Accident Analysis and Prevention 43 (2011) 1751–1758

Contents lists available at ScienceDirect

Accident Analysis and Prevention

journal homepage: www.elsevier.com/locate/aap

Motor vehicle–bicycle crashes in Beijing: Irregular maneuvers, crash patterns, and injury severity

Xinping Yan[a], Ming Ma[b,c], Helai Huang[d,*], Mohamed Abdel-Aty[e], Chaozhong Wu[b]

[a] Intelligent Transport System Research Center, Wuhan University of Technology, China
[b] Engineering Research Center of Transportation Safety (Ministry of Education), Wuhan University of Technology, Wuhan, China
[c] Transport Planning and Research Institute, Ministry of Transport, Beijing, China
[d] Urban Transport Research Center, School of Traffic and Transportation Engineering, Central South University, Changsha, Hunan 410075, China
[e] Department of Civil, Environmental and Construction Engineering, University of Central Florida, United States

ARTICLE INFO

Article history:
Received 5 October 2010
Received in revised form 10 February 2011
Accepted 4 April 2011

Keywords:
Motor vehicle–bicycle crash
Irregular maneuver
Crash pattern
Injury severity
Logit model

ABSTRACT

This research presents a comprehensive analysis of motor vehicle–bicycle crashes using 4 years of reported crash data (2004–2007) in Beijing. The interrelationship of irregular maneuvers, crash patterns and bicyclist injury severity are investigated by controlling for a variety of risk factors related to bicyclist demographics, roadway geometric design, road environment, etc.

Results show that different irregular maneuvers are correlated with a number of risk factors at different roadway locations such as the bicyclist age and gender, weather and traffic condition. Furthermore, angle collisions are the leading pattern of motor vehicle–bicycle crashes, and different irregular maneuvers may lead to some specific crash patterns such as head-on or rear-end crashes. Orthokinetic scrape is more likely to result in running over bicyclists, which may lead to more severe injury. Moreover, bicyclist injury severity level could be elevated by specific crash patterns and risk factors including head-on and angle collisions, occurrence of running over bicyclists, night without streetlight, roads without median/division, higher speed limit, heavy vehicle involvement and older bicyclists.

This study suggests installation of median, division between roadway and bikeway, and improvement of illumination on road segments. Reduced speed limit is also recommended at roadway locations with high bicycle traffic volume. Furthermore, it may be necessary to develop safety campaigns aimed at male, teenage and older bicyclists.

© 2011 Elsevier Ltd. All rights reserved.

1. Introduction

Bicycle riding is a common mode for short-distance transport in most cities of China. In the city of Beijing, up to late 2007, there were 13 million bicycles. As an everyday travel mode, about 6 million bicyclists travel on roads daily, accounting for more than 30% of the total traffic volumes. Obviously, the enormous amounts of bicyclists, while mixed with motor vehicles, result in numerous traffic crashes. It was recorded that a total of 528 motor vehicle–bicycle crashes occurred in Beijing city during the year of 2007. More noticeably, these crashes always lead to more severe injuries as bicyclists are vulnerable while colliding with motor vehicles (Robinson, 2001; Attewell et al., 2001; Ma et al., 2008).

Considerable research efforts have addressed bicyclist safety. Some studies have focused on associating crash frequency/risk with related risk factors, for example, the influence of alcohol (Olkkonen and Honkanen, 1990; Andersson and Bunketorp, 2002; Noland and Quddus, 2004), bicyclist demographic characteristics (e.g., Stone and Broughton, 2003; Rodgers, 1997; Eilert-Petersson and Schelp, 1997), roadway and traffic related characteristics (e.g., Garder, 1994; Fernandez de Cieza et al., 1999; Stone and Broughton, 2003; Koike et al., 2003), environmental factors (e.g., Rodgers, 1995), and driver or bicyclist related causes (e.g., Thom and Clayton, 1992; Garder, 1994; Kim and Li, 1996).

Some other attempts have also been made on bicyclist injury severities and motor vehicle–bicycle crash patterns. For example, Klop and Khattak (1999) investigated the injury severities of motor vehicle–bicycle crashes on two-way and undivided roadways in North Carolina, whereas Kim et al. (2007) further generalized the analysis to various types of roads. Moreover, since head injuries were one of the most common types of bicycle-related injuries (Maki et al., 2003; Macpherson et al., 2004), the safety effects of helmets on protecting against bicyclist head injury were examined (Povey et al., 1999; Robinson, 2001; Schieber and Sacks, 2001; Depreitere et al., 2004). In addition, regarding the crash patterns,

* Corresponding author. Tel.: +86 731 82655326.
E-mail address: huanghelai@csu.edu.cn (H. Huang).

0001-4575/$ – see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.aap.2011.04.006

Table 1
Data description.

