A Study of Fatality Risk and Head Dynamic Response of Cyclist and Pedestrian Based on Passenger Car Accident Data Analysis and Simulations

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Objective: The current study aims to compare the fatality risk of pedestrians and cyclists in urban traffic through an analysis of real-world accident data in China.

Methods: First, 438 cases, including 371 pedestrian cases and 67 cyclist cases, were selected as a sample from the accidents collected through an in-depth investigation of vehicle accidents in China. A statistical measurement of the fatality risk with respect to impact velocity was carried out using a logistic regression analysis. Furthermore, 21 pedestrian and 24 cyclist accidents were selected for reconstruction with the MADYMO program. A comparative analysis was conducted based on the results from accident analysis and simulations for the fatality risk and head dynamic response of pedestrians and cyclists.

Results: The results indicate that the vehicle impact velocity has a significant relationship with the fatality risk of both pedestrians and cyclists. The fatality risks at 50 km/h are more than twice as high as the risk at 40 km/h and about 5 times as high as that at 30 km/h for both pedestrians and cyclists. Moreover, cyclists suffered slightly lower fatality risk compared to pedestrians. The corresponding vehicle impact velocity is 65.4 km/h for pedestrian with a fatality risk of 50 percent, whereas for cyclists it is 67.6 km/h. In addition, the head impact conditions between pedestrians and cyclists are different.

Conclusions: These findings offer potential contributions for establishing a more reasonable speed limit for urban traffic in China and generating strategies for cyclists’ and pedestrians’ head protection.

Keywords: pedestrian, cyclist, fatality risk, head dynamic response

Introduction

As vulnerable road users, pedestrians and cyclists represent a population with a high risk of traffic fatalities and injuries because they are unprotected in vehicle collisions. In 2010, traffic accidents in China included 16,281 reported fatalities for pedestrians and 4616 for cyclists based on police data (Traffic Administration Bureau of China 2011). The total number of killed pedestrians and cyclists accounted for 32 percent of all traffic fatalities, which indicated a high risk of unprotected pedestrians and cyclists in public transportation in China. Therefore, it is vital to conduct in-depth investigations of the injury risk and mechanisms of such vulnerable road users in order to prevent accidents and injuries.

To date, many foreign studies focusing on the casualty risk of pedestrians and cyclists in traffic accidents have been carried out. Using a comparative analysis of vehicle–cyclist and vehicle–pedestrian accidents in Japan, Maki et al. (2003) found that cyclists were involved in only about 20 percent as many fatal accidents as pedestrians, and the cumulative frequency of cyclist and pedestrian fatalities in terms of vehicle velocity are similar in accidents involving both bonnet-type vehicles and minivans. Based on a subsample of 402 pedestrians and 940 cyclists from the GIDAS database, Peng et al. (2012) found that the percentage of collisions occurring at lower impact velocity is greater for cyclists than for pedestrians, and both the head Abbreviated Injury Scale (AIS) 2+ and AIS 3+ injury risks for cyclists are lower than that of pedestrians. Through a series of finite element (FE) simulations using 2 Total Human Model for Safety pedestrian models and 4 FE vehicle models with different front-end shape, Han et al. (2012) found that vehicle impact velocity has the most significant influence on injury severity for adult pedestrians. In China, the pedestrian casualty risk in terms of vehicle impact velocity has been quantitatively determined using logistical regression analyses based on 104 pedestrian accident cases (Kong and Yang 2010).
Cyclist and Pedestrian Fatality Risk

However, the exposure of cyclists in public transportation has never been measured quantitatively using real-world accident data in China. As approximately 6 million cyclists ride on roads daily in China (Yan et al. 2011), the exposure of cyclists—who are also a kind of vulnerable road user, like pedestrians—needs to be measured quantitatively using real-world accident data for comparison with data of pedestrians to generate strategies for vulnerable road user protection, such as setting appropriate velocity limits for urban traffic.

