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Effect of Vehicle Front-end Structure on Pedestrian-ground Impact Injury Risk

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Abstract: In the majority of road traffic accidents, pedestrian will finally collision with the ground after the vehicle-pedestrian impact. The studies of the relationship between vehicle front-end structure and pedestrian injuries in the vehicle-pedestrian impact have been conducted for years, while the researches on the pedestrian-ground impact is less. In this study, the multi-body models were used to adjust the parameters of the vehicle front structures, and the effects of vehicle front-end structure on pedestrian-ground impact kinematics and injuries were analyzed. By adjusting the parameters of windshield angle (WA), bonnet angle (BA), bonnet length (BL), and bonnet leading edge height (BLEH), ground clearance (GC), a series of analytical models were simulated, and the pedestrian rotation angle, HIC (ground), and head angular acceleration (ground) were calculated for each simulation. Regression analysis showed that the BLEH parameter had the greatest effect on pedestrian rotation angle (significant probability $p<0.01$), and WA, BL and GC had little effect on pedestrians kinematics and injuries. The results can provide a reference for the vehicle safety design.
Keywords: Vehicle front-end structure; Multi-body model; Pedestrian rotation angle; Regression analysis

1 Introduction

Road traffic accident investigation data show that the severity of pedestrian injury caused by the pedestrian-to-ground impact (secondary impact) may be more serious than pedestrian-to-vehicle impact (primary impact) caused by a more serious [1-2].For decades, the studies of pedestrian safety have continued to focus on the injury risk prevention from the primary impacts[3-5]. However, there are very few studies on the pedestrian ground impact injuries. In addition, the researchers have different understanding of the relationship between the vehicle front structural parameters and the ground collision injuries of the pedestrian. Some studies [6] has suggested that the vehicle front structural parameters will not affect the secondary impact. On the contrary, there is a correlation [7] between the structural parameters and the secondary impact that the pedestrian injuries caused by the ground is more serious in the lower velocity collisions.

Since the landing kinematics of pedestrians is affected by many variables, it is very difficult to study the pedestrian landing injury mechanism. By constructing the vehicle-pedestrian collision model, the literature [8] concluded that the pedestrian head injury caused by the SUV collision is more serious. The pedestrian kinematics after the primary impact also has an effect on the secondary impact. Literature [9] analyzed the pedestrian trajectory height, throw distance, launch angle, and velocity after the primary impact; and found that the pedestrian launch angle and velocity as well as the pedestrian trajectory height were rather stable against variations of the initial posture and impact position, while the pedestrians' rotation was highly influenced by the leg and arm posture. In addition, literature [10] replicated a series of vehicle-to-pedestrian crashes to investigate the contribution of secondary impacts to the severity of head or brain injury by using two full-scale vehicle and a 50th percentile adult finite element (FE) models. They found that a head-on landing would cause a more severe injury to the brain even when the vehicle velocity was reduced to 25 km/h at the moment of impact. With the deepening of the research, scholars began to analyze the relationship between the vehicle front structural parameters and the pedestrian secondary impact. Literature [11] studied the relationship between vehicle geometry and pedestrian landing mechanisms; and [12] indicated that the angle between pedestrian body and the ground decreases with the vehicle BLEH increase. The aim of this current study was to understand the influence of vehicle front-end structural parameters on pedestrian kinematics and injuries by quantitative adjustment of each structural parameters. Using multiple linear regression analysis method, the main influencing parameters were analyzed.

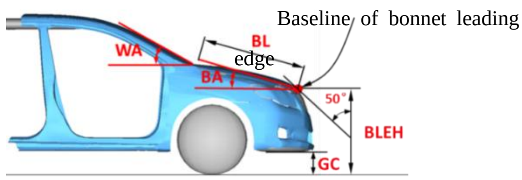
2 Methods

2.1 Vehicle model

The sedan model was selected for this study based on the vehicle finite element model [5, 14], and the facet surface was generated in MADYMO code form the corresponding finite element model with parameters of the windshield angle (WA) , bonnet angle (BA), bonnet length (BL), bonnet lead edge height (BLEH), and ground clearance (GC) as shown in Table 1. The contact stiffness characteristics were applied to all areas of the vehicle front-end structures where contact with a body part was expected (see Fig.1), which were simulated using the legform and headform impactors at impact velocities of 40 km/h.