Variable	Signalized intersections	Non-signalized intersections	Road segments
Overall crashes	419 (21.9%)	347 (18.1%)	1158 (60.5%)
Severe crashes	150 (35.8%)	118 (34.0%)	350 (30.2%)
Crashes with driver at fault	272 (64.9%)	217 (62.5%)	433 (37.4%)
Crashes with bicyclist at fault	147 (35.1%)	130 (37.5%)	725 (62.6%)
Driver irregular maneuvers			
Disobeying traffic signals	122	–	–
Failing to give way	96	172	80
Turning without due care	35	15	63
Too close following	7	18	28
Driving in wrong direction	7	4	82
Overtaking without due care	5	4	–
Non-compliant use of bikeway	–	–	179
Other	0	4	1
Bicyclist irregular maneuvers			
Disobeying traffic signals	123	–	–
Non-compliant roadway-crossing	–	86	445
Failing to give way when turning	24	44	–
Riding with traffic on roadway	–	–	217
Riding against traffic on roadway	–	–	63
Crash pattern			
Angle	341	270	650
Orthokinetic scrape	41	26	149
Opposite scrape	10	7	33
Head-on	18	18	129
Rear-end	9	26	197

it was found that angle collisions represent a large proportion of motor vehicle–bicycle crashes (Kroon, 1990).

In China, although increasing research efforts are being shifted to bicyclist safety (e.g., Xu and Li, 2008), there is a lack of comprehensive analysis for motor vehicle–bicycle crashes. Furthermore, due to the special operation characteristics and large proportion of bicyclists to total traffic volumes, research findings in other countries may not be applicable to solve the particular problems in China.

This study aims at a comprehensive analysis of motor vehicle–bicycle crashes using crash data in Beijing. The interrelationship of irregular maneuvers, crash patterns and injury severity are explicitly investigated by controlling for a variety of risk factors related to bicyclist demographics, roadway geometric design, road environment, etc.

2. Motor vehicle–bicycle crash data

All police-recorded motor vehicle–bicycle crashes occurred in the city of Beijing during 2004-2007 were filtered from the Traffic Accident Database System, which is maintained by the Beijing Traffic Management Bureau. In the dataset, each crash record comprises a succinct crash description and 56 fields regarding the information about crash pattern, pre-crash irregular maneuvers, injury severity, driver/bicyclist demographics, and other potential risk factors such as traffic condition, road geometry and environments. Hereinafter, "crash pattern" denotes the type of collisions, such as head-on, rear-end, and angle and so on; "irregular maneuver" represents the police-reported pre-crash irregular maneuvers for drivers or bicyclists who were identified to be at-fault in the crash occurrence; and "risk factors" include all other factors available for bicyclist demographics, road, traffic, and environment.

By excluding a few records with substantial missing information (less than 1%), a total of 1914 crash records were used for the analysis. Due to the distinct traffic operation characteristics, the dataset was separated into three subsets for signalized intersections, non-signalized intersections and road segments, which correspond to 419, 347, and 1158 crashes, respectively. Table 1 presents the distribution of those crashes associated with injury severity, irregular maneuvers, and crash patterns. Table 2 shows the risk factors included in the analysis.

Table 2
Risk factors considered in the analysis.

Risk factor	Categorization
Bicyclist age	<20; 20–45[a]; 46–65; >65
Bicyclist gender	Male; female[a]
Median	The presence of median; no median[a]
Roadway–bikeway division	The presence of division; no division[a]
Speed limit	<50 km/h[a]; ≥50 km/h
Heavy vehicle	Light vehicle[a]; heavy vehicle: truck, bus, etc.
Running over bicyclist	Occurrence of running over bicyclist; non-running over[a]
Road surface condition	Normal[a]; abnormal: uneven, wet, oily, sandy, etc.
Lighting condition	Day[a]; night with streetlight; night without streetlight
Peak time	Peak hours: 7am–9am, 5pm–8pm; non-peak hours[a]
Weather	Fine[a]; inclement: foggy, rainy, snowy, etc.

[a] Reference category in modeling.

In this study, severe crashes include fatality and incapacitating injury, and non-severe crashes otherwise. Table 1 shows that severe crashes account for more than 30% out of all crashes. Regarding the irregular maneuvers, drivers are more prone to be at-fault at intersections (64.9% and 62.5%) while bicyclists' faults are more at road segments (62.6%). Disaggregate analysis on specific irregular maneuvers shows that disobeying traffic signals is the leading at-fault cause both for drivers and bicyclists at signalized intersections. As for non-signalized intersections, failing to give way is the leading at-fault cause for drivers, while non-compliant roadway-crossing for bicyclists. Moreover, on road segments, non-compliant occupation of bikeway and non-compliant roadway-crossing are the leading at-fault causes for drivers and bicyclists, respectively. In addition, among patterns of these crashes, angle collision occurred most frequently, accounting for 81.4%, 77.8%, and 56.1%, respectively, for the three types of roadway locations.

3. Methodology

3.1. Objectives and research strategy

A research strategy was proposed to comprehensively investigate the interactions among irregular maneuvers, crash patterns and bicyclist injury severity. The underlying research hypotheses are that irregular maneuvers are supposedly correlated with various risk factors at different roadway locations, while different irregular maneuvers may lead to specific crash patterns, and bicyclist injury severity is affected by crash patterns and other risk factors. Accordingly, a threefold research objective was formulated:

(1) Analysis of irregular maneuvers: to associate specific irregular maneuvers with risk factors regarding bicyclist demographics, traffic condition, road geometry and environments, using multinomial logit models (MNL);
(2) Crash pattern propensity analysis: to explore the propensity of specific irregular maneuvers to various crash patterns; and
(3) Bicyclist injury severity analysis: to identify the major crash patterns and significant risk factors affecting bicyclist injury severity, using binary logit models (BL).

