Influence of Vehicle Speed and Front Structure on Driver Brain Injury of Scooter-like Electric Bicycle

Xilei Zhao[1], Jikuang Yang[1,2], Guibing Li[1]

[1]*State Key Laboratory of Advanced Design and Manufacturing for Vehicle Body, Hunan University, China*

[2]*Department of Applied Mechanics, Chalmers University of Technology Gothenburg, Sweden*

Email: leige-9999@163.com, jikuangyang@hnu.cn

Abstract: The reduction of the brain injury risk of electric-bicycle driver was investigated in relation to improvement of vehicle front shape. An analytic model of crash situation between the vehicle and electric bicycle was developed and validated by reconstruction of accident from in-depth investigations. The program MADYMO was used in this reconstruction and has been approved in further study. The front shape parameters of three common types of passenger vehicles (sedan, SUV, and MPV) were evaluated in the study, including bumper central height, bumper lead length, hood edge height, hood length, hood angle, windscreen angle. Influences of vehicle velocity and front structure on brain injury of electric-bicycle driver were analyzed. Moreover, some feasible measures to protect driver of electric-bicycle from brain injury are discussed. The simulation results confirm that vehicle impact velocity had remarkable effect on severity of brain injury of electric-bicycle driver. The design parameters, such as height of hood edge and bumper also affect the brain injury risk, especially for the sedan. Therefore the brain injury risk of electric-bicycle driver can be decreased by reduction the height of sedan's hood edge and bumper

Keywords: electric bicycle; head injury; multi-body dynamics; accident reconstruction

1. Introduction

In China, currently we have a rapid economical development and the improvement of people's living standards. This cause the expansion of cities and ordinary bicycles gradually can not meet the needs of peoples. Because of serious pollution, poor safety performance, motorcycles are not accepted by all peoples, especially the young generation. Also many cities have banned the motorcycles. Family car, for its relatively high price and maintenance cost, for most peoples is not an alternative. In this case, the electric-bicycle, as a new type vehicle, due to its convenience, low price, low energy consumption and pollution, has gradually become the ideal transportation means. Coupled with its flexibility and convenience, the demands for electric bicycle are increasing rapidly, and the production has increased year by year. It is reported that there are around 2 500 electric-bicycle manufacturers in China, and more than 20 million such vehicles are sold each year, of which about 6 million are exported. Totally it is estimated that only in China about 130 million consumers are using electric-bicycle [1].

The speed of electric-bicycle is usually much higher than bicycle, and electric-bicycles not always run on the non-motorized vehicle lane together with bicycles. Electric bicycles always get in the motorized vehicle lanes when crossing the road, often with over speed and showing other unlawful traffic behaviors, which directly impact the flow of traffic and people's safety. In 2008, 73484 persons died in traffic accidents, 304919 were injured, of which 3107 electric bicycle riders died, 17303 were injured, which accounted for 4.23% and 5.67%, respectively [2].

There are debates about the definition of electric bicycle. In European, there are two categories, E-bike and Pedelec. E-bike can be propelled solely by means of its motor. Pedelec is equipped with pedals and an auxiliary electric motor and cannot be propelled exclusively by means of this engine [5]. In China, electric bicycle can be categorized as bicycle-style electric bikes (BSEBs) or scooter-style electric bikes (SSEBs) [7] (Figure 2). BSEBs equipped with functional pedals and typically have 36 V batteries and 180-250 W motors. SSEBs usually have 48 V batteries and 350-500 W motors. According to the Chinese National E-Bicycle Standard (GB17761-1999) [6], which deals with product quality, regulations prohibit electric bicycle from going faster than 20 km/h; however, most of them, especially the scooter-style ones, can go at a faster speed. To meet consumer demands for faster, more comfortable electric bicycle, some manufactures increased the power, operating speeds, weight, and other parameters of electric bicycles.

The occupant and pedestrian safety has been carried out quite extensive in domestic researches. However, the research on the injury and protection of electric bicycle riders is less. In the study, the influences of vehicle impact speed and front shape on head injury of electric bicycle driver were evaluated by using a validated collision model of vehicle to electric bicycle. The effects of dif-

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ferent vehicle types, including sedan, SUV and MPV, were assessed. It is aimed to demonstrate the feasibility and effectiveness of travel speed control and vehicle front design to mitigate electric-bicycle driver head injury severity.

