Safety Analysis of Urban Arterials Under Mixed-Traffic Patterns in Beijing

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Many studies have dealt with modeling crash occurrences on urban arterials. There is a dearth of research on urban arterials with mixed-traffic patterns in China, however, because of the large traffic flow volume of bicyclists and pedestrians in most Chinese cities. This study investigates the risk factors associated with severe crash occurrences on arterial roads in Beijing. Through use of the generalized estimating equations modeling technique with a negative binomial link function, statistical relationships were established to relate severe crashes to a variety of factors related to geometric design, traffic control, and other traffic-related characteristics. Crash records from 2004 to 2007 for 108 signalized intersections and 123.5 km of road segments were used to estimate the models. Results showed that arterial roads with heavier traffic volumes, more road lanes, and higher speed limits tended to have more severe crashes. Medians were helpful in reducing severe crash risk. Higher risks of severe crashes were generally associated with intersections having small angles and countdown signals and road segments having higher side-access densities and the presence of bus stops. With regard to nonmotorist protection facilities, results revealed that a combined use of crosswalks and overpasses was the most desired pedestrian-crossing facility for safety, especially at sites with heavy traffic or sites located in primarily residential areas. Barriers that separated bikeways from roadways on minor roads were found effective in significantly reducing severe crash risk at intersections.

Urban arterial networks are an important component of the transportation system in most cities in China. The total length of the arterial roads in Beijing is about 1,500 km, which accounts for 30% of the total urban road mileage and carries more than 62% of the total urban traffic volume. Traffic crashes, especially severe crashes, have led to a substantial number of fatalities, injuries, and property damage. In 2006, Beijing had 5,808 reported crashes, which caused 1,373 deaths and 6,681 injuries (*1*). Moreover, because of the heavy traffic volume, particularly on urban arterials, crash events significantly reduced the operational efficiency of the roadway network. It was reported that a minor sideswipe crash that occurred on an arterial road in Beijing in October 2003 led to traffic congestion that lasted more than 1 h, and affected more than 3,000 vehicles. Among all the types of arterials in Beijing, the mileage proportion of principal arterials and minor arterials has approached 85%. They generally have unrestricted access with mixed-traffic patterns, which means more complicated traffic conditions and increased side conflicts. This study aimed to analyze the safety of urban arterials under mixed-traffic patterns in Beijing.

Considerable research efforts have been made to investigate crash risk factors associated with urban arterials in many developed countries and regions (*2–7*). Research findings in these countries may not be applicable to Beijing, however, because of significant variance in traffic-related characteristics. As of late 2007, Beijing was home to more than 16 million permanent residents. Motor vehicles totaled 3 million and bicycles (including bicycles and electric bikes) 13 million. As an everyday travel mode, more than 6 million bicycles traveled on urban roads. Moreover, walking was also a popular travel mode, which led to a large amount of pedestrian flow. Specific road facilities have been provided for bicyclists and pedestrians, which include barriers that divide roadways from bikeways and pedestrian-crossing facilities such as crosswalks, overpasses, underpasses, and so forth. These traffic and road components, which mix with motorized traffic, are associated with special road hazards that account for most traffic injuries. Crash records in Beijing city (2004–2007) showed that about 80% of severe crashes on urban arterials under mixed-traffic conditions involved pedestrians or bicyclists. Although traffic safety research studies have increased in China (*8, 9*), there is a dearth of literature that investigates the nature of crash occurrences on urban arterials under mixed-traffic conditions by controlling for various risk factors. Hence, special effort is called for to conduct traffic crash analysis for such mixed-traffic patterns as found in Beijing.

The objective of this study was to examine the relationship between severe crash occurrence and traffic-related characteristics of urban arterials with unrestricted access in Beijing. A 4-year traffic crash data set from the Traffic Accident Database System (TADS) maintained by the Beijing Traffic Management Bureau (BJTMB) was employed. By using generalized estimating equations (GEE), longitudinal analyses of signalized intersections and road segments were conducted to understand the influence of a variety of factors, including geometric design, road environment, traffic control, and other traffic characteristics on severe crash occurrence. Specific effort was made to focus on factors related to nonmotorist protection facilities by investigating their interaction effects with control factors. Since the mixed-traffic pattern is common in most Chinese urban areas, the results are relevant to other cities with a similar mode of traffic operation (i.e., a large volume of bicyclist and pedestrian traffic flow).

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PRELIMINARY ANALYSIS AND DATA PREPARATION

BJTMB maintains the TADS, which records reported road crashes in Beijing city. Generally, crashes in China are categorized into five levels of injury severity: (*a*) fatal; (*b*) incapacitating injury (e.g., disability, limb cut, blindness); (*c*) nonincapacitating but visible injury; (*d*) slight injury (no visible signs); and (*e*) no injury. According to the procedures for handling traffic crashes, severe crashes (i.e., fatal, incapacitating, and nonincapacitating but visible injury crashes) must be reported to the traffic police department immediately after occurrence. To avoid the underreporting of minor crashes, this study merely employed the severe crash data for analysis.

A manual review of the reports of crashes that occurred at four-legged, signalized intersections and road segments with unrestricted access in 2007 indicated that the vast majority of severe crashes were associated with vehicles that collided with pedestrians or bicyclists. As shown in Table 1, the crashes related to pedestrians and bicycles represented 78.6% of the overall severe crashes. As recorded in the crash reports, the overwhelming factors that contributed to the vehicle–pedestrian–bicycle crashes were (*a*) noncompliance of pedestrians and bicyclists at roadway crossings and (*b*) driver failure to yield. These results lent strong support to a comprehensive investigation of nonmotorist road facilities as well as of other relevant factors that may account for noncompliant behavior of pedestrians and bicyclists, which have resulted in numerous severe crashes.

To establish a reliable relationship between crash occurrence and various risk factors on urban arterials with unrestricted access, a total of 108 four-legged, signalized intersections and 123.5 km of urban roadways were selected from the arterial network of Beijing. The chosen sites were spread out over the city and represented wide variations in geometric, traffic, and control characteristics.

