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Injury Analysis of Vehicle-Pedestrian Collision Based on Orthogonal Experiments

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This paper studies the influence of different factors on pedestrian head injury in vehicle-pedestrian collisions. PC-Crash software is used to construct simulation experiments under ten factors. The research shows that the injury to pedestrians in reverse impact is greater than that to pedestrians in forward impact. With the acceleration of vehicle speed, the HIC value of pedestrians will increase with the increase of the height of the front hood from the ground. When the vehicle speed is less than 40 km/h, the injury to pedestrians in a forward-leaning emergency posture is smaller, and the injury to a standing emergency posture is the highest.

Keywords: collision, simulation, pedestrian injury, orthogonal test, range analysis method

1. INTRODUCTION

According to research, 40,000 people were injured in car accidents in the United States in 2018. Among them, 6227 pedestrians died in traffic accidents. Compared with the number of deaths in 2017, the number of deaths decreased by 1%. However, relevant authorities pointed out that the number of deaths was still 14% higher than ten years ago. Hence, researchers at home and abroad have conducted a great deal of research into unavoidable accidents. Hong et al. (2017) compared the predator algorithm with the firefly algorithm. Ganesh et al. (2017) conducted qualitative and quantitative analysis of the segmented image. This method has better visual quality and minimum mean square error. Gu et al. (2017) used PC-Crash to simulate the scene of an accident and the simulation of vehicle parameters and pedestrian position, comparing the positional relationship between them, and analyzing the relationship between vehicle trajectory and pedestrian position.

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Han et al. (2017) and other research based on image data showed that pedestrians adopt emergency postures in the face of fast-moving vehicles. Apaxio et al. (2018) reconstructed two vehicle motorcycle collisions with detailed information by using PC collision simulation and MADYMO reconstruction technology. He et al. (2018) and other researchers pointed out that people are affected by various factors in vehicle collision accidents. Yin et al. (2018) and others studied the dynamic response and injury to pedestrians in different postures after collision. Tiefang et.al. (2018) used PC-Crash software to reproduce 57 real automobile electric bicycle accidents, and directly collected information about cyclists' injuries from the simulated cases.

Being the most vulnerable groups in traffic accidents, the incidence of pedestrians in road accidents leading to death is becoming more and more serious. Therefore, in this paper, we conduct another simulation experiment for a traffic accident based on PC-Crash software, and analyze the impact that the pedestrian's body shape, speed and emergency posture has on the injuries sustained in collision accidents.

Table 1 Main parameters of accident participants.

Traffic accident participants	Collision velocity/(km/h)	Collision angle/ (Degree)	Quality/(kg)
automobile	58	90	1625
pedestrian	5	90	65

2. ACCIDENT RECONSTRUCTION AND MODEL RECONSTRUCTION

2.1 Brief Introduction to an Accident Case

An SUV, travelling at a uniform speed from north to south, collided violently with a pedestrian speeding up suddenly on a zebra crossing. The collision point was on the zebra crossing. Because of the sudden occurrence, the driver did not apply the brakes in time, and the pedestrian did not see the oncoming vehicle. The two collided and the contact position was the right inclination angle of the car engine hood. The accident caused serious injuries to the pedestrian and dented the right side of the hood. The pedestrian sustained multiple fractures and cardiopulmonary contusion.

2.2 Accident Process and Calculating Verification

The accident reconstruction software, PC-Crash, is selected to reconstruct the whole case. The sedan model, the most common type in the garage, and Pedestrian 20061127 are selected as the pedestrian model. The mechanical features of the vehicle model are defined according to the collision results of similar Euro-NCAP, and then adjusted according to the body size parameters of the vehicle on site. The pedestrian multi-rigid-body model is modified and scaled according to the real data of the injured person.

Accident reconstruction includes many parameters such as the velocity at the time of collision, the position of collision and the friction coefficient of car, pedestrian and road.

Taking the car as the object of analysis, the optimal trajectory of the car is determined by the speed of the collision time, the braking distance of the car, the turning time and the final stationary position. Then, the pedestrian is taken as the object of study and its initial velocity, the time of the first collision, the time of lagging behind the collision and the final stationary position are considered. Both the vehicle and the pedestrian are simulated and reproduced via PC-Crash.

