Evaluation of Pedestrian Kinematics and Head-Injuries by Reconstruction of Accidents with One-box vehicles and Passenger Cars

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Abstract: In vehicle-pedestrian impact, the kinematics and severity of pedestrian injuries are affected by the shape of vehicle front. The objective of current study was to investigate the overall kinematics (impact point, head impact time, head relative velocity and impact angle, and throw out distance) of pedestrian, causes and types of head-injuries in accidents with one-box vehicles and passenger cars. Twelve pedestrian accident cases from an in-depth accident database from Changsha (China) that contains information collected through on-spot and retrospective investigations were selected to the reconstructions. The twelve selected cases include details of pedestrian injuries, car involved in the accident, and the environment. The reconstructions of accidents were performed using mathematical models of the pedestrians and vehicles in MADYMO environment. The pedestrian throw kinematics and head-brain injuries were compared between accidents involving one-box vehicles and passenger cars. The reconstructions showed that there are great differences of pedestrian kinematics and head-injuries in collisions involving such vehicles.
Key words: Pedestrian kinematics, Head-injuries, Accident reconstruction, One-box vehicle

1 Introduction

Pedestrians are the most vulnerable road users and their safety is thus a public health issue evident worldwide. In China, the national statistic authority reported about 100,000 traffic fatalities each year and a quarter of which are pedestrians [1]. However, the fatalities were caused by which kind of vehicle was not statement in China.

From January to September in 2009, the sales of one-box vehicles have reached 141.38 million, which increased with 71.46% compared to the corresponding period in 2008 [2]. With such big change in the vehicle fleet in China, it is important to investigate the safety repercussions on pedestrians.

A lot of research were made about dynamic response and head-injuries in automobile to pedestrian collisions [3] [4], but these studies were primarily restricted to passenger car to pedestrian impacts. The compatibility of cars and LTVs (light trucks and vans) in impacts with pedestrians was investigated by Mizuno and Kajzer using Japanese traffic accident data [5]. They found that LTVs showed a significantly greater fatality risk than passenger cars. Jarrett and Saul present the clinical study from a US and also found that LTVs might show a more serious threat to pedestrian life than passenger cars [6]. After analysis of the three major sources of road accident data, which incorporates Fatality Analysis Reporting System (FARS), the General Estimates System (GES) and the Pedestrian Crash Data Study (PCDS), Lefler and Gabler also found that pedestrian have two to three times greater likelihood to die when struck by an LTV than by a passenger car[7]. Based on the studies above, the increasing number of one-box vehicles in China may result in a serious risk of injury and fatality of vulnerable road users such as pedestrians.

According to Mizuno and Ishikawa, in car-to-pedestrian crash accidents the head-brain injuries are the most common, accounting for approximately 30% of total AIS2+ injuries; such injuries often result in fatal consequences and significant social and economic losses [8]. Mizuno and Kajzer compared the head injuries risk between bonnet-type cars and mini van, and they showed that the pedestrian is at high risks of serious and fatal injury to the head when they impacted by mini vans [9]. Consequently, preventing and minimizing head-brain injuries has become a priority in the vehicle traffic safety field [10].

One of the vital issues is to understand the differences of pedestrian kinematics, the type of head-injuries and the causes to head-injuries in real-world vehicle-pedestrian collisions involving different types of vehicles that are currently on roads. However, although the number of one-box vehicles is increasing in China, pedestrian behavior and the injury risk to each body region have not been assessed for these types of vehicles. The study aims to analyze the differences of pedestrian kinematics and head injuries between one-box vehicles and passenger cars in pedestrian collisions through the new set of real-world accident cases from an in-depth database from Changsha in China (IAVC).

2 Methods and materials

For reconstructions of the accidents we decided to use in-depth database IAVC. This database contains information from accident site, hospital clinic reports and police records. The detail information about accident vehicle and pedestrian victim and road environment (Table 1) was used in the study.

Table 1 Summary of accident data for reconstruction based on [4]

	Pre-crash	Crash	Post-crash
Vehicle	Travel speed Pre-crash braking Driver maneuver	Impact speed Contact point	Maker, model, year, weight Damage - dents - scratch
Pedestrian	Initial posture Moving speed Orientation	WAD Throw distance -Landing point -Sliding distance -Resting point Ground impact mode -Body contact	Gender, Age, Height, Weight Injuries -Injury patterns -Injury distribution - Severity - Cause of injury
Road and Environment	Road type Road surface Weather condition	Ground impact	Skid mark and other traces

Twelve real-world adult accidents from IVAC were reconstructed by MADYMO simulations. Six of selected cases involving passenger cars were reconstructed previously [4]. Other six cases are one-box-pedestrian accidents which were reconstructed for the purpose of current study.