Head injuries of cyclists have been shown to be the main causes of death, which is similar to that of pedestrians, although the head impact location of cyclists and pedestrians against bonnet-type vehicles is different (Maki et al. 2003). In recent years, many studies have focused on the dynamic responses of adult and child pedestrians in vehicle collisions (Crandall et al. 2006; Han et al. 2011; Liu and Wagner 2002; Liu and Yang 2003). Pedestrian head impact conditions such as head impact time and resultant velocity are different when colliding with different front-end shape vehicle (Han et al. 2012). Li and Yang (2010) investigated the head kinematics and injuries in 6 real-world car–pedestrian accidents collected through an in-depth investigation in China. The results of this study offer some guidance, but the correlation between head kinematic parameters and injury severity cannot be clearly identified due to the limited number of cases. Moreover, due to the different postures between pedestrians and cyclists before the impact, the head impact conditions of pedestrians and cyclists, including impact time, impact velocity, and impact angle, should be further investigated and compared. Therefore, research on safety issues facing pedestrians and cyclists using real-world accident data from in-depth investigation is limited and seldom compared with other studies in China.

The current study quantitatively measures the fatality risk of pedestrians and cyclists in urban traffic in China through the analysis of real-world accident data. The data set selected for the study was based on real-world traffic accident data collected from several cities in China through in-depth investigations. Logistic regression analyses were conducted using the data set to find the risk function for pedestrians’ and cyclists’ fatalities related to the vehicle impact velocity. Furthermore, the head impact conditions are investigated for the protection of both pedestrians and cyclists from traffic accidents using accident reconstructions. The knowledge developed from this study would be a prerequisite for generating strategies for pedestrians’ and cyclists’ protection from vehicle collisions in China.

Methods and Materials

Data and Criteria of Selection

The original data set in the current study was sampled from pedestrian and cyclist accidents in several cities, including Changsha, Beijing, and Ningbo. The sample criteria were as follows: (1) the accidents occurred between 2003 and 2010; (2) the first contact point between the vehicle and bicycle/cyclist was located on the front of the car; (3) the age of the cyclist/pedestrian was above 14; (4) the pedestrian/cyclist must have suffered AIS 1+ injuries; (5) the accident vehicle must have been a passenger car; (6) the vehicle impact velocity could be estimated; (7) each accident involved only one passenger vehicle and one pedestrian/cyclist; and (8) the pedestrian/cyclist had to be in a normal walking or riding posture (pedestrians lying on the ground or cyclists standing on the ground with a bicycle prior to impact were excluded). A total of 438 cases (371 pedestrian cases and 67 cyclist cases), including 51 pedestrian fatalities and 8 cyclist fatalities, was selected as a sample for quantitatively studying the fatality risk of pedestrians and cyclists in China. The pedestrian fatality risk from other countries was used to draw comparisons with this study. Table 1 presents the distributions of pedestrian and cyclist injuries and fatalities for the final sample in this study.

| Sample                  | Injury (%) | Fatality (%) |
|-------------------------|------------|--------------|
| Final sample (pedestrians) | 86.3       | 13.7         |
| Final sample (cyclists)  | 88.1       | 11.9         |

Impact Velocity Estimation

For determination of vehicle impact velocity, 4 methods were used in this study. The first method considered the skid mark available from accident investigations. In this case, vehicle impact velocity \( v \) in kilometers per hour can be estimated according to the formula

\[
v = 3.6 \times \sqrt{2ugL},
\]

where \( u \) is the friction coefficient (\( u \) equals 0.7 for a dry road surface and 0.6 for a wet road surface (Z. X. Yang 2002); \( g = 9.8 \) m/s\(^2\); and \( L \) is the distance of the skid mark in meters. The second method is based on thrown out distance of pedestrians and cyclists. Vehicle impact velocity \( v \) in kilometers per hour can be estimated according to the empirical formula:

\[
v = 3.6 \times \sqrt{2aw},
\]