Table 1. Vehicle front-end structural parameters

Structural parameter
WA：Windshield angle (°)
BA：Bonnet angle (°)
BL：Bonnet length (cm)
BLEH：Bonnet leading edge
GC：Ground clearance (cm)



Deformation (M)

Fig .1. Stiffness characteristics

2.2 Impact conditions

The 50th percentile adult model was developed by Professor Yang Jikuang [15,16], and the validity of the model was verified by comparing the model responses with Postmortem Human Subject (PMHS) test results in terms of overall kinematic and dynamic responses of the body segments. The model height 1.75m, weight 78kg. The right side [18] of the pedestrian was impacted by the center of vehicle front. The pedestrian normal walking velocity was defined as 5 km/h [17]. The impact configuration is shown in Fig.2. The friction coefficient was defined as 0.2 for the contact between the body segments and the car. The road surface was modelled utilizing a rigid body with the friction coefficient of 0.58[11].

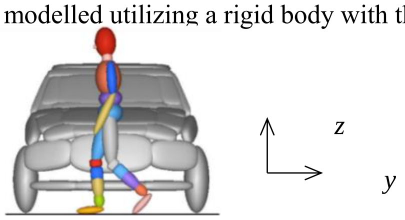


Fig .2. Impact configuration

Table 2. Adjustment of vehicle structural parameters. "-" for the minus, "+" for the plus.

Structural parameter	Original Dimension	Adjusted value						
WA: Windshield angle (°)	32	−15	−10	−5	+5	+10	+15	+20
BA: Bonnet angle (°)	15	−10	−5	+5	+10	+15		
BL: Bonnet length (cm)	86	−15	−10	−5	+5	+10	+15	
BLEH: Bonnet leading edge height (cm)	74	−15	−10	−5	+5	+10	+15	+20
GC: Ground clearance (cm)	22	−10	−5	+5	+10			

In order to investigate the influence of vehicle structural parameters on pedestrian secondary impact, the values of each dimensions were adjusted based on the recorded value ranges [11, 19]. The original vehicle structural dimensions was regard as the baseline. Table 2 shows the parametric matrix of the adjusted values.

2.3 Data statistics

This paper focuses on the kinematics and injuries of pedestrian secondary impact. The selected parameters are: pedestrian angular velocity, pedestrian rotation angle, head HIC (ground), head angular acceleration (ground). The main influencing parameters of vehicle front-end structure on pedestrian secondary impact were analyzed by using the multiple linear regression analysis method of the vehicle front-end structure parameter as the independent variable, the head HIC (ground), the head angular acceleration (ground) and the pedestrian rotation angle as the dependent variable respectively. Considering that $p < 0.01$ is statistically significant.

3 Results

3.1 Pedestrian kinematics

Fig. 3 shows the kinematics of the pedestrian landing moment. In the current study, the pedestrian rotation angle is specified as the angle at which the body rotated around the *y*-axis from the time of primary impact to body first landing moment. During the pedestrian making impact with the ground, the velocity and direction of the rotation could affect the pedestrian landing kinematics which could reduce different injuries. It can be seen from Fig. 3 that the change of parameters WA, BA, BL and GC have little effect on pedestrian rotation angle. However, the influence of BLEH adjustment on pedestrian rotation angle is very obvious. With the decrease of BLEH, the pedestrian rotation angle decreases rapidly, resulting in the changes of landing sequence of different body parts.