The video obtained from the scene shows the location of the car-pedestrian collision. The collision speed at the instant of contact between car and pedestrian can be calculated by GA/T643-2006 "Technical Identification of Vehicle Speed in Typical Traffic Accident Forms" (see Table 1 below).

Figure 1 shows the pedestrians and cars after the collision in a comparison of the simulation with the surveillance video.

According to the pedestrian-related damage curve in the simulation experiment shown in Figure 2, the maximum synthetic acceleration of the head is between $t = 0.591$s and 0.626s with a time interval of 36 Ms. HIC36 is a new head injury tolerance limit criterion defined by the US government. The calculation formula is as shown in formula (1). From the data of $HIC_{36} = 1040.45$ (Head Injury Criterion, FMVSS213 (Hu Huimin et al. 2015) is less than 1000), it can be seen that the data is consistent with the serious head injuries of pedestrians in accidents. From the curve, we can know that t = 1.180 s, the pedestrian's chest suffered the greatest impact force, 9.57 kN, seriously exceeding the chest impact threshold value of 6.4 kN (Zou et.al. 2018), which explains the pedestrian's internal organ contusion and rib fractures. At t= 0.031s, the impact force caused by the first contact of the pedestrian's hip with the vehicle was 4.61kN, which did not exceed the impact limit stipulated by FMVSS213 (Liu et.al. 2018). This was consistent with the pedestrian's hip fracture in the accident.

$$HIC = \max\left[\frac{1}{t_2 - t_1}\sum_{i_1}^{t_2} a(t)dt\right]^{25} (t_2 - t_1) \quad (1)$$

In formula (1), the symbol (t) is the synthesis acceleration of the head centroid, expressed by a multiple of the center of gravity acceleration. Symbols t_1 and t_2 represent the start time and end time of the maximum integration time interval respectively, and the interval is within 36ms.The value of t1 and t2 must be such that the calculation result reaches the maximum value.

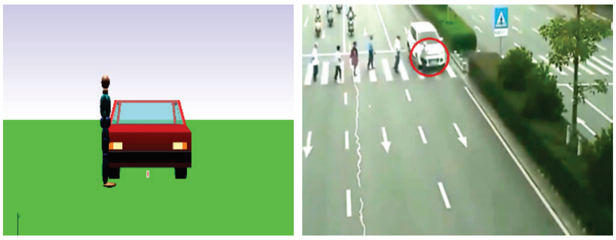
The above results confirm the validity of PC-Crash model reconstruction, and further analysis is carried out.

3. FACTOR WEIGHT ANALYSIS BASED ON ORTHOGONAL EXPERIMENTS

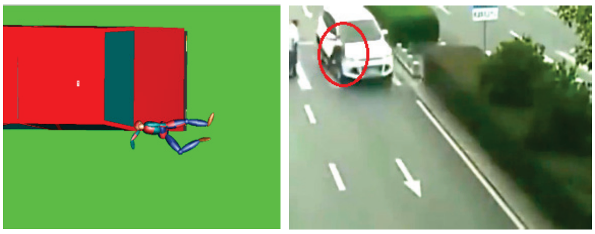
3.1 Selection of Test Factors

According to the above actual case and the relevant parameters of cars, through the possible influence of various factors in the simulation process, the HIC of pedestrians can be determined by car speed A, pedestrian speed B, pedestrian emergency attitude C, pedestrian facing direction D, ground adhesion coefficient E, the height of the front hood F, pedestrian mass G, impact angle H, the height of the front bumper I and pedestrian height J. Nine factors were taken as independent variables in the orthogonal experiment. Head Injury Criterion (FMVSS213 stipulates less than 1000) is the dependent variable of pedestrian head injury, and the influence weight of each factor on pedestrian injury is analyzed.