where \( w \) is the throw-out distance (TOD) of the pedestrian/cyclist in meters, \( a \) is the average deceleration and the value equals 7.0 and 6.0 for pedestrians and cyclists, respectively (Otte 2004). In the third method, the impact velocity can be calculated through accident reconstructions using MADYMO (Yao et al. 2008). The fourth method was based on interviews with the driver, pedestrian/cyclist, and other eyewitnesses. In these cases, vehicle impact velocity can be derived from interviews with these 3 groups. If the bias of the estimated values is smaller than 10 km/h, the estimated impact velocity is equal to the mean of their estimated velocity. Otherwise, the cases will be rejected.
velocity. The corresponding risk function \( P(v) \) is shown as Eq. (3):

\[
P(v) = \frac{1}{1 + \exp(-\alpha - \beta v)},
\]

(3)

where \( v \) is the impact velocity, and the 2 parameters \( \alpha \) and \( \beta \) are estimated using the method of maximum likelihood (Dobson 2002).

Wald’s chi-square test with 95 percent confidence intervals was used to validate whether the impact velocity had a statistically significant relationship with risks of pedestrian casualty. The chi-square \( (\chi^2) \) and \( P \) values were calculated, and the \( P \) value was associated with \( \chi^2 \). If the \( P \) value was lower than .05, the impact velocity had a statistically significant relationship with the risk of pedestrian casualty.

**Accident Reconstruction**

**Examples of Car-to-Pedestrian Accident**

A 26-year-old male adult pedestrian was hit by a Buick Excelle (2006 model) at a velocity of about 60 km/h. The car was driving from east to west, and the pedestrian was running to cross the road from south to north. The driver did not notice the pedestrian until the collision happened. The contact dents and cracks were visible on the leading edge of the hood, the hood top, and windscreen. The contact dents were identified as a result of the pelvis and upper torso impact, and the cracks on the windscreen were due to the head impact (Figure A1, see online supplement). The measured wrap distance (WAD) was 1980 mm.

The entire length of the skid mark was about 8.2 m. The TOD of the bicyclist and bicycle were about 5.5 and 6.5 m, respectively. The windscreen was damaged due to the head and upper torso impact (Figure A2, see online supplement). The measured WAD was 1980 mm.

The cyclist sustained a cerebral concussion as well as skin and soft tissue contusions on many parts of body.

**Reconstruction Models and Simulation**

A validated pedestrian model was employed in the current study (J. K. Yang 1997; Yang et al. 2000), from which the computed models were scaled according to the real height and weight of the victim in each reconstruction using the GEBOD code in MADYMO. This model was efficiently used in previous studies of vehicle–pedestrian and vehicle–bicyclist reconstructions (Li and Yang 2010; Mo et al. 2010).

The mathematical models for the vehicle and bicycle were developed based on a drawing of the production cars and bicycles involved in the accidents. The stiffness characteristics of the car front were defined based on the European New Car Assessment Programme test results of similar cars (Martinez et al. 2007). The relative motion between each part of the bicycle was modeled using different types of joints, and the contact stiffness properties of the bicycle model were obtained from test results (Maki and Kajzer 2001; Soden et al. 1986). The initial velocity and posture of pedestrians and bicyclists were defined based on the collected accident information. Figure A3 (see online supplement) gives an example of the car–pedestrian and car–bicycle reconstruction models.

The friction coefficients were applied to various contact surfaces according to different weather and other environmental conditions (Z. X. Yang 2002). The accident reconstruction flow used in this study has been published in Kong and Yang (2010). Accident data such as contact location, WAD, and TOD of pedestrian/cyclist and bicycle between simulations and real-world accidents are compared to validate the accident reconstruction.