Severe crashes that occurred at the selected traffic sites over a period of 4 years (2004–2007) were filtered from TADS. In the data set, each severe crash record contained 56 fields and a succinct description of the crash occurrence, with reference to the driver, pedestrian, vehicle, and roadway particulars related to the crash. In addition to the crash data, traffic volume data were also monitored by BJTMB. These data included traffic volume on road segments, traffic volume on each approaching roadway for intersections, and left-turn traffic volume on each approach for intersections. Moreover, geometric and traffic control features associated with each site were obtained by examining the real-scene digital map and validated by field survey or Google Earth (*10*). BJTMB confirmed that there was no significant change during the study period for the variables used in this analysis.

Signalized Intersection Data

The intersection crashes included those that occurred within an intersection's physical area and that were influenced by intersection conditions. In Beijing, traffic police officers investigate whether any maneuver (e.g., stopping, turning, decelerating, and lane-changing) of any vehicle involved in a crash had some connection with the intersection before crash occurrence. For example, a driver wanted to turn left at an intersection while he was in a through lane and suddenly changed lanes, which led to a collision with another vehicle in the left lane. In this case, even though the crash site location was at a little distance from the intersection, it was considered an intersection-related crash. To validate the crash data, each crash was relocated at the intersection by using Google Maps (*11*) and reexamined on the basis of the detailed crash report. As a result, a total of 417 severe crashes were confirmed for the selected 108 intersections.

Intersection characteristics used as explanatory variables in this analysis included number of lanes, exclusive right-turn lanes, median type, posted speed limit, intersection angle, location type, left-turning protection signal, countdown signal, type of land use, total traffic volumes, and left-turn traffic volumes. Descriptive statistics of all variables are summarized in Table 2. Most of the variables are self-explanatory. Among these, medians were categorized into four types: (*a*) wide median green strip (≥4 m), (*b*) narrow

TABLE 1 Severe Crash Frequencies by Contributing Factors in 2007

	Severe Crash Frequency		
Crash Contributing Factor	Vehicle Versus Pedestrian	Vehicle Versus Bicycle	Vehicle Versus Vehicle
Driver-related factors			
Failing to give way	167	128	31
Disobeying traffic signs and signals	27	80	60
Failing to have proper control	32	34	9
Driving in the wrong direction	12	30	30
Drinking and fatigue driving	22	17	8
Noncompliantly changing and overtaking	11	16	13
Following too closely	3	10	30
Bicyclist-related factors			
Noncompliant roadway-crossing	—	90	—
Disobeying traffic signs and signals	—	45	—
Noncompliantly riding in the roadway	—	40	—
Riding in the wrong direction	—	28	—
Pedestrian-related factors			
Noncompliant roadway crossing	179	—	—
Disobeying traffic signs and signals	28	—	—
Severe crash frequency	532	562	198
Percentage in total severe crashes	38.2	40.4	14.2

NOTE: — = not applicable.

TABLE 2 Descriptive Statistics for Signalized Intersection Data

Variable	Mean	Min.	Max.	SD
Annual total number of severe crashes for intersection	0.96	0	7	0.97
logADT: logarithm of ADT for entire intersection	11.06	9.07	12.38	0.62
logLEFTADT: logarithm of total left-turn traffic volumes	8.70	0	10.43	2.36
Total number of lanes on major roadway	8.85	2	14	2.40
Total number of lanes on minor roadway	5.47	2	12	2.45
Intersection angle (degrees)	86.89	30	90	8.60
Speed limit on major roadway (3 if = 70 km/h; 2 if = 60 km/h; 1 if = 50 km/h)	2.67	1	3	0.62
Speed limit on minor roadway (3 if = 70 km/h; 2 if = 60 km/h; 1 if ≤ 50 km/h)	1.61	1	3	0.70
Medians on major road (3 if ≥ 4 m median green strip; 2 if < 4 m median green strip; 1 if median barrier; 0 if no median)	1.33	0	3	0.71
Medians on minor road (3 if ≥ 4 m median green strip; 2 if < 4 m median green strip; 1 if median barrier; 0 if no median)	0.78	0	3	0.67
Left-turn protection on major road (1 if at least one left-turn protected approach; 0 if otherwise)	0.48	0	1	0.50
Left-turn protection on minor road (1 if at least one left-turn protected approach; 0 if otherwise)	0.14	0	1	0.35
Exclusive right-turn lanes on major road (1 if at least one approach has exclusive right-turn lanes; 0 if otherwise)	0.73	0	1	0.44
Exclusive right-turn lanes on minor road (1 if at least one approach has exclusive right-turn lanes; 0 if otherwise)	0.58	0	1	0.49
Division type between roadway and bikeway on major road (2 if green strip; 1 if barrier; 0 if no division)	1.69	0	2	0.50
Division type between roadway and bikeway on minor road (2 if green strip; 1 if barrier; 0 if no division)	0.70	0	2	0.82
Pedestrian-crossing facilities on major road (3 if crosswalk and overpass; 2 if crosswalk only; 1 if overpass only or underpass only)	1.94	1	3	0.39
Pedestrian-crossing facilities on minor road (3 if crosswalk and overpass; 2 if crosswalk only; 1 if overpass only or underpass only)	1.99	1	3	0.22
Countdown signal (1 if countdown signal; 0 if noncountdown signal)	0.03	0	1	0.16
Land use (2 if primarily residential; 1 if primarily business; 0 if scattered housing)	1.22	0	2	0.75

median green strip (<4 m), (*c*) median barrier, and (*d*) no median. In Beijing, tall grass and trees are generally planted in the median strips, which therefore are called median green strips. The total entering traffic volume for each intersection was obtained by summing the traffic volumes on all corresponding major and minor approaching roads. As suggested by several previous intersection safety studies (*12–14*), the natural logarithm transformation was applied to traffic volume factors in this analysis.