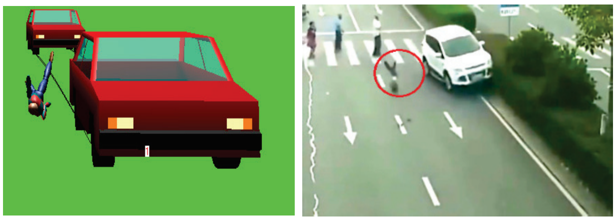
According to the actual situation of the simulation test, the car speed distribution in this case is 20–60 km/h. Therefore, the vehicle speed is selected at four levels: 30, 40, 50 and 60 km/h. Based on the reference (Li et al. 2015) the pedestrian speed at the zebra crossing and the signal intersection is selected at three levels: 3 km/h, 4 km/h and 5 km/h. The vehicle is used as the collision object, and the pedestrian is used as the obstacle



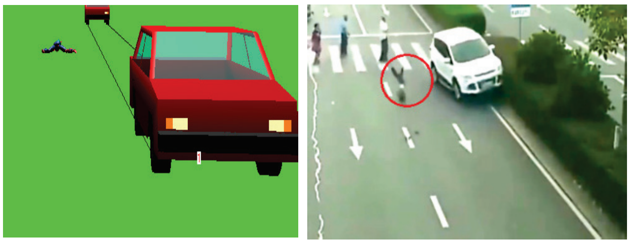
(a) The moment before the collision of a T = 0ms car with a pedestrian



(b) The first collision of t=85ms car with pedestrian's head occurred on the right-side hood of automobile engine

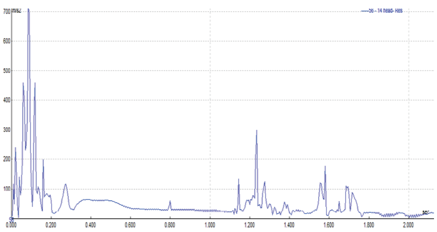


(c) t = 1.230s pedestrian chest landing

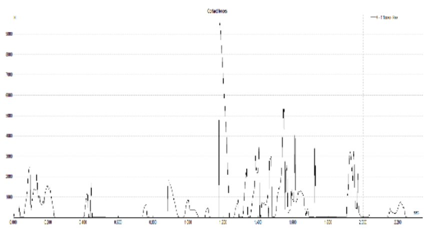


(d) t = 3.038s, cars and pedestrians in a relatively static state

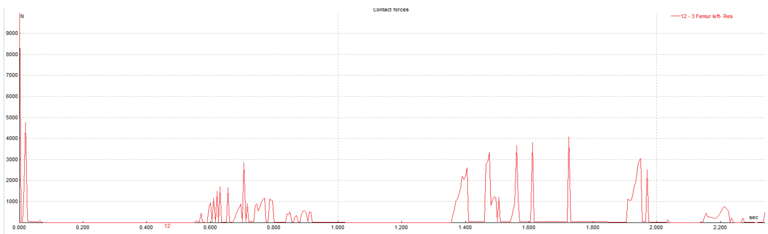
Figure 1 Comparison of animation and video data of 3D simulation model