**Definition of Head Impact Conditions**

Head impact conditions consist of relative impact velocity relative to the car, impact angle, and impact location (J. K. Yang 2005). As shown in Figure A4 (see online supplement), the head impact velocity \( V_R \) can be calculated as Eq. (4):

\[
V_R = \sqrt{V_{RX}^2 + V_{RY}^2 + V_{RZ}^2}.
\]

(4)

where \( V_{RX} \) is the horizontal component of head velocity relative to the car and \( V_{RZ} \) is the vertical component of head velocity relative to the car. Head impact angle \( \alpha \), as represented in Eq. (5), is defined as the head’s resultant velocity
Cyclist and Pedestrian Fatality Risk

Table 2. Summary of epidemic data for pedestrian cases

| Velocity (km/h) | Case number | Fatalities | Rate (%) |
|----------------|-------------|------------|----------|
| 0–9            | 2           | 0          | 0        |
| 10–19          | 15          | 0          | 0        |
| 20–29          | 54          | 0          | 0        |
| 30–39          | 107         | 4          | 3.7      |
| 40–49          | 77          | 11         | 14.3     |
| 50–59          | 58          | 5          | 8.6      |
| 60–69          | 27          | 10         | 37       |
| 70–79          | 22          | 13         | 59.1     |
| 80–89          | 6           | 5          | 83.3     |
| 90+            | 3           | 3          | 100      |

The head impact location was estimated using WAD along the car’s front surface, as shown in Figure A4.

Results

Statistical Analysis Results

The proportion of pedestrian accidents and cyclist accidents observed at different impact velocity intervals is presented in Figure 1.

As Figure 1 indicates, the distribution of vehicle impact velocity for pedestrian and cyclist cases is similar. Approximately 50 percent of both pedestrian and cyclist accidents occurred at a vehicle impact velocity below 40 km/h, whereas only 8.3 percent of pedestrian accidents and 7.5 percent of cyclist accidents happened at a high velocity (e.g., over 70 km/h). The average impact velocity for pedestrian accidents and cyclist accidents is 43.6 and 41.9 km/h, respectively.

The number of pedestrians and cyclists as well as their fatality rates observed at different impact velocity intervals are presented in Tables 2 and 3, respectively.

Logistic regression analysis was applied to fit an analytical function to the weighted fatality rates of pedestrians and cyclists at all observed impact velocities. The resulting fatality risk functions for pedestrians and cyclists are presented in Eqs. (6) and (7), respectively, where the vehicle impact velocity \((v)\) is measured in kilometers per hour.

\[
\alpha = \arctan \frac{V_{KZ}}{V_{RX}}. \quad (5)
\]

Based on the functions, the statistically significant relationship was validated using a chi-square test. The values are \(\chi^2 = 98.2386\) and \(P < .0001\) for Eq. (6) and \(\chi^2 = 15.269\) and \(P < .0001\) for Eq. (7). These test results indicated that the impact velocity not only has a statistically significant relationship with the fatality risk of the pedestrian but also has a statistically significant relationship with that of the cyclist. Some detailed results of the logistic regression analysis are shown in Table 4.

The curves of fatality risk function for the pedestrian and cyclist are also displayed in Figure 2. The pedestrian and cyclist fatality risk trends are very similar, and both of them increase with vehicle impact velocity. Zooming in on the fatality risk curves of the pedestrian and cyclist at vehicle impact velocity below 60 km/h (Figure A5, see online supplement), we see that the absolute risk of a cyclist is somewhat smaller than that of a pedestrian. The corresponding fatality risk of pedestrians and cyclists at a vehicle impact velocity of 40 km/h is 5.2 and 4.2 percent, respectively; these rates increase to 25.8 and 22.6 percent, respectively, when the vehicle impact velocity reaches 60 km/h.