3.2. Multinomial logit model

In a motor vehicle–bicycle crash, the crash occurrence is the result of some specific pre-crash irregular maneuvers. Those related to driver/bicyclist, as the response variable, have multiple categories. The problem can be well formulated using the MNL model. Specifically, two separate MNL models are developed for each of the three types of roadway locations, with one modeling the multinomial bicyclist-related irregular maneuvers in comparison with all other crashes with at-fault drivers, and the other dedicated to the multinomial driver-related irregular maneuvers with all other crashes with at-fault bicyclists as reference.

To validate a MNL model, it is crucial to test the underlying assumption of the independence from irrelevant alternatives (IIA). For a MNL model, the odds ratio of alternative irregular maneuvers j and l, is

$$\frac{P_{ij}}{P_{il}} = \frac{\exp(\beta_j \mathbf{X}_i)/\sum \exp(\beta_k \mathbf{X}_i)}{\exp(\beta_l \mathbf{X}_i)/\sum \exp(\beta_k \mathbf{X}_i)} \quad (1)$$

where β_j and β_l are coefficients for the specific irregular maneuvers i and l, respectively; X_j are explanatory variables representing various risk factors. The IIA property means that the ratio of probabilities of any two irregular maneuvers is necessarily the same regardless of what other alternatives are in the choice set or what the characteristics of the other alternatives are.

To test the IIA property, the SUEST procedure (Stata Corporation, 2007), as a generalized Hausman test (Hausman and McFadden, 1984), is employed. Specifically, if one irregular maneuver i is removed from the alternatives, the before-and-after estimators are b_0 and b_1, respectively; under the null hypothesis, both the estimators are consistent. A small p-value at the significance level below 0.10 indicates the null hypothesis is rejected.

3.3. Crash pattern propensity analysis

In order to understand the relation of the major crash patterns and irregular maneuvers, the relative crash pattern propensities for each specific irregular maneuver are calculated. This can be done by calculating the ratio of pattern propensity of each category of irregular maneuvers to the average pattern propensity for a specific irregular maneuver. Specifically, suppose R_{ij} represents the propensity of an irregular maneuver i to crash pattern j, n_{ij} represents the number of crashes with pattern j which is attributed to the irregular maneuver i, and m denotes the total number of crash patterns.

$$R_{ij} = \frac{n_{ij}}{(1/m)\sum_{j=1}^{m} n_{ij}} \quad (2)$$

The ratios which are greater than 1.10 are considered empirically to be significantly above the average level.

3.4. Binary logit model

A BL model is employed to identify major crash patterns and significant risk factors affecting bicyclist injury severity. Specifically, the binary outcomes, i.e., severe and non-severe, represented by a dummy variable (i.e., 1 indicates severe outcome, and 0 indicates non-severe outcome), are used as the response variable; while other factors (i.e., crash patterns and risk factors) are specified as explanatory variables.

4. Analysis of irregular maneuvers

In the analysis of irregular maneuvers, six MNL models were developed for two at-fault parties, i.e., driver and bicyclist, at three types of roadway locations, i.e., signalized intersection, non-signalized intersection and road segment. The explanatory variables considered include all the factors listed in Table 2. In model estimation, Pearson correlation tests were applied to lessen the potential multi-collinearity among explanatory variables. Backward step-wise was used to exclude insignificant explanatory variables at the significance level with p-value >0.1, and the final models were re-calibrated with only significant variables. The IIA property tests using SUEST procedure confirmed the model validity as all the p-values of the tests are greater than 0.10. The results of parameter estimation are summarized in Tables 3 and 4. Detailed discussions on those significant factors are shown in this section.

4.1. Bicyclist demographics

As shown in Table 3, the results indicate that in a given motor vehicle–bicycle crash at signalized intersections, young bicyclists (under 20 years old) are more likely to be involved in crashes due to disobeying traffic signals compared to 20–45 years of age. Dewar et al. (2007) have also reported that teenage bicyclists are more likely to disobey a signal. This result is rational as young bicyclists may tend to be inexperienced and have a stronger propensity of risky behavior. While at road segments, compared to a middle-aged group (20–45 years old), bicyclists aged over 65 are more likely to be involved in collisions with motor vehicles when they cross the roadway illegally. As reasoned by Maring and Van Schagen (1990), older bicyclists tend to have increased perception and reaction time, which contribute to higher probability of being in collisions with motor vehicles. Moreover, bicyclists aged between 46 and 65 were found less likely to ride against the direction of traffic on the roadway.

Compared to female bicyclists, male bicyclists were found more likely to be involved in crashes due to disobeying the traffic signal at signalized intersections. Moreover, non-compliant roadway-crossing is a significant factor closely associated with male bicyclists at roadway segments. As found by Liu et al. (2005), male bicyclists have relatively high propensity to conduct various illegal behavior including disobeying traffic signals, non-compliant roadway-crossing and so on. This result implies that male bicyclists may have a higher tendency towards disregarding potential risks.

Table 3
Model estimation: leading bicyclist irregular maneuvers.

