclist accidents are frequently involved in the crashes with the passenger cars (Berg et al., 2005). Thus, it is important to study the head injury risk of motorcyclist during the impacts against vehicle.

Comprehensive studies on the impact safety of motorcyclist, cyclist and pedestrian are available in open literatures mainly through in-depth accident investigation along with field data (Berg et al., 1998; Serre et al., 2012) , numerical simulation (Chinn et al., 2001; Mukherjee et al., 2001; Toma et al., 2010; Xu et al., 2016) and mechanical test (Schaper and Grandel, 1985). It was revealed by computational and experimental methods that impact speed (Cialdai et al., 2014; Simms and Wood, 2006b), impact angle (Nie et al., 2015; Serre and Llari, 2010;) , vehicle shapes (Li et al., 2017a; Li et al., 2017b) and impact location (Mukherjee et al., 2001; Schaper and Grandel, 1985; Serre et al., 2012) have great influences on the head injuries. However, the studies on motorcyclist head injuries are still insufficient. Effects of impact scenarios and vehicle front-end shape design on motorcyclist injuries are still not fully clarified. In addition, head injuries are evaluated mainly by HIC (Head Injury Criterion) based on head linear acceleration in previous studies, while head angular acceleration was the primary reason related to diffuse axonal injury (DAI) and subdural hematoma (SDH) of the human head according to previous pedestrian safety investigations (Kleiven, 2005; Zhang et al., 2004). The relation of

motorcyclist head injuries to head angular acceleration was rarely reported. Therefore, it is important to analyze the head injuries caused by angular acceleration in motorcycle accidents.

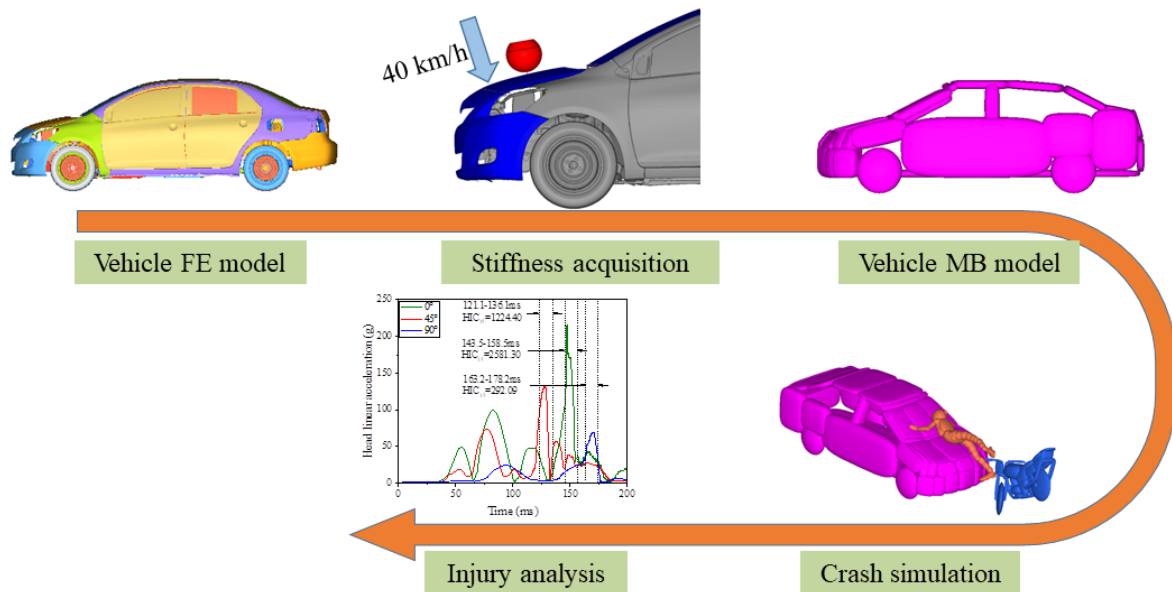
The objective of the present study is to investigate the influences of different impact scenarios and vehicle front-end design on head injury risk of motorcyclists during motorcycle-vehicle impact environments in consideration of both head linear acceleration and angular acceleration. Five general vehicle types, different impact speeds of both motorcycles and vehicles, and different impact angles were selected for a parametric analysis.  $HIC_{15}$  index calculated from head linear acceleration data, head angular acceleration and CSDM (Cumulative Strain Damage Measure) calculated from both head angular velocity and acceleration were adopted to evaluate head injury risk of the motorcyclists during various impact conditions.

## **2 Materials and Methods**

### **2.1 Vehicle models**

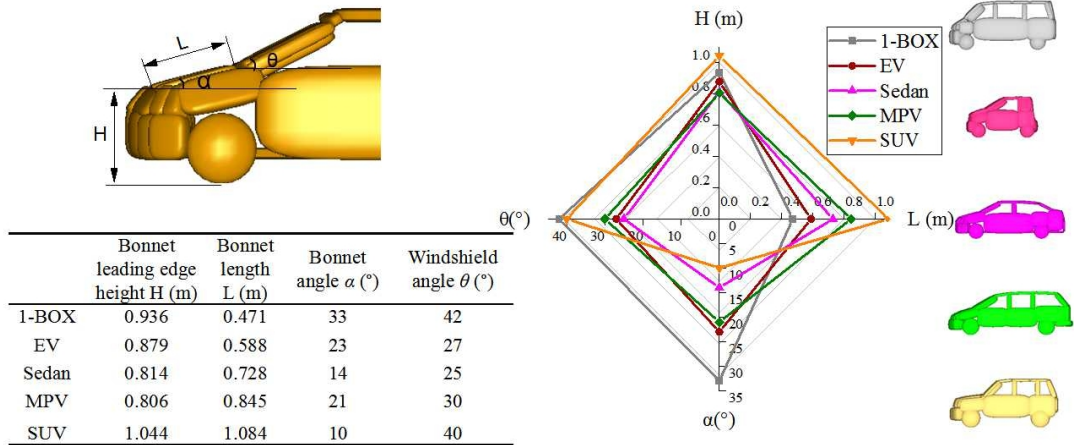
To globally evaluate the performance of vehicle front-end design on head injury risk of the motorcyclist, five common vehicle types were selected including a sedan, a MPV ( multi-purpose vehicle), a SUV ( sport utility vehicle), a EV (electric vehicle) and a 1-Box vehicle. All multi-body vehicle models were established according to the finite element models of corresponding vehicles.

The establishment process of the vehicle and motorcycle-vehicle crash model is presented in **Fig. 1**. Simulations of the rigid impactor colliding with different part of FE vehicle models were performed to acquire the contact stiffness of each ellipsoid. Through the simulations, the acceleration history curves of impactor at different regions were obtained. Then, referring to the method used by Rooij et al.(Rooij et al., 2003), these acceleration history curves were transferred to stiffness curves. Typical stiffness curves of different impact regions are shown in Appendix **Fig. A1**. The front bumper of the vehicle was tested with a motorcycle tire shaped impactor weighted of 117 kg at an impact speed of 100 km/h. While the hood, hood edge, windshield and A-pillar were tested by an EEVC adult headform perpendicular to the surface of the impact points at a speed of 40 km/h.



**Fig. 1** The modeling and analysis process of the motorcycle-vehicle impact accidents

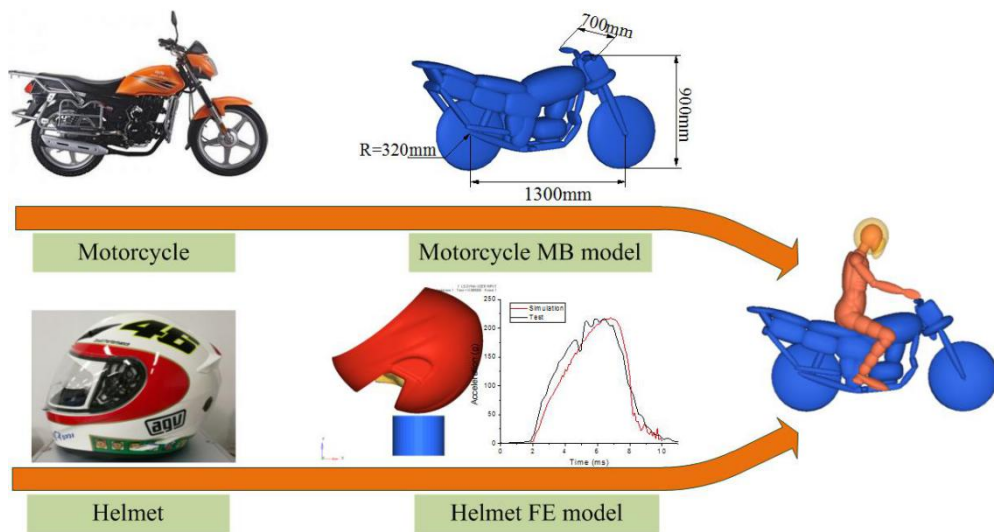
Among them, the sedan and MPV models were developed based on Toyota Yaris and Dodge Grand Caravan FE models created by the National Crash Analysis Center (NCAC) (NHTSA). The SUV, EV and 1-Box vehicle models were built according to Changfeng Liebao, and Dongfeng EJ02, GM Wuling N300 vehicle FE models from Chinese automotive companies. Each vehicle model consists of one rigid body with several ellipsoid surfaces to describe the vehicle shape. To compare design variance of different vehicle types, four main shape parameters of the aforementioned vehicles were measured and summarized as shown in **Fig. 2**. Bonnet leading edge height ( $H$ ), bonnet length ( $L$ ), bonnet angle ( $\alpha$ ), and windshield angle ( $\theta$ ) were included. SUV presents an extremely long bonnet and high bonnet leading edge, while 1-Box presents the largest bonnet angle.