Table 3. Summary of epidemic data for cyclist cases

| Velocity (km/h) | Case number | Fatalities | Rate (%) |
|----------------|-------------|------------|----------|
| 0–9            | 0           | 0          | 0        |
| 10–19          | 6           | 0          | 0        |
| 20–29          | 15          | 0          | 0        |
| 30–39          | 14          | 0          | 0        |
| 40–49          | 10          | 0          | 0        |
| 50–59          | 10          | 3          | 30       |
| 60–69          | 7           | 3          | 42.9     |
| 70–79          | 3           | 1          | 33.3     |
| 80–89          | 2           | 1          | 50       |

Table 4. Results from logistic regression analysis

|         | \(\alpha\) | \(\beta\) | Standard error | \(P\) value |
|---------|------------|-----------|----------------|-------------|
| Pedestrian | -5.576    | 0.092     | 0.0121         | <.0001      |
| Cyclist  | -6.929     | 0.095     | 0.0307         | <.0001      |

The fatality risk function derived for pedestrians is

\[
P(v) = \frac{1}{1 + \exp (6.576 - 0.092v)}. \quad (6)
\]

The fatality risk function derived for cyclists is

\[
P(v) = \frac{1}{1 + \exp (6.929 - 0.095v)}. \quad (7)
\]

Based on the functions, the statistically significant relationship was validated using a chi-square test. The values are \(\chi^2 = 98.2386\) and \(P < .0001\) for Eq. (6) and \(\chi^2 = 15.269\) and \(P < .0001\) for Eq. (7). These test results indicated that the impact velocity not only has a statistically significant relationship with the fatality risk of the pedestrian but also has a statistically significant relationship with that of the cyclist. Some detailed results of the logistic regression analysis are shown in Table 4.

The curves of fatality risk function for the pedestrian and cyclist are also displayed in Figure 2. The pedestrian and cyclist fatality risk trends are very similar, and both of them increase with vehicle impact velocity. Zooming in on the fatality risk curves of the pedestrian and cyclist at vehicle impact velocity below 60 km/h (Figure A5, see online supplement), we see that the absolute risk of a cyclist is somewhat smaller than that of a pedestrian. The corresponding fatality risk of pedestrians and cyclists at a vehicle impact velocity of 40 km/h is 5.2 and 4.2 percent, respectively; these rates increase to 25.8 and 22.6 percent, respectively, when the vehicle impact velocity reaches 60 km/h.

Fig. 2. Pedestrian and cyclist fatality risk curves (pedestrians: \(N = 371\), cyclists: \(N = 67\)).
**Comparison of Pedestrian Fatality Risk**

The pedestrian fatality risk curves acquired from the studies of Kong and Yang (2010), Rosén and Sander (2009), and Oh et al. (2008, 2009), are presented in Figure 3 to make comparisons with the results of this study. These studies show that the pedestrian fatality risk can be expressed as a function of the passenger car’s impact velocity; in addition, a significant relationship exists between vehicle impact velocity and pedestrian fatality risk. The pedestrian fatality risk increases sharply at impact velocity of 40 km/h or faster, as indicated in Figure 3. Moreover, the pedestrian fatality risk is different among these studies, and the risk calculated based on the pedestrian accident data of Korea and China is larger than that from GIDAS data in Germany.

**Accident Reconstruction Results**

The location of the head impact point on the vehicle greatly affects the head injuries of pedestrians and cyclists because of the different amounts of stiffness. Figure 4 shows the distribution of head impact points on the bonnet, windscreen, and screen frame. For pedestrians, the head struck the bonnet, lower part of the windscreen, or screen frame, whereas most of head impact points occurred on the middle and upper parts of the windscreen for cyclists. The average WAD values for pedestrians and cyclists are 1819 and 1972 mm, respectively. Figure 4 also obviously indicates that head collisions with the windscreen frame and locations close to the frame are more likely to result in serious injuries (AIS 3+).

As shown in Figure 5, the ratios of WAD to the height of pedestrians and sitting height of cyclists present a rising trend with the increase of vehicle impact velocity. However, the growth rate of the ratios for cyclists is obviously larger than that for pedestrians. The WAD ratios to the height of pedestrians are distributed in the range of 1.0 to 1.4, and that of cyclists are in the range of 1.0 to 1.7.

