A Study on Injuries and Kinematics in Pedestrian Accidents involved Minivan and Sedan

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Abstract-The paper aims to study the injury risk and kinematics of pedestrians involved in different passenger vehicle collisions. Furthermore, the difference of pedestrian kinematics in the accidents involved minivan and sedan was analyzed. The 18 sample cases of passenger car to pedestrian collisions were selected from the database of In-depth Investigation of Vehicle Accident in Changsha of China (IVAC) , of which the 12 pedestrian accidents involved in a minivan impact for each case, and the 6 accidents in a sedan impact for each. The selected cases were reconstructed by using mathematical models of pedestrians and accident vehicles in a multi-body dynamic code MADYMO environment. The logistic regression models of the risks for pedestrian AIS 3+ injuries and fatalities were developed in terms of vehicle impact speed by analyzing the minivan-pedestrian and sedan-pedestrian accidents. The difference of pedestrian kinematics was identified by comparing the results from reconstructed pedestrian accidents between the minivans and sedans collisions. The result shows that there is a significant correlation among the impact speed and the severity of pedestrian injuries. The minivan poses greater risk to pedestrian than sedan at the same impact speed. The kinematics of pedestrian was greatly influenced by vehicle front shape.

Key Word: pedestrian injury; kinematics; MADYMO; logistic regression model

1 BACKGROUND

An overwhelming majority of traffic injuries involve vulnerable road users such as pedestrian especially in developing countries. In China more than 16,000 pedestrians died in road traffic accidents in 2010, accounting for approximately 25% of all traffic fatalities [1]. In recent years, owing to the lower price of the minivans, the sales of minivan in China increased rapidly. According to the statistic report of China Association of Automobile Manufacturers (2009), the sales volume of the cross type passenger vehicle (mainly made up by minivans) was more than 1.9 millions, which increased 83.39% compared to the same time in last year **Fehler! Verweisquelle konnte nicht gefunden werden.**. The increase of the minivans makes that the study of pedestrian safety involving minivans become more and more important. A lot of researches were made about dynamic response and injuries based on sedan to pedestrian collisions [3-6]. However, the injury and dynamic response in minivan-pedestrian accidents are different from that of sedan-pedestrian.

The purpose of this study is to provide some basic information for use in mitigating pedestrian's injuries by comparing the injury and dynamic response under which pedestrians suffer injuries in collisions with sedans and minivans. In this paper, sedan–pedestrian and minivan-pedestrian accidents were analyzed using in-depth accidents data in Changsha. The results of the comparative analyses have made clear specific measures for pedestrian protection in sedan-pedestrian and minivan-pedestrian accidents.

2 METHODOLOGY

The sedan-pedestrian and minivan-pedestrian accidents in the statistic sample of the current paper were selected from IVAC (In-depth Investigation of Vehicle Accident in Changsha of China) data. The distributions of body regions of pedestrian injury in the accidents of this statistic sample were analyzed based on the data. The dynamic responses of pedestrians in sedan-pedestrian and minivan-

pedestrian accidents were compared based on the reconstruction of the accident cases, in which the detail information of vehicles, pedestrians and the scene of the accidents were recorded. The accidents reconstructions were performed in the multi-body dynamics software MADYMO. Single logistic regression analyzes were applied to study the association between pedestrian casualty and impact speed.

2.1 Statistic Sample

The sedan-pedestrian and minivan-pedestrian accidents data for this study were available from the IVAC database from 2003 to 2011. The pedestrians were older than 14, and the pedestrians injury were AIS 1+. The data used for single logistic regression analyzes were the accident cases for which the vehicle speed could be estimated. The vehicle drive speed identified in this study is the speed before braking. The vehicle collision speed is the speed of the vehicle contacting with the pedestrian. The severity of pedestrian injury in the data sample were defined to be within and more than 30 days of hospitalization and death within 24 h after a collision according to the AIS [7] (Abbreviated Injury Scale) injury severity classification standard. The injury levels AIS 3+ are serious injury.

2.2 Accidents Reconstruction

2.2.1 Examples of accident cases

Accident case 1: a sedan to pedestrian accident.

A male pedestrian was impacted by a Honda Civic at speed about 70 km/h. The car was driving from south to north and the pedestrian was running to cross the road from west to east. The driver did not notice the pedestrian until the collision happened. The contact dents were visible on the bonnet and the windscreen was smashed by the pedestrian's head. The contact dents were identified as the result of the pelvis and upper torso impact, and the cracks on windscreen were due to head impact (Figure 1). The pedestrian was 80 years old, 168cm, and 45kg. The pedestrian was seriously injured on the brain and lower limbs, including particularly severe brain injury and brain herniation (AIS 6), tibia fracture, and fibula fracture of the right side (AIS 3).