**Fig. 2** Multi-body models and front-end shape parameters of different vehicle types

## 2.2 Motorcycle and motorcyclist models

The establishment process of the motorcycle and motorcyclist models is shown in **Fig. 3**. The motorcycle model was established according to the parameters of Jialing JH150-6-a Chinese mainstream brand. The total mass of the motorcycle is 117 kg. The MBS motorcycle model consists of six rigid bodies, such as frame, headstock, upper front fork, lower front fork, front wheel and rear wheel respectively. The frame is connected to the reference space by a free joint. For simulating the steering behavior, the upper front fork is connected to the headstock by a rotational joint. The lower front fork is also linked to the upper front fork by a rotational joint for modeling the bending behavior of the front fork during the impacts. Each wheel is linked to the frame by a rotational joint. Each rigid body is made up with several ellipsoids to represent the shape of the motorcycle. The contact stiffness of motorcycle components is defined according to the previous study (Chinn et al., 2001), as shown in **Fig. A2**.



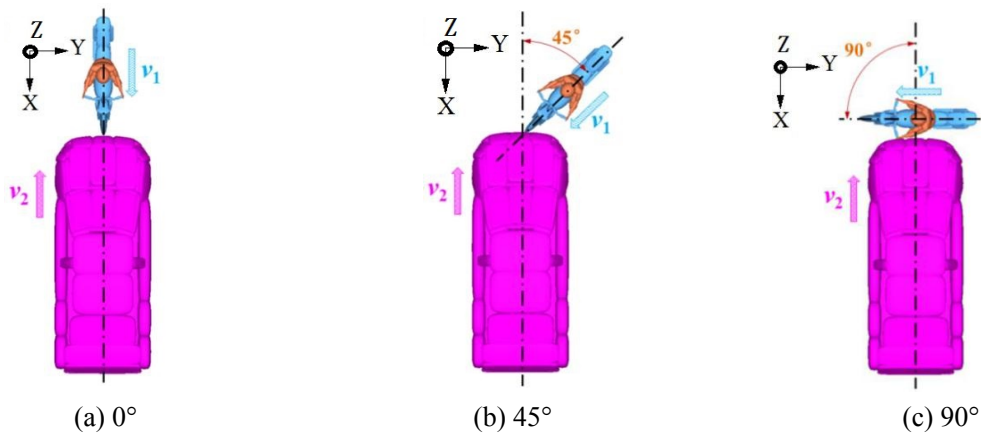
**Fig. 3** The MBS models of the motorcycle and motorcyclist

The MBS model of 50th percentile male pedestrian in MADYMO database was selected for motorcyclist modeling which has been globally employed for cyclist and motorcyclist impact analysis as well as pedestrian impact (Ballesteros et al., 2004; Han et al., 2018). The human model consists of 52 rigid components that represent head, neck, chest, abdomen, hip, upper and lower extremities of a human body. All the components are connected together as a tree structure by different types of joints. The driving posture is adjusted by setting DOFs (Degree Of Freedom) of joints (**Fig. 3**). A helmet is attached to the motorcyclist in all simulation cases. The helmet is represented by a rigid body with two ellipsoids. The rigid body of the helmet was connected to the motorcyclist head by a bracket joint. The helmet stiffness is defined according to the drop test results of the AGV K3 helmet, as shown in Fig. A3.

### 2.3 Impact scenarios

In order to analyze the motorcyclist responses during various motorcycle-vehicle impact scenarios, different impact angles and speeds of motorcycle and vehicles were used in the simulation matrix refer to ISO 13232 regulation (Ballesteros et al., 2004; Han et al., 2018). As shown in **Fig. 4** and **Table 1**, three impact angles including  $0^\circ$ ,  $45^\circ$  and  $90^\circ$ , and corresponding impact speeds were selected. Considering impact angles of  $0^\circ$  and  $45^\circ$ , the motorcycle speed was defined from 0 m/s to 13.4 m/s. The lower motorcycle speeds for  $90^\circ$  impact were set as 0

m/s, 2.25 m/s, 4.5 m/s, and 6.75 m/s, because the motorcyclist head would not collide with the vehicle if the motorcycle speed is too large in this type of impact situation. In all impact angles, the vehicle impact speeds were set from 3.3 m/s to 13.4 m/s. The simulation matrix was shown in **Table 1**. Contacts were defined to simulate the interactions between the ground, motorcycle, motorcyclist and vehicles. Including five vehicle types, a total of 240 simulations were conducted in this simulation matrix design. In addition, despite of the importance of head ground impact (Simms and Wood, 2006; Shang et al., 2018; Han et al., 2018), only the head injuries caused by colliding with the vehicle were investigated in this study.



**Fig. 4** Impact scenarios of motorcyclist, motorcycle and vehicle

**Table 1** Simulation matrix of motorcycle-vehicle impact scenarios

	Level 1	Level 2	Level 3	Level 4
Motorcycle speed ( $v_1$ ) in cases with $0^\circ$ and $45^\circ$ impact angles (m/s)	0	4.5	9.0	13.4
Motorcycle speed ( $v_1$ ) in cases with $90^\circ$ impact angles (m/s)	0	2.25	4.5	6.75
Vehicle speed ( $v_2$ ) (m/s)	3.3	6.7	9.8	13.4

## 2.4 Injury evaluation indexes

To assess head injury risk during motorcycle-vehicle impact accidents, it is necessary to choose suitable head injury evaluation indexes. First,  $HIC_{15}$  was used to evaluate head injuries.  $HIC_{15}$  was originally defined by Versace in 1971 and was adopted by Federal Motor Vehicle Safety Standards (FMVSS) as head injury criterion with the safety margin of  $HIC_{15}=700$  (Chen et al., 2013; Mchenry, 2004). The  $HIC_{15}$  value of 700 represents the 5% risk of severe head injury (Mertz et al., 1997).  $HIC$  is defined as Equation (1):



$$HIC = \max \left[ \frac{1}{t_2 - t_1} \int_{t_1}^{t_2} a(t) dt \right]^{2.5} (t_2 - t_1) \quad (1)$$

where  $t_1$  and  $t_2$  are the initial and final time points of the interval during which HIC attains a maximum value and  $t_2 - t_1 \leq 15$  ms,  $a$  is the resultant head acceleration. However,  $HIC_{15}$  is calculated from translational acceleration of head gravity center without considering of angular acceleration.

It was suggested that the contusion was likely to arise and the bridging vein can be ruptured if the maximal angular acceleration exceeded  $4500 \text{ rad/s}^2$  (Löwenhielm, 1975). Following this threshold, head angular acceleration was studied in this study. Based on the head angular velocity and angular acceleration, the CSDM was also estimated by Equation (2) indicated by Gabler et al.'s Study (Gabler et al., 2018).

$$CSDM = \sqrt{\sum (\omega_i^* + (\alpha_i^* - \omega_i^*) * e^{-\alpha_i^* / \omega_i^*})^2} \quad (2)$$

where  $\omega_i^*$  and  $\alpha_i^*$  are the directionally dependent ( $i = x, y, z$ ) maximum magnitudes of head angular velocity and angular acceleration each normalized by a critical value;  $\omega_i^* = \omega_i / \omega_{icr}$ ,  $\alpha_i^* = \alpha_i / \alpha_{icr}$ ,  $\omega_{xcr} = 117 \text{ rad/s}$ ,  $\omega_{ycr} = 119 \text{ rad/s}$ ,  $\omega_{zcr} = 85.8 \text{ rad/s}$ ,  $\alpha_{xcr} = 17700 \text{ rad/s}^2$ ,  $\alpha_{ycr} = 7030 \text{ rad/s}^2$  and  $\alpha_{zcr} = 6450 \text{ rad/s}^2$ . The threshold of 0.25 was used as the indicator of DAI in the present study based on the previous studies (Gabler et al., 2018).

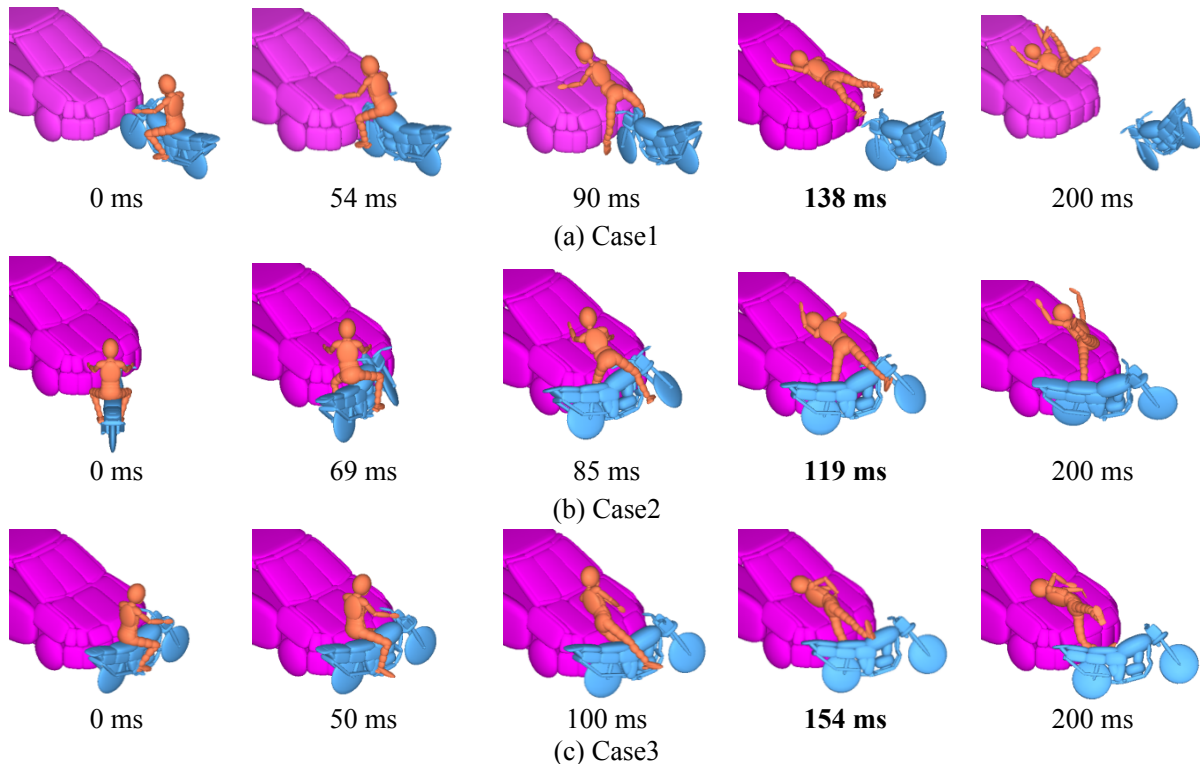
### 3 Results

#### 3.1 General kinematic responses of motorcycle-vehicle impacts

Three typical impact scenarios of motorcycle-sedan impacts were selected to analyze the general kinematic response of motorcyclist, as shown in **Fig. 5**. In the first case (Case1), the motorcycle velocity and vehicle velocity were  $13.4 \text{ m/s}$  and  $6.7 \text{ m/s}$  respectively, according to scenario 114 in the standard of ISO 13232, while the impact angle was set to  $0^\circ$ . The second case (Case2) was set according to scenario 114 in the standard of ISO 13232, with impact angle