The head impact time was defined as the length of time during the first contact of the human body and head contact with the vehicle. Figure 6 shows that the head impact time for both the pedestrian and cyclist appear to be an inverse proportion to the vehicle impact velocity. Strong correlations were found between the head impact time and vehicle impact speed, with the calculated correlation coefficients ($R^2$) of 0.827 and 0.638 for pedestrian and cyclist, respectively. The pedestrian head impact time varies from 82 to 221 ms and the range for the cyclist is from 110 to 200 ms. The cyclist head impact time usually occurs later compared to that of pedestrian in accidents under similar impact conditions.

Figure 7 shows the correlation of the head’s relative impact velocity of both pedestrians and cyclists to vehicle impact velocity. It can be seen from the figure that the head’s relative impact velocity of both pedestrians and cyclists increases with an increase in vehicle impact velocity. There is a strong correlation for both of them, with $R^2 = 0.839$ and $R^2 = 0.863$, respectively. The ratios of the cyclist’s head relative impact velocity to vehicle impact velocity range from 0.6 to 1.1, and these ratios in most cases are smaller than 1. For pedestrians, the ratios of the head’s relative impact velocity to vehicle impact velocity are distributed in the range of 0.6 to 1.2, which is similar to that of cyclists. However, the ratios of the pedestrian head relative impact velocity to vehicle impact velocity in most of cases are close to 1. The average value of the vehicle impact velocity and head relative impact velocity are 40.3 and

![Fig. 3. Comparison of pedestrian fatality risk.](image)

![Fig. 4. Distribution of head impact location.](image)

![Fig. 5. Ratios of WAD to pedestrian height or cyclist sitting height.](image)
36.5 km/h for pedestrian cases and the means are 43.5 and 33.9 km/h for cyclist cases.

The head impact angle of pedestrians and cyclists can be affected by several factors, including pedestrian height/cyclist sitting height, car front structure, and impact velocity. The distribution of head impact angles for pedestrians and cyclists is presented in Figures 8a and 8b, respectively. It can be seen that the pedestrian head impact angles fluctuate between 30 and 80°, with a mean value of 59.1°, whereas those for cyclists range from 10 to 85°, with a mean value of 45.7°.

Nonlinear regression models such as quadratic polynomial function and power function are widely used to determine the relationship between vehicle impact velocity and TOD of pedestrian and cyclists (Li and Yang 2010; Rau and Otte 2001). In this study, a power function was selected to fit the data of vehicle impact velocity and TOD for all considered cases. The relationship is shown in Figure 9. The TOD of both pedestrians and cyclists grows with the increase in vehicle impact velocity. A strong correlation between TOD and vehicle impact velocity is found for cyclists with an $R^2$ of 0.86. Similarly, for pedestrians, a significant relationship between TOD and vehicle impact velocity is found, with an $R^2$ of 0.9. Figure 9 also demonstrates that the difference in TOD observed in pedestrian and cyclist cases is small when the vehicle impact velocity is less than 45 km/h. However, this discrepancy expands as vehicle impact velocity increases.

Discussion

All accidents in the final sample in the current study were collected through in-depth traffic accident investigations in
The current study found that the fatality risk of cyclists as well as pedestrians has a statistical relationship with vehicle impact velocity, although the fatality risk of cyclists is somewhat lower than that of pedestrians in passenger car–pedestrian/bicycle accidents, which coincides with the conclusion of the study by Maki et al. (2003). Regarding the fatality risk of pedestrians in the current study, the risk at 50 km/h (21.2%) is more than twice as high as the risk at 40 km/h (10.2%) and about 5 times as high as the risk at 30 km/h (4.6%). For the fatality risk of cyclists, a similar situation was found, with the risks at 50, 40, and 30 km/h being 15.7, 6.7, and 2.7 percent, respectively.