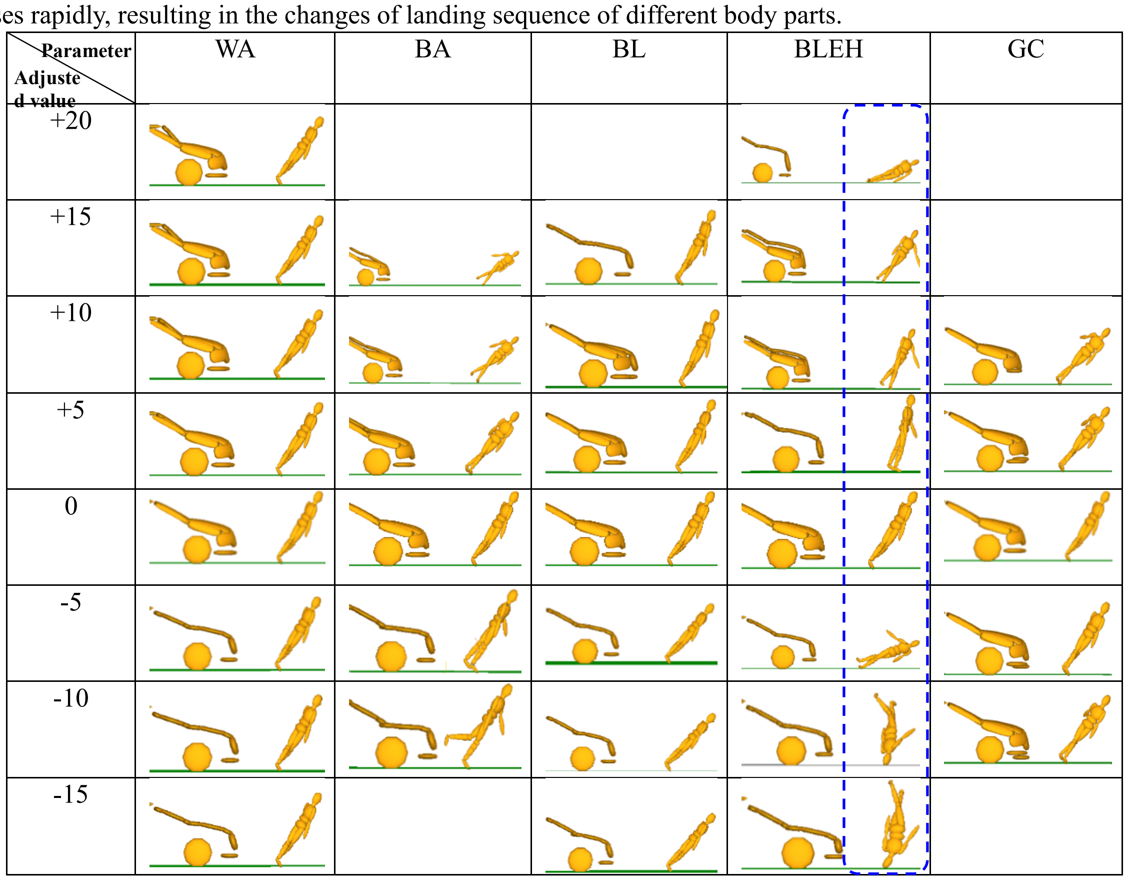


Fig. 3. Pedestrian landing kinematics

2.2 The influence of vehicle front-end structural parameters on pedestrian secondary impact

Fig. 4, 5, 6 show the influence of vehicle front-end structural parameters on pedestrian rotation angle, head HIC (ground), and head angular acceleration (ground), respectively. It can be seen from Fig.4 that BLEH has the most significant influence on pedestrian rotation angle. When BLEH reduced by 10cm or 15cm, the pedestrian rotation angle is reduced to about 180°. Parameters BA, WA, BL and GC shows little effect on pedestrian rotation angle.