of 45°, motorcycle velocity of 13.4 m/s and vehicle velocity of 6.7 m/s. The third case (Case3) was defined according to scenario 143 in the standard of ISO 13232, with impact angle of 90°, motorcycle velocity of 0 m/s and vehicle velocity of 9.8 m/s respectively.

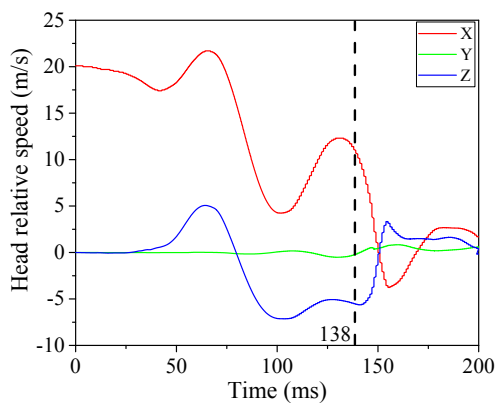
In Case1, the motorcycle tire contacts with the vehicle bumper first and the relative velocity between motorcycle and vehicle starts to decrease. At the time of 54 ms, the knees and legs start to contact with the vehicle bumper and the motorcycle handles, hence the motorcyclist is decelerated and rotates forward around the vehicle front structure. Around 90 ms, the motorcycle rebounds reward, while the motorcyclist still moves forward and the head directly collides with the windshield at the time of 138 ms. In Case2, after that the motorcycle tire starts to contact with the vehicle bumper, the motorcyclist rotates with the motorcycle around z-axis and the rear part of the motorcycle becomes closer to the vehicle. The left lower leg first contacts with the vehicle bumper at 69 ms and then the head impacts with the windshield at 119 ms. In Case3, it can be noted that the shoulder of the motorcyclist first contacts with the bonnet, then the head impacts with the windscreen at 154 ms.



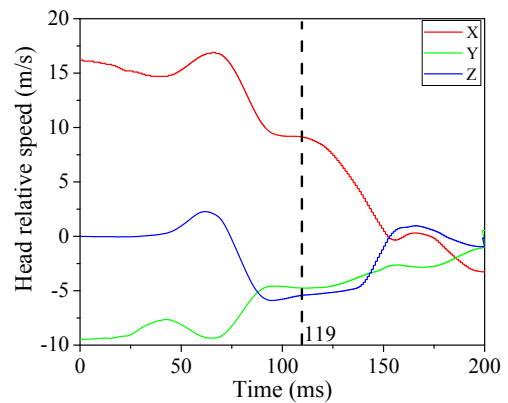
**Fig. 5** Kinematics of different impact scenarios

During the impact process of the 3 cases, the relative speeds of head and vehicle in global

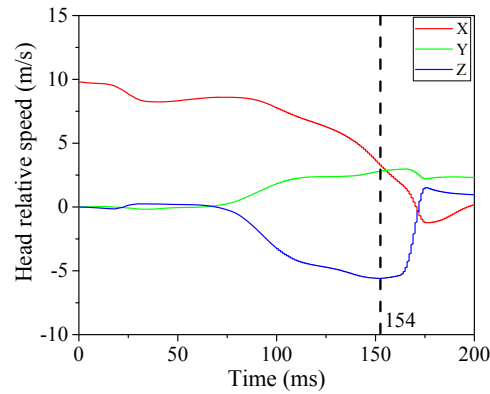
coordinates are shown in **Fig. 6**. The coordinate system is shown in **Fig. 4**. In Case1, after the motorcycle tire impacts with the vehicle bumper, the head-vehicle relative velocity of x-direction starts to decrease because of the friction force between the pelvis and motorcycle. At the time of 54 ms when the lower extremities begin to contact with the vehicle bumper, the relative velocities in x- and z- directions increase slightly due to the rotation of motorcyclist around vehicle and then decreases fast until 100 ms. The relative velocity in x- direction decreases dramatically and the velocity in z- direction increases after the head impacts with windshield at 138 ms. In Case2, the head-vehicle relative velocities in x- and z- directions are similar to Case1, except that the relative velocity in y- direction is not negligible. In Case3, the head-vehicle relative velocity in x- direction decreases gradually almost in the whole impact period, due to the torso is stiffer and hard to deform in side impact. The relative velocity in z- direction decreases fast after the left lower extremity contacts with the vehicle, and increases after the head impacted with the vehicle at 154 ms. It is worth noting that in Case 1 and Case 2, when the legs impact with the vehicle bumper, the torso will rotate forward to the vehicle. This will lead to an increase of relative velocity between the head and vehicle before the head contacts with the vehicle. While in Case 3, the impact velocity is relatively lower and the legs are restricted by the motorcycle which obstructs the rotation of the torso, therefore the relative velocity does not increase before the head contacts with the vehicle.



(a) Case1



(b) Case2



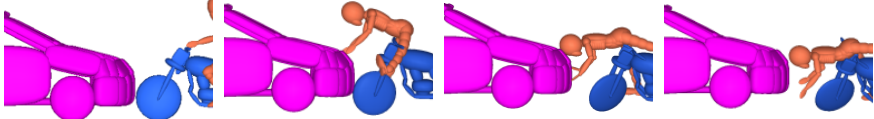
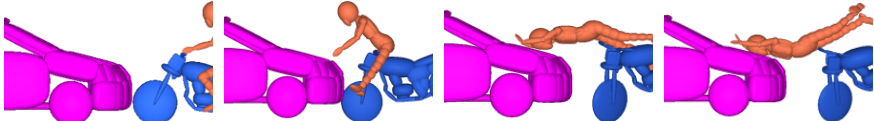
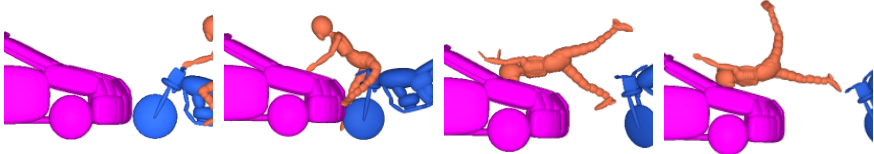
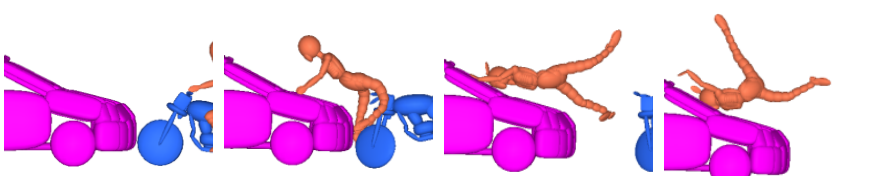
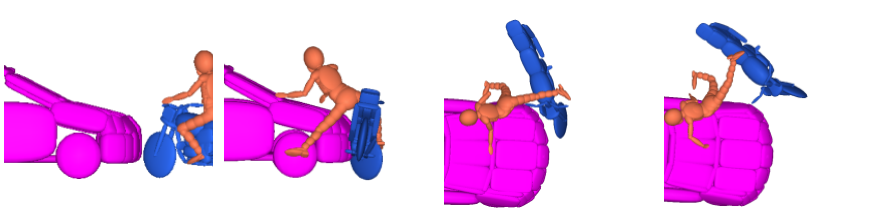
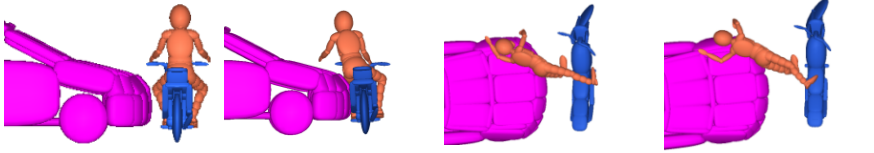
(c) Case3

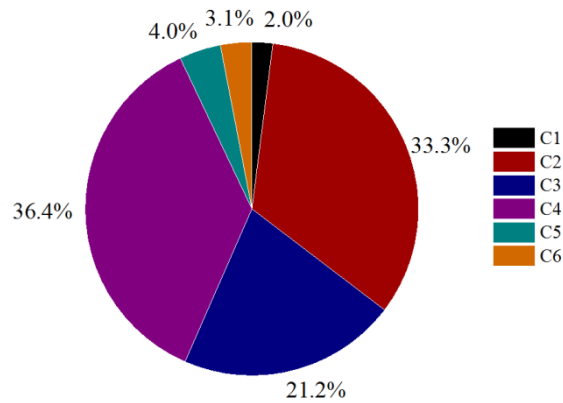
**Fig. 6** History curves of head-vehicle relative velocities

### 3.2 Categories of kinematics

Referring to Crocetta 's analysis method (Crocetta et al., 2015), **Table 2** illustrates the kinematic gestures categorized by quantifying the head impact position. Such a criterion is used for classification in consideration of the indirect effects of impact position on head injury risk. Category 1 represents the head impacts with the bonnet leading edge. Category 2 means the head impacts with the vehicle bonnet. The head impact with the transition region between the vehicle bonnet and the windshield is classified as Category 3. And, Category 4, 5 and 6 represent the motorcyclist head impacts with the vehicle windshield, A pillar and wheel fender, respectively. The proportion of each impact category is shown in **Fig. 7** within the parametric study of 5 vehicle types, 4 different vehicle speeds, and 4 different motorcycle speeds. Most of the simulation cases show the impact region located on the vehicle bonnet, windshield or transition region between them, as indicated by the distribution of C2, C3 and C4. Sum of C1, C5 and C6 only accounts for 9.09% of the simulation group. It is noted that C3 impact region generally has a higher stiffness due to the windshield wiper. This category presents a large proportion of 21.21%. Compared with pedestrian-vehicle impact, this region should be highly concerned in motorcycle-vehicle impact.