Accident reconstruction results indicated that the head impact conditions, including impact time and relative impact velocity of pedestrians, have a strong relationship with vehicle impact velocity, which concurs with the conclusions of Li and Yang’s study (2010). There is some difference in head impact time and impact locations between pedestrians and cyclists. Potential reasons include the different postures of pedestrians and cyclists before impact and different kinematic responses during the impact with the vehicle. In a collision between a passenger car and a cyclist, the cyclist slides toward the vehicle along the bonnet first, and then the head rotates to impact with the vehicle in a rearward position, whereas in a collision between a passenger car and a pedestrian, the kinematic response of the pedestrian dominates in the rotation movement. The pedestrian’s head rotates toward the vehicle and impacts the rear part of the bonnet or the lower part of windscreen directly. Therefore, the head impact time of cyclists is greater than that of pedestrians.

Figures 8a and 8b show a large variation in head impact angle values for both pedestrians and cyclists. The main reason for this phenomenon is that, besides vehicle impact velocity, the head impact angle of pedestrian and cyclist was also influenced by pedestrian height/cyclist sitting height and car front structure. Therefore, a single factor such as car velocity could not determine the trend of pedestrian and cyclist head impact angle.

Figure 4 illustrates that the TOD of both pedestrians and cyclists has a stronger correlation with vehicle impact velocity, which coincides with the results of the study by Otte (2004). The main reason for the discrepancy in TOD between pedestrians and cyclists is that the bicycle absorbs some energy during impact.

Vehicle impact velocity was shown to have a significant positive relationship with fatality risk of pedestrians and cyclists. The fatality risk of pedestrians is 5.2 percent at a vehicle impact velocity of 40 km/h, 12.2 percent at 50 km/h, 46.6 percent at 70 km/h, and 50 percent at 71.5 km/h, whereas the fatality risk of cyclists is 4.2 percent at a vehicle impact velocity of 40 km/h, 10.2 percent at 50 km/h, 43.1 percent at 70 km/h, and 50 percent at 72.9 km/h. This can provide the theoretical foundation for determining the vehicle velocity limit in areas with a high frequency of car–pedestrian accidents or car–cyclist accidents. Based on the results of the fatality risk in this study, 40 km/h can be used as velocity limit for passenger cars in high-frequency regions for pedestrians and cyclists in cities in China.
The accident reconstruction results indicate that the head impact conditions differ between pedestrians and cyclists in collisions with passenger cars. Therefore, the head impactor test in pedestrian protection regulations should be modified when applied to evaluate cyclists’ head protection performance with passenger cars. In terms of distribution of head impact point, the area with a WAD of 2000 cm should be the main area for testing vehicle performance for cyclists’ head protection. A head impact velocity of 34 km/h and impact angle of 46° is more reasonable for representing the cyclists’ head impact conditions in real-world accidents that involve collisions with passenger cars. These results can be applied for establishing theoretical foundations to formulate cyclist protection regulations in China.

The TOD of both pedestrians and cyclists has a stronger correlation with vehicle impact velocity. Accurate empirical formulas of vehicle impact velocity and TOD derived from reliable pedestrian and cyclist accident information can be used in accident reconstructions to estimate the vehicle impact velocity, especially for accidents in which there are no clear skid marks at the accident scene.

Supplemental Material

Supplemental data for this article can be accessed on the publisher’s website.

References

Crandall JR, Lessley DJ, Kerrigan JR, Ivarsson BJ. Thoracic deformation response of pedestrians resulting from vehicle impact. Int J Crashworthiness. 2006;11:529–539.

Dobson AJ. An Introduction to Generalized Linear Models. UK: Chapman & Hall/CRC: 2002.

Han Y, Yang JK, Mizuno K, Matsui Y. Effects of vehicle impact velocity, vehicle front-end shapes on pedestrian injury risk. Traffic Inj Prev. 2012;13:507–518.

Han Y, Yang JK, Nishimoto K, et al. Finite element analysis of kinematic behaviour and injuries to pedestrians in vehicle collisions. Int J Crashworthiness. 2011;17(2):141–152.

Kong CY, Yang JK. Logistic regression analysis of pedestrian casualty risk in passenger vehicle collisions in China. Accid Anal Prev. 2010;42:987–993.

Li F, Yang JK. A study of head–brain injuries in car-to-pedestrian crashes with reconstructions using in-depth accident data in China. Int J Crashworthiness. 2010;15(2):117–124.