2.1 Example of pedestrian accident cases

To give a general view of the quality of the information collected in IVAC, two pedestrian accident cases will be described; one case when passenger car and one when one-box vehicle is involved.

2.1.1 Accident case 1: one-box vehicle to pedestrian accident

A 30-year-old female pedestrian was hit by Jinbei en one-box type vehicle as shown in Figure 1 at an estimated impact velocity of around 30 km/h on a crosswalk. Before the accident occurred, the car was running from east to west at a high speed. At that time, the woman was walking across the road on the crosswalk from south to north carrying an umbrella． She didn’t paid attention to the traffic situation. When the driver saw the pedestrian, he braked and turned right to avoid the accident, but the car still hit the woman’s leg on the left side of the front bumper then the windscreen impacted her head.

Figure 1. Photos of the accident spot

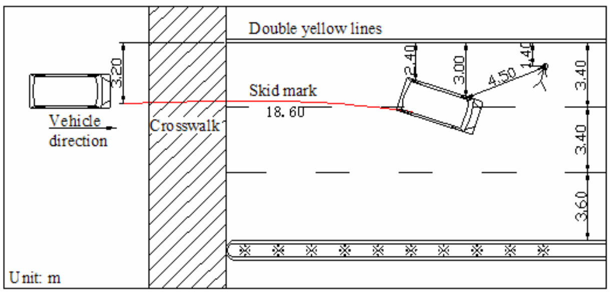


Figure 2. Sketch of the accident spot

There were obvious skid marks on scene with a maximum length of 18.6 m (Figure 2). The contact dents were visible on the hood and the fractures of the windscreen were identified as the result of the head impact (Figure 1). The measured wrap around distance (WAD) was 1.6 m.

The pedestrian victim was 163 cm tall and weighed 50 kg. The car hit her right leg; threw distance was 8.3 m. She sustained scalp haematoma (AIS 1). Injury to other body parts included a comminuted fracture at right fibula.

2.1.2 Accident case 2: passenger car to pedestrian accident

A 17-year-old male pedestrian was hit by 2001 VW Jetta passenger car (Figure 3) at an estimated impact velocity of around 30 km/h. The distracted driver, who was watching a traffic accident occurring to the left, saw the pedestrian when the car was only 2-3 m away. He braked, but the car hit the pedestrian on the left side of the bumper. The pedestrian wrapped around the car front, and his head was impacted with the interface of the bonnet and windscreen.

Figure 3. Car involved in accident

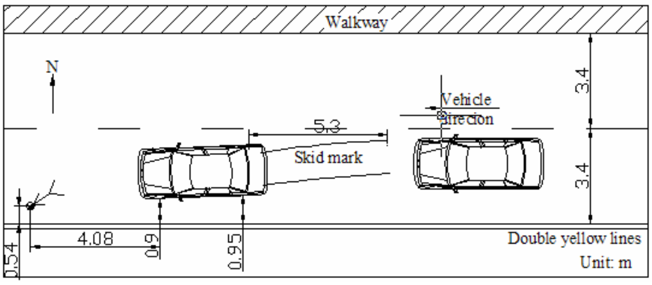


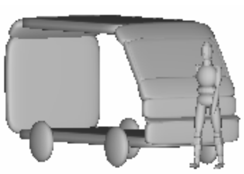
Figure 4. Sketch of the accident spot

There were obvious skid marks on accident spot with a maximum length of 5.3 m (Figure 4). Impact dents were found on the bumper and bonnet edge. There were cracks on the lower windscreen. The WAD was 1.85 m.

The pedestrian victim was 171 cm tall and weighed 81 kg. The car hit his left leg; threw distance was 5.8 m. He sustained cerebral concussion (AIS 2). Injury to other body parts included a trauma to left leg, which means – minor injury.

2.2 Reconstruction of pedestrian accidents

The accidents were reconstructed by the simulations performed in MADYMO. In the reconstruction we used the validated pedestrian model [11, 12]. The mathematical models of one-box vehicle and passenger cars were created based on the drawings of the vehicle involved in the accident. All important structures were represented (Figure 5).