2. Method and Material

A parametric study involving a set of variables such as impact speed and describing the vehicle front shape is conducted with the validated collision model of vehicle to electric bicycle. The effect of vehicle impact speed is examined from 20 to 50 km/h in collisions with three vehicle types according to their frequency of involvement in real world accidents in terms of the calculated injury parameters. To concisely clarify the specific effects of geometric variables of each vehicle type, this effect is discussed separately at a given vehicle impact speed of 40 km/h, and electric bicycle speed of 20 km/h.

2.1. Model Setup

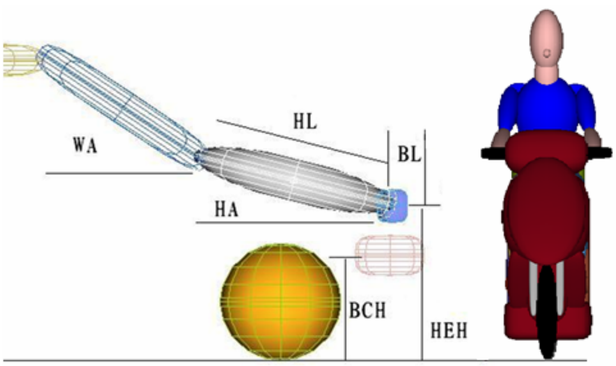


Figure 1. The baseline mode setup for car to electric bicycle simulations, BCH-Bumper Central Height, BL-Bumper Leading Length, HEH-Hood Edge Height, HL-Hood Length, HA-Hood Angle, WA-Windshield Angle

2.1.1. Driver Model of Electric Bicycle

The Chalmers Pedestrian Model 1 (CPM1) multi-body human model [4] was used in the study. This human model is generated by the GEBOD program and based on the 50th percentile male adult (height 175 cm, total body mass 78 kg). It consists of 24 ellipsoids representing the following body segments: head, neck, chest, abdomen, pelvis, upper limb, thigh, leg, and foot. The body segments are connected to each other by 14 joints. The knee joints and the leg elements have a human-like knee model and a breakable-leg model. The human body model was further validated against cadaver tests and we decided to use it in current study.

2.1.2. Electric Bicycle Model

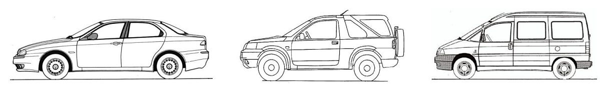
In the study, the electric bicycle model is built to represent SSEB. As shown in Figure 2, it consists of 22 ellipsoids to represent the structure of the SSEB. The model segments are connected to each other by 6 joints. And the contact characteristics acquired from component tests done by Deguchi M. [13]

(a) BSEB (b) SSEB (c) Multi-body model

Figure 2. Classification of electric bicycles and multi-body model

2.1.3. Vehicle model

Front shape of passenger car was investigated and categorized into three groups (Figure 3), Sedan, Sport Utility Vehicle (SUV), and Multi-purpose Vehicle (MPV). Car front model consists of bumper, hood edge, hood top and windscreen ellipsoids to approximate the exterior profile of a vehicle, and the mechanical properties are defined in terms of stiffness properties acquired from Euro NCAP sub-system tests summarized by Martinez et al. [8].