Liu XJ, Wagner J. Design of a vibration isolation actuator for automotive seating systems—Part II: controller design and actuator performance. Int J Veh Des. 2002;29:357–375.

Liu XJ, Yang JK. Effects of vehicle impact velocity and front-end structure on dynamic responses of child pedestrians. Traffic Inj Prev. 2003;4:337–344.

Maki T, Kajzer J. The behavior of cyclists in frontal and rear crash accidents with cars. JSAE Rev. 2001;22:357–363.

Maki T, Kajzer J, Mizuno K, Sekine Y. Comparative analysis of vehicle–cyclist and vehicle–pedestrian accidents in Japan. Accid Anal Prev. 2003;35:927–940.

Martinez L, Guerra LJ, Ferichola G. Stiffness corridors of the European fleet for pedestrian simulation. Paper presented at: 20th ESV (International Technical Conference on the Enhanced Safety of Vehicles); 2007.

Mo FH, Yang JK, Li SQ. Influence of vehicle front structure on protective characteristic of brain injury [in Chinese]. J Mech Eng. 2010;46(5):105–112.

Oh C, Kang YS, Kim W. Assessing the safety benefits of an advanced vehicular technology for protecting pedestrians. Accid Anal Prev. 2008;40:935–942.

Oh C, Kang YS, Youn Y. Evaluation of a brake assistance system (bas) using an injury severity prediction model for pedestrians. International Journal of Automotive Technology. 2009;10:577–582.

Otte D. Use of Throw Distances of Pedestrians and Cyclists as Part of a Scientific Accident Reconstruction Method. Warrendale, PA: SAE; 2004. SAE Paper 626.

Peng Y, Chen Y, Yang JK, Otte D, Willinger R. A study of pedestrian and cyclist exposure to head injury in passenger car collisions based on accident data and simulations. Saf Sci. 2012;59:1749–1759.

Rau H, Otte D. Car to pedestrian collisions with high impact speed. Journal Verkehrsunfall und Fahrzeugtechnik. 2001.

Rosén E, Sander U. Pedestrian fatality risk as a function of car impact speed. Accid Anal Prev. 2009;41:536–542.

Soden PD, Millar MA, Adeyefa BA, Wong YS. Loads, stresses and deflections in bicycle frames. J Strain Anal Eng. 1986;21(4):185–195.

Traffic Administration Bureau of China. Statistics of Road Traffic Accidents in PR. of China. Traffic Administration Bureau of China, Ministry of Public Security; 2011.

Yan XP, Ma M, Huang H, Abdel-Aty M, Wu C. Motor vehicle–bicycle crashes in Beijing: Irregular maneuvers, crash patterns, and injury severity. Accid Anal Prev. 2011;43:1751–1758.

Yang JK. Injury Biomechanics in Car–Pedestrian Collisions: Development, Validation and Application of Human-Body Mathematical Models [thesis]. Gothenburg, Sweden: Department of Injury Prevention, Chalmers University of Technology; 1997.

Yang JK. Review of injury biomechanics in car–pedestrian collisions. Int J Veh Saf. 2005;1:100–117.

Yang JK, Lövsunda P, Cavallerob C, Bonnot J. A human-body 3D mathematical model for simulation of car–pedestrian impacts. Traffic Inj Prev. 2000;2(2):131–149.

Yang ZX. The Dynamic Identification of Road Traffic Accidents [in Chinese]. Guangxi Science and Technology Press; 2002.

Yao JF, Yang JK, Otte D. Investigation of head injuries by reconstructions of real-world vehicle-versus-adult-pedestrian accidents. Saf Sci. 2008;46:1103–1104.

Youn Y, Kim S, Oh C, et al. Research and Rule-making Activities on Pedestrian Protection in Korea. Paper Presented at the 19th International Technical Conference on the Enhanced Safety of Vehicles (ESV), Washington D.C., June 6–9, 2005.