(a)

(b)

Figure 5. Vehicle-pedestrian crash reconstruction models (a. one-box; b. passenger car)

The force-deformation properties of the vehicle models were simplified. We used the same set of propertied in all vehicle models. This set of properties was defined in terms of stiffness properties acquired from Euro NCAP sub-system tests (Figure 6) [13]. All other parameters necessary to the MADYMO input file were based on the data obtained from IVAC database. The impact speed of the cars and the pedestrian speed were estimated, considering the car braking skid marks on the road surface and the pedestrian moving postures before the impact. The main formula for estimation of impact speed of the car is [14]:

$$v = \sqrt{2g\mu L\cos\theta} \qquad [m/s] \tag{1}$$

where, g is the acceleration of gravity, μ is the friction coefficient, L is the length of skid mark, θ is the slope angle of road surface. The friction coefficient between the wheels and road surface was defined according to road surface conditions. The diving angle of emergency braking and steering effect were also simulated.

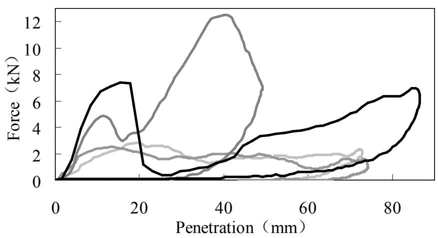


Figure 6. Stiffness definition using Euro NCAP test results

The reconstruction procedure of real-world pedestrian accident cases in MADYMO is schematically illustrated in Figure 7.

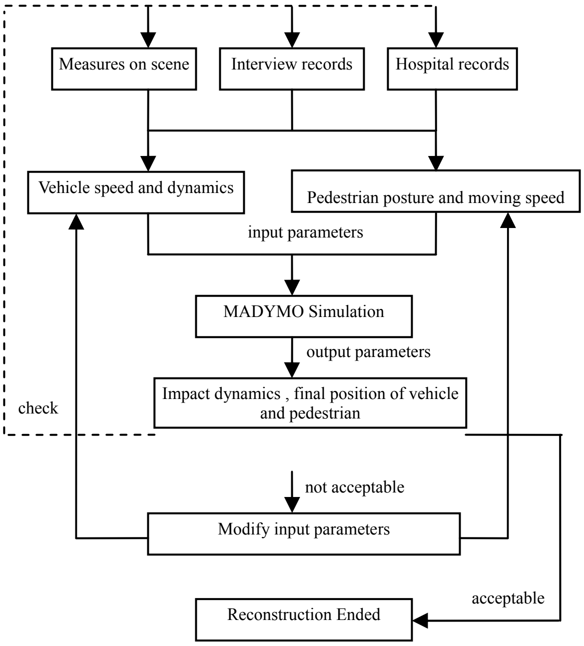


Figure 7. Simulation flow of accident reconstruction.

Accident data on final position of the vehicle, throw out distance, and head impact position were used in tuning of reconstruction. From the tuned reconstructions the parameters related to pedestrian kinematics and head-injuries were obtained. These results were analyzed and discussed in terms of differences between both vehicle types.

WAD, head relative velocity and impact angle can provide background to improve the front structure of vehicles [15]. Therefore in the study, regarding overall kinematics, we analyzed the WAD (from the database) and the correlation between the vehicle velocity and head relative velocity, head impact angle in accidents involving the two types of vehicles. We decided to analyze also the head impact time.

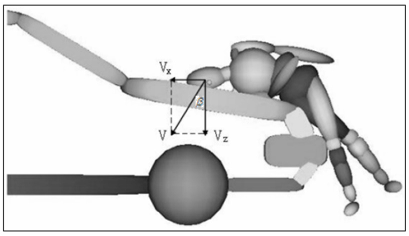


Figure 8. Head impact angle

In the present study, a head impact angle β is defined as the head resultant velocity vector with respect to horizontal line（Figure 8）

$$\beta = \arctan v_x / v_z \tag{2}$$

where v_x is the horizontal component of head velocity and v_z is the vertical component of head velocity.

In the current study we concentrated our efforts to analyze the causes and types of head-injuries. In the absence of a more appropriate criterion expressing the severity of pedestrian head injuries, HIC is commonly used and we also used this criterion in the study. To distinguish the different causes of head-injuries in the accidents involving two types of vehicles, HIC from head-vehicle impact and head-ground impact were compared. Because there are various mechanisms of head injury we compared also the injury related parameters such as head linear acceleration (HLAC) and head angular acceleration (HAA) from tuned simulations with outcome from accidents.