Risk variable	Parameter estimation (S.E.)	
	Disobeying traffic signals	Failing to give way when turning
Signalized intersection		
Intercept	−1.343 (0.259)***	−2.181 (0.460)***
Bicyclist age <20	0.558 (0.333)*	–
Male bicyclist	0.757 (0.240)**	–
Inclement weather	–	−1.768 (1.034)*

Risk variable	Parameter estimation (S.E.)	
	Non-compliant roadway-crossing	Failing to give way when turning
Non-signalized intersection		
Intercept	−0.872 (0.429)**	−2.171 (0.753)***
Speed limit ≥50 km/h	–	1.461 (0.771)*
Peak time	−0.501 (0.258)*	–

Risk variable	Parameter estimation (S.E.)		
	Non-compliant roadway-crossing	Riding with traffic on roadway	Riding against traffic on roadway
Road segments			
Intercept	−0.595 (0.188)**	−0.684 (0.215)**	−1.176 (0.321)***
Bicyclist age 46–65	–	–	−0.771 (0.341)**
Bicyclist age >65	0.866 (0.237)***	–	–
Male bicyclist	0.250 (0.145)*	–	–
The presence of median	0.415 (0.151)**	–	−0.984 (0.282)***
Night without street light	–	0.529 (0.311)*	–
Peak time	–	–	−0.664 (0.300)**

* Level of significance: <0.10.
** Level of significance: <0.05.
*** Level of significance: <0.01.

4.2. Roadway characteristics

Non-compliant roadway-crossing for bicyclists and failing to give way for drivers are more associated with roadways with median (Tables 3 and 4). These results may be reasonable. Normally, divided roads are wider, and the long distance of crossing would increase the risk of bicyclists being hit by motor vehicles. Moreover, the medians (i.e., tall grasses, trees, etc.) may obstruct drivers from observing the bicyclists who are crossing the roadway. As shown in Table 3, bicyclists may less likely ride against traffic on divided roads, which conforms to the finding by Kim et al. (2007).

The speed limit has a significant effect in the models. It was found that occurrence of motor vehicle–bicycle crashes on high speed limit roads are more likely to be the result of bicyclists failing

Table 4
Model estimation: leading driver irregular maneuvers.

Variable	Parameter estimation (S.E.)		
	Disobeying traffic signals	Failing to give way	Turning without due care
Signalized intersection			
Intercept	−0.435 (0.203)**	−0.385 (0.209)*	−1.369 (0.292)***
Night with street light	0.462 (0.254)*	−1.146 (0.332)***	–
Peak time	–	0.527 (0.270)*	–

Variable	Parameter estimation (S.E.)		
	Too close following	Failing to give way	Turning without due care
Non-signalized intersection			
Intercept	−2.539 (0.424)***	–	−2.133 (0.352)***
Peak time	0.963 (0.529)*	0.410 (0.232)*	–

Variable	Parameter estimation (S.E.)			
	Non-compliant occupation of bikeway	Driving in wrong direction	Failing to give way	Turning without due care
Road segments				
Intercept	−1.304 (0.207)***	−2.101 (0.276)***	−3.082 (0.387)***	−2.510 (0.335)***
The presence of median	–	–	0.724 (0.331)**	–
Speed limit (≥50 km/h)	–	−0.539 (0.289)*	–	–
Abnormal road surface	–	–	–	1.370 (0.658)**
Night without street light	−0.785 (0.418)*	0.947 (0.364)***	–	–
Peak time	–	–	–	0.477 (0.266)*
Inclement weather	–	–	–	−1.354 (0.639)**

* Level of significance: <0.10.
** Level of significance: <0.05.
*** Level of significance: <0.01.

to give way when turning at non-signalized intersections (Table 3). Since higher speed would shorten the time for divers to perceive and evade the bicyclists who are turning, it is not surprising to find a high probability of crash occurrence. It is noted that, according to the traffic regulation in China, turning bicycles should yield to the vehicles which are traveling straight. As such, bicyclists would be judged to be at fault as "failing to give way when turning" in such cases. Moreover, it was also found that at high speed limit roads there are fewer crashes resulting from drivers driving in the wrong direction (see Table 4). This result is reasonable as there are usually better traffic signs or marking systems such as "wrong way" sign or double yellow lines on high-speed roads to direct the traffic.

As shown in Table 4, abnormal road surface is a significant factor in increasing the probability of crash occurrence resulted from drivers turning without due care on road segments. Since drivers may pay more attention to the bad condition of the road surface while turning, they are likely to miss the bicyclists traveling on the roadside.

4.3. Environmental factors

During the peak hours, it was found that drivers are more prone to be at fault in motor vehicle–bicycle crashes. As shown in the results, the major irregular maneuvers include failing to give way, too close following and turning without due care. The results conform to previous findings (Rodgers, 1995; Eilert-Petersson and Schelp, 1997; Kim et al., 2007) that motorists tend to drive more aggressively during the peak hours. In contrast, bicyclist seems less likely to be at fault in crashes at peak time.

As for the lighting condition, results show that crash risk to bicyclists resulted by drivers disobeying traffic signals increases at night (Table 4). Moreover, on road segments without street light, the crashes occurring at night are more likely to be the result of bicyclists riding with traffic (Table 3) and drivers driving in the wrong direction, while less likely to be a result from drivers non-compliant occupation of bikeway (Table 4).