(a) Sedan (b) SUV (c) MPV

Figure 3. Different Vehicle types used in parametric study

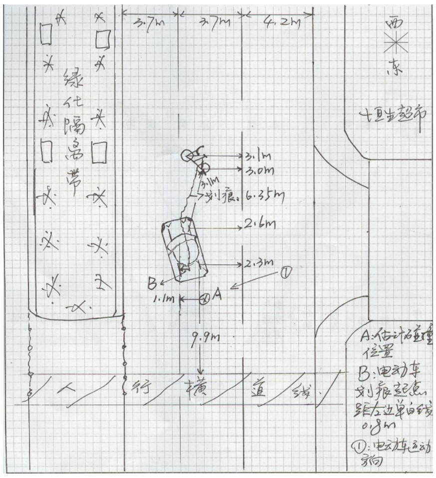
2.2. Model Evaluation

2.2.1. Accident Information

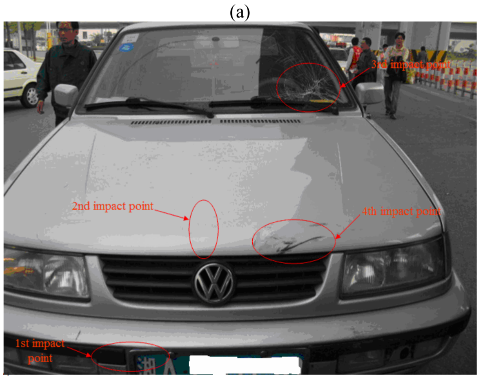
The model was evaluated by accident reconstruction that happened in Yuelu District in Changsha. Before the accident, the car was running from east to west while the electric bicycle was running from north to south. When the driver of the car recognized the bicycle he braked the car, however the front part of the car impacted the left side of the electric-bicycle. The estimated impact speed was 38 km/h. As shown in Figure 4a, the throwing distance of the electric bike was 3.1 m from the car's front right wheel. This distance was used as a criterion of validation of the bike model. In the configuration of the impact we also used the scratches on the car as shown in Figure 4b.

2.2.2. Accident Reconstruction

As shown in Figure 5, at the initial moment of collision, the car hit left rear side of the electric bicycle by central area of front bumper, and then the front hood collide with the rider's thigh, finally the lower left windshield impact the head. In the accident reconstruction the final position of electric bicycle is 3.5 m to the car's front right wheel. The results are basically comparable with the accident, so the simulation models can be used as further analysis.

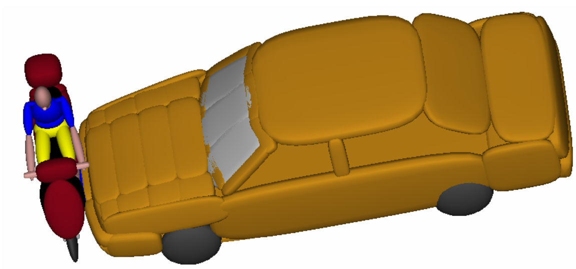


(a)



(b)

Figure 4. Scene sketch and photo from the accident



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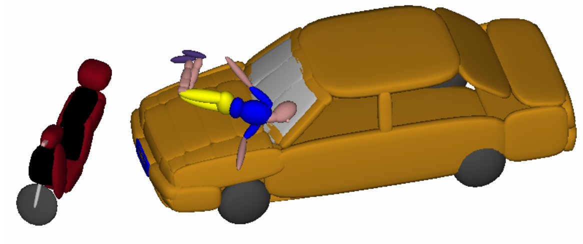


(b)

Figure 5. Accident reconstruction

2.3. Design of Parametric Study

The parametric study is divided into two parts. The first part concerns the influence of impact speed, taking into account the involvement of different vehicle models including sedan, SUV and MPV. The main purpose is to predict the effect of impact speed on the head injury risk of electric bicycle driver. The head injury patterns with regard to the three vehicle types are also compared. Secondly, the effects of parameters describing front shape on the levels of injury related parameters of the driver head of electric bicycle are discussed. We considered the effect of three vehicle models at certain impact speed of 40 km/h. It is aimed to reveal the possible improvement of vehicle shape to mitigate the head injury severity of electric bicycle drivers.

The effect of impact speed is examined at four levels, i.e. 20, 30, 40 and 50 km/h. The selected geometric variables remain constant at their median levels listed in Table 1[9].

In the investigation of influence of geometric variables of vehicle fronts at the impact speed of 40 km/h, the electric bicycle speed was 20 km/h. As one geometric variable is varied in three levels from minimum to maximum, other variables remain constant at their middle levels as shown in Table 1. Such matrix was used in investigation of the influence of bumper and hood edge height of three types of vehicles, however in the case of sedan the influence of the windshield angle on brain injury risk was combined with three values of hood angle.