3 Results

3.1 Overall kinematics of impacts

The impact location of the pedestrian head in the twelve cases is shown in Figure 9. For passenger car, there are 4 cases involving head impact to the bonnet and 2 cases of head impact to the windscreen. The WAD varies from 146 cm to 185 cm, while the heights of pedestrians range from 155 cm to 171 cm. However, all the one-box cases involved head impact to the windscreen. The WAD varies from 143 cm to 161 cm, while the heights of the pedestrians range from 151 cm to 166 cm. The WAD in accidents involving one-box vehicles are almost the same to the height of pedestrian and is smaller than that in accidents involving passenger car.

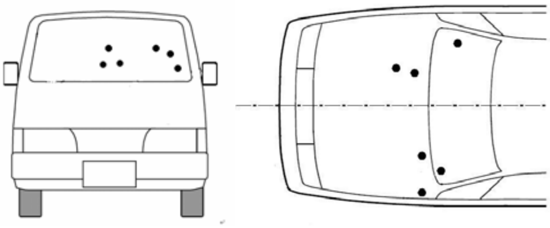


Figure 9. Impact point (a. one-box; b. passenger car)

Figure 10 illustrate the relationship between head impact time and vehicle impact velocity in the accidents involving one-box vehicles and passenger cars. Head impact time appears to be an inverse proportional to the vehicle impact velocity for both types of vehicles.

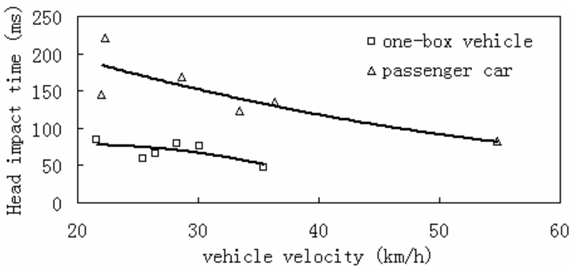
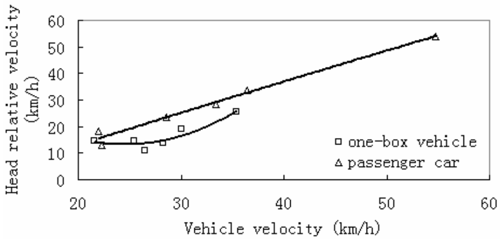


Figure 10. Head impact time versus vehicle velocity

The time of head impact to one-box vehicle is much smaller than that to passenger car at the same vehicle impact velocity. It is due to the flat front of one-box vehicle, the head is impacting to vehicle immediately after the first contact; while in accidents with passenger car head impact occurs later after rotation movement of pedestrian. Therefore, the head impact time is strongly influenced by the front shape of vehicle.



Figures 11. Relationship between head-impact relative velocity and vehicle velocity

Figure 11 shows the difference of the relationship between head-impact relative velocity and vehicle velocity for the two types of vehicles. The head relative velocity in cases of one-box vehicle is lower than that in passenger car. In impacts the one-box all the values of head relative velocity are lower than the initial velocity. It is clear that the relative head velocity is different between the two types of vehicle.

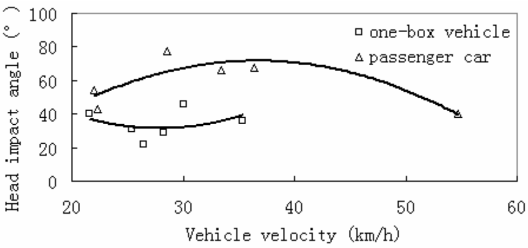


Figure 12. Relationship between head-impact angle and vehicle velocity

Figure 12 shows the relationship between head impact angle and vehicle velocity for the two types of vehicles. Head impact angle in cases of one-box vehicle are smaller than that in cases of passenger car. In the case of one-box vehicle and passenger car the head impact angle seems not be dependent to velocity.

Figure 13. Relationship between throw out distance and vehicle velocity

The difference of the relationship between vehicle impact speeds and throw distance in accidents with the two types of vehicles is presented in Figure 13. The pedestrian throw out distance in the cases involving one-box vehicle is larger than that for passenger car. This distance is increasing with the vehicle velocity.

3.2 Differences of head injuries

The differences of HIC between the two types of the vehicle that caused by the front of car are compared in Figure 14. HIC values from reconstructions of one-box vehicle accidents are lower than these of passenger cars, especially at high impact speed. Generally, all calculated values of HIC from reconstructions of one-box vehicle accidents are below 500. Therefore, the front part of one-box isn't the main cause of pedestrian head injury.