(a) Acceleration Response Time Curve of the Cyclist's Head



(b) Response time curve of chest contact force of cyclists



(c) Response time curve of pedestrian hip and thigh left contact force

Figure 2 The correlation curve of major injuries to cyclists in the accident

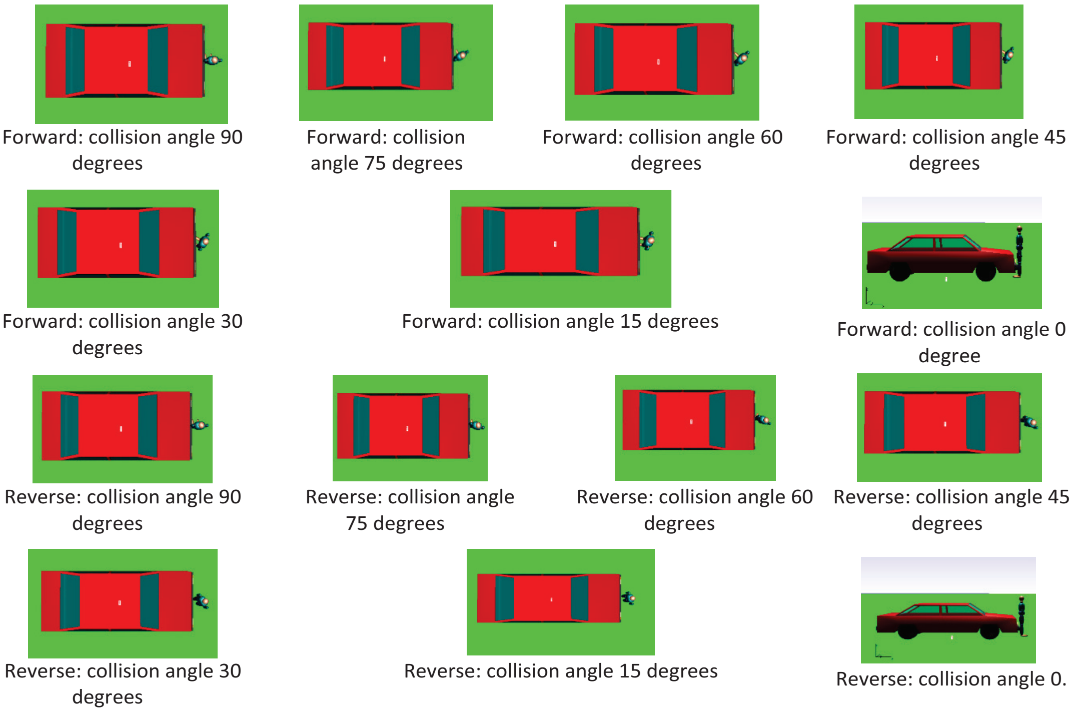


Figure 3 Collision angle position relation

to select the collision. The angles are 0, 15, 30, 45, 60, 70 and 90 degrees, respectively, as shown in Figure 3. The directions are set as the pedestrian facing the vehicle, and not facing the vehicle, which can be divided into front and back. The pedestrian emergency posture can be selected according to literature (Quan et al. 2002), including forward tilt (lower limbs immobile, trunk forward 45 degrees, upper limbs supporting), squatting (legs together, squatting, center of gravity reduced by about 20 cm), standing at three levels. In order to truly reflect the friction coefficient of the ground, the ground adhesion coefficient is 0.8 for dry ground, 0.6 for wet ground, 0.4 for snow cover and 0.2 for icing ground, 0.8, 0.7 and 0.6 m for front hood, 0.45, 0.35 and 0.25 for front bumper, and 0.45, 0.35 and 0.25 for pedestrian geometric parameters referring to GB10000-88 Chinese adults. For size (Kim et al. 2015), pedestrian weight is 50, 60, 70 kg and pedestrian height is 1.6, 1.65, 1.7, 1.75 m.

3.2 Pairwise Algorithm and Orthogonal Test Table

The pairwise algorithm (Zhang, et. al.2016), also known as the pairing algorithm, was proposed by L.L. Thurstone in 1927. It is a product of optimization based on mathematical statistics and traditional orthogonal analysis.

In this study, 36 experiments were conducted based on the level of each factor as input, without considering the interaction between factors, as shown in Table 2.

3.3 Weight Analysis of Each Factor Based on Range Method

Using the orthogonal table listed by the pairwise algorithm, according to the experimental serial number and experimental parameters of each group, the simulation is carried out using PC-Crash software, and the R 'value of HIC of the first collision time interval between the head of the traveler and the car is calculated by range method, and its size is analyzed. The following conclusions are drawn:

The weight of the first collision time interval of pedestrian's head is from large to small: pedestrian height, front hood height, vehicle speed, direction, impact angle, pedestrian speed, ground adhesion coefficient, front bumper height, pedestrian quality.

The weight of the HIC value of pedestrian head ranges from large to small: vehicle speed, height of front hood, height of front bumper, collision angle, pedestrian height, ground adhesion coefficient, direction, pedestrian quality, pedestrian speed.

The above weights indicate that the main factors affecting the interval time of the first pedestrian head impact are the height of the front hood, the speed of the car, the height of the front bumper and the speed of the car. The main factors influencing the HIC value of head are vehicle speed, height of front hood, height of front bumper, impact angle and pedestrian height. The index of pedestrian head injury was further studied in the context of those factors.