To explore the safety issues related to pedestrians and bicyclists, two kinds of nonmotorist protection facilities were included (i.e., pedestrian-crossing facilities and divisions that separate roadways from bikeways). Pedestrian-crossing facilities are usually different on major and minor roads. Four typical types of pedestrian-crossing facilities are depicted in Figure 1. In this analysis, the four types were pooled into three categories: crosswalk and overpass on two approaches (Type A); crosswalk only on both approaches (Type B); and overpass only or underpass only on both approaches (Types C and D).

Road Segment Data

All of the selected 123.5 km of urban roads are links between intersections, and their lengths vary significantly. In this study, a link with homogeneous, geometric characteristics and a length of less than 2 km was considered as one segment. If the link was longer than 2 km, it was divided to make each segment about 1 km long. A link with varied geometric characteristics was divided to make each segment consistent. As a result, the urban roads were separated into 146 homogeneous segments.

Through examining the crash reports and Google Maps (*11*), a total of 599 severe crashes were allocated to the 146 road segments. To ensure the validity of the crash data, all crashes near intersections were re-examined to check whether they were influenced by intersections.

Road segment characteristics considered in this analysis, as summarized in Table 3, included traffic volume; length of road segment; total number of lanes; number of minor intersections, side roads, and exits; curvature; median type; bus stops; two-way traffic; speed limit; and type of land use. As in the intersection data, the traffic volume values were converted to the natural logarithm form.

Similar to signalized intersections, both types of nonmotorist protection facilities on road segments (i.e., pedestrian-crossing facilities and divisions between roadways and bikeways) were also included. Pedestrian-crossing facilities were categorized into four types: (*a*) crosswalk and overpass, (*b*) crosswalk only, (*c*) overpass only, and (*d*) no pedestrian-crossing facility.

MODEL DEVELOPMENT

In modeling the sporadic, random, and discrete crash occurrence, Poisson and negative binomial (NB) models were commonly used in previous studies with cross-sectional data. While the NB model is able to account for overdispersed data (*15*), it is subject to the assumption that individual observations are independent of one another (*16*). However, this assumption may be invalid when longitudinal data applied as serial observations at a site may be correlated. As such, use of the basic cross-sectional models for longitudinal data may produce biased estimators and invalid test statistics (*17, 18*).

To overcome the problem, the GEE model proposed by Liang and Zeger was applied in this study to analyze the correlated data (*19*). Several recent studies in crash analysis have shown that the GEE model is a reliable analytical tool to account for the time correlations

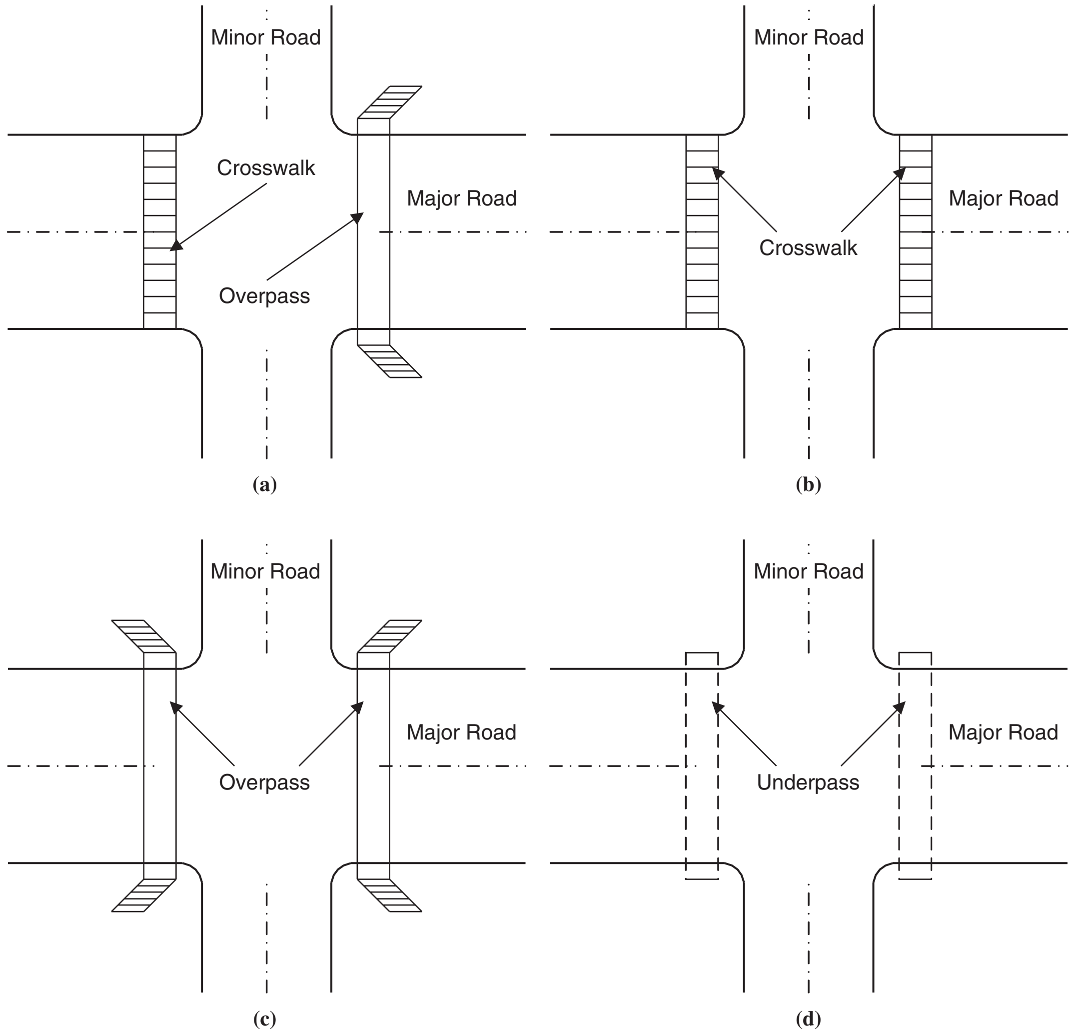

FIGURE 1 Pedestrian-crossing facilities on major roads with four-legged, signalized intersections: (*a*) crosswalk and overpass, (*b*) crosswalk only, (*c*) overpass only, and (*d*) underpass only.