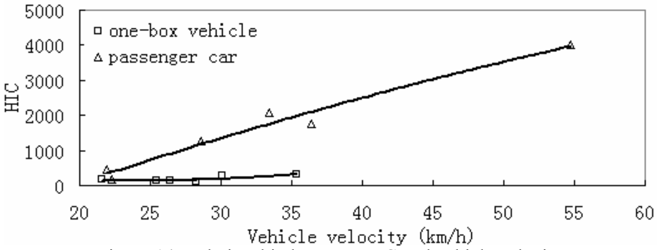


Figure 14. Relationship between HIC and vehicle velocity

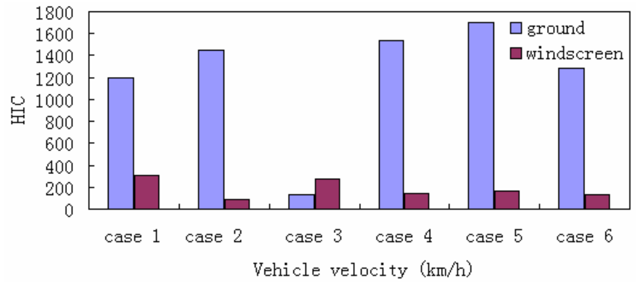


Figure 15. HIC at impact to the ground and windscreen

HIC calculated in reconstructions of one-box vehicle accidents in contact with windscreen and ground respectively are compared in Figure 15. HIC value in head-ground impacts is much higher than that caused by head-windscreen impact except case 3. Reconstruction of case 3 indicated that pedestrian was thrown forward and followed to the ground such a way that lower extremity contacted the ground first, then the upper torso and finally the head. Therefore, HIC value from head-ground impact of this case is low.

The maximum values of head injury related parameters calculated from pedestrian accident reconstructions involving the two types of vehicle are presented in Table 1 and Table 2, respectively. The corresponding head-brain injuries from accidents are summarized in Table 3.

Table 1. Results from accident reconstructions (one-box)

Injury parameter	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
HIC	1198.9	1452.2	132.4	1537.6	1706.0	1282.1
HLAC [g]	337	306	111	300	253	239
HAA[rad/s^2]	41826	42498	8458.1	43104	18109	25974

Table 2. Results from accident reconstructions (passenger car)

Injury parameter	Case 7	Case 8	Case 9	Case 10	Case 11	Case 12
HIC	1281.2	463.25	168	3998.0	1746.3	2081.3
HLAC [g]	244	123	56	313	217	227
HAA [rad/s^2]	30400	15300	3899.0	40090	19350	9352

Table 3. Summary of head-brain Injuries

One-box vehicle	Injuries	Passenger car	Injuries
Case 1	scalp laceration	Case 7	cerebral concussion
Case 2	cerebral contusion, subarachnoid hemorrhage, skull fracture at right orbit nasal bone fracture	Case 8	cerebral concussion
Case 3	scalp haematoma	Case 9	scalp haematoma
Case 4	severe closed head injury	Case 10	acute closed head injuries, right subdural haematoma, left temporal lobi occipitalis contusion, scalp laceration
Case 5	subdural haematoma, skull fracture, cerebral hernia	Case 11	closed head injuries, right Subdural haematoma, right temporal lobi occipitalis contusion, subarachnoid hemorrhage, basal fracture, scalp laceration
Case 6	head trauma	Case 12	cerebral concussion

Table 1 and Table 2 show that the values of head linear acceleration (HLAC) and head angular acceleration (HAA) from reconstructions of one-box-pedestrian accidents are larger than these from pedestrian accidents involve passenger cars.

According to Yang [16] common head injury patterns are skull damage and cerebral injuries. Skull damage mainly is in form of the fracture. Cerebral injuries can be divided into concentrated and diffused. Concentrated cerebral injuries include contusion (Coup contusions and Contrecoup contusions), intracranial haematoma (subdural and subarachnoid) etc. The cause of concentrated cerebral injuries is mainly linear acceleration and angular acceleration. Diffused cerebral injuries include concussion and diffuse axonal injury (DAI).

All the cerebral injuries in one-box-pedestrian cases, see Table 3, belong to concentrated cerebral injuries. This corresponds to our calculation results of HLAC and HAA. In the cases of passenger car accidents the injury pattern is different. Almost in all cases we could find cerebral injuries that were of diffused character.