In inclement weather, bicyclists seem to be less likely to be at fault due to failing to give way when turning at signalized intersections compared to drivers' fault (Table 3). This may be due to the reduction of visibility when driving in inclement weather. Furthermore, as argued by Kim et al. (2007), people who ride bicycles in inclement weather may be more experienced. However, it is also interesting to find that crashes on road segments are less likely to result from drivers turning without due care in inclement weather (Table 4).

5. Crash pattern propensity analysis

Table 5 shows the results of relative propensities of different crash patterns to specific irregular maneuvers. It shows that angle collision is the leading crash pattern associated with all the leading irregular maneuvers. This agrees with other studies (e.g., Kroon, 1990) that angle collision is the most frequent pattern in motor vehicle–bicycle crashes. It is also not surprising to find more head-on collisions when drivers drive in the wrong direction or bicyclists travel against traffic. Regarding the occurrence of rear-end collisions, riding with traffic on roadway is the leading bicyclist-related at-fault cause, while non-compliant occupation of bikeway and too close following are the leading irregular maneuvers related to drivers. Moreover, orthokinetic scrape was also found to be associated with driver-related irregular maneuvers at intersections including turning or overtaking without due care, while on road segments, this pattern is closely associated with bicyclists riding with traffic on roadway, and drivers non-compliant use of bikeway and turning without due care.

6. Bicyclist injury severity analysis

The BL models were fitted using the SAS LOGISTIC procedure (SAS Institute Inc., 2004). It is noted that we aggregated the data for signalized and non-signalized intersections in the analysis as irregular maneuvers were excluded in the model. Eight variables were found significantly affecting bicyclist injury severity (Table 6). Within those, six variables are significant for both types of road location (intersection and road segment), and they are crash pattern, type of road cross section, speed limit, vehicle type, bicyclist age, and occurrence of running over bicyclists. Additionally, peak time and light condition were also found as significant factors for intersection and road segment, respectively. Specific interpretations of the significant variables are presented in this section.

6.1. Crash characteristics

Among the crash patterns, opposite scrape is considered as the reference category. It was found that head-on and angle collisions are the significant crash patterns associated with severe injuries at both intersections and road segments. Kim et al. (2007) also found that head-on collisions increase the probability of fatal injuries in crashes. This result seems to be logical since these crash patterns mean the direct impact of motor vehicles on bicyclists, which are more likely to lead to severe outcomes. In addition, rear-end collision was found as a significant pattern in increasing the possibility of severe injuries on road segments. This result implies that an impact on those bicyclists who are unaware of the oncoming motor vehicles is likely to result in severe injuries; however, this effect is not significant at intersections presumably as result of a relatively lower traveling speed of vehicles.

Running over bicyclists was found as a significant factor closely associated with severe injuries. This may be related to crash patterns. To explore this relationship, a relative proportion of occurrence of running over bicyclist to each crash pattern is further analyzed. Fig. 1 shows that orthokinetic scrape is more likely to lead to running over bicyclists (37.3% and 24.2%). In case of orthokinetic scrape, drivers may not be sensible and alert for the occurring collision with bicyclist beside the vehicle. This may increase the risk of occurrence of running over bicyclists.

6.2. Bicyclist demographics

Compared to younger age group, bicyclists aged over 65 are more likely to be severely injured when they are involved in a crash. This finding is consistent with other studies (Rodgers, 1995; Eilert-Petersson and Schelp, 1997; Stone and Broughton, 2003; Kim et al., 2007). As reasoned by Kim et al. (2007), due to increased perception and reaction times, older bicyclists are hard to evade a direct blow; additionally, greater fragility and various medical conditions ubiquitously in older adults would increase the probability of severe injuries for older bicyclists in motor vehicle–bicycle crashes.

6.3. Vehicle characteristics

Heavy vehicle was found as a significant factor in contributing to severe injury compared to other types of vehicles. This result is consistent with other studies (McCarthy and Gilbert, 1996; Kim et al., 2007) that heavy vehicles are more frequently involved in fatal bicycle crashes. This seems logical since heavy vehicles have greater momentum at a particular speed than other vehicles, and hence tend to have more damaging impact on bicyclists.

Table 5
Relative propensities: irregular maneuvers to crash patterns.