**Table 2** Description of identified kinematic categories

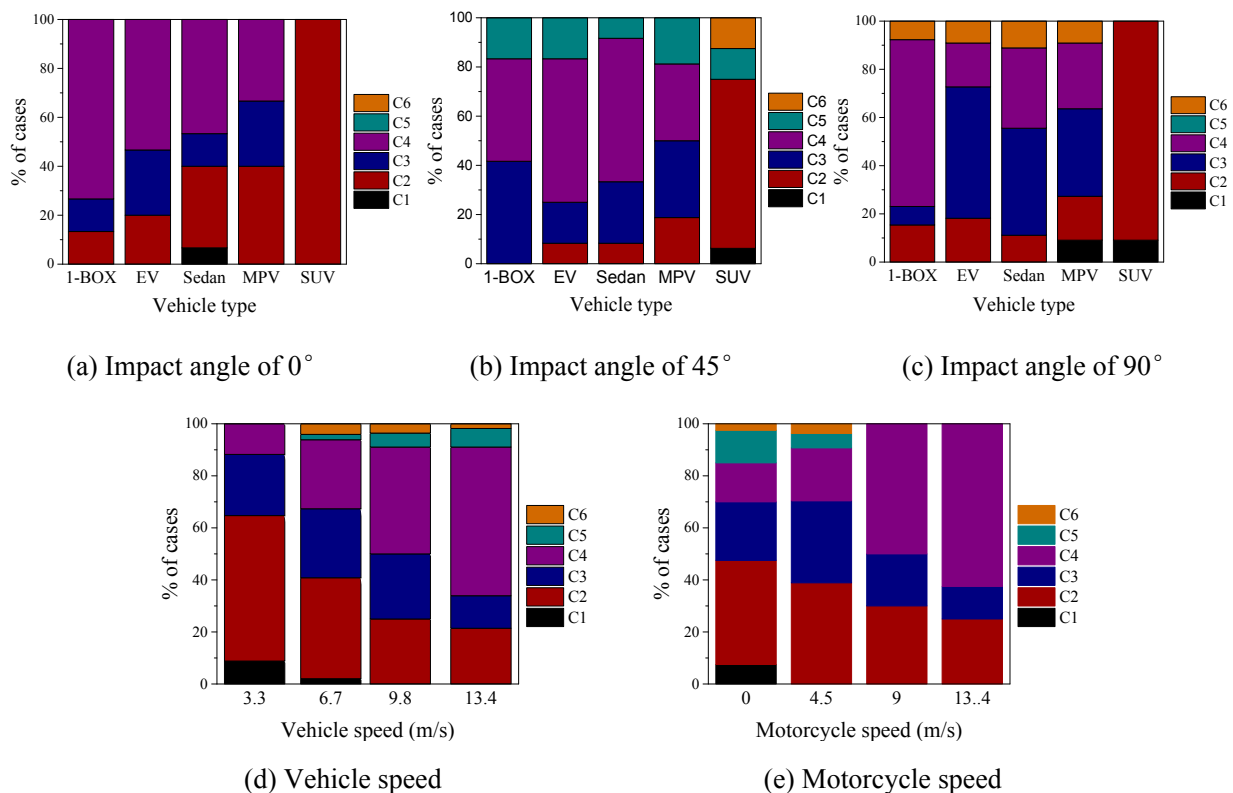
Kinematic gestures	Classification	Impact position
	Category 1	Bonnet leading edge
	Category 2	Bonnet
	Category 3	Between bonnet and windshield
	Category 4	Windshield
	Category 5	A pillar
	Category 6	Wheel fender



**Fig. 7** Breakdown of kinematic categories

### 3.3 Correlation of the kinematic categories to the vehicle types and impact scenarios

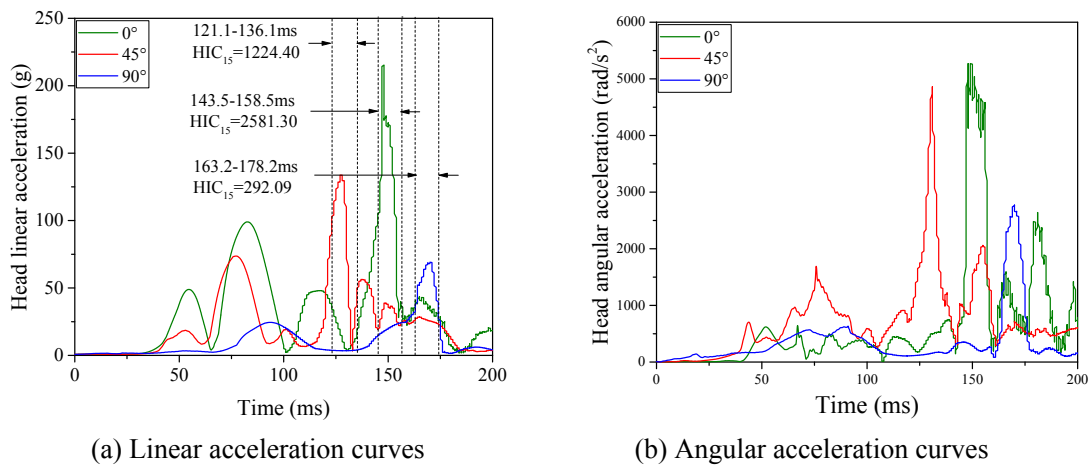
As shown in **Fig. 8**, the impact locations of the head to the vehicle are significantly influenced by the vehicle type, namely the shape of the vehicle front end. Motorcycle to 1-Box, EV, sedan and MPV impact groups show that the impacts on the windshields occupy the largest portion. Almost all the head impact points on SUV are located on the bonnet, which can be attributed to its longer and higher bonnet as compared with the other vehicles. While for 1-Box vehicle, motorcyclist head often impacts with the windshield because of its shorter bonnet. Focusing on impact angles (**Fig. 8a-c**), it seems that C5 group only occurs in 45° cases, C6 group mainly occurs in 90° cases. Regarding impact velocities (**Fig. 8d-e**), both vehicle and motorcycle impact velocities show similar influences on the head impact locations. With the increase of the impact velocity, the portion of head impact location on the bonnet gradually decreases while that on the windshield gradually increases. C1 group only occurs when the motorcycle velocity is 0 and vehicle velocity is below 6.7 m/s. C5 and C6 groups seem to happen during accidents of high vehicle impact velocities and low motorcycle velocities.



**Fig. 8** Occurrences of the 6 kinematic categories for different vehicle types and impact scenarios

### 3.4 Typical resultant head acceleration (RHA) and injury index calculation

Three typical impact scenarios of motorcycle-sedan impacts described in section 3.1 are selected to analyze the representative acceleration results, as shown in **Fig. 9**. The head maximum linear and angular accelerations occur due to the head contacts with the vehicle, while other smaller peak values are often caused by the contacts of other body parts with the vehicle or the motorcycle. The head maximum linear accelerations in these 3 cases are 215.2, 133.4 and 69.1 g, occurring at time of 148, 127 and 170 ms, respectively. The head maximum angular accelerations in these 3 cases are 5268, 4857 and 2770 rad/s<sup>2</sup>, occurring at time of 148, 131 and 167 ms, respectively. In these 3 cases, head maximum linear and angular accelerations all occur after the head impacts with the vehicle. The appearing time of maximum linear acceleration is very close to that of maximum angular acceleration in each case. Based on these acceleration and angular velocity values, HIC<sub>15</sub> and CSDM values are calculated for head injury risk evaluation. HIC<sub>15</sub> in the 3 cases are 2581.30, 1224.40 and 292.09, respectively, and CSDM are 0.505, 0.465 and 0.307, respectively.