Fig. 5 and Fig. 6 show the head HIC (ground) and head angular acceleration (ground) changes were more complex, it is difficult to find the correlation between vehicle front-end structural parameters and landing injury. The reason is that pedestrian landing injury is correlated not only the pedestrian rotation angle, but also the pedestrian-ground impact velocity, the face orientation, the landing sequence of the each body region and so on, these factors resulted in more unpredictable injuries of secondary impact. In the simulation of parameter BA plus 5cm, 10cm and 15cm and GC minus 10cm, plus 5cm and10cm, pedestrian face the *y*-axis direction in the landing moment (see Fig.3), and correspondingly, the pedestrian head HIC (ground) is higher, but this is not reflected on head angular acceleration (ground).

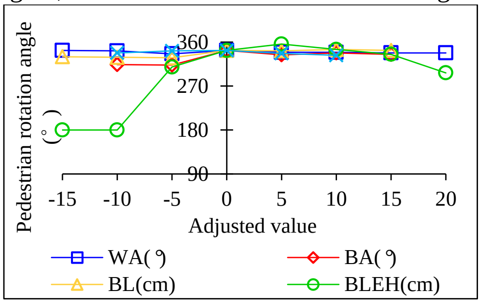


Fig. 4. Pedestrian rotation angle

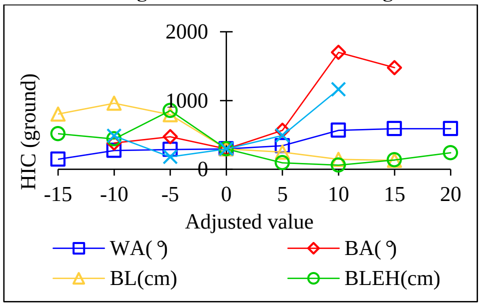


Fig. 5. Head HIC (ground)

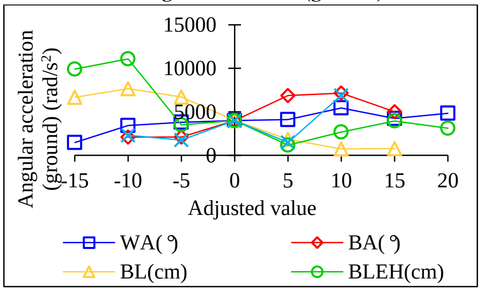


Fig. 6. Head angular acceleration (ground)

3 Discussion

3.1 Analysis on the effect of vehicle front-end structure parameters on pedestrian secondary impact

The main influencing parameters of vehicle front-end structure on pedestrian secondary impact were analyzed by using the multiple liner regression model that the vehicle front-end structure parameter as the independent variable, the pedestrian rotation angle as the dependent variable. It is assumed that the pedestrian rotation angle are influenced by WA, BA, BL, BLEH and GC, and constitute a multiple linear regression relationship, the regression model can be obtained:

$$PRA = \beta_0 + \beta_{WA} \times WA + \beta_{BA} \times BA + \beta_{BL} \times BL + \beta_{BLEH} \times BLEH + \beta_{GC} \times GC$$

Among them, PRA is the pedestrian rotation angle dependent variable, βWA，βBA，βBL，βBLEH andβGC are the fitting regression coefficient of the five independent variables (WA, BA, BL, BLEH and GC). The significant probability p-values of parameters WA, BA, BL, BLEH and GC were 0.21, 0.90, 0.34, <0.01, 0.91, respectively, which indicated that the influence of BLEH on pedestrian rotation angle is the most significant, and the statistical characteristics of other parameters are not significant, the analysis result is shown in Table 3.