Table 1. Design parameters of three vehicle models

	Sedan			SUV			MPV		
	Minimum	Median	Maximum	Minimum	Median	Maximum	Minimum	Median	Maximum
Hood length HL [mm]	635	918	1 200	844	934	1 023	157	259	361
Windshield angle WA [°]	29	35	40	36	40	43	30	38	46
Hood angle HA [°]	11	15	18	9	10	11	40	40	40
Bumper center height BCH [mm]	436	476	516	544	640	736	448	576	704
Hood edge height HEH [mm]	565	702	839	832	1 000	1 168	864	1 004	1 144
Bumper lead length BL [mm]	127	127	127	195	195	195	188	188	188

2.4. Selected Injury Parameters

The study focuses on brain injury protection to the rider, so only the head-related output parameters are discussed. We selected Head Injury Criterion (HIC) value, the head linear velocity, angular velocity, angular acceleration, impact force as main injury related parameters. HIC is the most commonly used and is defined as:

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

Where: *a (t)* is the resultant acceleration in the centre of gravity of the head form, and t_1 and t_2 are time points during the impact.

HIC1000 is corresponding to 20% AIS 3+ [11] head injuries rate. In addition to analyze of HIC values we considered the evaluation of risks of brain injury. There are some methods to evaluate a threshold for brain injury [12] by using a critical strain curve expressed in terms of the peak angular acceleration and change in angular velocity (Figure 6). It was suggested that the bridging vein could be ruptured when the head angular acceleration exceeds 4 500 rad/s^2 and the change of the angular velocity is above 50 rad/s. We decided to use these values as a threshold in examination of risks of injuries to the head of bikes driver.

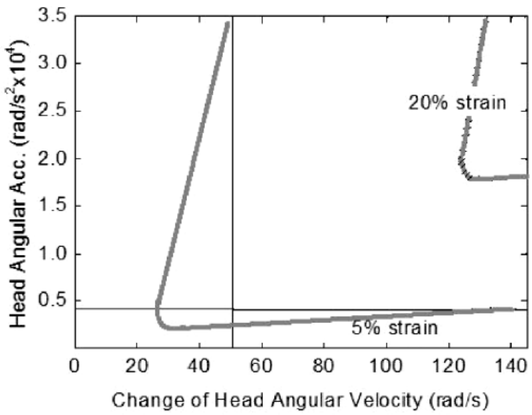


Figure 6. Injury tolerance corridor expressed in terms of the peak angular acceleration and change in angular velocity

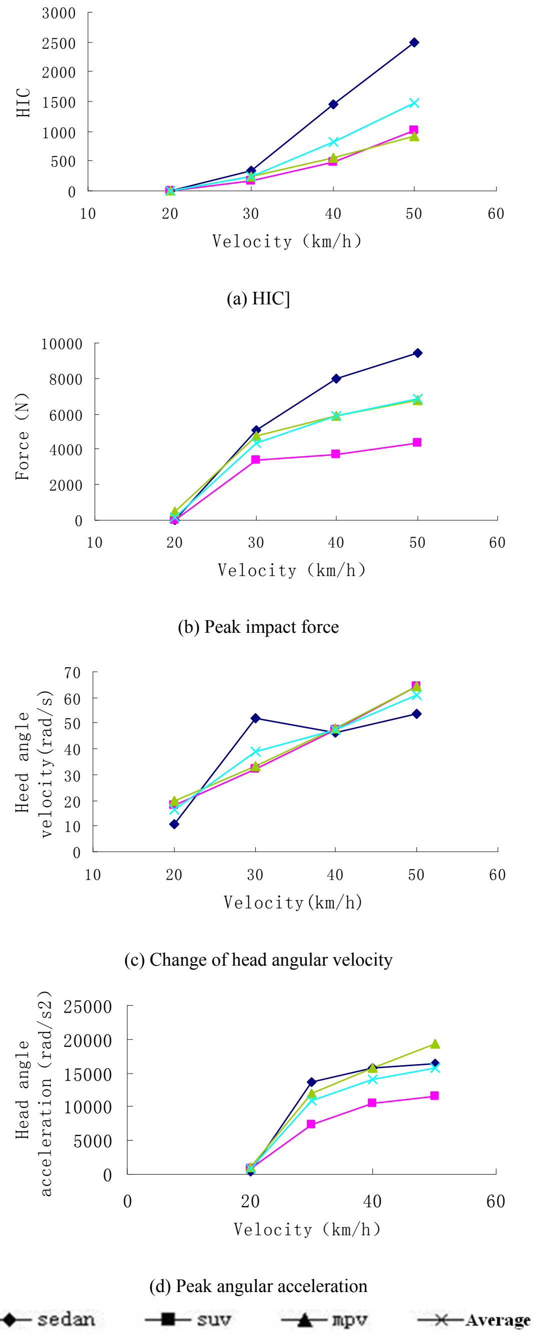
3. Results

3.1. Influence of Impact Speed

As shown in Figure 7(a), with vehicle speed increasing, the HIC value also increased, and at the same speed, the value of sedan was greater than MPV and SUV. Furthermore, we can see that when the speed was higher than 30 km/h, the value of HIC calculated from collisions with all vehicle types increased rapidly. When the speed exceeded 50 km/h, the average of HIC reached more than 1 500, in case of sedan's this value was highest, about 2 500. Thus, the higher speed of collision was, the more severe head injury are.