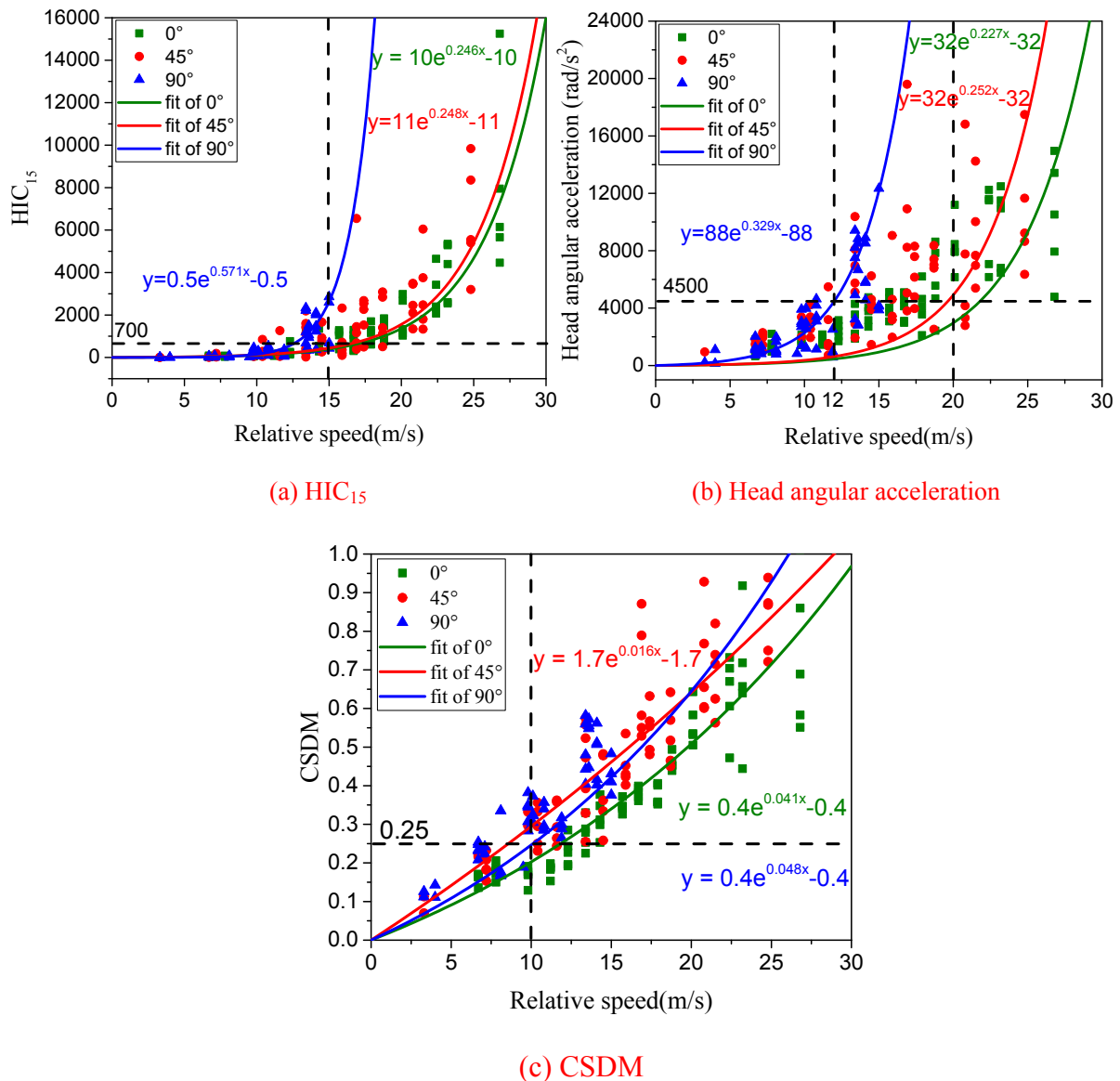
**Fig. 9** Head linear and angular acceleration curves

## 4 Discussion

### 4.1 Influences of relative impact speed on head injury risk

**Fig. 10** shows the relationship between the motorcycle-vehicle relative speeds and head injury risk. The motorcycle-vehicle relative speed was the sum of the vehicle speed vector and the motorcycle speed vector. On the whole, the HIC<sub>15</sub>, head angular acceleration and CSDM values increase with the increase of the relative speed. The exponential functions were used to fit these

trends, and the good correlations can be noticed. The thresholds set for the three injury indexes are 700 for  $HIC_{15}$ , 4500  $\text{rad/s}^2$  for head angular acceleration and 0.25 for CSDM, respectively. It can be noted that  $HIC_{15}$  and head angular acceleration increase sharply and exceed the thresholds when the relative impact speed increases to approximate 15 m/s. For CSDM values, this critical speed is around 10 m/s as shown in **Fig. 10c**. These results indicate that the test impact speed for a motorcyclist's head injury should be around 10-15 m/s.



**Fig. 10** Relations of the motorcycle-vehicle relative speed with motorcyclists' head injury indexes

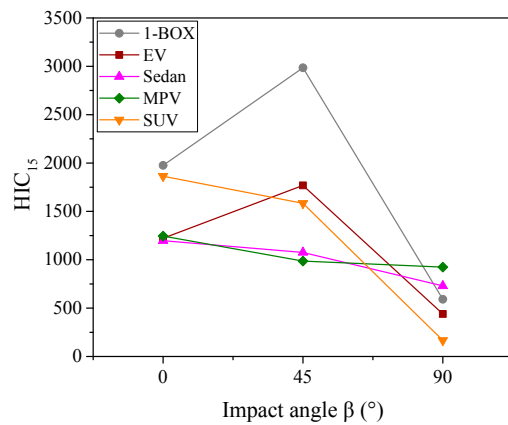
In addition, the relationships between the vehicle speeds and the average values of head injury indexes are illustrated in **Fig. A4**. In some scenarios, the head injuries were not studied because the motorcyclist head didn't impact with the vehicles directly. Considering different impact



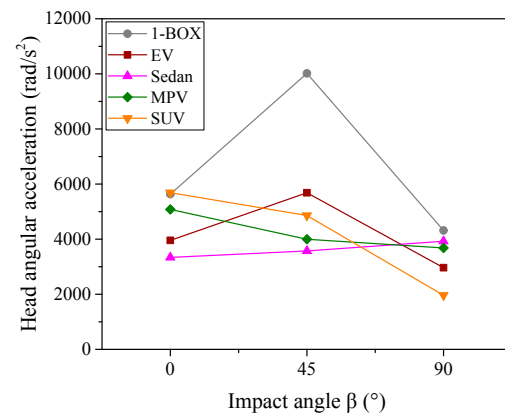
angles and different vehicle types, these index values all increase with the increasing of impact velocities. The relationships between the motorcycle speed and the average values of head injury indexes are presented in Fig. A5. In the situation with the impact angle of  $0^\circ$  and  $45^\circ$ , the index values increase with the increasing motorcycle speed. While in  $90^\circ$  cases, non-significant influence of the motorcycle speed on head injury indexes can be found.

## 4.2 Influences of impact angles on head injury risk

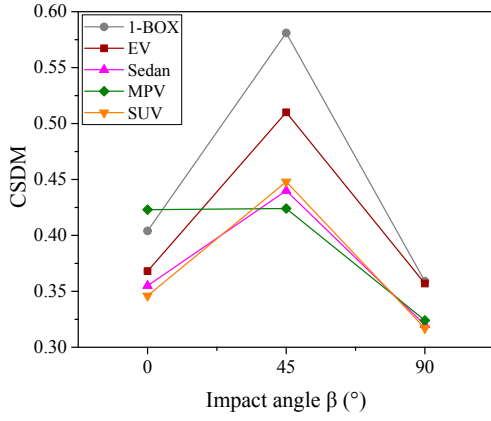
The relationships between the impact angles and the averaged values of  $HIC_{15}$ , head angular acceleration and CSDM are illustrated in Fig. 11a-c. The averaged relative head-vehicle impact speeds under different initial impact angles are shown in Fig. 11d. In most cases especially when the motorcycle impacts with 1-Boxvehicle and EV, the head injury indexes and relative head impact velocities obtained in  $45^\circ$  impact cases are larger than other impacts of  $0^\circ$  and  $90^\circ$  angles, as shown in Fig 11. Other cases involving SUV, MPV did not show this trend clearly because of their larger bonnet length. The reason can be that in  $0^\circ$  impact cases the motorcyclist body contacts with the handle bar and the control rod of the motorcycle and decrease the relative impact velocity between the motorcyclist and vehicle. This situation can highly mitigate the head impact force during the motorcyclist-vehicle collisions.



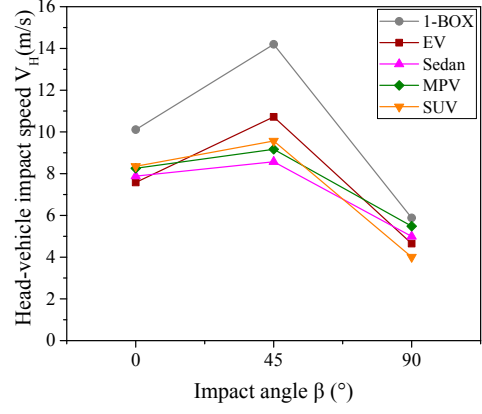
(a)  $HIC_{15}$



(b) Head angular acceleration



(c) CSDM



(d) Head-vehicle impact speed

**Fig. 11** Relations of the impact angle with the average values of the head injury indexes and relative head-vehicle impact speed

### 4.3 Influences of vehicle shape parameters on head injury risk

In order to analyze the sensitivity of each parameter on head injury risk, regression analysis was implemented for the simulation results. Four vehicle front-end shape parameters described in section 2.1 along with motorcycle speed  $v_1$ , vehicle speed  $v_2$  and impact angle  $\beta$  were normalized as shown in Equation (3) and the regression model is shown in Equation (4).