4 Discussion

In current study efforts have been made to compare the difference of pedestrian kinematics and head-brain injuries in pedestrian accidents involving one-box vehicles and passenger cars.

From the results of accidents reconstruction, it is confirmed that the vehicle front shape affected pedestrian kinematics severely.

The head impact time is different in the accidents involving the two types of vehicles. At the same vehicle impact velocity this time is much smaller in accidents involving one-box vehicles than that of passenger cars. Therefore, we should take this difference into consideration in design of safety devices such as A-pillar airbag or windscreen airbag. To reduce head-brain injuries of pedestrian in one-box vehicles, we must trigger these airbags earlier than in passenger cars.

The head impact relative velocity is influenced by the front shape of the vehicle. Due to the flat front, one-box vehicles impact to the whole body of pedestrian almost at the same time. Therefore, the whole body of pedestrian is pushed forward and the relative velocity of the head in relation to the vehicle is reduced. However, in the accidents involving passenger cars, the car always impact to the lower extremity first. In all the reconstructions of these accidents we could observe that after the first contact, the upper torso of pedestrian rotates toward the hood and windscreen of the car. After then, the whole body is pushed forward by passenger car. During this rotational movement of the upper body, the head impact relative velocity increases with the component velocity of head in vertical direction, then the head impact relative velocity decreases due to the component velocity of head in direction of impact. These are consistent with result found by Mizuno and Kajzer [9].

The front shape of vehicle also affects the head impact angle severely. In the study we found that head impact angle in cases of one-box vehicle are smaller than that in cases of passenger car. This is because in passenger car-pedestrian accidents the pedestrian head can gain a big vertical component of velocity during the rotation movement. But in one-box-pedestrian accidents, the translational movement dominates pedestrian kinematics and the pedestrian head just get low velocity in vertical direction. We also can find from the study that the head impact angle not depends on velocity; this is because it is influenced not only by impact speed but also by pedestrian height and car front structure. A single factor such as vehicle velocity could not determine the impact angle of the head.

The pedestrian throw out distance is also different in the accidents involving the two types of vehicle. This is due to the different movement of pedestrian in such accidents. From the reconstruction of accidents involving one-box vehicles we could observe that the translational movement is dominant, the whole body of pedestrian gains a large velocity component in direction of impact because is pushed forward directly after impact. However in the accidents involving passenger cars, the pedestrian's upper body rotates against the vehicle, and this rotational movement is dominant. The velocity component in impact direction, which pedestrian is exposed, is less than that in one-box-pedestrian accidents. Although the time pedestrian fly in the air is small in the one-box-pedestrian accidents, the velocity component in impact direction is the main factor that influences the throw out distance. Therefore, the pedestrian throw out distance in the cases involving one-box vehicle is larger than that for passenger car. According to this, the formula that uses throw out distance to estimate the impact velocity of passenger car should be modified when used in one-box-pedestrian accident cases.

The causes of head injuries are also affected by front shape of vehicle. In one-box-pedestrian accident cases fatal and severe head injuries are frequently caused by head-ground impact. However, in cases of passenger car-pedestrian accident, fatal and severe head injuries are most frequently caused by head-vehicle impacts; this is consistent with result found by Yang [16]. Therefore, it is necessary to pay more attention to the secondary impact in discussions about head-brain injuries in the accidents involving one-box vehicles.

Due to the differences in kinematics of pedestrian in accidents involving the two types of vehicle, the cerebral injuries are also different. In one-box accidents, the pedestrian cerebral injuries mainly manifested as concentrated; while in the accidents with car the pedestrian suffered not only concentrated cerebral injuries, but also diffused cerebral injuries.

5 Conclusions

The difference of pedestrian kinematics and the head-brain injuries pedestrian suffered in the accidents involving one-box vehicles and passenger cars was compared based on the accidents reconstruction.

From the results of accidents reconstruction, it is confirmed that the vehicle front shapes affected the head kinematics response parameters such as head relative velocity, impact time, angle, and throw out distance strongly.

The results of accident reconstructions also show that the ground is found to be the main cause of head injuries in one-box-pedestrian accidents, while severe injuries are most often caused by head-bonnet or head-windscreen frame impact in accidents with passenger car. The type of cerebral injuries pedestrians suffered is also different between the two kinds of accidents.

The results of reconstructions can provide background knowledge about the kinematics of pedestrian in real accidents, causes of head-brain injuries and can be used in development of pedestrian protection countermeasures for the vehicle with high profile of frontal structures.

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