Irregular maneuvers	Crash pattern				
	Orthokinetic scrape	Opposite scrape	Rear-end	Angle	Head-on
Signalized intersection					
Bicyclist-related factor					
Disobeying traffic signals	0.24	0.04	0.08	4.47*	0.16
Failing to give way when turning	0.62	0	0.21	3.75*	0.42
Driver-related factor					
Disobeying traffic signals	0.25	0.16	0.08	4.39*	0.12
Failing to give way	0.52	0.21	0.31	3.65*	0.31
Turning without due care	1.89*	0.14	0.28	2.71*	0
Too close following	0.71	0	2.86*	1.43*	0
Driving in wrong direction	0	0	0	3.57*	1.43*
Overtaking without due care	2.00*	0	1.00	2.00*	0
Non-signalized Intersection					
Bicyclist-related factor					
Non-compliant roadway-crossing	0.35	0	0.06	4.24*	0.35
Failing to give way when turning	0.57	0.11	0.11	3.86*	0.34
Driver-related factor					
Failing to give way	0.15	0.20	0.17	4.21*	0.26
Turning without due care	2.00*	0	0.33	2.67*	0
Too close following	0.55	0	2.50*	1.67*	0.28
Driving in wrong direction	0	0	0	3.75*	1.25*
Overtaking without due care	2.50*	0	0	2.50*	0
Road segment					
Bicyclist-related factor					
Non-compliant roadway-crossing	0.18	0.06	0.23	4.25*	0.28
Riding with traffic on roadway	1.61*	0.05	2.05*	1.24*	0.05
Riding against traffic on roadway	0.16	0.56	0	1.11*	3.17*
Driver-related factor					
Non-complaint occupation of bikeway	1.24*	0.14	1.88*	1.54*	0.20
Driving in wrong direction	0	0.67	0	1.34*	2.99*
Failing to give way	0.13	0.06	0.13	4.50*	0.18
Too close following	0.18	0	3.04*	1.78*	0
Turning without due care	1.11*	0.16	0	3.49*	0.24

* Irregular maneuver factor with relative propensity to crash patterns >1.10.

6.4. Roadway characteristics

Among the geometric characteristics, the presence of median and/or division was found to significantly reduce the probability of severe injuries to bicyclists on road segments. Kim et al. (2007) also found that medians can help to reduce bicyclist injury severity. As shown in Table 3, bicyclists are less likely to ride against traffic on divided roads, and hence fewer head-on collisions would occur. Moreover, divisions, which can separate bicycles from motor vehicles, would reduce the possibility of bicyclists riding with traffic, and thus decrease the risk for leading to several patterns of crashes, e.g., rear-end, angle, etc. (Table 5). These crashes have been found to

Table 6
Injury severity of motor vehicle–bicycle crashes.

Variable	Parameter estimation (S.E.)	
	Intersection	Road segment
Intercept	−4.825 (1.160)***	−2.231 (0.679)***
Crash pattern ("opposite scrape" as reference)		
Head-on	3.493 (1.128)***	1.045 (0.660)***
Angle	2.642 (1.069)**	1.400 (0.625)**
Rear-end	–	2.027 (0.639)***
Occurrence of running over bicyclist	3.058 (0.676)***	4.027 (0.643)***
Bicyclist age > 65	0.804 (0.377)**	0.686 (0.311)**
Heavy vehicle	1.793 (0.209)***	1.639 (0.186)***
Type of road cross section ("absence of median and division" as reference)		
The presence of both median and division	–	−0.762 (0.228)***
The presence of only division	–	−1.467 (0.347)***
The presence of only median	–	−0.702 (0.288)**
Speed limit (≥50 km/h)	1.209 (0.452)***	1.357 (0.247)***
Night with street light	–	0.208 (0.102)***
Night without street light	–	1.167 (0.285)***
Peak time	−0.317 (0.179)*	–
Summary statistics		
Number of observations	766	1158
−2 Log-likelihood	775.055	1110.199

* Level of significance: <0.10.
** Level of significance: <0.05.
*** Level of significance: <0.01.

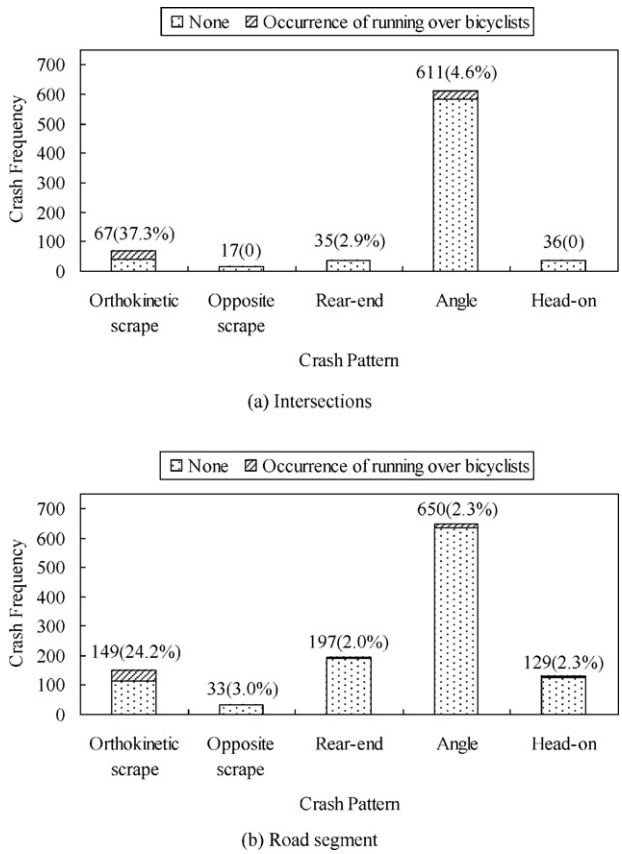

Fig. 1. Occurrence of running over bicyclists by crash patterns. (a) Intersections and (b) road segment.

be associated with severe injuries (Table 6). Additionally, divided roads, which tend to be wider, can provide drivers and bicyclists more space to evade, and hence more crashes are glancing blows instead of direct blows (Kim et al., 2007).