Figure 1. The vehicle (Honda Civic) after the accident of sedan-pedestrian

Accident case 2: a minivan to pedestrian accident.

A Dongfeng minivan collided with a male pedestrian, the collision velocity is about 30 km/h. Before the accident, the vehicle was driving from east to west and the pedestrian was running to cross the road from south to north. The driver applied the emergency brake, when he found that the pedestrian was in the front of the vehicle only for few meters. Unfortunately, the pedestrian was still impacted by the front of vehicle. The front panel of the minivan was dented significantly by the pedestrian's pelvis and the middle of the windshield was smashed by the pedestrian's head (Figure 2). Field measurement of the left front wheel braking distance was 7.32m (Figure 3).The pedestrian was 28 years old, 171cm,

and 50kg. Throw distance of the pedestrian was about 9 m, and the measured wrap distance (WAD) was 1.7m. Pedestrian's main injury was record as bilateral lung contusion (AIS 4), 3rd, 5th and 6th ribs fracture (AIS 3), and right tibia fracture fractures (AIS 3).

Figure 2. The vehicle (Dongfeng) after the accident of minivan-pedestrian

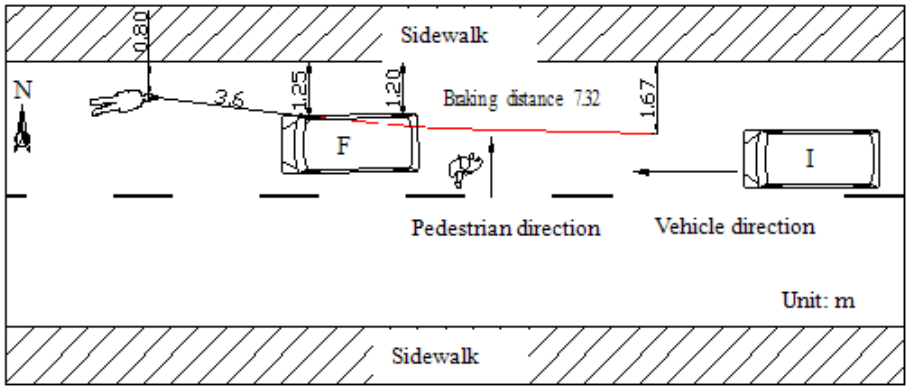
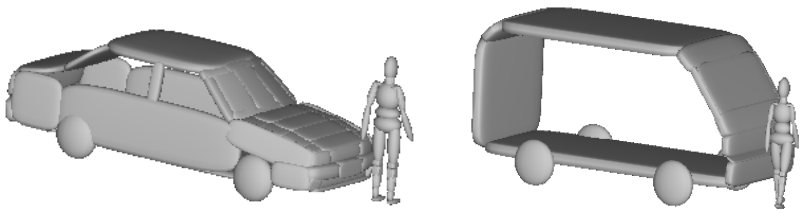


Figure 3. Sketch of the minivan-pedestrian accident scene

2.1.2 Accident reconstruction models

To identify the difference pedestrian dynamic responses and the correlation of head-injury risk and calculated physical parameters between sedans and minivans, 12 sedan cases and 6 minivans case form statistic sample were reconstructed. The validated pedestrian model was used in the reconstruction [9]. The mathematical models of minivans and sedans were created based on the drawing of the vehicle involved in the accidents. As shown in Figure 4 are two vehicle -pedestrian reconstruction models, (a) is sedan-pedestrian model, (b) is minivan-pedestrian model. The mechanical properties of vehicle models were defined by the simplified force-deformation properties of the vehicle parts which acquired from Euro NCAP sub-system tests respectively [11].