TABLE 3 Descriptive Statistics for Road Segment Data

Variable	Mean	Min.	Max.	SD
Annual total number of severe crashes for road segment	1.02	0	6	1.19
logADT: logarithm of ADT for entire road segment	9.72	8.12	10.99	0.64
length of road segment (km)	0.85	0.35	1.72	0.31
Total number of lanes in one direction	2.69	1	5	0.90
Number of minor intersections per km	2.92	0	14.47	3.24
Number of minor side access per km	6.67	0	20.73	4.14
Speed limit (3 if = 70 km/h; 2 if = 60 km/h; 1 if ≤ 50 km/h)	1.94	1	3	0.76
Two-way traffic (1 if two-way traffic; 0 if one-way traffic)	0.98	0	1	0.12
Median type (3 if ≥ 4 m median green strip; 2 if < 4 m median green strip; 1 if median barrier; 0 if no median)	0.75	0	3	0.74
Division type between roadway and bikeway (2 if green strip; 1 if barrier; 0 if no division)	0.88	0	2	0.95
Curve segments (1 if curving; 0 if straight)	0.12	0	1	0.33
Bus stops (1 if of bus stops; 0 if no bus stops)	0.85	0	1	0.36
Pedestrian crossing facilities (3 if crosswalk and overpass; 2 if crosswalk only; 1 if overpass only; 0 if no pedestrian-crossing facility)	1.94	0	3	0.71
Land use (2 if primarily residential; 1 if primarily business; 0 if scattered housing)	1.10	0	2	0.72

that may exist between longitudinal observations at the same sites (*14, 16, 17, 20*).

Specifically in GEE models, suppose Y_{ij} ($i = 1, \ldots, K; j = 1, \ldots, n_i$) represents the crash frequency at location i in year j, and $\boldsymbol{X}_{ij} = (x_{ij1}, \ldots, x_{ijp})'$ represents a $p \times 1$ vector of explanatory variables associated with Y_{ij}. Let the vector of crash frequency for the ith location be $\boldsymbol{Y}_i = (Y_{i1}, \ldots, Y_{in_i})'$ with corresponding means $\boldsymbol{\mu}_i = (\mu_{i1}, \ldots, \mu_{in_i})'$, and $\boldsymbol{V}_i$ be an estimator of the covariance matrix of $\boldsymbol{Y}_i$. The mean of crash frequencies is supposed to be related with the linear predictor $\boldsymbol{X}'_{ij}\boldsymbol{\beta}$ by using a link function $g(\cdot)$, formulated as $g(\mu_{ij}) = g(E(Y_{ij})) = \boldsymbol{X}'_{ij}\boldsymbol{\beta}$. The GEE for estimating the $p \times 1$ regression parameters vector $\boldsymbol{\beta}$ can be obtained by solving the equations

$$\sum_{i=1}^{K} \boldsymbol{D}_i' \boldsymbol{V}_i^{-1}\left(\boldsymbol{Y}_i - \boldsymbol{\mu}_i(\boldsymbol{\beta})\right) = 0 \quad (1)$$

where $\boldsymbol{D}'_i$ is a $p \times n_i$ matrix of partial derivatives of the mean with respect to the regression parameters for the ith location given by

$$\boldsymbol{D}'_i = \frac{\partial \boldsymbol{\mu}'_i}{\partial \boldsymbol{\beta}} = \begin{bmatrix} \dfrac{x_{i11}}{g'(\mu_{i1})} & \cdots & \dfrac{x_{in_i1}}{g'(\mu_{in_i})} \\ \vdots & & \vdots \\ \dfrac{x_{i1p}}{g'(\mu_{i1})} & \cdots & \dfrac{x_{in_ip}}{g'(\mu_{in_i})} \end{bmatrix} \quad (2)$$

The covariate matrix of $\boldsymbol{Y}_i$ is modeled as $\boldsymbol{V}_i = \phi \boldsymbol{A}_i^{1/2}\boldsymbol{R}_i(\boldsymbol{\alpha})\boldsymbol{A}_i^{1/2}$, where

ϕ = dispersion parameter of the response variable,
$\boldsymbol{A}_i$ = $n_i \times n_i$ diagonal matrix with $v(\mu_{ij})$ as the jth diagonal element, and
$\boldsymbol{R}_i(\boldsymbol{\alpha})$ = $n_i \times n_i$ working correlation matrix that is fully specified by the vector of parameters $\boldsymbol{\alpha}$.

To specify the correlation structure, four working correlation matrices were applied in the analysis of the correlated crash data (i.e., independent, exchangeable, unstructured, and autoregressive) (*14, 16*). The independent correlation structure assumes that repeated observations for a given location are independent; the exchangeable correlation structure makes the temporal correlations between any two observations within a location constant; the autoregressive correlation structure weighs the correlation between two observations by their separated time gap; and the unstructured correlation structure assumes different correlations between any two observations for a location. The detailed estimating procedures for $R_i(\alpha)$ were explained in detail in several previous studies (*14, 16, 21*).

In model evaluation, the cumulative residuals method proposed by Lin et al. is a valid tool for GEE (*22*). If the model specification is appropriate, the residuals should center at zero and exhibit no systematic tendency against any coordinate. Correspondingly, the maximum absolute value of the observed cumulative sum and the p-value for a Kolmogorov-type supremum test can be obtained, and a larger p-value indicates better modeling performance.

RESULTS AND DISCUSSION

The Pearson correlation test was employed to lessen the potential for multicollinearity among the explanatory variables. GEE models with NB link function were estimated by using the SAS GENMOD procedure. In this process, a manual, backward, stepwise strategy was applied to exclude the insignificant variables at the significant level below 0.1, and the final models were recalibrated with the significant variables. By using the cumulative residuals test, different working correlation structures (i.e., independent, exchangeable, autoregressive, and unstructured) were assessed and the most fitted one was selected for model estimation. Further analysis was done to explore the interaction effects between the nonmotorist protection facilities (i.e., pedestrian-crossing facilities and divisions between roadways and bikeways) and other factors. To better estimate and interpret the effect of each interaction variable, the main effects of the two factors that constituted interaction variables were excluded from the model, whereas other variables were kept as controls.