$$X_i = \frac{x_{i,0} - x_{\min}}{x_{\max} - x_{\min}} \quad (3)$$

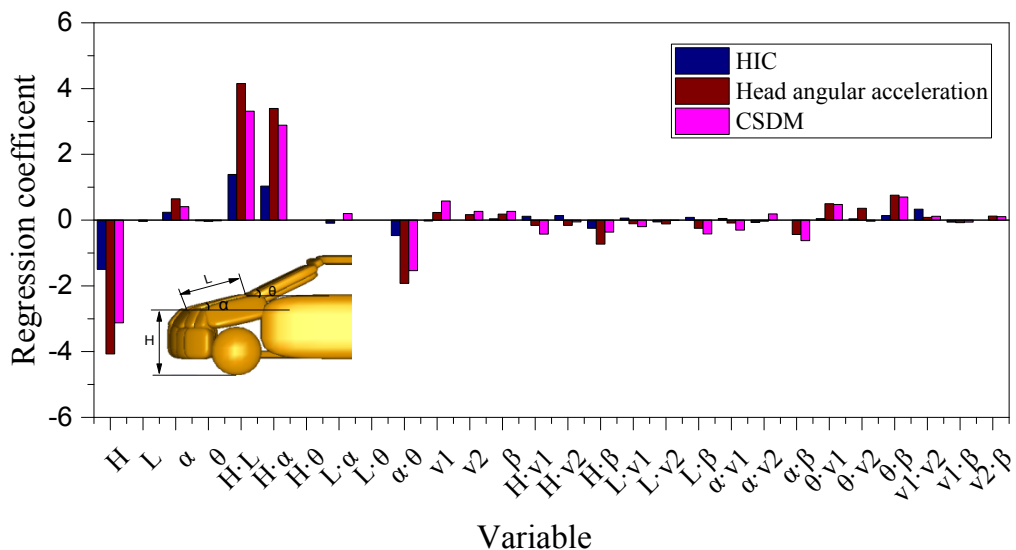
$$y = \sum_{i=1}^7 a_i x_i + \sum_{i=1}^6 b_i x_i x_{i+1} + \sum_{i=1}^5 c_i x_i x_{i+2} + \sum_{i=1}^4 d_i x_i x_{i+3} + \sum_{i=1}^3 e_i x_i x_{i+4} + \sum_{i=1}^2 f_i x_i x_{i+5} + \sum_{i=1}^1 g_i x_i x_{i+6} + \varepsilon \quad (4)$$

where  $x_{i,0}$  represents the original values of four vehicle front-end shape parameters, motorcycle speed  $v_1$ , vehicle speed  $v_2$  and impact angle  $\beta$  of each simulation case;  $x_i$  is the normalized value of  $x_{i,0}$ ;  $x_{i,\max}$  and  $x_{i,\min}$  are the maximum and minimum values of  $x_i$  in all the cases;  $y$  is the head injury values,  $a_i$ ,  $b_i$ ,  $c_i$ ,  $d_i$ ,  $e_i$ ,  $f_i$  and  $g_i$  are the regression coefficients;  $\varepsilon$  is the regression error.

The  $R$ -values of regression models for  $HIC_{15}$ , angular acceleration and  $CSDM$  are 0.845, 0.877 and 0.928, respectively. This means that the regression model can be used to analyze the influence of the variables on injury results. The regression coefficients of different vehicle design parameters are shown in **Fig. 12**. We can note that the coefficients have a similar trend

for the three injury indexes. But the coefficients of angular acceleration and *CSDM* are larger than those of *HIC*<sub>15</sub>. The higher coefficient value represents the higher influence of design parameter on the corresponding injury index. Hence, the vehicle shape variables influence the angular acceleration and *CSDM* much greater than *HIC*<sub>15</sub>. Considering the single design parameter, bonnet leading edge height *H* presents the largest influence on the three injury indexes. **Fig. 12** also shows the coupling effects of different parameters. The coefficients of combined parameters, such as *H*·*L*, *H*· $\alpha$  and  $\alpha$ · $\theta$  generally show obviously large influence on head injury results.

During the regression analysis, the P-values of variables were output, as shown in Table 3. Some variables are not used in the regression analysis because of their low significance, and their P-values are not shown in this table. From Table 3, it can also be found that bonnet leading edge height *H* presents the largest influence on the injury indexes among the four shape design parameters, and *H*·*L*, *H*· $\alpha$  and  $\alpha$ · $\theta$  also show higher significance.



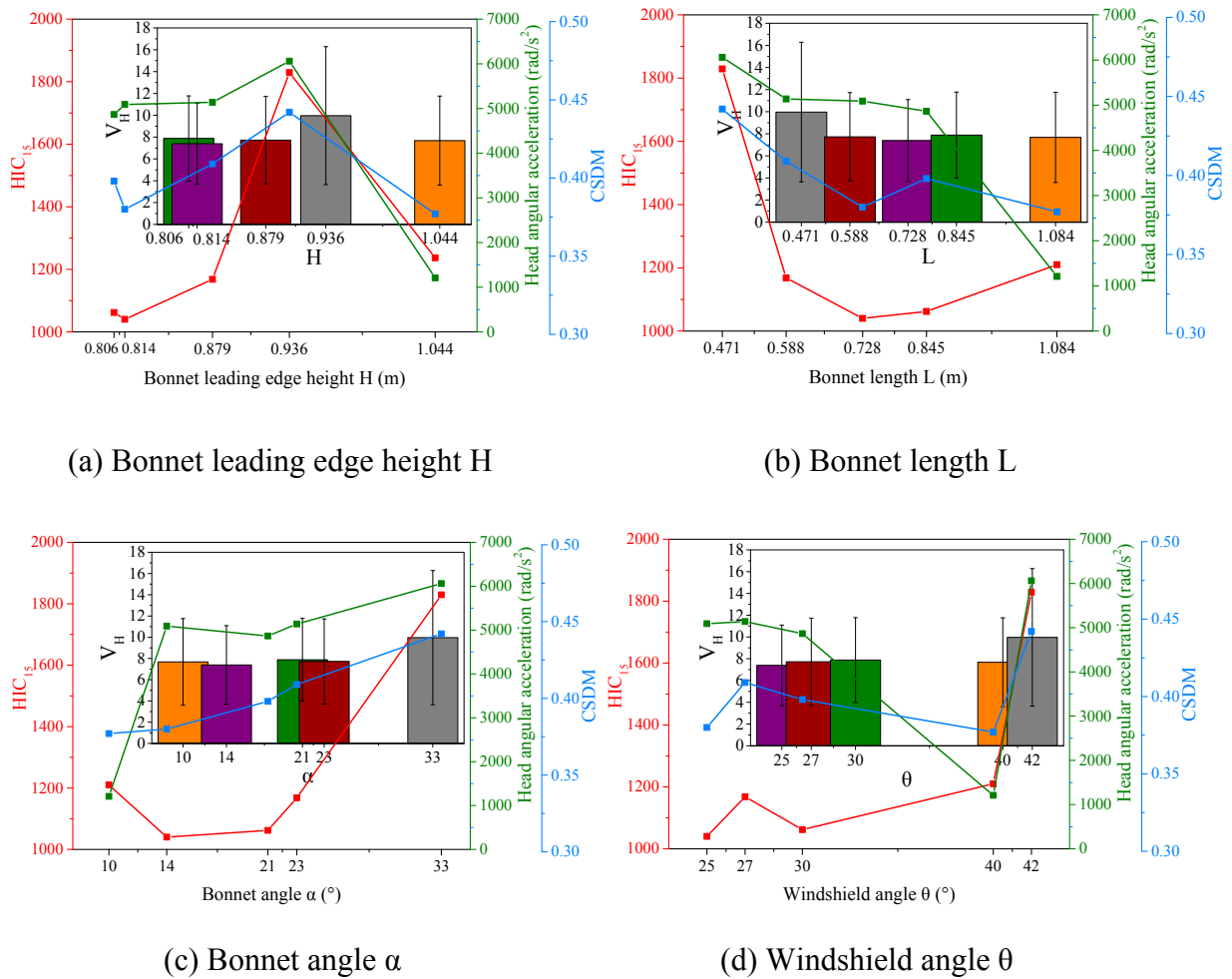
**Fig. 12** Regression analysis of vehicle front end shape parameters on head injury indexes

**Table 3** P-values of variables in the regression models

	$H$	$L$	$\alpha$	$\theta$	$H \cdot L$	$H \cdot \alpha$	$H \cdot \theta$	$L \cdot \alpha$	$L \cdot \theta$	$\alpha \cdot \theta$
$HIC_{15}$	0.230	-	0.349	0.622	0.265	0.259	-	0.480	-	0.303
Angular acceleration	0.013	0.910	0.018	0.577	0.016	0.012	-	-	-	0.006
$CSDM$	0.052	-	0.178	0.693	0.040	0.023	-	0.268	-	0.017
	$v_1$	$v_2$	$\beta$	$H \cdot v_1$	$H \cdot v_2$	$H \cdot \beta$	$L \cdot v_1$	$L \cdot v_2$	$L \cdot \beta$	$\alpha \cdot v_1$
$HIC_{15}$	0.684	-	0.304	0.331	0.164	0.220	0.599	0.420	0.443	0.683
Angular acceleration	0.033	0.080	0.143	0.317	0.242	0.015	0.527	0.413	0.279	0.647
$CSDM$	0.000	0.003	0.020	0.000	0.665	0.000	0.197	0.000	0.045	0.092
	$\alpha \cdot v_2$	$\alpha \cdot \beta$	$\theta \cdot v_1$	$\theta \cdot v_2$	$\theta \cdot \beta$	$v_1 \cdot v_2$	$v_1 \cdot \beta$	$v_2 \cdot \beta$		
$HIC_{15}$	0.270	-	0.706	0.681	0.288	0.000	0.024	-		
Angular acceleration	0.849	0.124	0.009	0.020	0.017	0.232	0.042	0.082		
$CSDM$	0.208	0.016	0.005	0.814	0.015	0.067	0.075	0.105		

Furthermore, **Fig. 13** shows the influence of each single design parameter on  $HIC_{15}$ , head angular acceleration and  $CSDM$  values. The results show that the index values of  $H=0.936$ ,  $L=0.471$ ,  $\alpha=33^\circ$  and  $\theta=42^\circ$  cases are evidently higher than those of the other cases. When checking the head-vehicle impact speeds, the corresponding high head impact speeds can be found. In this case, it is believed that the head impact speed against vehicle can be responsible for these results. The smaller bonnet length  $L$  represents the earlier time of the head begins to contact with the vehicle, so it would lead to higher head-vehicle impact speed and higher head injury indexes. That can be one reason for the higher sensitivity of head injury risk to the bonnet length  $L$ . When comparing the present results with the previous studies on pedestrian head injuries, significant differences were noted. While the previous studies indicated that reducing bonnet height (Shang et al., 2018; Crocetta et al., 2015) and increasing windshield angle (Lyons and Simms, 2012) can improve a vehicle's performance in protecting the

pedestrian head considering head-ground impact, the present results on motorcyclist head injuries show uncertain trends with obvious fluctuations of injury indexes concerning these parameters' change. While Han et al. (2012) and Li et al. (2017b) studies showed that a shorter bonnet was preferable for pedestrian protection, the present study show a trend of decreasing bonnet length can increase head injury risk. These differences can be further studied by considering both head-vehicle and head-ground impacts of motorcyclists.