(a) (b)

Figure 4. Vehicle-pedestrian reconstruction models (a. sedan-pedestrian; b. minivan-pedestrian)

2.2 Logistic Regression Method

A single logistic regression model of the risks for pedestrian casualty was developed in terms of vehicle impact speed. The corresponding risk function $P(v)$ is

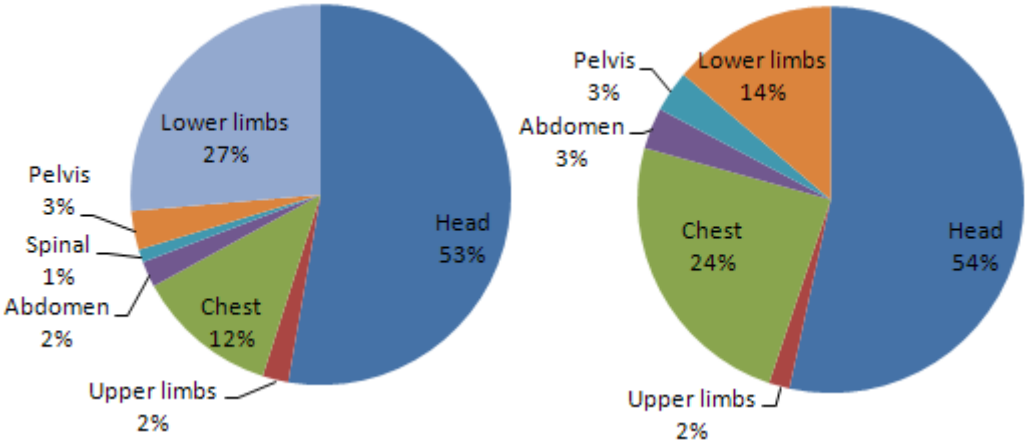
$$P(v) = \frac{1}{1+\exp(-a-bv)} \tag{1}$$

Where v is the impact speed, and the coefficients a and b are estimated using the method of maximum likelihood method. The Wald Chi-Square test was used to validate whether the impact speed had a statistically significant relationship with risks of pedestrian casualty. First, a null hypothesis was established, assuming that factors such as impact speed had no effect on the risk of pedestrian casualties. Second, the values of Chi-Square and p were calculated. If the p value is lower than 0.05, the impact speed or pedestrian age has a statistically significant relationship with the risk of pedestrian casualty [13].

3 RESULTS

3.1 Accident Data Analysis

The distributions of the primary body regions of the serious injuries sustained by pedestrians in sedan-pedestrian and minivan-pedestrian accidents are shown in Figure 5 (a) and (b). More than 50% of the serious injuries are to the head when the collision of pedestrian to sedan or minivan. About 27% of the serious injuries are to the lower limbs in the case of sedan-pedestrian, while only 14% to this body region in minivan-pedestrian accidents. Another difference for the distributions is that the number of serious chest injuries is much smaller in collisions of pedestrians with sedans than in collisions with minivans, 12% to 24%.



(a) (b)

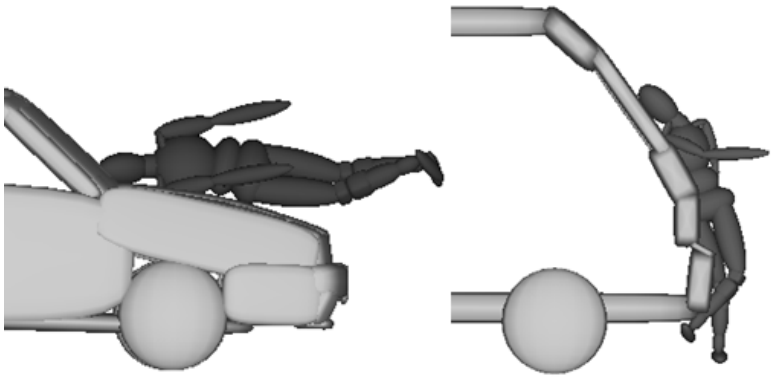
Figure 5. Distributions of the primary body regions of the serious injuries by pedestrians (a. sedan-pedestrian; b. minivan-pedestrian)

3.2 Pedestrian dynamics response

The impact behaviour and head impact speed of the pedestrian in the collision with sedan and minivan were compared using accident reconstruction. Figure 6 shows the impact behaviour of a sedan-pedestrian accident and a minivan-pedestrian accident. In the collision with the sedan, after the front of the vehicle impacts the pedestrian's leg, the pedestrian goes onto the bonnet and slides over it when the hip contact the bonnet. Then the upper body then rotates and the head strikes the windscreen area or the front part of the roof. While in the case of minivan, the hip and chest of the pedestrian will

impact with the front of the minivan as the time of the vehicle impacts the pedestrian's leg, and then the head strikes the windscreen area. There is no obvious rotates in the upper body.

As shown in Table 1, is the relationship of the head impact speed to the vehicle collision speed. The minivan collision speed is much higher than the head impact speed for all the five cases. While the sedan collision speed is close to the head impact speed for most of cases. For the same vehicle collision speed, the pedestrian head relative speed in sedan-pedestrian accidents is higher than that of the minivan-pedestrian accidents.