4. THE INFLUENCE OF SIGNIFICANT FACTORS ON PEDESTRIAN INJURY

4.1 Impact of Vehicle Speed on Pedestrian Direction

Fig. 4 shows the relationship between vehicle speed and pedestrian direction. From the curve of Fig. 4, it can be seen that the HIC of pedestrians will increase with the acceleration of car speed. Moreover, in a real collision accident, if there

Table 2 Orthogonal test table.

Experiment number	Factor										Time (s)	HIC
	A	B	C	D	E	F	G	H	I	J		
1	30	3	Anteversion	1	0.8	0.6	60	0	0.25	1.6	0.165	29
2	30	4	Stand	1	0.4	0.8	50	60	0.35	1.75	0.216	45
3	30	4	Squat	1	0.6	0.8	50	30	0.25	1.7	0.15	52
4	30	4	Squat	1	0.2	0.7	50	75	0.45	1.6	0.185	18
5	30	3	Anteversion	1	0.4	0.6	50	15	0.25	1.7	0.105	184
6	30	4	Anteversion	1	0.8	0.6	60	30	0.25	1.75	0.205	249
7	30	4	Squat	1	0.6	0.7	70	0	0.35	1.75	0.185	142
8	30	5	Squat	1	0.6	0.7	60	60	0.25	1.65	0.185	59
9	30	4	Squat	1	0.2	0.7	50	30	0.25	1.6	0.15	328
10	30	4	Squat	1	0.6	0.8	60	45	0.25	1.6	0.13	72
11	30	4	Squat	1	0.6	0.7	50	90	0.25	1.75	0.253	2.5
12	30	4	Squat	1	0.6	0.7	50	90	0.25	1.65	0.16	13
13	40	4	Squat	−1	0.6	0.7	50	15	0.35	1.6	0.115	815
14	40	3	Stand	1	0.6	0.6	50	90	0.35	1.7	0.165	74
15	40	5	Stand	−1	0.8	0.7	70	90	0.45	1.7	0.165	24
16	40	5	Anteversion	−1	0.6	0.8	60	75	0.25	1.65	0.135	293
17	40	5	Anteversion	−1	0.4	0.6	70	45	0.45	1.6	0.135	467
18	40	5	Stand	1	0.2	0.7	70	15	0.25	1.75	0.155	126
19	40	3	Squat	1	0.8	0.7	50	60	0.25	1.6	0.105	472
20	40	4	Squat	1	0.4	0.7	50	0	0.25	1.6	0.105	799
21	40	4	Squat	1	0.6	0.8	50	30	0.25	1.6	0.105	304
22	50	5	Stand	−1	0.4	0.8	50	30	0.45	1.65	0.106	1259
23	50	3	Squat	1	0.4	0.7	70	75	0.25	1.75	0.135	152
24	50	4	Anteversion	1	0.8	0.7	60	45	0.35	1.65	0.125	196
25	50	3	Squat	1	0.8	0.6	60	15	0.45	1.65	0.09	1433
26	50	5	Anteversion	1	0.6	0.8	70	0	0.45	1.7	0.12	381
27	50	3	Squat	1	0.2	0.6	50	90	0.25	1.6	0.205	36
28	50	4	Squat	1	0.6	0.7	50	60	0.25	1.7	0.1	1344
29	60	5	Squat	1	0.2	0.8	50	45	0.35	1.7	0.075	2676
30	60	4	Anteversion	−1	0.2	0.6	60	60	0.45	1.75	0.095	2757
31	60	3	Stand	−1	0.2	0.7	50	0	0.25	1.65	0.095	515
32	60	3	Stand	1	0.8	0.8	50	30	0.35	1.6	0.085	3517
33	60	4	Anteversion	1	0.4	0.8	50	90	0.25	1.6	0.09	2069
34	60	3	Stand	1	0.6	0.6	50	45	0.25	1.75	0.11	495
35	60	4	Stand	1	0.8	0.6	60	75	0.35	1.7	0.111	545
36	60	4	Squat	1	0.6	0.8	70	15	0.25	1.6	0.06	2985

is a frontal impact, in an emergency situation, the human brain will temporarily lose consciousness, unable to decide the next step to take. Out of the static state, the violent impact of the car will make the pedestrian lean in the direction of the car because of inertia, which will lead to the reduction of the pedestrian's head acceleration due to the cushioning effect caused by the limbs. If the direction of pedestrian impact is the back, the impact force of the head will be further increased after the inertia of pedestrian is greatly increased after the first impact, which leads to the difference between the trend line of the back impact and the front impact curve.