**Fig. 13** Relations of vehicle shape parameters with the average values of the head injury indexes and the relative head- vehicle impact speeds

## 5 Conclusions

This study analyzed the influences of impact scenarios and vehicle front-end design on head injury risks of the motorcyclist during motorcycle-vehicle impacts through the parametric analysis. Multibody models of five vehicles were established to study the head injuries during

the motorcycle-vehicle impacts. A total of 240 simulations of different vehicle types, impact angles and impact speeds of the vehicles and motorcycle were conducted in this study. The results show that the injury index values of  $HIC_{15}$ , head angular acceleration and CSDM all inclined with the increase of relative impact speed at exponential functions. It is noted that the critical relative impact speed is approximately 15 m/s for  $HIC_{15}$  and head angular acceleration, while for CSDM this velocity is around 10 m/s. Based on the present ISO 13232 regulation,  $90^\circ$  impact is found to be the most uncertain situation without obvious trend, and  $45^\circ$  impacts seems to be the most vulnerable situation. With regard to vehicle front end design parameters, bonnet length  $L$  and its combination with other parameter presented high influences on motorcyclist head injuries. In this case, 1-Box vehicle can be more likely to cause head injuries than other four vehicle types. It is also worth noting that the effects of vehicle shape parameters on motorcyclist and pedestrian head injuries are quite different, which can be further studied. Based on the sensitivity analysis, the trend of decreasing the bonnet angle and increasing the bonnet length can potentially reduce head injury risk of motorcyclists. In addition, the present study was focused on the frontal impact of motorcycle-vehicle as well as interactions between motorcyclists and vehicles. All these limited further understanding on head injuries of motorcyclists. Impacts in other directions as well as head injuries due to ground impacts should be also investigated in the future.

## **Acknowledgement**

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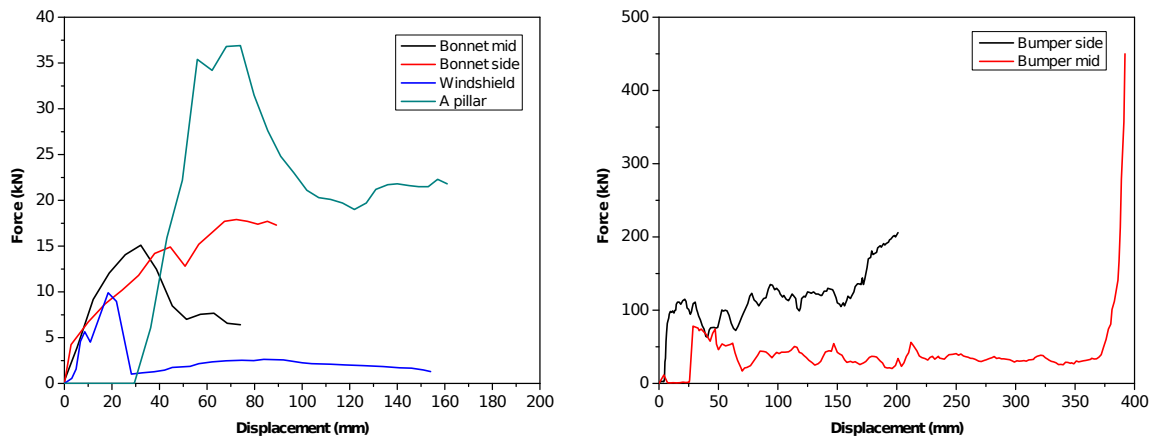
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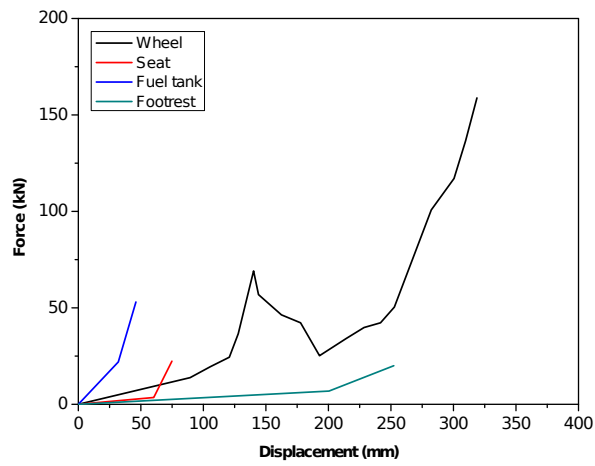


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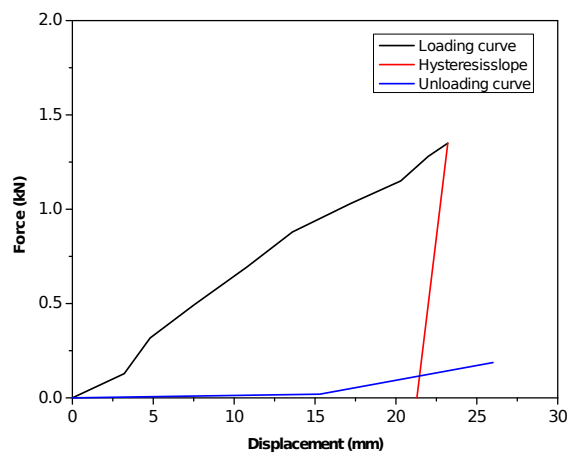
# Appendix



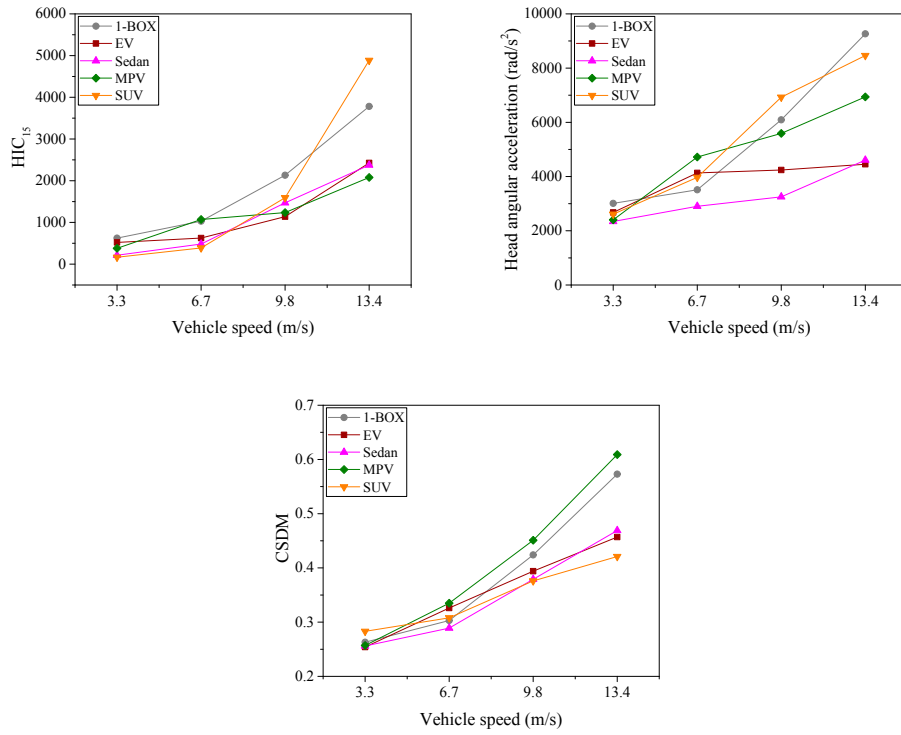
**Fig. A1** Contact stiffness of the Sedan



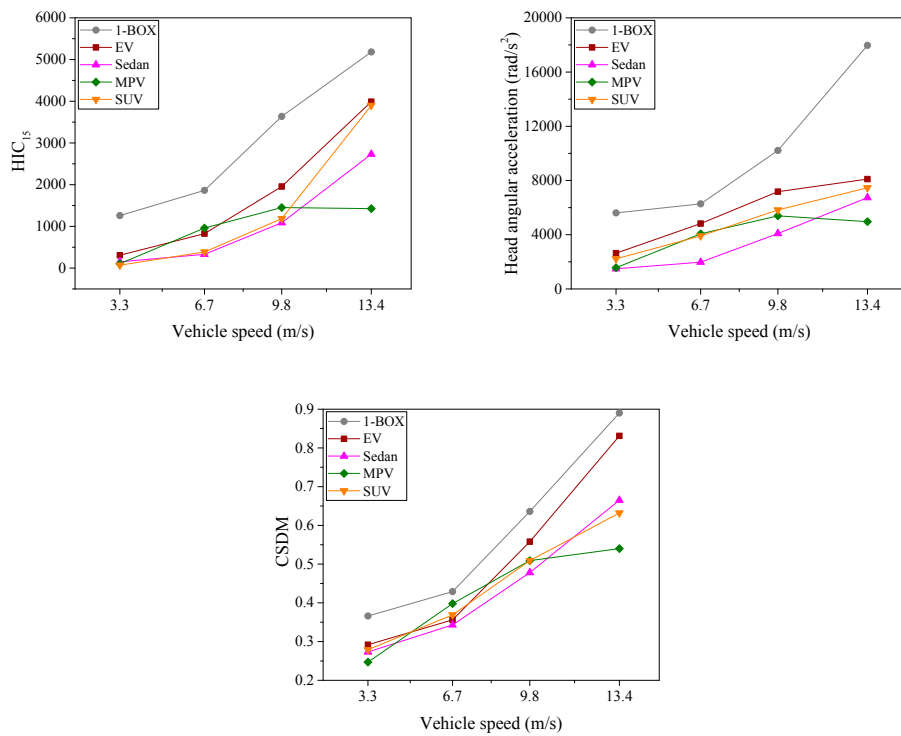
**Fig. A2** Contact stiffness of the motorcycle