(a) (b)

Figure 6. Comparison of pedestrian collision behaviour for sedan-pedestrian and minivan-pedestrian (a. sedan-pedestrian; b. minivan-pedestrian)

Table 1. Summary of head relative impact speed, vehicle impact speed and WAD

Case number	Impact speed (km/h)	Head relative impact speed (km/h)	WAD (m)
Sedan 1	21.8	18.4	1.35
Sedan 2	22.3	13.1	1.46
Sedan 3	27.0	24.0	2.10
Sedan 4	28.6	23.6	1.85
Sedan 5	30.2	27.9	1.94
Sedan 6	31.0	36.0	1.92
Sedan 7	33.4	28.3	1.65
Sedan 8	36.4	33.6	1.72
Sedan 9	40.1	33.0	1.75
Sedan 10	43.6	45.2	1.73
Sedan 11	57.6	66.6	1.93
Sedan 12	65.6	63.7	2.20
Minivan 1	35.4	25.4	1.43
Minivan 2	28.3	13.7	1.45
Minivan 3	30.1	19.1	1.55
Minivan 4	26.4	11.0	1.50
Minivan 5	29.5	16.4	1.70
Minivan 6	25.4	14.5	1.45

3.3 Logistic Regression Analysis

The logistic regression models of the risk for pedestrian AIS 3+ injuries in sedan-pedestrian and minivan-pedestrian cases were developed respectively in terms of vehicle impact speed at the 95% confidence level. The corresponding AIS 3+ injury risk $P(v)$ derived from sedans cases is

$$P(v) = \frac{1}{1+\exp(3.7751-0.0944v)} \tag{2}$$

And derived from minivans cases is

$$P(v) = \frac{1}{1+\exp(4.2251-0.1450v)} \tag{3}$$

Based on function (2), the Chi-Square test was conducted and validated the statistically significant relationship with p<0.0001, and $\chi^2 = 24.2936$. The null hypothesis was rejected. In other words, the impact speed had a statistically significant relationship with the risk of pedestrian AIS 3+ injury. Based on function (3), the value p =0.0011, and $\chi^2 = 10.6395$, indicate that this model was also acceptable. The AIS 3+ injury risk curves are generated and illustrated in Figure 7.

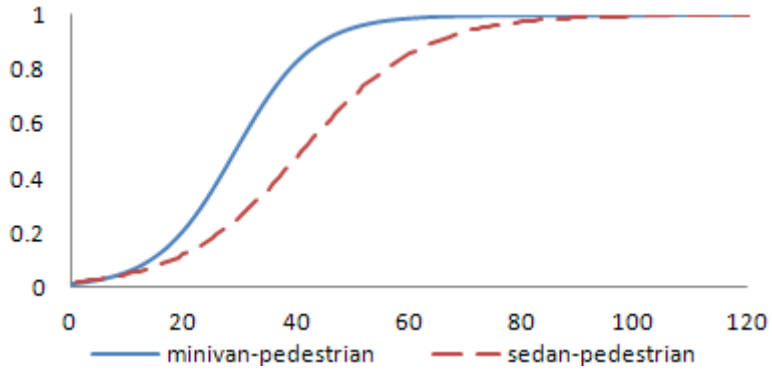


Figure 7. Comparison of pedestrian AIS3+ injury risks for sedans and minivans

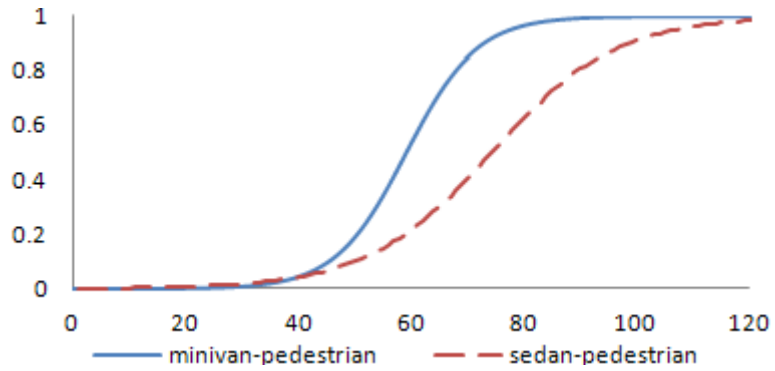


Figure 8. Comparison of pedestrian fatality injury risks for sedans and minivans

Similarly, the logistic regression models of the risk of pedestrian fatalities in minivans and sedans cases were developed in terms of vehicle impact speed using the fatalities cases selected from the statistic sample at the 95% confidence level. The corresponding fatal risk $P(v)$ derived from sedans cases is

$$P(v) = \frac{1}{1+\exp(6.6112-0.0902v)} \tag{4}$$

And derived from minivans cases is

$$P(v) = \frac{1}{1 + \exp(9.4568 - 0.1602v)} \tag{5}$$

The Chi-Square was calculated as p=0.0001, $\chi^2 = 16.0797$ based on function (4); and p<0.0001, $\chi^2 = 18.704$ based on function (5). So the impact speed had a statistically significant relationship with the pedestrian fatality risk. The fatal risk curves are generated and illustrated in Figure 8.