Estimation Results for Signalized Intersections

Main Effects

In the final intersection model, nine significant variables were retained, which were the logarithm of average daily traffic (ADT), logarithm of left-turn traffic volumes, speed limits on major and minor roads, median types on major roads, countdown signals, divisions between roadways and bikeways on minor roads, pedestrian-crossing facilities on major roads, and intersection angles. Results of the cumulative residual tests showed that the GEE NB model with an autoregressive correlation structure had the best-fitting performance with the largest p-value, .8864, and the correlation value 0.1248 implied a temporal correlation in the longitudinal severe crash data. The model parameters estimated in the GEE NB model with autoregressive correlation structure are shown in Table 4, and the specific interpretations of the significant variables are presented as follows:

Traffic Volume Factors Both the total entering traffic volume (β = 0.4225, p-value = .0179) and left-turn traffic volume (β = 0.0583, p-value = .0337) were significant in their effects on severe crash occurrences at intersections. Because the traffic volume represented the exposure factor, it was not surprising to find that more crashes occurred at the higher-volume sites. Although some studies (*12, 23*) have indicated that increased traffic volume usually means decreased speed, which may lead to a reduction in severe crash risk, under the mixed-traffic pattern, increased traffic volume would increase the exposure of pedestrians and bicyclists to crash involvement nonetheless. Furthermore, at most sites included in this study, the left-turn traffic flow shared the same signal phase with crossing pedestrians and bicyclists. This led to substantial conflicts between vehicles and pedestrians and bicyclists, and between left-turning vehicles that failed to yield the right-of-way to pedestrians and bicyclists at intersections, which could cause severe outcomes. Wang and Abdel-Aty found that left-turning traffic volume was a significant factor in left-turn crash occurrences, which are prone to be severe (*14*).

Speed Limits Speed limits in this analysis were classified into three levels, [i.e., high speed limit (70km/h), medium speed limit (60km/h), and low speed limit (≤50km/h)]. As shown in Table 4, compared with the low-speed limit, the high-speed limit was significant in its contribution to more severe crashes (β = 1.2309, p-value = .0164 for major road and β = 0.4152, p-value = .0423 for minor road). Speed limit is usually considered a surrogate measure of actual vehicle speed. Vehicles at high speed that collide with other road users could increase severe outcomes because of the higher impact. Anderson et al. found

TABLE 4 GEE Estimation Results of Main Effects for Signalized Intersections

Variable	Estimate (β)	*p*-Value	95% Confidence Limits 2.5%	97.5%
Intercept	−3.6079	.0865	−7.7335	0.5178
Logarithm of ADT (logADT)	0.4225	.0179	0.0726	0.7723
Logarithm of left-turn traffic volumes for entire intersection (logLEFTADT)	0.0583	.0337	0.0045	0.1121
Speed limit on major road (km/h)				
70	1.2309	.0164	0.2256	2.2362
60	0.6632	.2075	−0.3680	1.6945
50	0	—	0	0
Speed limit on minor road (km/h)				
70	0.4152	.0423	0.0144	0.8161
60	0.0456	.7729	−0.2643	0.3556
≤50	0	—	0	0
Median type on major road				
Wide median green strip (≥4m)	−0.9652	.0771	−2.0351	0.1048
Narrow median green strip (<4m)	−0.9066	.0952	−1.9715	0.1584
Median barrier	−0.9507	.0593	−1.9387	0.0372
No median	0	—	0	0
Countdown signal type				
Countdown signal	0.4960	.0939	−0.0843	1.0762
Noncountdown signal	0	—	0	0
Division between roadway and bikeway on minor road				
Green strip	−0.1914	.2489	−0.5168	0.1340
Barrier	−0.4272	.0246	−0.7997	−0.0547
No division	0	—	0	0
Pedestrian crossing facilities on major road				
Crosswalk and overpass	−1.1495	.0020	−1.8779	−0.4212
Crosswalk only	−0.6367	.0038	−1.0673	−0.2061
Overpass only or underpass only	0	—	0	0
Intersection angle (degrees)	−0.0146	.0239	−0.0273	−0.0019
Dispersion parameter	1.0259	—	—	—

NOTE: — = not applicable. Summary statistics: number of observations = 432; log likelihood at convergence = −359.8362; maximum absolute value = 0.9340; Pr > MaxAbsVal = 0.8864.

that a higher speed limit corresponded to an increase in the number of fatal pedestrian crashes (*24*).

Median Type on Major Road Compared with no median on major roads, all types of medians on major roads were significant in the reduction of severe crashes [i.e., wide median green strip (β = −0.9652, *p*-value = .0771); narrow median green strip (β = −0.9066, *p*-value = .0952); and median barrier (β = −0.9507, *p*-value = .0593)]. This result seems logical since medians at intersections not only block vehicle interactions in different directions but also provide safe refuge areas for pedestrians that cannot cross the road in one signal phase (*25*).

Countdown Signal Countdown signal (β = 0.4960, *p*-value = .0939) is a significant factor among traffic control features in the increase of severe crash risk. The countdown signal displays the exact time left for signal change, and hence driver behavior might be influenced by it. Some aggressive drivers may speed up to beat the light to cross the intersection at the end of the green-signal phase, which could lead to a collision with the crossing vehicle from the conflicting approach. In the presence of a pedestrian crosswalk, the resulting collisions with pedestrians are more likely to be severe. In a recent safety study about countdown signals in Longyan City, China, the presence of countdown signals was also found to be a risk factor in severe collisions at signalized intersections (*26*).