As shown in Figure 7(b), when the vehicle speed is increasing, impact force increased gradually, and at the same speed, the impact force in case of sedan was greater than SUV and MPV.

As shown in Figure 7(c) and 7(d), when the speed exceeded 40 km/h, the angular velocity for all vehicle types was above 45 rad/s. At this velocity, the angular acceleration for all vehicle types was over 15 000 rad/s^2, which clear above than 4 500 rad/s^2. This means that when the collision speed is 40 km/h, the electric bicycle rider is at a high risk of rupture injuries to bridging veins, and may get a concussion. It is interesting that based on the simulations when this criteria as used it seems that the risk of brain injuries exist already at the velocity just above 20 km/h.



(a) HIC]

(b) Peak impact force

(c) Change of head angular velocity

(d) Peak angular acceleration

Figure 7. Influence of vehicle speed on rider's brain injury

3.2. Influence of Vehicle Front Shape Parameters

3.2.1. Influence of Bumper Height

As shown in Table 2, for sedan, when the bumper height varied from 516 to 435 mm, HIC value decreased by 10%, and the peak angle acceleration value decreased by 80%, but the change of the impact force and the angular velocity was not big. Therefore, we can say that the decrease of the bumper height reduce some risks of head injury to bike rider. Compared with sedan, the change of bumper height of SUV and MPV, the influences the rider's head injury risk was not notable.

3.2.2. Influence of Hood-Edge Height

As show in Table 3, with the increase of hood-edge height of three vehicle models, HIC value and impact force decreased strongly. In case of sedan, as the hood-edge height varied from 565 to 839 mm, the HIC value reduced by 78%, the impact force decreased by 21%, while the peak angular acceleration increased a little. For SUV and MPV, when the hood-edge height changed from minimum to max, peak angular acceleration decreased This acceleration has been reduced in case of SUV's from 17 to 8 krad/s^2, and in case of MPV from 17 to 12 krad/s^2.

Table 2. Influence of bumper height on brain-related injury parameters

Models	Bumper height [mm]	HIC15	Force [N]	Angular velocity Change [rad/s]	Angular acceleration [rad/s^2]
	435	1345	8272	45	11316
Sedan	476	1410	8006	49	18325
	516	1475	7683	53	20361
	544	331	3794	44	10052
SUV	640	467	3705	47	10446
	736	353	3777	43	9947
	448	548	6122	46	15552
MPV	576	559	5866	48	15725
	704	587	5981	46	16397

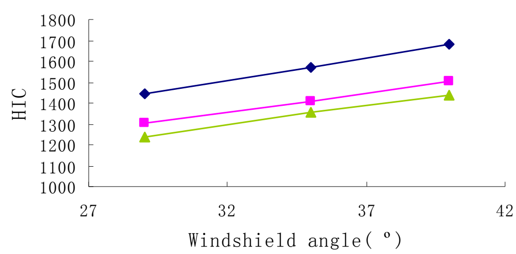
Table 3. Influence of hood-edge height on brain-related injury parameters

Models	Hood edge height [mm]	HIC15	Force [N]	Angular velocity Change [rad/s]	Angular acceleration [rad/s^2]
	565	1856	8256	63	14083
Sedan	702	1410	8006	49	18325
	839	415	6556	39	18098
	832	627	3452	36	17454
SUV	1000	467	3705	47	10446
	1168	211	3399	40	8310
	864	1130	7307	58	17536
MPV	1004	560	5866	48	15725
	1144	324	4921	47	12203

3.2.3. Influence of Hood Angle and Windshield Angle

Due to design limitations the angles of the windshield and hood of SUV and MPV have been changed a little, so the influence on head injury-related parameters is not obvious.