Higher speed limit was confirmed to be a significant factor to elevate the probability of severe injuries. Since the speed limit is usually considered as a surrogate measure of the actual vehicle speed, this finding conforms to other studies that injury severity are directly associated with vehicle speed (e.g., Garder et al., 1998; Fernandez de Cieza et al., 1999; Stone and Broughton, 2003). This may be expected since vehicles traveling at higher speeds have increasing kinetic energy and greater impact (Kim et al., 2007).

6.5. Environmental factors

As shown in Table 6, it was found that motor vehicle–bicycle collisions during peak hours tend to be less severe which conforms to the general understanding on crash severity (Huang et al., 2008). The reduced injury severity is due to the substantially reduced speed at peak time. This may become more obvious in Beijing where there are a large amount of bicycles traveling on the roads during rush hours. Nevertheless, it is worth noting that several previous studies (Eilert-Petersson and Schelp, 1997; Kim et al., 2007) have found a higher injury severity for bicyclist related crashes at peak time which contradict the current result.

Compared to night without street light, better lighting conditions (i.e., day and night with street light) seem to be helpful to reduce the injury severity of crashes on road segments. This result is consistent with other studies (e.g., Rodgers, 1995; Kim et al., 2007). As reasoned by Kim et al. (2007), night without street light, which are certainly associated with reduced visibility, can increase the perception time of both bicyclist and driver, and affect their evasive action. This is likely to result in direct impact and thus severe injuries.

7. Conclusion, implication and limitation

This study aimed at a comprehensive analysis of motor vehicle–bicycle crashes in Beijing. The interrelationships between irregular maneuvers, crash patterns and bicyclist injury severity were examined by controlling for various risk factors.

Irregular maneuvers were associated with several significant risk factors. At the intersections, teenage and male bicyclists are more likely to disobey the traffic signals. The problem of bicyclists failing to give way is more serious at non-signalized intersections with higher speed limit. Although non-compliant roadway-crossing is a leading at-fault cause related to bicyclists, results show that the non-compliant behavior is less noticeable at the peak time. Drivers disobeying traffic signals is a major irregular maneuver leading to vehicle–bicycle crashes at night, while at peak time higher likelihood is associated with drivers failing to give way and too close following. On road segments, older and male bicyclists are more prone to crashes caused by illegal road crossing. The roads with median seem to be helpful to reduce the likelihood of bicyclists riding against traffic. Crash risks by bicyclists traveling with traffic on roadways, and drivers traveling in the wrong direction, increase at night for roadways without street light. Moreover, abnormal road surface is associated with higher crash likelihood by drivers turning without due care.

Based on the analysis on crash pattern propensity, it was found that angle collision is associated with all leading irregular maneuvers. Head-on collision is associated with bicyclists riding against traffic and drivers driving in the wrong direction. Drivers too close following and bicyclists riding with motor-traffic tend to lead to more rear-end collisions while scrape collision is more likely resulted by drivers turning/overtaking without due care and bicyclists riding with traffic.

In the severity analysis, there are several factors that significantly increase the level of bicyclist injury severity at both intersections and road segments, including head-on and angle collisions, higher speed limit, involvement of heavy vehicle and older bicyclists, as well as the occurrence of running over bicyclists. Better lighting condition and the presence of median and division tend to reduce the injury severity on road segments.

To sum up, this study suggests that there is a need to consider median, division between roadway and bikeway, and illumination especially on road segments. Reduced speed limit is also recommended to be considered both at intersections and road segments with high bicycle traffic volume. Furthermore, it may be necessary to develop safety campaigns aimed at male, teenage and older bicyclists.

This study was based on the police-reported crash data. Similar to other countries, minor or non-injury bicycle-related crashes are not always well recorded in the database, and as such, under-reporting of minor crashes may be a problem. Another limitation in the police data is the lack of comprehensive crash contributing factors. Instead of the reported irregular maneuvers as employed in this study, more contributing factors could be collected through in-depth case investigation in future studies. Moreover, the inclusion of traffic volumes contributed by motor vehicles and bicycles, as well as more detailed road characteristics (e.g., median width, number of lanes) would undoubtedly make the analysis more comprehensive. Future studies are recommended to update the results of the current research if those data are available.

Acknowledgements

This work is co-funded by National Nature Science Foundation of China (60974094), the National Basic Research Program of China (2005CB724205) and National Basic Research Program of China (2006CB705505). The author would also thank the Technology Department of Beijing Traffic Management Bureau for providing crash records used in this paper.