Division Between Roadway and Bikeway on Minor Road Compared with no division on a minor road, it was found that the installation of a barrier (β = −0.4272, *p*-value = .0246) to separate a bikeway from a roadway was an efficient way to reduce severe crashes at signalized intersections. Further examination of crash records in this study showed that many severe crashes result from collisions between vehicles on major roads and pedestrians and bicyclists on minor roads. A separated bikeway may provide the necessary protection to pedestrians and bicyclists on the minor road. Results also showed, however, that installation of a green strip on a minor road (β = −0.1914, *p*-value = .2489) did not seem as useful as a barrier. A barrier on a major road may offer drivers a better sight scope than a green strip does to observe pedestrians and bicyclists as they enter the intersection from the minor road.

Pedestrian-Crossing Facilities on Major Road As shown in Figure 1, four types of pedestrians-crossing facilities on major roads were classified into three categories in this study. If the type of underpass or overpass is considered only as a reference, the result indicates that the types with a crosswalk (i.e., Type A, β = −1.1495, *p*-value =

.0020; and Type B, β = –0.6367, *p*-value = .0038) are more effective in the reduction of severe crashes at intersections. At first glance, this seems to contradict the fact that overpasses and underpasses provide better protection for pedestrians. Because of the inconvenience of crossing when only overpasses or underpasses are provided, however, pedestrians and bicyclists may be unwilling to exert the extra effort to walk up and down the overpass or underpass to cross the road. Instead, some may take a risk and walk across the roadway even if there is no crosswalk, and thus they are more likely to be hit by vehicles with the right-of-way. This assumption may be supported by numerous crashes attributed to pedestrians and bicyclists who were noncompliant at roadway crossings (see Table 1). Wang and Nihan made a similar finding (*27*). A combined use of crosswalk and overpass (Type A) could significantly reduce severe crashes compared with conventional crosswalks only (Type B). To enhance the effectiveness of the overpass, the implication is that it should be coupled with a crosswalk to protect pedestrians.

Intersection Angle A decrease of intersection angle was found to significantly increase severe crashes at signalized intersections (β = –0.0146, *p*-value = .0239). This conforms to the findings by Wong et al. (*12*). It is rational to assume that a small angle could hinder drivers from observing traffic conditions on the crossing approach. Drivers may not have enough time to respond to emergencies, and therefore are more prone to crash involvement. The pedestrian and bicyclist crossing distance might be longer at skewed intersections, and hence the increased exposure could result in a higher crash risk.

Interaction Effects

The interaction effects of both kinds of nonmotorist protection facilities with other variables were examined, and the significant estimates are shown in Table 5. The results indicate that, for pedestrian-crossing facilities on major roads, two other factors had significant interaction effects on severe crash occurrence. They were the logarithm of ADT and land use. Moreover, the logarithm of ADT and the intersection angle were found to significantly interact with different roadway and bikeway division types on the minor road.

Pedestrian-Crossing Facilities on Major Road and Logarithm of ADT As shown above, heavier traffic volume is generally associated with more severe crashes. The interaction effects that involved traffic volume and Type A and Type B, however, had significant negative coefficients (β = –0.1105, *p*-value = .0006 and β = –0.0671, *p*-value = .0003). The results indicated that, as traffic volume increased, provision of Types A and B could significantly decrease severe crash risks compared with the use of an overpass only or an underpass only on both approaches (Types C and D). In the case of heavy traffic, the combined use of the crosswalk and the overpass would be more desirable in the effort to reduce severe crashes.

Pedestrian-Crossing Facilities on Major Road and Land Use The result indicated that in primarily business areas, provision of Types A and B could significantly reduce severe crash risk (β = –0.8896, *p*-value = .0312 and β = –0.4391, *p*-value = .0563) compared with Types C and D. Moreover, crosswalk only (Type B) would be more effective in scattered housing areas (β = –0.7973, *p*-value = .0239) and primarily residential areas (β = –0.8269, *p*-value = .0004) than in primarily business areas. Especially in primarily residential areas, the combined use of crosswalk and overpass (Type A) may be the most effective approach (β = −1.6439, *p*-value = .0164). The results are rational, because crosswalks could protect bicyclists as they crossed roadways, while overpasses could provide an alternative facility for pedestrians to cross. These facilities had a more significant protective effect than other facilities, especially in areas with heavy pedestrian and bicyclist flow.

Division Between Roadway and Bikeway on Minor Road and Logarithm of ADT Compared with no division between roadway and bikeway, the barrier was found to significantly interact with traffic volume in its effect on severe crash occurrence (β = –0.0283, *p*-value = .0802). The result implies that installation of a barrier to separate the bikeway from the roadway on minor roads could reduce severe crash risk especially at intersections with heavy traffic volumes. This is not surprising, because a barrier can channel pedestrian and bicycle traffic while it provides a better sight range for road users than other facilities, and therefore can reduce conflicts especially at sites with heavy traffic.

TABLE 5 GEE Estimation Results of Interaction Effects for Signalized Intersections

Variable	Estimate (β)	*p*-Value
Pedestrian crossing facilities on major road × logarithm of ADT		
Crosswalk and overpass × logarithm of ADT	–0.1105	.0006
Crosswalk only × logarithm of ADT	–0.0671	.0003
Overpass only or underpass only × logarithm of ADT	0	—
Pedestrian crossing facilities on major road × land use		
Crosswalk and overpass × primarily residential	−1.6439	.0164
Crosswalk only × primarily residential	–0.8269	.0004
Crosswalk only × scattered housing	–0.7973	.0239
Crosswalk and overpass × primarily business	–0.8896	.0312
Crosswalk only × primarily business	–0.4391	.0563
Overpass only or underpass only × primarily business	0	—
Division between roadway and bikeway on minor road × logarithm of ADT		
Barrier × logarithm of ADT	–0.0283	.0802
No division × logarithm of ADT	0	—
Division between roadway and bikeway on minor road × intersection angle		
Barrier × intersection angle	–0.0057	.0090
No division × intersection angle	0	—

NOTE: — = not applicable.