According to the curve analysis, when the speed is 30–40 km/h, the HIC value of the pedestrian's head does not exceed 1000, regardless of whether it is the back or front, and it is not seriously injured. When the speed of the car exceeds 50 km/h, the HIC value of pedestrian rises sharply, and the damage caused by both front and back impact will be further increased. In the same case, the impact to the back of the pedestrian's head is more harmful than frontal impact, and the faster the speed of the vehicle, the greater the gap between the injuries.

According to Fig. 5, the relationship between vehicle speed and head time in the direction of pedestrians being hit is that at the speed of 30–50 km/h, the same frontal impact takes less time than the back impact the pedestrian's first head impact is caused by a strong back impact. However, when the speed is increasing, the first head impact will occur. In a front impact, the weak cushioning force will be offset instantaneously, which confirms that the interval between the first head collision and the back impact will exceed the time of the first head collision at a speed of more than 50 km/h. Therefore, this also confirms that, under the same condition, pedestrian head injury caused by the reverse impact is greater than that caused by the front impact.

Table 3 Range analysis of orthogonal experimental table.

(a) Weight relationship of factors affecting the time interval of first head contact

Experimental index	Factor								
	A	B	C	D	E	F	G	H	I
K1	2.089	1.26	4.03	0.96	1.386	2.77	0.67	2.903	1.635
K2	1.185	2.54	0.846	0.892	2.218	0.915	0.525	1.077	0.896
K3	0.881	1.076		1.973	1.272	1.191	0.801	0.896	0.991
K4	0.721			1.051			0.575		1.354
K5							0.701		
K6							0.566		
K7							1.038		
k1	0.174	0.126	0.1389	0.137	0.1386	0.1385	0.134	0.138	0.125
k2	0.1316	0.141	0.1208	0.1274	0.1478	0.13	0.105	0.1346	0.128
k3	0.1258	0.134		0.1409	0.115	0.132	0.1335	0.128	0.123
k4	0.091			0.1313			0.115		0.169
k5							0.1402		
k6							0.141		
k7							0.173		
R	0.0406	0.015	0.0181	0.0135	0.0328	0.0085	0.0352	0.01	0.046
R'	0.05	0.022	0.034	0.0161	0.054	0.0117	0.0246	0.013	0.0547
Primary and secondary order	C	F	D	G	B	I	E	H	A

(b) Weight relationship of factors affecting HIC

Experimental index	Factor								
	A	B	C	D	E	F	G	H	I
K1	1193.5	6907	18797.3	6456	6269	11379	1866	10578.5	11911
K2	3374	12190.5	6130	4975	5005.5	5549	5543	8010	3768
K3	4801	5261		7031.5	13653	8000	5709	6339	5280
K4	15559			6465			3906		3968.5
K5							4677		
K6							1008		
K7							2218.5		
k1	99	691	648	922	623	569	373	504	916
k2	375	717	876	711	334	793	1109	1001	538
k3	686	752		502	1241	889	952	906	660
k4	1945			808			781		496
k5							935		
k6							252		
k7							370		
R	1846	61	228	420	907	320	857	497	420
R'	2198	89	428	500	1491	440	600	684	500
Primary and secondary order	A	I	G	E	B	H	D	C	F

4.2 Pedestrian Emergency Attitude and Vehicle Speed

Fig. 6 shows the relationship between vehicle speed and pedestrian HIC, and the self-protective posture that pedestrians can instinctively adopt when encountering danger. Three postures are studied: standing, leaning forward and squatting, and depicted in Fig. 6. When the vehicle speed is relatively low, at the same speed, the HIC value of pedestrians squatting as an emergency posture is the highest; the HIC value of pedestrians standing as an emergency posture is the lowest, which is mainly caused by the following reasons: when the vehicle and pedestrians collide for the first time and the pedestrians squat posture collides, the body will subconsciously put their feet together to squat posture, reducing their center of mass by about 20cm. The posture greatly reduces the contact distance between the head and the car.