References

Andersson, A.L., Bunketorp, O., 2002. Cycling and alcohol. Injury 33 (6), 467–471.
Attewell, R.G., Glase, K., McFadden, M., 2001. Bicycle helmet efficacy: a meta-analysis. Accident Analysis and Prevention 33 (3), 345–352.
Dewar, R.E., Olson, P.L., Alexander, G.J., Caird, J.K., Green, P., 2007. Human Factors in Traffic Safety, 2nd ed. Lawyers & Judges Publishing Company, Inc., Tucson.
Depreitere, B., Van Lierde, C., Maene, S., Plets, C., Vander Sloten, J., Van Audekercke, R., Van der Perre, G., Goffin, J., 2004. Bicycle-related head injury: a study of 86 cases. Accident Analysis and Prevention 36 (4), 561–567.
Eilert-Petersson, E., Schelp, L., 1997. An Epidemiological study of bicycle related injuries. Accident Analysis and Prevention 29 (3), 363–372.
Fernandez de Cieza, A.O., Ortiz Andino, J.C., Archilla, A.R., Gomez, A.M., Gonzalez, C.G., Mengual, S., Morrall, J., 1999. Nonmotorized traffic accidents in San Juan, Argentina. Transportation Research Record 1695, 19–22.
Garder, P., 1994. Bicycle accidents in Maine: an analysis. Transportation Research Record 1438, 34–41.
Garder, P., Leden, L., Pulkkinen, U., 1998. Measuring the safety effect of raised bicycle crossings using a new research methodology. Transportation Research Record 1636, 64–70.
Hausman, J., McFadden, D., 1984. Specification tests for the multinomial logit model. Econometrica 52 (5), 1219–1240.
Huang, H., Chin, H.C., Haque, M.M., 2008. Severity of driver injury and vehicle damage in traffic crashes at intersections: a Bayesian hierarchical analysis. Accident Analysis & Prevention 40 (1), 45–54.
Kroon, P., 1990. Bicycle accidents in Gothenburg 1983–1984. Doctoral Thesis at Gothenburg University.
Kim, K., Li, L., 1996. Modeling fault among bicyclists and drivers involved in collisions in Hawaii, 1986–1991. Transportation Research Record 1538, 75–80.
Klop, J.R., Khattak, A.J., 1999. Factors influencing bicycle crash severity on two-lane undivided roadways in North Carolina. Transportation Research Record 1674, 78–85.
Koike, H., Morimoto, A., Kitazawa, A., 2003. Unevenness of intersection pavement and bicycle safety. Transportation Research Record 1846, 56–61.
Kim, J.K., Kim, S., Ulfarsson, G.F., Porrello, L.A., 2007. Bicyclist injury severities in bicycle–motor vehicle accidents. Accident Analysis and Prevention 39 (2), 238–251.
Liu, N., Yang, G.H., Ma, J.M., Ch, A.P., 2005. Injury associated health risk factors in Chinese people, in 2002. Chinese Journal of Epidemiology 26 (10), 746–750.
Maring, W., Van Schagen, I., 1990. Age dependence of attitudes and knowledge in cyclists. Accident Analysis and Prevention 22 (2), 127–136.
Maki, T., Kajzer, J., Mizuno, K., 2003. Comparative analysis of vehicle–bicyclist and vehicle–pedestrian accidents in Japan. Accident Analysis and Prevention 35 (6), 927–940.
Macpherson, A.K., To, T.M., Parkin, P.C., Moldofsky, B., Wright, J.G., Chipman, M.L., Macarthur, C., 2004. Urban/rural variation in children's bicycle-related injuries. Accident Analysis and Prevention 36 (4), 649–654.
Ma, S.Q., Liu, D., Shao, C.F., 2008. Research on traffic crashes and safety countermeasures in Beijing. Journal of Chinese People's Public Security University (Science and Technology) 3, 69–73 (in Chinese).
McCarthy, M., Gilbert, K., 1996. Cyclist road deaths in London 1985–1992: drivers, vehicles, maneuvers and injuries. Accident Analysis and Prevention 28 (2), 275–279.
Noland, R.B., Quddus, M.A., 2004. An analyses of pedestrian and bicycle casualties using regional panel data. Transportation Research Record 1897, 28–33.
Olkkonen, S., Honkanen, R., 1990. The role of alcohol in nonfatal bicycle injures. Accident Analysis and Prevention 22 (1), 89–96.
Povey, L.J., Firth, W.J., Graham, P.G., 1999. Cycle helmet effectiveness in New Zealand. Accident Analysis and Prevention 31 (6), 763–770.
Rodgers, G.B., 1995. Bicyclist deaths and fatality risk patterns. Accident Analysis and Prevention 27 (2), 215–223.
Rodgers, G.B., 1997. Factors associated with the crash risk of adult bicyclists. Journal of Safety Research 28 (4), 233–241.
Robinson, D.L., 2001. Changes in head injury with the New Zealand bicycle helmet law. Accident Analysis and Prevention 33 (5), 687–691.
2004. SAS 9.1.3 Help and Documentation. SAS, SAS Institute Inc., Cary, NC.
Schieber, R.A., Sacks, J.J., 2001. Measuring community bicycle helmet use among children. Public Health Reports 116 (2), 113–121.
Stata Corporation, 2007. Stata User's Guide: Release 10. Stata Press, College Station, TX.
Stone, M., Broughton, J., 2003. Getting off your bike: cycling accidents in Great Britain in 1990–1999. Accident Analysis and Prevention 35 (4), 549–556.
Thom, R.G., Clayton, A.M., 1992. Low-cost opportunities for making cities bicycle-friendly based on a case study analysis of cyclist behavior and accidents. Transportation Research Record 1372, 90–101.
Xu, J., Li, Y.B., 2008. A Simulative analysis on bicyclist's head injury in vehicle–bicycle collision accident. Automotive Engineering 30 (8), 667–670.