Division Between Roadway and Bikeway on Minor Road and Intersection Angle It was found that the barrier type had a significant interaction effect with intersection angle (β = –0.0057, *p*-value = .0090). Specifically, the result indicates that the safety effect of barriers increases with an increase in interaction angle. The effect of barriers is presumably offset by hazards such as reduced sight distance, which are particularly associated with small-angle intersections. Hence, at those sites, auxiliary countermeasures may be needed to enhance safety, such as the installation of caution signs that read "Intersection Ahead."

Estimation Results for Road Segments

Main Effects

With the GEE NB model, seven explanatory variables were found to significantly affect severe crash occurrences on road segments. They were length of road segment, number of lanes in one direction, number of minor side accesses per kilometer, speed limit, median type, bus stops, and land use. Although the factor of traffic volume was not significant, it was still retained in the model as a control for exposure. With the cumulative residuals test, it was found that the GEE NB model with unstructured correlation structure had the best performance (The largest *p*-value .7117). The temporal correlation of the longitudinal data was confirmed with the correlation coefficient –.1208. The estimated results are shown in Table 6. Interpretations for each significant variable are presented as follows:

Length of Road Segment Among geometric features, length of road segment was identified to be highly significant in its effect on severe crash occurrences on road segments (β = 0.9085, *p*-value < .0001). This result indicates that the number of severe crashes increases as the length of road segment increases, which conforms to the finding by Caliendo et al. (*28*). The result was expected, because more conflict areas may exist on a longer road segment.

Number of Lanes in One Direction The number of lanes in one direction, which indicates the physical road width, is another significant geometric factor (β = –0.2395, *p*-value = .0021). The result implied that severe crashes were more prone to occur on narrow roads. Greibe also found that roads with widths of 5.0 to 7.5 m (i.e., one lane in one direction) were associated with the highest crash risk, while an increase in road width could relatively reduce the associated crash risk (*6*). This may be expected for two reasons. First, more lanes on a roadway could separate vehicles that traveled at different speeds, and thus reduce risky maneuvers, such as aggressive overtaking and close car-following. Second, when the road is narrow, many pedestrians and bicyclists may take the risk and cross outside the crosswalk, whereas they may choose a safer alternative crossing facility (e.g., crosswalk, overpass) when the road is wider.

Number of Minor Side Accesses per Kilometer In this study, minor side accesses included side streets, parking places, and so forth. The number of side accesses was found to be a significant factor that affected severe crash occurrences on road segments (β = 0.0212, *p*-value = .0542). This result is consistent with Bird and Hashim, who found that an increase in side accesses per kilometer would lead to more severe crashes on road segments (*29*). Karlaftis and Golias also found that roads without access control had significantly higher crash rates than those with access control (*30*). Commonly in Beijing, no proper warning signs exist on minor side accesses. It is intuitive to

TABLE 6 GEE Estimation Results of Main Effects for Road Segments

Variable	Estimate (β)	*p*-Value	95% Confidence Limits 2.5%	97.5%
Intercept	–1.4754	<.0001	–2.0248	–0.9261
Length of road segment (km)	0.9085	<.0001	0.6587	1.1583
Number of lanes in one direction	–0.2395	.0021	–0.3923	–0.0868
Number of minor side accesses per km	0.0212	.0542	–0.0004	0.0427
Speed limit (km/h)				
70	0.4399	.0421	0.0156	0.8641
60	0.3568	.0044	0.1110	0.6026
≤50	0	—	0	0
Median type				
Wide median green strip (≥ 4m)	–0.4591	.1492	–1.0831	0.1648
Narrow median green strip (< 4m)	–0.6762	.0007	–1.0676	–0.2848
Median barrier	–0.4258	.0012	–0.6843	–0.1673
No median	0	—		
Bus stops				
Presence of bus stops	0.4472	.0046	0.1393	0.7571
No bus stops	0	—	0	0
Land use				
Primarily residential	0.2812	.0496	0.0005	0.5619
Primarily business	0.6536	<.0001	0.3904	0.9168
Scattered housing	0	—	0	0
Dispersion parameter	1.0040	—	—	—

NOTE: — = not applicable. Summary statistics: number of observations = 584; log likelihood at convergence = –494.5252; maximum absolute value = 1.0006; Pr > MaxAbsVal = 0.7117.

assume that drivers on arterials are prone to overlook the traffic from minor side accesses. As a result, the risk of angle, turn, and pedestrian- and bicycle-involved crashes are relatively high around minor side accesses. These crash types usually lead to severe outcomes.

Speed Limits Similar to the factor in the intersection model, the speed limits on road segments were also classified into high speed limit (70km/h), medium speed limit (60km/h), and low speed limit (≤50km/h). High speed limit (β = 0.4399, *p*-value = .0421) and medium speed limit (β = 0.3568, *p*-value = .0044) were found to be significant in the increase of the number of severe crashes on road segments compared with low speed limit. High speed limit caused more severe crashes relative to medium speed limit. Eluru et al. also found that higher speed limits led to higher injury severity levels on the roadway (*31*). This result was generally expected because of the greater impact of vehicles at higher speed.

Median Type As shown in Table 6, it was found that the installation of a narrow median green strip (β = –0.6762, *p*-value = .0007) and median barrier (β = –0.4258, *p*-value = .0012) were significant in the reduction of severe crashes on road segments. The safety benefit obtained from a wide median green strip was not significant, however (β = –0.4591, *p*-value = .1492). This may be due to the low sample size in this category (only five segments). Berhanu also found that medians would be significant in the decrease of the numbers of both multiple-vehicle and pedestrian-involved crashes (*32*). The result was expected because medians can help prevent conflicts by separating opposing lanes of traffic and also provide refuge to pedestrians and bicyclists when they cross the road.