The reason why pedestrians in the former leaning emergency posture have much lower HIC than those in the squatting and

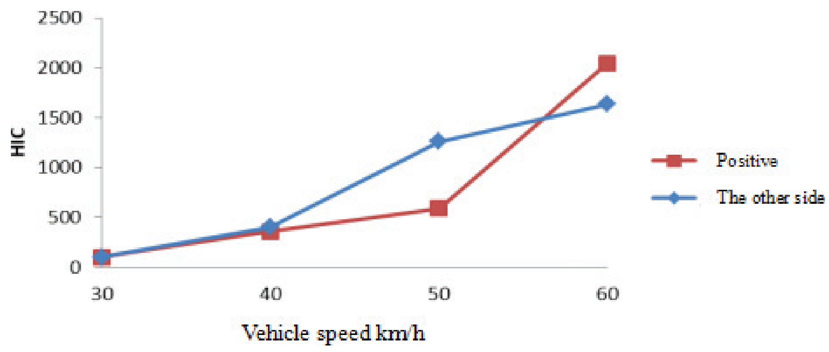


Figure 4 HIC value relation between vehicle speed and pedestrian direction

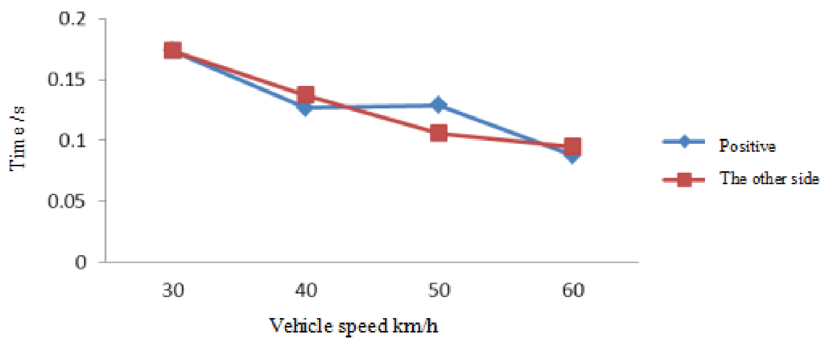


Figure 5 Relation between vehicle speed and head contact time in pedestrian direction

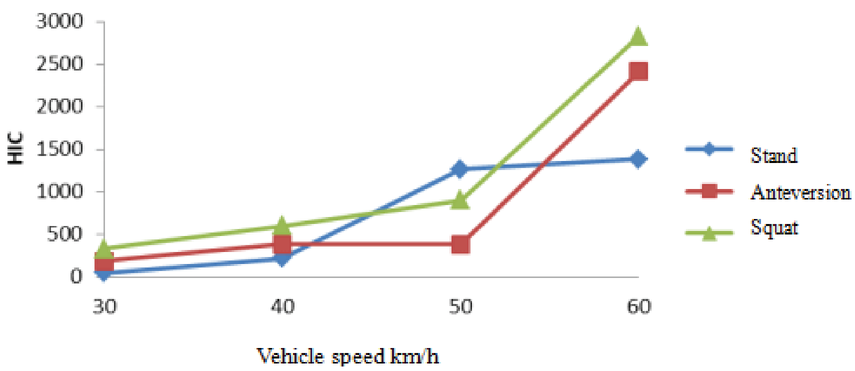


Figure 6 Relationship between vehicle speed and pedestrian posture and pedestrian HIC value

standing posture at the speed of 30–50km/h is that pedestrians in the forward leaning emergency posture instinctively stand still with their lower limbs and their bodies tending to lean forward by 45%. Their hands are used to safeguard them. When the car collides with the pedestrian, the first part of the collision is the hands, which further reduces the acceleration given by the car to the pedestrian, and delays the contact time between the pedestrian's head and the vehicle.