Table 3. Fitting regression coefficient and p - value of regression model

Dependent variable	Independent variable	Fitting regression coefficient	Standard error	p – value
PRA (Pedestrian Rotation Angle)	Baseline (β_0)	-174.840		
	WA	-0.129	1.174	0.210
	BA	1.093	1.790	0.900
	BL	0.436	1.463	0.341
	BLEH	6.136	1.174	<0.01
	GC	-0.129	2.448	0.910

3.2 Relationship between BLEH and pedestrian landing response

Fig. 7 shows the pedestrian kinematics of the primary impact phase, flight phase, and secondary impact phase in the parameter BLEH plus 15cm, 0 and minus 15cm simulations. The primary impact phase can be divided into three kinematic stage of Ⅰ, Ⅱ, and Ⅲ respectively. Among them, Ⅰ is the stage of vehicle-to-lower extremity contact. In this stage, the front of the vehicle (mainly the bumper) collides with the pedestrian's lower limbs. The pedestrian starts to rotate counterclockwise with the bonnet leading edge as the fulcrum. Ⅱ is the stage of upper body-to-vehicle contact. In this stage, the upper body collide with the bonnet or the windshield. Due to the difference of BLE height, resulting in the pedestrian head and vehicle collision parts changes. The bonnet and the windshield can stop the rotation of the pedestrian upper body, while the lower body will maintain the trend of counterclockwise rotation without any block. Ⅲ is the stage of pedestrian rebound. With the impact of bonnet and windshield, the upper body of pedestrian will rebound and separate with the vehicle. The upper body appears the clockwise rotation trend, while the lower body will still maintain the trend of counterclockwise rotation, and eventually, the pedestrian rotation direction is affected by the upper and lower body together.

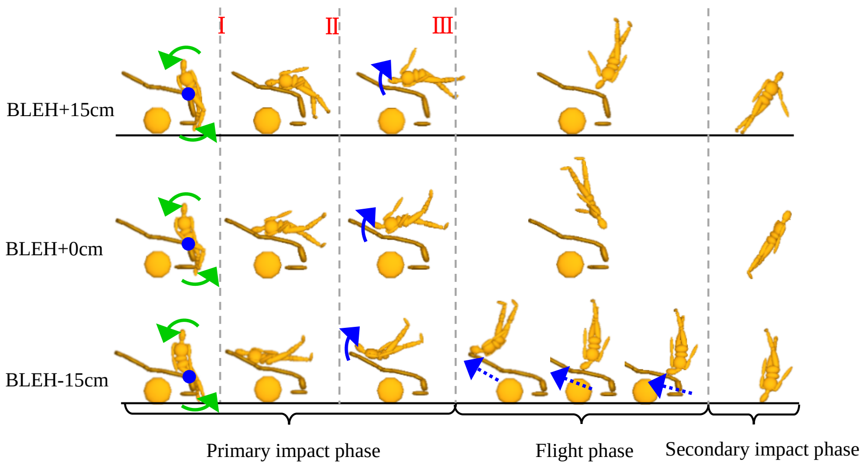


Fig. 7 Pedestrian kinematics

In Fig.7 of the simulation of parameter BLEH minus 15cm, the pedestrian lower limbs are very small in the range of direct impact to the vehicle. So the rotational energy of the lower limbs is relatively small in the stage of IIand III, which cannot completely separate the pedestrian upper body from the vehicle, then the head and the vehicle maintained a frictional contact, and further reduced the pedestrian counterclockwise rotation. Finally, head is the first landing region when pedestrian contact the ground, the injury risk of the head and neck will be very high. In the simulation of parameter BLEH plus 15cm and 0cm, pedestrian rotation angles are roughly the same because the pedestrian are completely separate with the vehicle in the flight phase.

4 Conclusion

In this paper, five vehicle front-end structural parameters were quantitatively adjusted and the effect on the secondary impact was analyzed. After the above analysis, we arrived at the following conclusions: 1. Regression analysis showed that the effect significant of five vehicle front-end structural parameters on pedestrian rotation angle from large to small was: BELH>WA>BL>BA>GC. The parameter BLEH was the most significant ($p <0.01$). 2. Pedestrian landing injury is correlated not only the pedestrian rotation angle, but also the pedestrian landing sequence of the each body region and the face orientation, which always results in more unpredictable injuries. When pedestrian face the y-axis direction in the landing moment, the pedestrian head HIC (ground) was correspondingly higher.

5 Acknowledgements

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