In the case of the sedan the influence of the hood and the windshield angle to the head injury-related parameters is shown in Figure 8. .When the angle of the hood increased from 11° to 18°, HIC and impact force decreased, while the angular acceleration increased., When the angle of the windshield increased from 29° to 40°, the value of head injury-related parameters also increased.



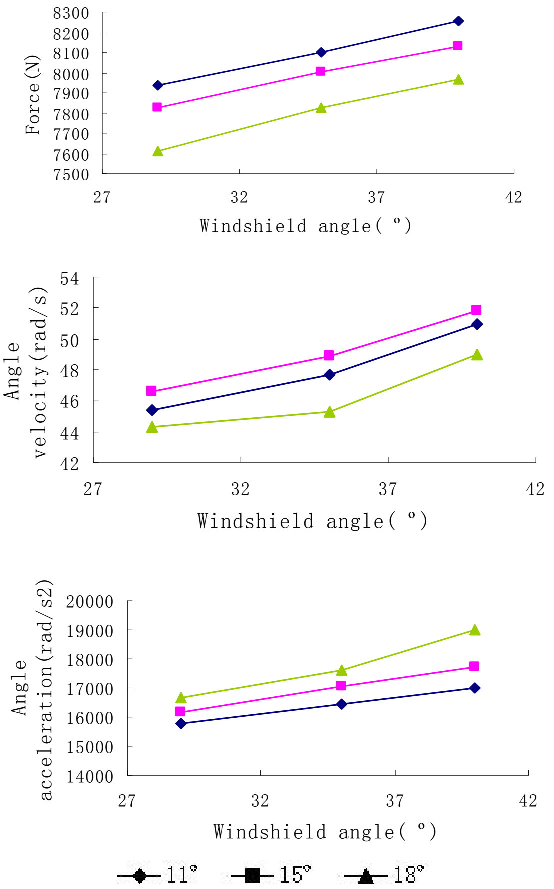


Figure 8. Influence of the windshield angle in combination with three values of hood angle of the sedan on brain injury risk

4. Discussion

The results from the study confirmed strong relation between the impact speed and the risks of head injuries also for the driver of electric bicycle, there is the risk to sustain head injuries at so low speed as just above 20 km/h. Vehicle travel speed is usually higher than impact speed, which is the major concern in crash safety research. Therefore the results have confirmed the necessity of reducing speed limit in urban area and also pointed out necessity to consider head protection when the people are using the electric bike. In the study, a reduction of severe head injuries is found if the vehicle impact speed changes from 40 to 30 km/h.

In addition, compare with the pedestrians, the risk of head injuries to electric bicycle rider is smaller [3].When the speed is 50 km/h, the average impact force is more than 5 kN, which would increase the risk of skull fracture [10]. In the simulations the head of electric bicycle driver has mostly a contact with the windshield, so the rider's wrap around distance (WAD) seems be greater than in the case of pedestrian at the same situation.

There are several limitations of the present study. First, the initial impact location of electric bicycle is restricted at the central line of vehicle model. Other accident situations are not included. Second, due to the involvement of various vehicle types at different impact speeds, we need more detailed accident data to refine the simulation matrix and better validate the model. Third, only the 50th percentile adult male is considered. Other body sizes, like of female and children at various ages are not included. Fourth, we didn't simulate the wearing of personal protective equipment, such as helmets, which impact the severity of injury

5. Conclusions

The results from this parametric study indicate that the head injury severity of electric bicycle driver is strongly affected by the impact speed, and can be mitigated by altering front shape of impacting vehicle.

As the impact speed decreases from 40 to 30 km/h, the probability of severe head injury decreases strongly. Considering the possible improvement of front structure of impacting vehicle, a speed limit of 40 km/h in urban area is feasible way to reduce the head injury risk of electric bicycle driver.

As considering the kinematics and resultant head velocity of electric bicycle driver struck by cars, the hood edge height has been identified as the dominant factor. The effect of the bumper center height on these parameters is slight. In general, the head injury risk decreases with raising hood edge height and a lowing bumper center height.

There is difference between vehicle to electric bicycle and vehicle to pedestrian collision. The HIC value of electric bicycle rider was lower than one of pedestrian at the same vehicle speed. Therefore in the design of the vehicle, we should take the safety of pedestrians and electric bicycle riders into account and current study can be used as a reference.

Acknowledgement

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