When the vehicle is travelling at high speed, regardless of the emergency posture adopted by the pedestrian, the HIC will rise to a peak. The weakening ability of the upper limb of the pedestrian with forward leaning posture to the acceleration is greatly reduced, which makes the HIC value of the pedestrian increase rapidly. While in squatting, the pedestrians in the forward-leaning posture will have a long HIC due to the relatively short contact distance between the head and the vehicle. It also proves that in this situation, the forward leaning emergency posture can effectively reduce pedestrian head injury.

4.3 Analysis of the Influence of the Height of the Front Hood From the Ground and the Vehicle Speed

Fig. 7 shows the relationship between the height of the front hood from the ground and pedestrian head injury. According to the analysis of the broken line graph, when the vehicle speed is 30 km/h, the HIC of pedestrians will gradually decrease with the height of the front hood of the vehicle. When the vehicle speed increases, the HIC of pedestrians will increase with the height of the front hood of the vehicle.

When a car is travelling at a lower speed, with the increase of the height of the front hood from the ground, when pedestrians collide with the car, the area of first contact with the car becomes larger, and the inertia force acting on the pedestrian will be relatively weakened. This leads to an increase in the time of the secondary collision between pedestrians and cars, and a decrease in the HIC of pedestrians.

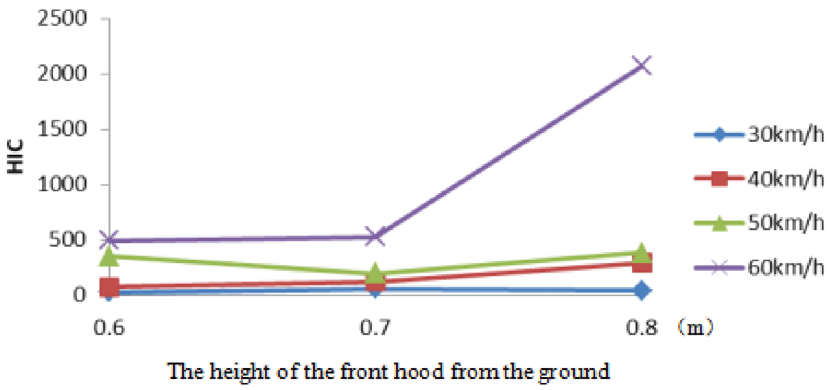


Figure 7 The relationship between the height of the front hood off the ground and the vehicle speed

However, if the car is driven at a higher speed, the moment of pedestrian-car collision will be caused by a huge inertia force. The violent impact will force pedestrians to obtain an acceleration and quickly come into contact with the car for a second time.

At the same time, the greater the height of the front engine, the faster the speed of secondary collision between pedestrians and cars. Moreover, at high speeds, the effects of the other limbs are offset instantaneously, so fast that the pedestrian's head or body tissues can accelerate their collision with the car. Therefore, if the height of the front hood can be reduced appropriately, the pedestrian injury caused by vehicle collision can be effectively reduced.

5. CONCLUSION

(1) The validity of digital simulation is verified by reconstructing the parameter simulation of real cases, verifying the whole process of the accident based on PC-Crash and comparing with the trace of the scene of the case.

(2) A pairwise algorithm is used to scientifically present the main factors of pedestrian head injury by orthogonal experiment. Vehicle speed, the height of the front hood, the direction of the pedestrian being hit and the angle of the impact have significant effects on pedestrian injury.

(3) The HIC of pedestrians is greater with a rear impact than with a front-end impact. In a frontal impact, the pedestrian's HIC is affected by the trunk, and this cushioning effect will be weakened with the increase of vehicle speed. When the vehicle is below the impact, the pedestrian's HIC in the leaning emergency posture will be less, and the HIC of pedestrians in the lower crouching emergency posture will be affected. When the speed of the vehicle exceeds 30 km/h, the HIC of pedestrians will increase with the increase of the height of the front hood of the vehicle from the ground. An increase in vehicle speed will result in greater injuries to the pedestrian. The impact of other factors on pedestrian injury still needs to be studied future.

6. ACKNOWLEDGMENT

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