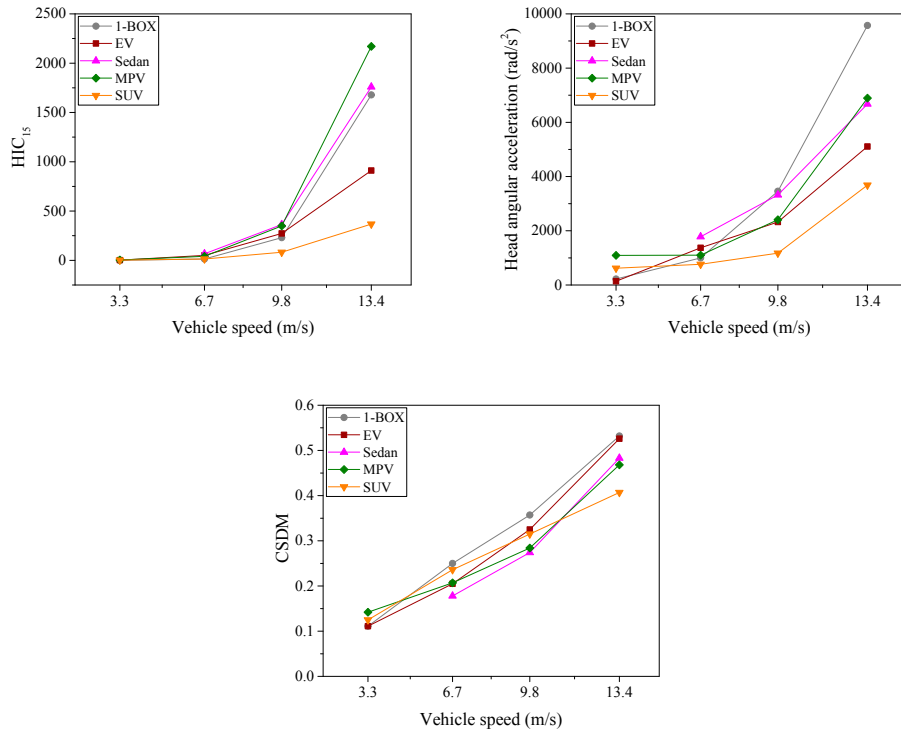
**Fig. A3** Contact stiffness of the helmet



(a) 0°

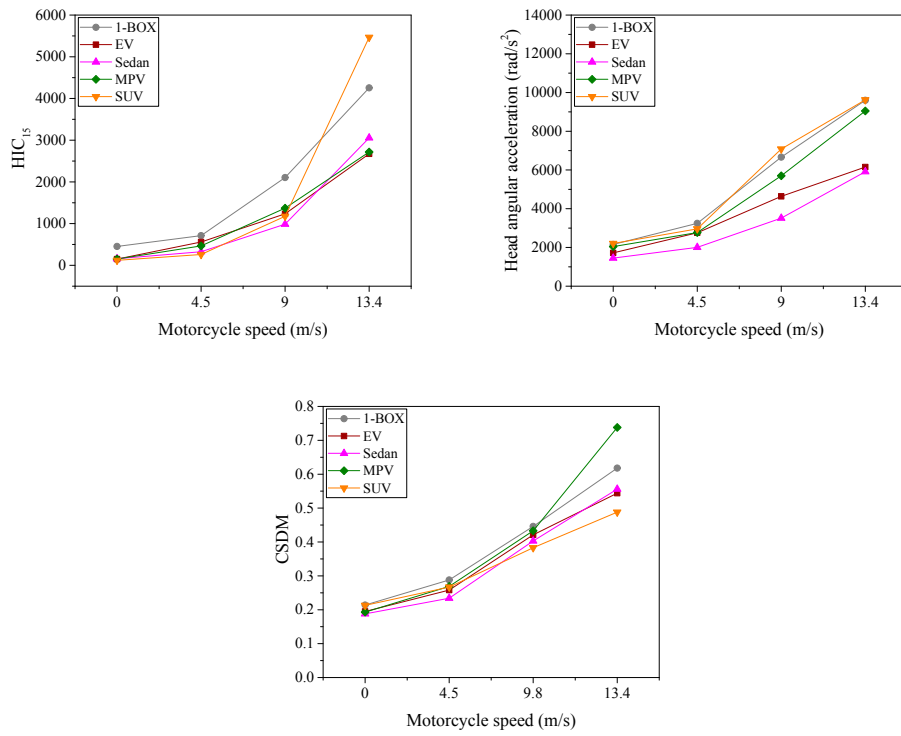


(b) 45°

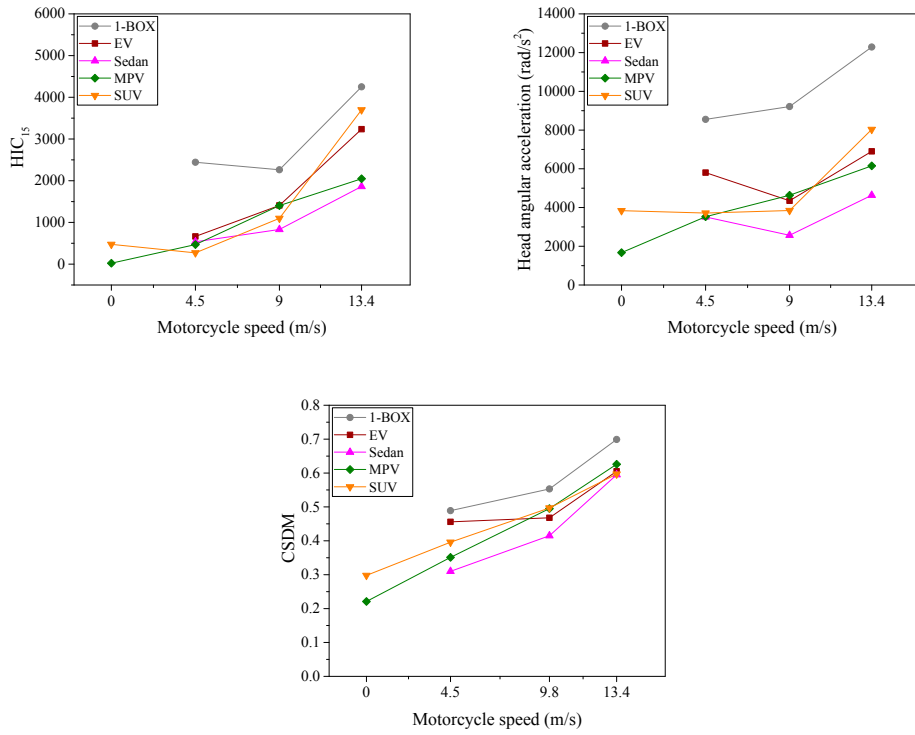


(c) 90°

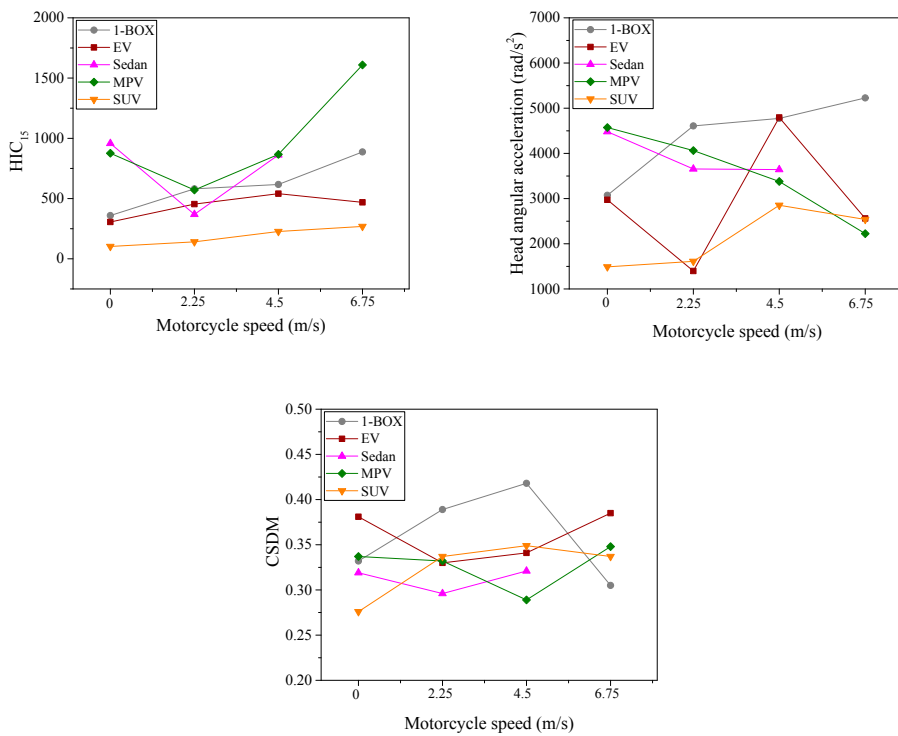
Fig. A4 Relation of the vehicle speed with motorcyclists' average values of head injury indexes



(a) 0°



(b)45°



(c)90°

Fig. A5 Relation of the motorcycle speed with motorcyclists' average values of head injury indexes

**Zhi Xiao:** Conceptualization, Methodology, Software, Writing-Original Draft

**Li Wang:** Validation, Investigation, Resources, Data Curation

**Fuhao Mo:** Software, Supervision, Project administration, Funding acquisition

**Xiaojiang Lv:** Investigation, Resources, Data Curation

**Chuihui YANG:** Writing- Reviewing and Editing, Visualization