Bus Stops It was not surprising to find that the presence of bus stops on road segments negatively affected the severe crash risk (β = 0.4472, *p*-value = .0046). Generally, the need of buses to merge into the roadway from bus stops increases the risk of colliding with other vehicles. Moreover, it is not common to set crossing facilities (i.e., crosswalk, overpass, underpass) around the bus stops in Beijing. Several pedestrians on the opposite roadside may take a risk and cross the roadway to catch a bus. Such noncompliant crossing behavior has been found to be dangerous, which may result in a substantially elevated risk of pedestrian–vehicle collisions (*33*).

Land Use With regard to the types of land use, the primarily business area (β = 0.6536, *p*-value < .0001) was found to be associated with the highest crash risk. Furthermore, the primarily residential area (β = 0.2812, *p*-value = .0496) had a significantly higher severe crash risk than areas with scattered housing. This result was consistent with Greibe (*6*) and Bonneson and McCoy (*34*) who found that crashes were more frequent when the land use was business-oriented. According to Greibe, land use to some extent represented the level of pedestrian and bicyclist activity, and therefore pedestrian- and bicyclist-involved crashes occurred more often in business and residential areas. These types of crashes tend to be severe (*6*).

Interaction Effects

As shown above, the average effects of both kinds of nonmotorist protection facilities (i.e., pedestrian-crossing facilities and divisions between roadways and bikeways), were not significant in the analysis of road segment safety. It may still be useful nevertheless to investigate their disaggregate effects in different environments. By examining their interactions with other factors, several interaction effects were found to be significant, as presented in Table 7.

Pedestrian-Crossing Facilities and Number of Lanes in One Direction As shown in Table 7, the effect of pedestrian-crossing facility interaction with lane number was significant. The result implies that the combined use of crosswalk and overpass (β = –0.1195, *p*-value = .0183) or overpass only (β = –0.1463, *p*-value = .0121) was more effective on road segments with more lanes. The varied effects can be presumably explained by pedestrian road-crossing behavior. On relatively narrow roads, especially without a median, the possibility of noncompliant pedestrian crossing behavior may be higher and probably offsets the effect of pedestrian-crossing facilities.

Pedestrian-Crossing Facilities and Land Use Types of pedestrian-crossing facilities located in various land use areas have different safety effects. Generally, establishment of specific pedestrian-crossing facilities is more effective in primarily residential areas than in primarily business areas. In primarily residential areas, the combined use of crosswalk and overpass was found to significantly

TABLE 7 GEE Estimation Results of Interaction Effects for Road Segments

Variable	Estimate (β)	*p*-Value
Pedestrian-crossing facilities × number of lanes in one direction		
Crosswalk and overpass × number of lanes in one direction	–0.1195	.0183
Overpass only × number of lanes in one direction	–0.1463	.0121
No pedestrian crossing facility × number of lanes in one direction	0	—
Pedestrian-crossing facilities × land use		
Crosswalk and overpass × primarily residential	–1.7666	.0006
Crosswalk only × primarily residential	–0.4158	.0732
No pedestrian-crossing facility × primarily business	0	—
Division between roadway and bikeway × land use		
Green strip × primarily residential	–0.2710	.0792
Barrier × primarily residential	–2.0569	.0415
No division × primarily residential	–0.4234	.0013
Green strip × scattered housing	–0.8535	<.0001
No division × scattered housing	–0.5113	.0018
No division × primarily business	0	—

NOTE: — = not applicable.

reduce severe crashes (β = −1.7666, *p*-value = .0006). The result suggests that the combined use of crosswalk and overpass is a desirable protective facility in primarily residential areas. The proportion of bicyclists was found to be relatively high in the nonmotorist flow around such areas. Therefore, the crosswalks specifically facilitated the crossing activities of the bicyclists.

Division Between Roadway and Bikeway and Land Use The result indicated that the effects of divisions between roadways and bikeways varied across types of land use. In primarily business areas, no significant difference was found among different types of divisions between roadways and bikeways. In residential areas, however, it was found that the installation of barriers to separate bikeways from roadways was much more effective to reduce severe crashes than were other types (β = −2.0569, *p*-value = .0415). This may be because barriers help reduce vehicle–bicycle collisions by channeling nonmotorist traffic while providing a good sight range for drivers on segments to observe the traffic coming from side accesses. In scattered housing areas, green strip divisions were found to be a safety facility (β = −0.8535, *p*-value < .0001). It is intuitive to interpret the result to mean that vehicle speed is usually high in scattered housing areas and that solid green strips can separate nonmotorist flow from vehicle flow effectively.

CONCLUSIONS

Among the traffic-related characteristics considered in this study, several factors were found to significantly affect severe crash occurrence at both intersections and road segments. It was confirmed that arterials with heavier traffic volume and more road lanes tended to have more severe crashes. Sites with lower posted speed limits and those with medians generally were associated with fewer severe crashes.

In an examination of the factors associated with signalized intersections, severe crashes were found to occur more often at sites with a small intersection angle than at standard, orthogonal intersections. Countdown signals were associated with less safety at intersections. For road segments, higher side access density and the presence of bus stops tended to result in more severe crashes. In comparison with scattered housing areas, roads located in primarily residential or business areas were associated with more severe crashes.

Although overpasses and underpasses seemed to provide better protection to pedestrians, the results showed that in Beijing, their safety effects were not as good as the combined use of a crosswalk and an overpass. Installation of barriers to separate bikeways from roadways on minor roads helped to reduce severe crashes at signalized intersections. The safety effects of these facilities seemed more significant at sites with heavy traffic and at sites located in primarily residential areas. Future policies on safety investments, such as funding better road infrastructure and facilities, should be specific and well targeted so as to maximize the benefit in safety improvement.

Future study is recommended to specifically examine pedestrian- and bicyclist-involved crashes, if traffic volumes of pedestrians and bicyclists are available. The inclusion of nonmotorist traffic volumes would be necessary and informative to further investigate crash risks associated with pedestrians and bicyclists in different traffic environments. Moreover, it is likely that some nonmotorist protection facilities were installed in response to road crashes, which raises the endogeneity problem (*35*). Currently it is difficult, however, to take into account the endogeneity effects of multiple factors by controlling for other variables. In future research this limitation could be mitigated once advanced techniques become available.

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