4 DISCUSSION

The front shape of minivan is similar to a vertical plane, when the pedestrian impacts with the minivan, the whole body parts contacts the vehicle front structure nearly at the same time. The impact load would distribute in the whole body. While in the collision of pedestrian to sedan, the impact load is only applied on the lower limbs at the beginning of the collision. So the injury risk of the lower limbs is low in the case of minivan-pedestrian than sedan-pedestrian. And in minivan-pedestrian crash pedestrian's chest impacts with the vehicle at the first time of the collision, higher load would be applied on it. While in the collision of sedan-pedestrian, the pelvis will precede the chest contact with the vehicle and the pedestrian will slide over it, which will reduce the impact load from the chest contact with the vehicle, thereby reducing the risk of chest injury.

The motion of the pedestrian approaches to a Horizontal Projectile Motion in the collision of minivan-pedestrian, the pedestrian head would be with a velocity in the direction of impact before contacting with the vehicle, and pedestrian's head strikes the windscreen area in most cases. While in sedan-pedestrian collision, the head impact velocity would much lower than the vehicle speed in the direction of vehicle driving. But a higher velocity in the direction of vertical would be applied to pedestrian's head in rotation of the upper body. And the location of pedestrian's head impacting with the sedan is in the hard place of the front part of the vehicle, such as the lower edge of the windshield. So in minivan-pedestrian accident, pedestrian's head impact velocity (relative velocity) is much lower than the minivan collision speed, while in the collision of sedan-pedestrian they are very close.

In this study, the association between impact speed and pedestrian serious injury and fatality risk is significant. The risk curve of pedestrian AIS 3+ injury (Figure 5) demonstrates that relative risk rapidly increases with impact speed, especially after the impact speed greater than 20 km/h. For sedans, equation (2) demonstrates that the risk of pedestrian AIS3+ injury is approximately 13% at an impact speed of 20 km/h, 50% at 40 km/h, and 86.9% at 60km/h. Similarity, for minivans, equation (3) demonstrated that the risk of pedestrian AIS 3+ injury is approximately 21% at an impact speed of 20 km/h, and 83% at 40 km/h-nearly 4 times higher than the risk at 20km/h. Furthermore, from Figure 6, we can see that the fatality risk for pedestrians in minivans accidents and sedans accidents was the same when the impact speed lowers than 40 km/h. For more than 40 km/h, the relative risk increases rapidly with impact speed. When the impact speed reached to 80km/h, the risks were 96.6% for minivans, while for sedans is only 64.7%. So, the minivans are with higher injury risk than the sedans. It is very useful to limit the vehicles' driving speed to decrease the pedestrian casualties.

5 CONCLUSIONS

In the current paper, the statistical analysis of the sedan-pedestrian and minivan-pedestrian accidents was conducted based on IVAC database. The differences of pedestrian dynamic response in sedan-pedestrian and minivan-pedestrian accidents were analyzed by comparing the accident reconstruction results. The relationship of pedestrians seriously injured and the risk of death to the vehicle collision speed was analyzed based on the accidents data. The principal findings and conclusions of this study are summarized below.

1. The pedestrian's head injury is a major factor to cause pedestrian seriously injured in the accident. In sedan-pedestrian accident, pedestrian's lower extremity is vulnerable. In minivan-pedestrian accident, pedestrian's chest is in higher injury risk.

2. The kinematics of pedestrian is greatly influenced by vehicle front shape. For minivan-pedestrian accidents, the pedestrian's head relative speed is much lower than the vehicle collision speed; for sedan-pedestrian collisions, the relative collision velocity of the pedestrian head is close to the vehicle collision speed.

3. Vehicle collision speed was significantly associated with the pedestrian of AIS 3+ injury and fatal risk. The pedestrians in minivan-pedestrian accidents are with higher risk of serious injuries and death than that of sedan-pedestrian in the same collision speed.

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